Phase-Frequency Controlled In Virtual Synchronous Converter for Low-Voltage Microgrid-Inverter Synchronization

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Abstract-This paper explains an internal voltage controlled based on generator swing technique/dynamic response for inverter using virtual synchronous converter (VSCon) in order to achieve synchronization voltage between grid and inverter. As known, PLL is a common technique that is used to synchronize the amplitude, phase-angle and frequency between grid and source voltage. The VSCon is a technique which does not require any phase-locked-loop (PLL) circuit as an external control structure/source for the inverter to be synchronization with the grid. This VSCon has been modeled and simulated in inverter control using Matlab/Simulink software, which is connected to single-phase ac source input system connected and several loads. This VSCon has been implemented in inverter control strategy to generate reference voltage for pulse width modulation (PWM) signal that responds to the grid information in order to instruct the inverter voltage to be synchronized with the grid voltage. Several simulation tests have been conducted in order to prove the reliability of this VSCon. It is also has been tested if the grid frequency is changed from the rated frequency (50Hz) to 51Hz while at the meantime the phase-angle also has changed where the resulting results show that, VSCon takes nearly 40ms to synchronize to these changes.

Keywords: Grid voltage, Inverter, Phase-Locked-Loop, Synchronous Generator, Synchronization, Matlab/Simulink

1. Introduction

Distributed generations (DGs)[1] have captivated the energy experts around the world due to several benefits, for example; diminishing the greenhouse gases emission, increasing the reliability of the system and alleviating the burden on long transmission power system[2][3][4]. According to[5], the DG resources based on microgrid system are worthy solutions to transfer the electric power from DGs to the existing electrical grid and at the same time to supply the electric power to the local loads for islanded mode process in order to ensure reliable power supply when the primary power supply fail to deliver the power[6][7]. Most of the DGs need power converters circuit in order to control the power flows to the microgrid[8][9]. When the DGs share the power, the power system becomes noteworthy for preserving the synchronization and also will improve the stability of the power system[8][10]. As a result, the important task during power sharing is to maintain an accurate synchronization condition between both sources[11][12][13] that caused reverse current flows if not been taking care. After it has been synchronized, other control systems such as frequency and voltage droop can be applied to perform autonomous power flows to the microgrid[14][15][16]. This task only can be achieved when both inverter and grid are in synchronization in the stage of voltage magnitude, frequency and phase-angle[17]. Later, the inverter can feed the power to the grid; even the grid voltage changes it frequency, phase, and amplitude[18].

Figure 1 shows the typical synchronization and power control structure for microgrid-connected inverter. The synchronization unit, which is the PLL block is used to provide frequency, amplitude and phase information from the grid voltage in order to generate a reference phase signal for the inverter control, for synchronization and power delivery process [19]. Many power control approaches focus with the aim of transferring power into the microgrid from DGs such as explained in[19][20]are using voltage source control, power angle control, torque angle control and current control with the helps of PLL[12]. Conversely, to adopt the synchronization in PLL, all parameters which are the phase-angle and frequency information need to be included for inverter outer and inner loop controllers before it can perform the synchronized[12]. If the grid voltage is contaminated it will affect the overall control performances and increase the time of synchronization[21].

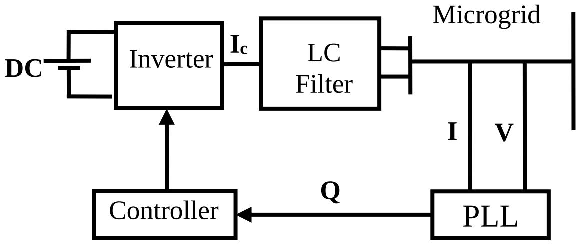


Fig. 1. Typical control structures for low-voltage microgrid-connected inverter.

Due to those issues, several researchers are proposing a concept of non PLL strategy[22][23][24]based on the synchronous generator topology. As known, the synchronous generator (SG) does not required a PLL to transfer the power to the electrical network. So, it has triggered a concept of self-synchronization for DGs inverter application suggested in[24][25][26]where the inverter output voltage profile depends only on the generator physical construction and input mechanical power in virtual mode condition. It is where, the frequency and amplitude of voltage depend on angular speed of prime mover and field excitation of rotor coil of generator will be the driving force to the controller.

With several mathematical models and algorithms that can behave as synchronous generator for the inverter control this technique is called a synchronverter that been proposed in[23][24]. In[23][27] the idea of operating an inverter as a synchronous generator has been developed after establishing a model for synchronous generator to cover all the SG dynamics without any assumptions to the grid voltage signals. The synchronous generator model is suitable to investigate the stability of power systems, in particular, those dominated by parallel converter in distributed generation as described in[22].

As improvement for this idea but remain the synchronization process as suggested in [22][24]is by combining with the SG swing equation which give a non-linear second order differential equation for better power stability[27] has been proposed by the authors for fast synchronization. Swing equation gives an angle between the synchronous generator internal voltage and grid voltage which is known as power angle for certain amount of power that need to be injected to the grid. Since, SG and grid frequency are dynamic, power angle also changes with change of loads. A unity line impedance is used to get the virtual torque from the grid voltage which then is converted to equivalent representative current for inverter switching. This voltage phase-angle and frequency are been feedback to phase-angle control and frequency control unit in order to control the output signal for inverter switching which has been suggested in[22][24]. Therefore, this improvement will give the same time of synchronization in [21][28][24] and also can give an alternative version of synchronverter that can work in grid-connected or stand-alone mode since it has ability to control the voltage and the frequency of the inverter output. Moreover, by maintaining the proper control on the voltage and the frequency on inverter, it will also able to share real power and reactive power into the grid at the same time.

In this paper, a SG model has been used to develop a virtual synchronous converter (VSCon) with improves the version of synchronverter in order to achieve the capability of fast synchronization in low-level microgrid system without the aid of a dedicated PLL synchronization unit. It will take away a redundancy element in the closed-loop system of PLL, which is the nonlinear element that affects the speed and accuracy during synchronization. In the results, the VSCon controller synchronization between the inverter and low-level microgrid can been attained in 40ms in case when phase shift happen to the ac voltage source. At the sametime, it has widened the frequency bandwidth of the system as well is able to reduce the time needed for synchronization, and improves the accuracy of synchronization. This paper is organized as follows: SG is discussed briefly in Section 2. The modelling of synchronverter has been overviews in Section 3 shortly, after that, the mathematical model of VSCon is discussed in Section 4, the Section 5 is comprised of simulation and discussion, followed by conclusion part is made in Section 6.

2. Synchronous Generator Model

In this section, modelling of SG has been discussed in details by[22][25] in steady state condition, balance sinusoidal voltage and current for simple analysis. Most of the cases, assumptions are been made to dynamic analysis of synchronous generator for example, for system analysis and controller design, damping-windings-less while the round rotor machine is chosen to having P pairs of poles per phase without effect of magnetic saturation of iron core. Since, synchronous generator is driven by mechanical power from prime-mover, this section is divided into two sections of electrical part and mechanical part.

2.1. Electrical Part

The fundamental parts of synchronous machine are the ferromagnetic construction which has hollow cylindrical portion which is known as stator or armature that been inserted for armature windings and the rotor. The winding on the rotor, is called the field windings. The DC current is applied to the field winding by an exciter to produce magnetomotive force (mmf). Figure 2 shows, three coils a , b and c which denote the three armature windings on the stator round-rotor machine and concerted coil f , which represent the distributed field winding on the rotor. The three stationary armature coils are alike in every respect and each has one of its two terminals connected to a common point o.

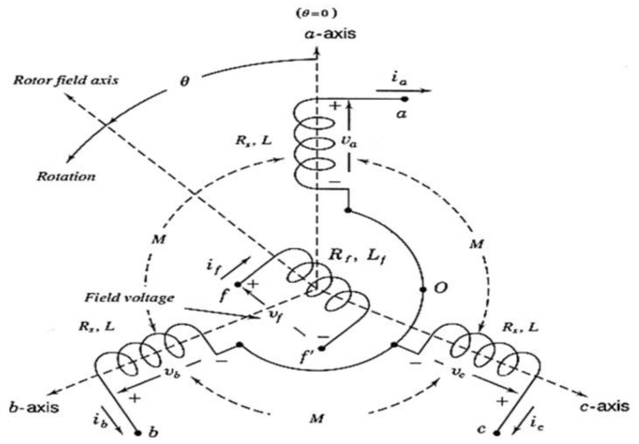


Fig. 2. An ideal three-phase synchronous generator model [29]

The axis of coil a is chosen at $\theta_d = 0°$ and in counter clockwise around the air gap are the axes of the b coil and c coil at $\theta_d = 120°$ and $\theta_d = 240°$ respectively. Assume that, each of the concentrated coils a, b and c have self-inductance L_s which is equal to the self-inductance of distributed armature windings. In addition, the mutual inductance between each adjacent pair of concentrated coils are negative constants $-M_s$. The mutual inductance between the field coil f and each of the stator coils varies with the rotor position θ_d as a sinusoidal function with maximum value M_f are shown in equation (1), (2) and (3),

$$L_{af} = M_f \cos\theta_d \tag{1}$$

$$L_{bf} = M_f \cos(\theta_d - 120°) \tag{2}$$

$$L_{cf} = M_f \cos(\theta_d - 240°) \tag{3}$$

The flux linkage with each of the coils a, b, c and f are due to its own current and the current in the three other coils. Flux-linkages equations are therefore written as follows in equation (4) and (5),

$$\text{Armature:}\begin{cases}\lambda_a = L_s i_a - M_s(i_b + i_c) + L_{af} i_f \\ \lambda_b = L_s i_b - M_s(i_a + i_c) + L_{bf} i_f \\ \lambda_c = L_s i_c - M_s(i_a + i_b) + L_{cf} i_f\end{cases} \tag{4}$$

$$\text{Field:} \quad \lambda_f = L_{af} i_a + L_{bf} i_b + L_{cf} i_c + L_{ff} i_f \tag{5}$$

For considering the steady state condition, it is assumed that, the current i_f is DC constant I_f and that the field rotates at constant angular speed ω, when the machine constructs with two-pole,

$$\frac{d\theta_d}{dt} = \omega; \ \theta_d = \omega t + \theta_{d0} \tag{6}$$

where angle θ_{d0} denotes the initial position of field winding in equation (6). Hence, equation (7) can be rewritten by considering the initial position of field winding as

Armature:

$$\begin{cases}\lambda_a = (L_s + M_s) i_a + M_f I_f \cos(\omega t + \theta_{d0}) \\ \lambda_b = (L_s + M_s) i_b + M_f I_f \cos(\omega t + \theta_{d0} - 120°) \\ \lambda_c = (L_s + M_s) i_c + M_f I_f \cos(\omega t + \theta_{d0} - 240°)\end{cases} \tag{7}$$

Equation (8) shows, λ_a has two flux-linkage components, one due to the field current I_f and the another due to armature current i_a, which are flowing out of the machine for generator action. When coil a has resistance R then the voltage drop v_a across the coil from terminal a to terminal o given as

$$v_a = -Ri_a - \frac{d\lambda_a}{dt} \tag{8}$$

$$v_a = -Ri_a - (L_s + M_s)\frac{di_a}{dt} + \omega M_f I_f \sin(\omega t + \theta_{d0}) \tag{9}$$

Equation (10) denotes an internal emf or generated emf or synchronous internal voltage and is defined as e_a as,

$$e_a = \omega M_f I_f \sin(\omega t + \theta_{d0}) \tag{10}$$

This will demonstrate the generated emf or synchronous internal voltage magnitude and frequency are directly proportional to the field excitation and angular velocity of field coil as well as prime mover of synchronous machine.

2.2. Mechanical Part

The mechanical part of the synchronous generator is generated by

$$J\ddot{\theta} = T_m - T_e + D_p\dot{\theta} \tag{11}$$

where J is the momentum of inertia of all parts rotating with the rotor, T_m is the mechanical torque, T_e is the electromagnetic torque and D_p is a damping factor. The T_e can be found from the total energy E stored in the machine, which is the sum of the magnetic energy stored in the stator and rotor magnetic fields and the kinetic energy stored in the rotating parts as follow,

$$E = \tfrac{1}{2}(i_a\lambda_a) + \tfrac{1}{2}(i_f\lambda_f) + \tfrac{1}{2}J\dot{\theta}^2 \tag{12}$$

Since the mechanical rotor position θ_m satisfy $\theta = p\theta_m$,

$$T_e = -\frac{\partial E}{\partial\theta_m} = -p\frac{\partial E}{\partial\theta}, \text{ or } T_e = pM_f I_f\left(i_a\frac{\partial}{\partial\theta}\sin\theta\right) \tag{13}$$

3. Synchronverter Model[30][29]

Similarly, Synchronverter is grid-friendly inverter that mimic synchronous generators (SG) are discussed in[22][28]in intensively. Precisely, a synchronverter is a model which performs as in same way of SG durign supply a voltage to the electrical network. The controlling principle of power controller is used voltage and frequency parameter that has integrated capability. It is where, the real power and reactive power are controlled by voltage regulation and frequency regulation. In synchronverter, a magnetic-saturation and non-damping rotor winding have been used which only contains one pair of poles per phase.

The phase voltage v at terminal can be obtained in equation below, where ϕ is flux per pole, L_s is self-inductance and R_s is stator coil resistance as,

$$v = -R_S i - \frac{d\phi}{dt} = -R_S i - L_S \frac{di}{dt} + e \tag{14}$$

$$e = M_f i_f \dot{\theta}(\sin\theta) - M_f \frac{di_f}{dt}(\cos\theta) \tag{15}$$

$$\ddot{\theta} = \frac{1}{J}\left(T_m - T_e - D_p \dot{\theta}\right) \tag{16}$$

$$T_e = M_f i_f \left(i, \sin\theta\right) \tag{17}$$

$$e = \dot{\theta} M_f i_f \sin\theta \tag{18}$$

$$Q = -\dot{\theta} M_f i_f \left(i, \sin\theta\right) \tag{19}$$

At the same time, it is assumed that, three phase SG stator currents i can be written as

$$i = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix}; (\sin\theta) = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}; (\cos\theta) = \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

where T_m, T_e, e, θ, $\dot{\theta}$ and Q are the mechanical torque applied to the rotor, the electromagnetic torque, the three-phase generated voltage, the rotor angle, rotor angular velocity and the reactive power respectively. Similarly, the controller of a synchronverter consits two channels for real power and reactive power control. The real power is controlled by a frequency droop control loop, using the (imaginary) mechanical friction coefficient D_p as the feedback gain [24]. In synchronverter[23], frequency droop loop regulates the (imaginary) speed $\dot{\theta}$ of the synchronous machine and creates the phase angle θ for the control signal e. The reactive power is regulated by a voltage droop control loop, using the voltage droop coefficient D_q. This loop adjusts the field excitation $M_f i_f$, which is proportional to the amplitude of the voltage generated.

4. A concept of Virtual Synchronous Converter (VSCon)

This concept is based on the generator swing equation[31], where the rotational inertia equation describes the effect of unbalance between the electromagnetic torque T_e and the mechanical torque T_m in individual machine is shown in Fig. 3. Here, P_{in} and P_{out} are as the input mechanical power and output electrical power respectively.

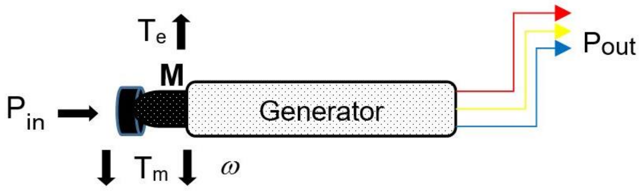


Fig. 3. Generator is connected to prime mover.

The synchronization inverter-based in single phase inverter can easily regulate the system frequency and voltage that mimic the synchronous generator functions. The dynamic swing equation for the generator can be expressed in equation (20),

$$\frac{M}{\omega_n}\frac{d^2\delta_m}{dt^2} + \frac{D}{\omega_n}\frac{d\delta_m}{dt} + K\,\delta_m = P_m - P_e \tag{20}$$

where M is inertia of rotor, D is friction coefficient, K is synchronizing gain or power factor gain, δ_m is the internal phase-angle and ω_n is nominal angular frequency of generator while P_m and P_e are mechanical and electrical power of the generator. At the meantime, the internal phase-angle δ of the synchronous generator can be determined by following equation (21),

$$\delta = \frac{\omega_n}{Ms^2 + Ds + K\omega_n}\left(P_{in} - P_{out}\right) \tag{21}$$

As a result, this power angle δ is substitute into equation (21).

5. Mathematical Model Developed on VSCon

The mathematical model of synchronous generator has been modeled where the output of VSCon is directly proportional with virtual angular speed of rotor as given in equations (22) and (23). Equation (24) shows the angular acceleration that been applied in single round rotor machine where the stator inductance is constant value in order to reduce the mathematical complexity in developing the VSCon. This model is not considering the rotor damper winding, iron core saturation and eddy currents at the machine. As a result, equation (25) shows the expression of electrical torque T_e is proportional directly to the grid current.

$$v = -R_S i - \frac{d\phi}{dt} = -R_S i - L_S \frac{di}{dt} + e \tag{22}$$

$$e = M_f i_f \dot{\theta}(\sin\delta) - M_f \frac{di_f}{dt}(\cos\delta) \tag{23}$$

$$\ddot{\theta} = \frac{1}{J}\left(T_m - T_e - D_p\dot{\theta}\right) \tag{24}$$

$$T_e = Z\left(\frac{P}{A}\right)M_f i_f\left(i, \sin\delta\right) \tag{25}$$

The electrical torque in a synchronous generator can be stated in another form where, the voltage is generated due to conductor reactance, which is given in equation (26). The number of current carrying conductor is given by Z while P is the pole machine number and A is number of current flows on the parallel paths. Since, this synchronous generator is considered to be lap-wounded coil in stator and it has two-poles,

$$T_e = K_f M_f i_f\left(E_r, \sin\delta\right) \tag{26}$$

where, $K_f = \left(\frac{P}{A}\right), E_r = X_z i$ is emf induced in the machine under load condition and it also called as air-gap emf or internal induced emf or internal voltage of synchronous machines [30]. Equation (27) until equation (28) are the internal electrical component of synchronous generator that been described in [22] which been used for developing the VSCon. It can be written as,

$$T_e = M_f i_f\left(E_r, \sin\delta\right) \tag{27}$$

$$e = \dot{\theta}M_f i_f \sin\delta\ . \tag{28}$$

Figure 4 shows the block diagrams of VSCon when it will be applied to the inverter control interface.

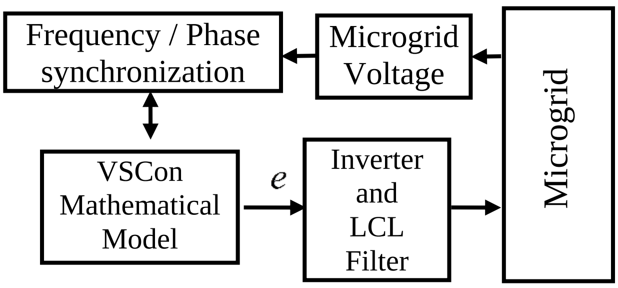


Fig. 4. Block diagram of VSCon inverter interfacing along with microgrid.

Figure 5 is the equivalent per-phase model of a synchronous generator that is connected to a grid electrical source with line impedance for real and reactive power flow concept.

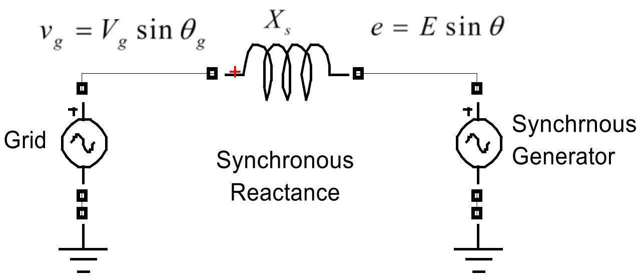


Fig. 5. Circuit diagram of synchronous generator connected with infinite bus.

5.1. Design of Virtual Synchronous Converter (VSCon)

The complete VSCon model is shown in Figure 6. The VSCon consists of several inputs targeting to produce output then pass through the PWM circuitry for switch the inverter switch. In this design, a round rotor machine is considered so that equilibrium distributed inductance is assumed to be balance.As shown also in Figure 6, the VSCon takes mechanical torque T_m and electromagnetic torque T_e for generating the virtual angular speed. This virtual inertia of rotor is added with motor coefficient (J) for having small constant value in order to create the virtual acceleration $\ddot{\theta}$ that is given in equation (29). The integration block is added to find the virtual angular speed $\dot{\theta}$ where it uses to limit the allowable microgrid frequency or real-time frequency $\dot{\theta}_g$ in order to fix the inverter output frequency for following the microgrid frequency level as shown in equation (30). Further, the output of VSCon is determined by grid phase θ_g as in equation (31) while the e is regulated signal that is generated from the grid voltage parameters.

In order to produce varying T_e in sinusoidal form, the voltage or current grid has to be directly feedback to VSCon input. Meanwhile, on the right side of the block diagram, the output e signal depends on field excitation $M_f I_f$. The difference between grid voltage V_g and nominal voltage V_n is taken and passed through gain 1/K in order to generate the value of $M_f I_f$. At the meantime, this gain K is used to attenuate the $M_f I_f$ during maximum difference when there is a case of abnormal condition on the microgrid source in equation (32). Furthermore, it also will reduce the rapid fluctuation of inverter output voltage, which caused by the increasing of magnitude of e signal. In this project, the VSCon technique can achieve fast synchronization between grid and inverter. The internal generated signal e is produced in equation (33) that has a function of the grid synchronization condition.

$$J\ddot{\theta} = T_e - T_m = \Delta T \tag{29}$$

$$\dot{\theta}(t) = J^{-1}\int_{49}^{51}\ddot{\theta}\,dt \qquad \left\{51 \geq \dot{\theta}_g \geq 49\right\} \tag{30}$$

$$\delta(t) = \int_{0^\circ}^{90^\circ} \dot{\theta}\, dt \qquad \{0^\circ \le \theta_g \le 90^\circ\} \tag{31}$$

$$M_f i_f = \frac{1}{K}\left(V_n - V_g\right) = \frac{\Delta V}{K} \tag{32}$$

Hence, the instantaneous equation of e can be written as,

$$e(t) = \left(\frac{\Delta v(t)}{K}\right) \dot{\theta}(t) \sin\delta(t) \tag{33}$$

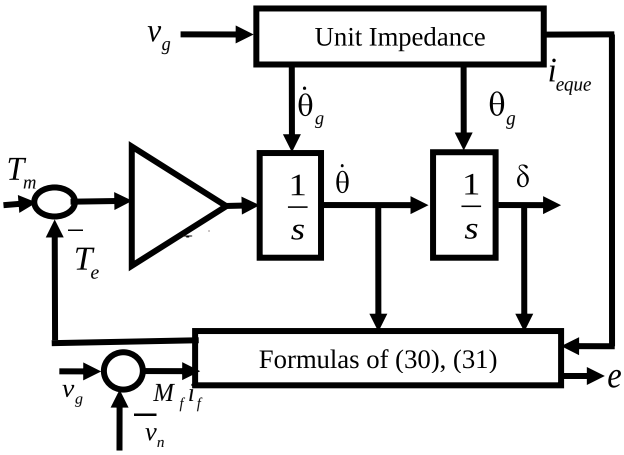


Fig. 6. The VSCon controller connecting microgrid voltage and frequency.

6. Results and Discussions

In this part, VSCon has been simulated and tested in 24V and 120V dc-linked inverter and ac source at 24V and 120V in 50Hz ac source supply using Matlab/Simulink respectively will be discussed. There are three different loads which are connected to the microgrid. The synchronization is happen when the inrveter is been connected to the grid. During loads switching, the synchronization and THD are also been analyzed thoroughly. The time duration of simulation is select up to 0.6s whereas some focus figures from the resultant figures have been zoomed in order to have clear visualization of signal during synchronization .Appendix 1 shows, the H-Bridge inverter, ac source and loads connected at point of common coupling (PCC). The inverter model structure that been created is based on the power system block-sets that is available in the Matlab. The Simulink powergui configuration is chosen to be in discrete simulation that has sample time of 1μs and solver type of Tustin

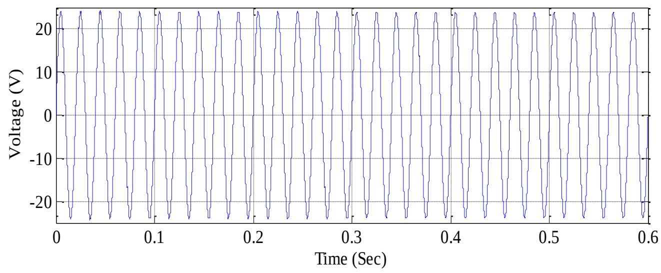
6.1. Case I: 24V DC-linked inverter

In this test, a 24V DC-linked inverter with a 24V, 50Hz ac source supply at low level microgrid side has been simulated. The time duration of simulation is selected up to 0.6s whereas some focused figures from the resultant figures have been zoom-in, in order to have clear visualization of theoutput signal during synchronization. Table 1 shows the load components and parameters that been used for in the simulation.

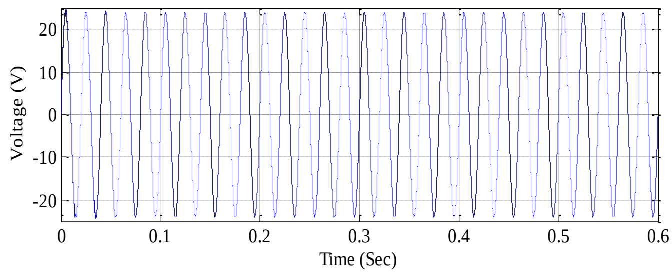
Table 1. System parameters and components

Parameters	Values	Parameters	Values
Ls	4 mH	Load 1	150 ohms and 1mH
Cf	7.5μF	Load 2	100 ohms and 1.896mH
Damping resistance	0.5 ohms	Load 3	100 ohms and 1.896mH
Lg	1.4 mH	dc-link	24 volts
Nominal frequency	50 Hz	Switching frequency	5kHz

Forthis simulation test, the ac source at the grid is considered to have same voltage level with inverter output. Initially, T_m is set to zero for VSCon input where the first task is to have self-synchronize condition between ac input source with the inverter output without any power transfer from the inverter.



(a)



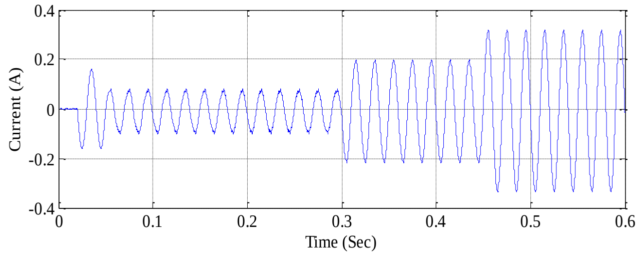
(b)

Fig. 7. (a) Inverter output voltage (b) nominal microgrid voltage 24V in 50 Hz.

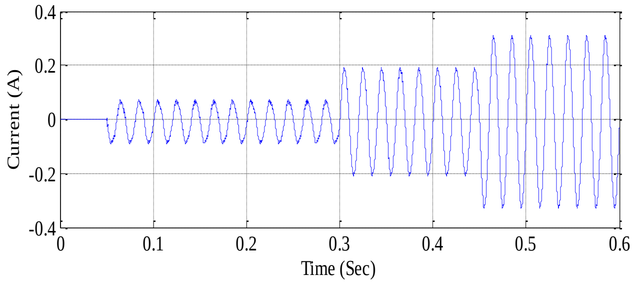
Figure 7 (a) and (b) shows the inverter output voltage and nominal microgrid voltagebefore the circuit breaker been switch on for the synchronization process. It shows that both outputs voltage are in the same magnitude, phase and frequency which indicate that both of them are ready to be synchronize.

Connecting microgrid-inverter and sharing load current

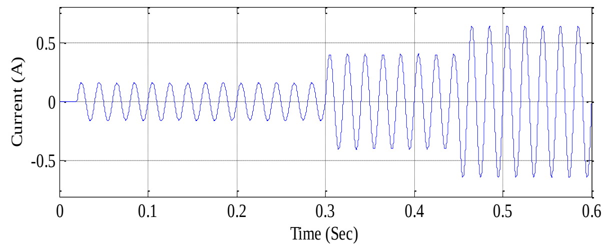
After the inverter-grid has been synchronized, load 1, load 2 and load 3 will be connected to the microgrid system at time of t = 0.02s, t = 0.30s and t = 0.45s respectively. At time t = 0.05s, the inverter is connected to the grid by activate the circuit breaker. Figure 8 (a) shows, the microgrid current is increasing when the loads are started to being inserted to the PCC. There is high transient current at the beginning when the first loads 1 is been connected at time of 0.02s with the grid. This transient is caused when the inverter is simultaneously connect to the grid at PCC. It is where the inverter is started been connected to the system at t = 0.05s and gives nearly 0.2A current, which shows that the inverter is start to share the current to load as shown in Fig. 8 (c). At the meantime Fig. 8 (b) shows the current injected by the inverter to the microgrid.



(a)



(b)



(c)

Fig. 8. (a) Microgrid current while connecting loads (b) inverter current while connecting loads and (c) load current while connecting loads.

The THD of grid current is also been analyzed in resistive and inductive load condition as shown in Fig. 9. Since the inverter contributes current to the loads, and at the same time, the inverter injects THD harmonic to the grid, it has been measured, it is about 2.62% which is below the specific value given in IEEE standard[32] when the inverter start to connect to the grid.

Phase and frequency synchronization with VSCon

Since, the VSCon signal controls the inverter through PWM signal, the angle and grid frequency are needed to be the inputs to the VSCon and it produces its own control signal that changes according to the changing of frequency grid signal. This second simulation test, has been conducted when the grid frequency is changed from 50 Hz to 51Hz. The inverter and grid have been connected at 0.3s during the simulation.

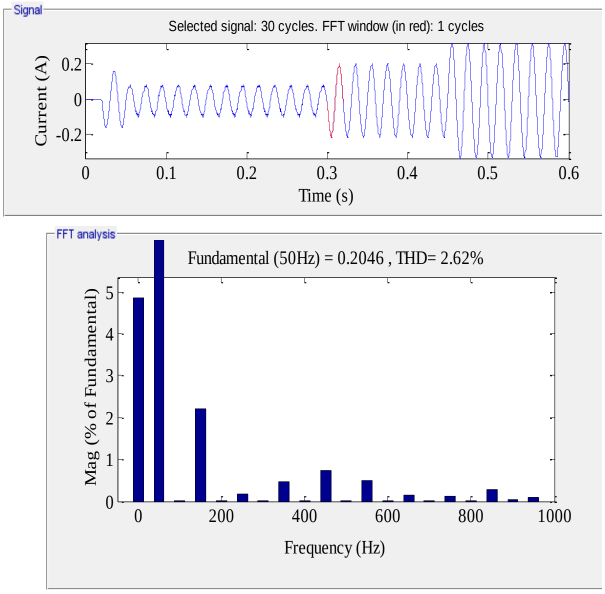
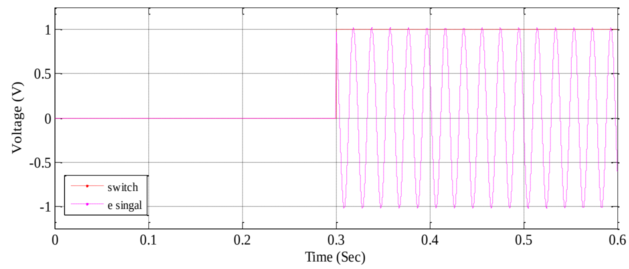
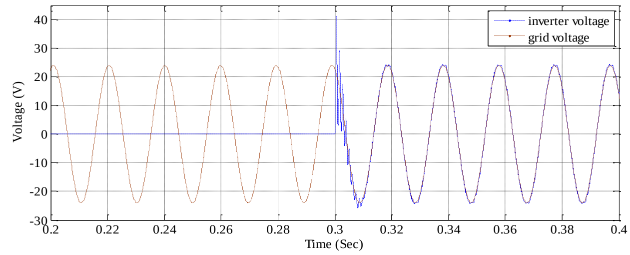


Fig. 9. THD analysis of microgrid current at 50 Hz.

The corresponded output switch signal which generates from the grid voltage, is shown in Fig. 10 (a) at the time when the inverter and input source are been connected.



(a)

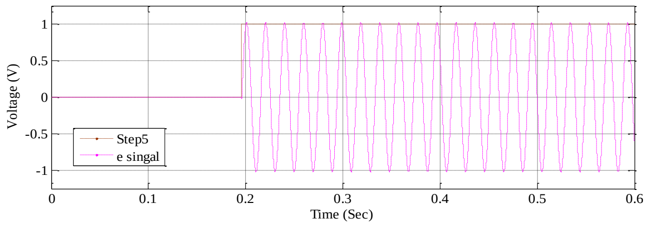


(b)

Fig. 10. (a) The is connected with PWM at 0.3s (b) microgrid voltage and inverter voltage is synchronized at 51 Hz.

Figure 10 (b) shows zoomed version between 0.2s to 0.4s when the microgrid and inverter voltage are synchronized at 0.3s after the circuit breaker start to be connectedwhen the grid frequency is changed to 51Hz. At the time 0.3s, the result shows that, the inverter is trying to follow the grid voltage and creates a ripple signal for about half cycle during transient process before it follows the grid frequency. It also can be observed that,during 0.3s, the inverter output voltage is having a spike signal up to 40V. This is because the *e* signal starts to respond to the PWM inverter switching after the circuit breaker is on. This condition can be avoided if the selecting of the PWM signal is embedded with zero crossing position. Figure 11 (a) shows, the e signal that will be the input to the PWM signal in sinusoidal form which is near to 1 with the Step 5 switch signal response which was used to connect the VSCon generated e to PWM input at the time of 0.19s. The allowable timing of e, is asignal before it can be connected to the PWM can be calculated according to frequency bandwidth in microgrid. For example, in Malaysia, the utility is allow for frequency variation between 50±1Hz [18]. Therefore, the time-period of each maximum and minimum frequency should be nearly 19.6ms to 20.6ms. Figure 11 (b) shows the clear version of inverter voltage and input source voltage at time of synchronized at 0.196s.

(a)



(b)

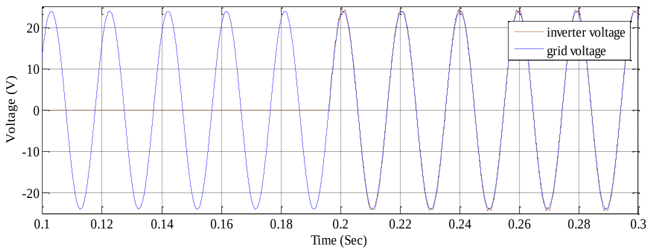


Fig. 11. (a) the e signal is connected with PWM signal at 0.196s; (b) The microgrid and inverter voltage are synchronized at 0.196s while changing the microgrid voltage frequency 51Hz.

The next simulation test is conducted when the grid voltage has a phase delay on the input source. It is when, the grid is having 10^0 phase delay at the 24V, 51Hz frequency in ac source grid. Figure 12 shows the generating e signal from the VSCon control value that has a signal shift at 0.02s at time axis. This shift is about 10^{o} or about 0.02s that caused by the grid to be delay. The test on the phase delay tracking has been conducted when the inverter and grid are being connected at 0.05s.

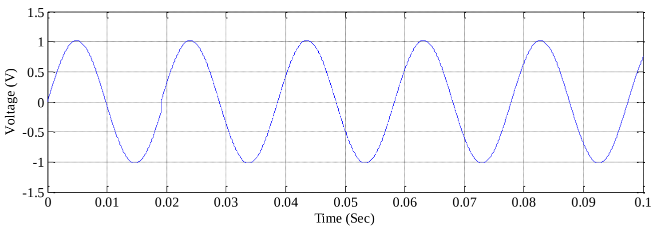


Fig. 12. The e signal shifts phase-angle by 10^{o} at 0.02s.

When the inverter is start to being connected to the grid voltage at the time of 0.05s, the synchronization has immediately effect, where both of the voltages are able to synchronize with a short period of time as shown in Fig. 13 with clear visualization of wave shape of grid and inverter voltage, the zoomed scope has been selected between 0s to 0.1s.

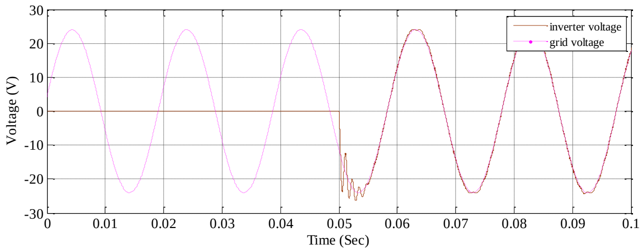


Fig. 13. The microgrid voltage phase and inverter voltage phase are synchronized at 0.05s.

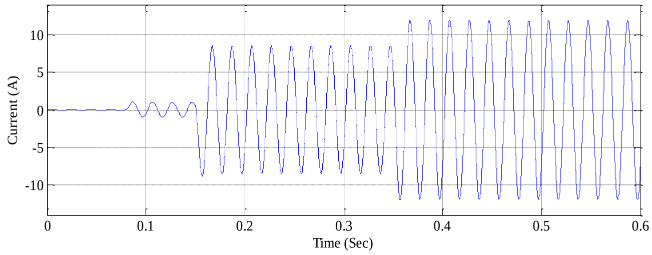
6.2. Case II: 120V DC-linked inverter

Three loads are chosen for this simulation when after ac input source is selected to be at 120V, 50Hz frequency at grid voltage. The load motor parameters are shown in Table 2.

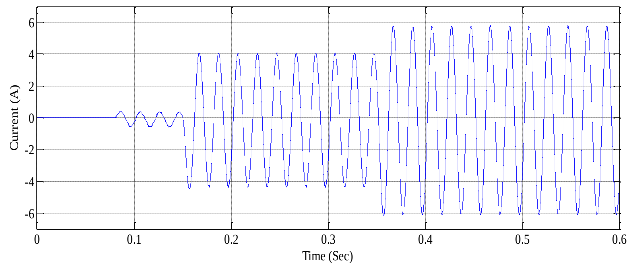
Ta**ble 2.** Appearance properties of accepted manuscripts

Loads	Items	Ratings	ON time
Load 1	Celling Fan	P=100Watt; Q=70VAR	0.08 s
Load 2	A.O. Smith Motor	P=373Watt; Q=250VAR	0.15 s
Load 3	A.O. Smith Motor	P=746Watt; Q=560VAR	0.35 s

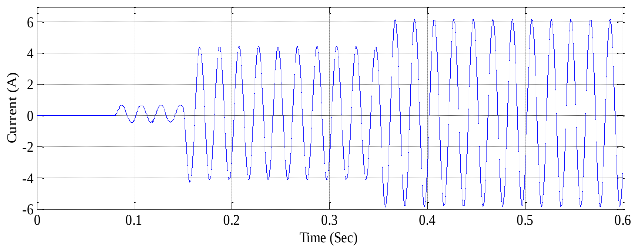
Figure 14 (a) shows the output current of the inverter which contributes to the PCC when load 1, load 2, load 3 are being connected to the system with time of connectionsare stated in Table 2. Load 1 consists of 100W and 70VAR which consumes about 1A from inverter,at time t=0.08s and it is shown in Fig. 14 (a). Load 2 and load 3 are to be 373W and 746W motors are been connected to the PCC at t=0.15s and t=0.35s respectively. Therefore, load 2 and load 3 take more current from the inverter. However, when all the loads are connected to the grid, inverter shares nearly 6A current to loads. The microgrid supplies a current is shown in Figure 14 (b) while the total current consumed by the load is shown in Figure 14 (c). The real and reactive power are contributed by inverter are also shown in Fig. 15 (a) and Fig. 15 (b) respectively. Its show that, when all loads are connected to the microgrid, inverter injects approximately 280Watt of real power as well as 235 VAR reactive power to the system.



(a)



(b)



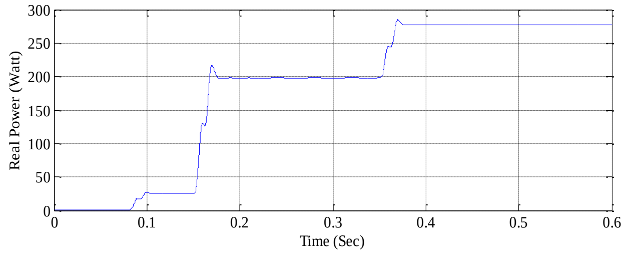
(c)

Fig. 14. (a) Inverter current contributes to loads, (b) microgrid current contributes to loads, (c) overall load current.

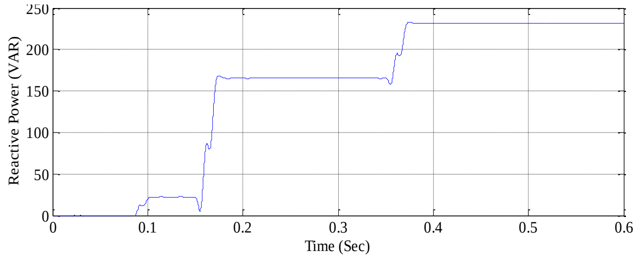
Figure 16 shows the THD grid current when the inverter is been connected to the microgrid system at 0.3s. Since the inverter contributes current to the loads, the THD has been measured at 0.57% which is below the given IEEE standard [32] after the inverter injected the current.

Phase and frequency synchronization with VSCon

In this simulation tests, ac input source has changed on the frequency and at the phase-angle value from therated value. These changes are been conducted in order to see the effectiveness of the VSCon controller in the inverter in order to have fast synchronization with the grid voltage at PCC. It is when, the grid frequency is changedto 51Hz at 120V voltage. Therefore, VSCon should produce the same level of frequency at suitable *e* signal for the PWM operation on the inverter, in order to make sure the synchronization can be established. Figure 17 (a) show the require*e*that will be connected to PWM switching at nearly 0.2s, where the step pulse indicates the circuit breaker is been switched on. Consequently, the inverter has been triggered at 0.2s. Figure 17 (b) shows the microgrid and inverter voltage are synchronized at 0.2s even the frequency and phase are changes.For the second simulation test, the frequency of microgrid has been changed to 51Hz frequency and with a 10^0 phase angle delay on the input source voltage. As a result, the VSCON generates *e* signal with has a shifted phase at 10^0.



(a)



(b)

Fig. 15. (a) Inverter supplies real power to microgrid and (b) Inverter provides reactive power to grid.

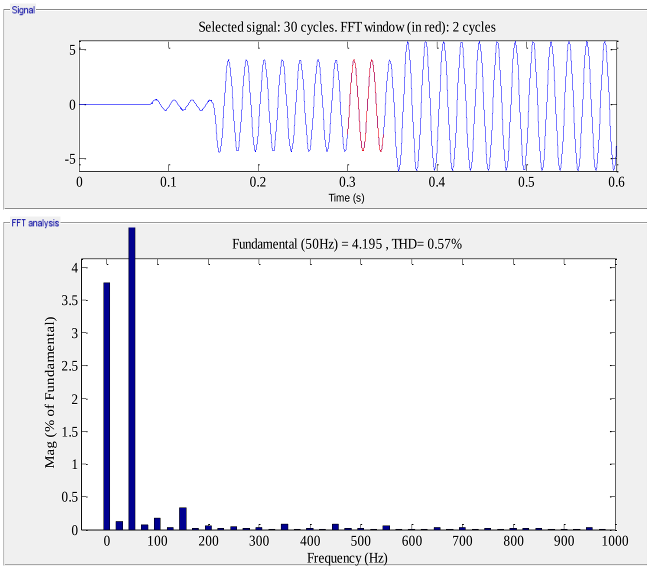
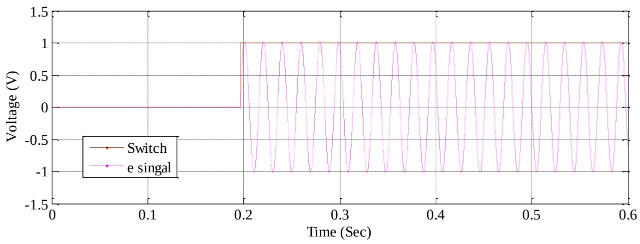
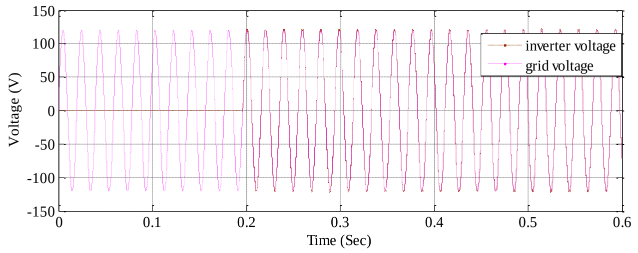


Fig. 16. THD analysis of microgrid current at 50Hz frequency.

This signal then is being connected to the PWM function at 0.21s exactly when the inverter is been triggered in 0.21s as shown in Fig. 18 (a). When the inverter is been connected to the microgrid, the synchronization oscillation is start to happen at the beginning but the VSCon is able to suppressed it by 1 cycle approximately to inverter voltage level as shown in Fig. 18 (b). Figure 18 (c) shows the microgrid and inverter voltage are synchronized after 0.21s when after the grid frequency is changed to 51Hz frequency. This is by at 0.21s, the inverter is trying to follow the grid voltage that creates a ripple signal for about half cycle. This condition shows that, the proposed VSCon is able to have fast synchronized situation either in frequency changing or phase changes or both in the ac input source.

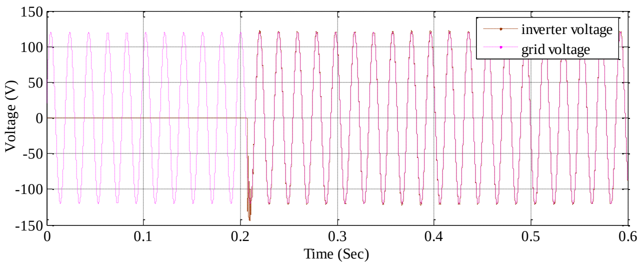


(a)

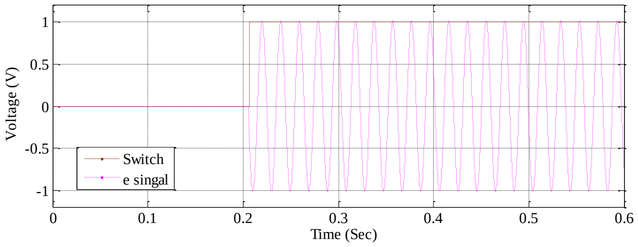


(b)

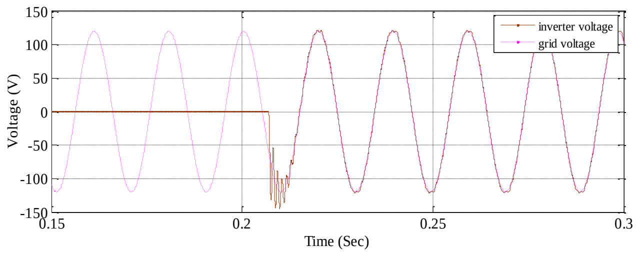
Fig. 17. (a) The microgrid voltage and inverter voltage is synchronized at 0.2s. (b) the VSCon produced e signal is connected with PWM at 0.2s.



(a)



(b)



(c)

Fig. 18. (a) The e is connected with PWM at 0.21s, (b) The inverter voltage and microgrid voltage is synchronized at 0.21s, (c) Inverter and microgrid voltage synchronization is zoomed at 0.15s to 0.30s.

7. Conclusion

As a conclusion for this research, the characteristics of synchronous generator can be used for synchronizing between the inverter and grid voltage by implementing the virtual synchronous converter platform to the inverter control strategy. It also enable the inverter to synchronize with the microgrid at PCC without using PLL circuitry or other phase detection that requires large computation process and methods. As a result, it reduces the computational burden on processing time for synchronization. From the results, if the ac grid voltage phase-angle changes from the rated value, the VSCon inverter can respond in 2-cycles after the inverter connected to the grid for synchronization. This technique also manages to recover the inverter output voltage when the grid frequency is changed suddenly before levelling back to the stated grid frequency. At the same time, it also able to response when there is 10° phase deviation in phase-angle. Therefore, this mathematical model of VSCon which is based to synchronous generator can be an alternative method for synchronization between the inverter and grid before the power from the inverter can be transferred to the microgrid system. Table 3 shows brief comparisons of response time and THD between VSCon and conventional PLLs for grid-inverter synchronization.

Table 3. Brief comparisons of response time and THD

Synchronization and Control Technique	Response Time (ms)	Harmonic information (V=voltage)(I=current)
*SOGI-PLL[33][34][8]	160	-
**MHDC[35][36]	100	V 2.93% THD
VSCon	40	I 0.57% THD

*Second Order Generalized Integrator PLL (SOGI PLL)
**Multi-harmonic Decoupling Cell(MHDC)

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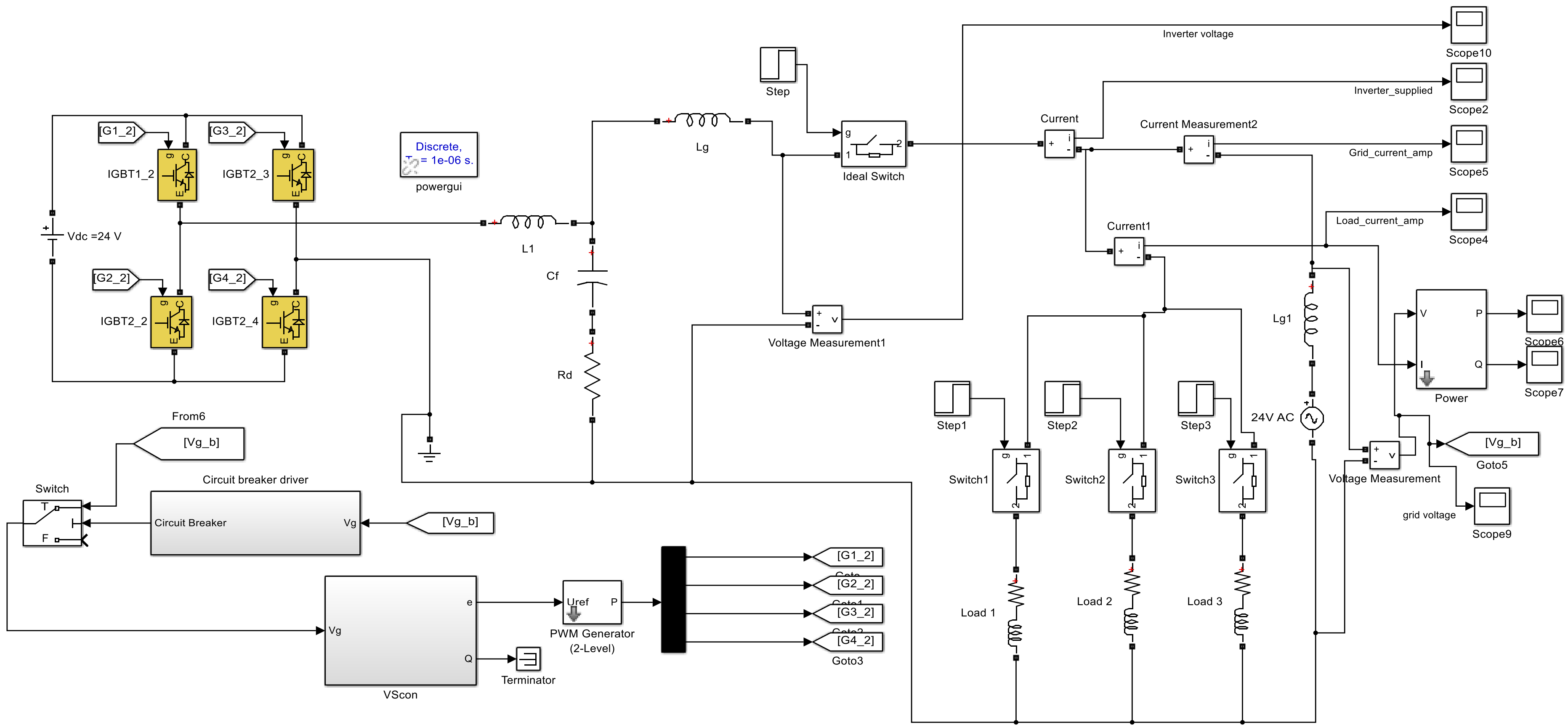
Appendix I



Single-phase H-bridge inverter with microgrid-load system.