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Modelling of Virtual Synchronous Converter for Grid-inverter Synchronization in Microgrids Applications

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ABSTRACT

In this paper, virtual synchronous converter (VSCon) is been developed which mimic the behavior of synchronous generator as in order to have fast synchronization between the inverter with the grid. This synchronization is important before can sent the power among inverter-grid connection. This technique can also been applied at the distributed generated sources when are connected to the local microgrids. Here, the frequency and voltage synchronization also can be controlled at the same time some improvement on synchronous generator mathematical model that is suitable to be implemented into the inverter control. The whole unit of VSCon is operated and simulated in Matlab/Simulink in order to observe all consequences during synchronizing the voltage, frequency and phase-angle. It has been verified by the simulation circuit where, the power converter can be synchronized with the microrids without using a PLL unit for self synchronization. This VSCon technique has proven that, by applying the concept of the synchronous generator model in inverter control, it can cause the inverter to behave as generator system, which does not required any phase information from the grid in order to be synchronized.

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1. INTRODUCTION

Nowadays, distributed energy resources (DERs) [1], [2] have growed into extra consideration in various technological advancements since petroleum based energy production produces large scale of greenhouse gases emission as well as high maintenance cost [3], [4]. The energy capacity is expected to reach 2,080MW by 2020, where renewable energy is contributing about 7.8% of total installed capacity in Peninsular Malaysia and Sabah [5]. The Consortium for Electric Reliability Technology Solutions (CERTS) [6] has proposed the definition of microgrids: CERTS Microgrid concept believes an aggregation of loads and micro-sources operating as a single system providing both electrical power and heat. Generally, remote microgrid in isolated area or islanded uses to heavily rely on local power generation based on DGs. In normal power generation system it is required a long distance and thus, high cost transportation that make the electrification on off-grid remote uneconomic and slowly developed [7]. On the other sides, some remote areas are abundant of DERs, such as wind energy, solar energy and biomass energy sources [2] which have motivated the authors to have DER near to the load to be studied and analyzed. Before these systems can transfer the power, the synchronization between the DER converters and the exixting grid is required. Mostly, DER generates DC form of signal and then converted to AC source using power electronic converters that have parallel effect on synronization with the grid interms of voltage, phase-angle and frequency. According to the ANSI C84.1, the steady sate voltage is ranged about 5% is required and total harmonics distortion is suppose to be less than 5% that have been declared in IEEE519 standard before the power can be transferred [6]. However, the quality of power as well the stability of power system need to be improved by proper synchronization between grid and inverter that been stated in [7]-[9]. The grid allows the energy transfers from DGs is through the Current-Source-Inverter (CSI) or Voltage-Source-Inverter (VSI). However, in application for standalone/islanded mode operation, VSI does not require any reference to preserve it synchronized [10] rather than grid connected operation mode [11] which give high priority on this case to maintain the grid stability. As a result, microgrid and other grid must be in condition where the voltage and frequency are in good power quality on the system [12] all over the time. As for synchronization process, it requires value of frequency and the amplitude, along with phase on the fundamental component from the grid voltage as to be the references for the controller design to the inverter [13]. As known, the Synchronous Generator (SG) where has been connected to the infinity bus does not required synchronization to the grid in order to control and deliver the power due to the advantage of generator control that used torque angle [14] control to control the angle between the grid and generator

This concept that uses a synchronouns generator to be one of the control strategies has been proposed by [15]. It shows that, the inverter can act as a synchronous generator if all dynamic properties which is driven by mechanical primemovers are been considered in the designing the control strategy for the inverter for self-synchronization ability. Paper [16] discussed another virtual sysnchronous generator model to control the virtual inertia for stabilizing the frequency in the system. For this paper, the virtual synchrnouous converter is developed by combining with torque-power mathematical expression in synchronous generator in order to be combined with the grid-inverter synchronization for creating a virtual synchronous converter (VSCon). This paper is organized with following sections. Section 2 is organized with short briefing on synchronous generator and term that are relevant to develop a VSCon. Section 3 consists of implementation of SG in virtual mode, followed by its validation in simulation and discussion in section 4. Some conclusions are made in section 5.

2. SYNCHRONOUS GENERATOR PHENOMENON

In this section, the modelling of synchronous generator [17], [18] will be discussed in steady state and during balance condition of the voltage or current for easy analysis in order to be used as a based mathematical structure of the VSCon. In this case, several assumptions are been made regarding to dynamic analysis of synchronous generator. For example, for system analysis and controller design, damping-windings-less round rotor machine is been considered to have 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 sub-sections which are electrical part and mechanical part of the synchronous generator.

2.1. Electrical Part

The basic part of synchronous generator is ferromagnetic structure that has hollow cylindrical part that known as stator or armature is used to slot the armature windings and then the rotor rotates inside the hollow cylinder. The winding on the rotor, is called the field windings. The DC current is supplied to the field winding by an exciter to produce high magnetomotive force (mmf). Figure 1 shows, the ideal structure of synchronous generator which represent the three armature windings on the stator round-rotor machine and concentrated coil f which represent the distributed field winding on the rotor.

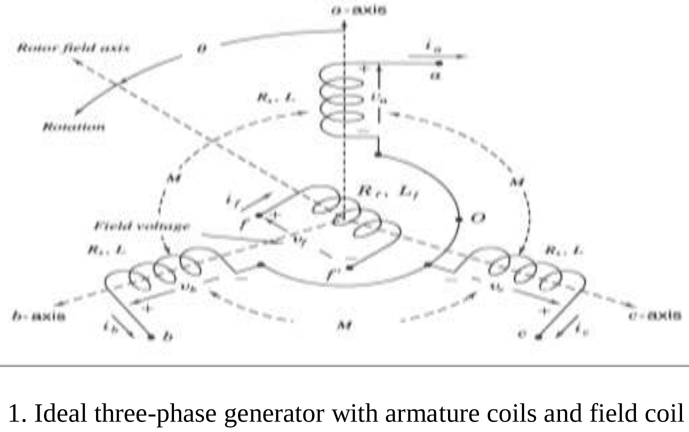

Figure 1. Ideal three-phase generator with armature coils and field coil [17]

The three stationary armature coils are identical in every phase which respect to each another that have two terminals connected to a common point *O*. The other three terminals are marked as a, b and c. The axis of coil a is chosen at $\theta_d = 0°$ and counter clockwise around the air-gap are the axes of the b coil and c coil are at $\theta_d = 120°$ and $\theta_d = 240°$ respectively. Assume that, each of the concentrated coils a, b and c has 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 is 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 consinusoidal function with maximum value M_f are shown in Equations (1), (2) and (3).

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

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

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

Flux linkage with each of the coils a, b, c and f are due to its own current in the three other coils. Flux-linkages equations are therefore written for all four coils as followed in Equations (4) and (5).

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

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

For considering the steady state condition, it is assumed that the current i_f is a AC signal and with a constant I_f when the field rotates at constant angular speed ω, on two-poled machine.

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

The angle θ_{d0} denotes the initial position of field winding which is given in Equation (6). Hence, Equation (4) can be rewritten by considering the initial position of field winding as,

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

Equation (7) shows that λ_a has two flux-linkage components, one due to field current I_f and the onther due to armature current i_a, which is flowing out from the generator. When coil a has resistance R then the voltage drop v_a across the coil from terminal a to terminal *O*,

$$v_a = -Ri_a - \frac{d\lambda_a}{dt} = -Ri_a - \left(L_s + M_s\right)\frac{di_a}{dt} + \omega M_f I_f \sin\left(\omega t + \theta_{d0}\right) \tag{8}$$

The most right hand side on term in Equation (8) denotes an internal emf or generated emf where the synchronous internal voltage is defined e_a and can be written as,

$$e_a = \omega M_f I_f \sin\left(\omega t + \theta_{d0}\right) \tag{9}$$

Hence, it shows that the generated emf magnitude and frequency is directly proportional to the field excitation and angular velocity of field coil as well as prime mover of machine.

2.2. Mechnical Part

The mechanical part of the synchronous generator is governed by,

$$J\ddot{\theta} = T_m - T_e + D_p\dot{\theta} \tag{10}$$

Where, J is the momentum of inertia of all parts when it is 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,

$$E = \tfrac{1}{2}\left(i_a\lambda_a\right) + \tfrac{1}{2}\left(i_f\lambda_f\right) + \tfrac{1}{2}J\dot{\theta}^2 \tag{11}$$

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

$$\begin{aligned} T_e &= -\frac{\partial E}{\partial \theta_m} = -p\frac{\partial E}{\partial \theta} \\ &= pM_f I_f \left(i_a \frac{\partial}{\partial \theta} \sin\theta \right) \end{aligned} \tag{12}$$

Hence, it is also proved that, electromagnetic torque T_e is directly proportional to field excitation $M_f I_f$ of rotor.

3. VIRTUAL SYNCHRONOUS CONVERTER (VSCon)

Abnormal grid changes along with dynamic change of frequency and voltage parameters are common issue in a grid. So, a dynamic mathematical model is required to cope the inverter system accordingly to the real time changes in the grid for power tansfer. For example, due to impose massive load in peak hour, the consumption of real power demand is increased as well as frequency to more then the rated frequency. To meet the power without hampering the voltage at the terminal, the primemover angular speed and/or control the excitation of rotor of synchronous machine can be applied for the synchronous generator. At the meantime, by changing the angular speed of the large power generation, it would overcome the frequency at rated but in case of small-scale integration, the frequency could be higher due to increase rpm of the generator. All these techniques can be applied at when the synchronous generator has been the primier input source to the grid. Due to this ability, the improved controller should be developed in order to respond in the same ways as the generator.

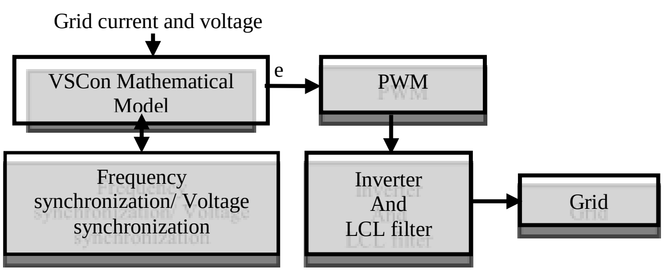

Figure 2. Block diagram of VSCon inverter interfacing along with grid

The improve controller that been mentioned about is shown in Figure 2 that known as VSCon. The VSCon consists of several inputs targeting to produce output e , which would pass through a PWM signal for inverter operation. First, it takes mechanical torque T_m to initialize the synchronous converter then deducts with VSCon internal generated electromagnetic torque T_e as synchronous generator operation principle. In this application, a virtual inertia of rotor is added as J that having small constant value to find the virtual acceleration $\ddot{\theta}$ as mentioned in Equation (13). Then, the integration block is added to find the virtual angular speed $\dot{\theta}$ where been limited by grid frequency or real-time frequency $\dot{\theta}_{r/g}$ to fix the output frequency at grid frequency are given in Equation (12) and Equation (14). It is also directly proportional to the magnitude of output e since it will increase generator rpm (revolution per minute) that caused the magnitude to be increased. Further, the output phase of VSCon is determined by grid phase θ_g shown in Equation (15).

$$J\ddot{\theta} = T_e - T_m = \Delta T \tag{13}$$

$$\dot{\theta}(t) = J\int_{49}^{51}\ddot{\theta}\,dt \quad \left\{51 \ge \dot{\theta}_{r/g} \ge 49\right\} \tag{14}$$

$$\theta(t) = \int_{0^\circ}^{90^\circ}\dot{\theta}\,dt \quad \left\{0^\circ \le \theta_g \le 90^\circ\right\} \tag{15}$$

To produce an internal T_e, a sinusoidal signal form the grid such as the voltage or current is directly feedback to the VSCon input. It has been mentioned, synchronous generator produces back electromagnetic force during machine starting that causes the efficiency of generator by repulsion of T_m been reduced. On the other hand, the magnitude of output e depends on excitation $M_f I_f$, which is fed for field excitation. The difference between grid voltage V_g and nominal voltage V_n is taken and passed through gain $1/K$ for generating $M_f I_f$ as given in Eq. (16). This gain K is used to attenuate the $M_f I_f$ during maximum difference between V_g and V_n in case of abnormal condition that happen in grid as in Equation (17) where this is the different between the suggested method in [13]. Since, the generator takes excitation in rotor and mechanical power to rotate the rotor it cuts the magnetic flux and produce emf at its armature. However, it reduces the rapid fluctuation of inverter output voltage caused by increasing of magnitude e. As a result, this VSCon generates internal reactive power since the grid current is feedback, hence it can be also used as power controller.

$$M_f i_f = \frac{1}{K}\left(V_n - V_g\right) = \frac{\Delta V}{K} \tag{16}$$

Hence, the instantaneous equation of e can be written.

$$e(t) = \left(\frac{\Delta v(t)}{K}\right)\dot{\theta}(t)\sin\theta(t) \tag{17}$$

The complete VSCon mathematical model is shown in Figure 3.

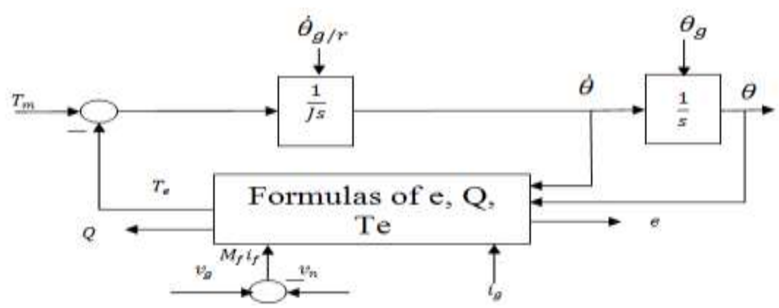

Figure 3. Mathematical model of VSCon with output e [13]

4. RESULTS AND DISCUSSION

The VSCon model and control technique have been developed in Matlab/Simulink as shown in Figure 4 with without the PLL sturcture. This controller contains mathematical equations of synchchonous generator, which takes mechanical torque T_m and field excitation $M_f I_f$ as inputs for generating the corresponding sinusoidal e signal that contains information from the grid without using PLL. The property of e is depend on magnitude of $M_f I_f$, mechanical torque T_m as well as virtual angular speed $\dot{\theta}$, which is denoted by 'theta dot' in Figure 3. The output e is further passed to PWM input for generates a signal for inverter operation. In the simulation analysis, a single-phase inverter has been considered which has similar voltage level with the grid source at 230V. The Simulink powergui configuration is chosen to be discrete simulation having sample time of 1µs with Tustin solver type. The filter is also been used at point of common coupling between them in order to reduce the harmonic level at the inverter output. The LCL filter has been used in this paper but will not been discussed here because this paper is focusing on modelling the VSCon and to observe the inverter-grid voltage output in various consequences within self-sysncronization effect when the grid phase-angle, frequency and amplitude is been changed. The inverter and VSCon parameters are given in Table 1.

Figure 5 shows, the VSCon generate a sinusoidal e signal that has 50 Hz frequency at 0^o phase-angle signal for PWM input in order to turn on the inverter if the grid source is fixed at 50Hz supply. Figure 6 shows the inverter output voltage when both inverter and grid have been connected at 0s. It explains that this technique is able to have self- synchronization without the usage of PLL. Meanwhile, Figures 7(a) and 7(b) show the synchronize signal which contains of 50 Hz frequency with ramp of ωt that varying between 0 and 2π and maintain the frequency that identical in PLL respond.

Table 1. Parameters of VSCon connected inverter

Parameters	Values	Parameters	Values
Ls	4.5mH	Switching frequency	5000Hz
Cf	0.006mF	Nominal frequency	50Hz
Damping resistance	0.5ohms	Virtual inertia	0.5 kgm^2
Lg	1.4mH	dc-link	230 volts

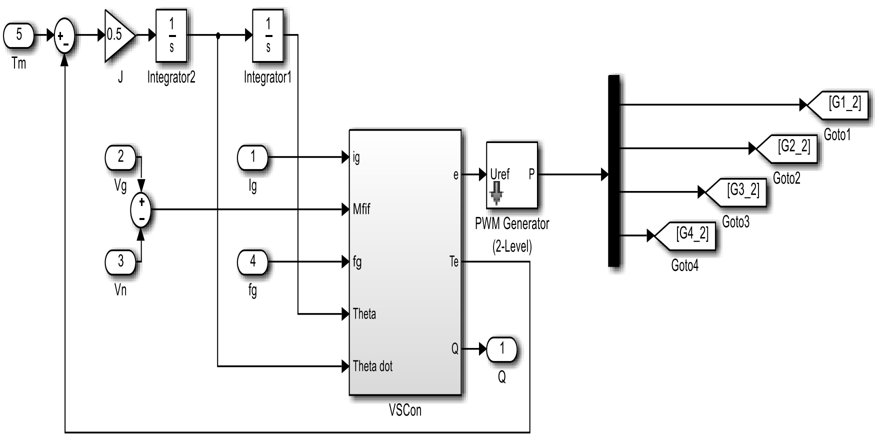

Figure 4. VSCon connected to inverter through PWM signal generation

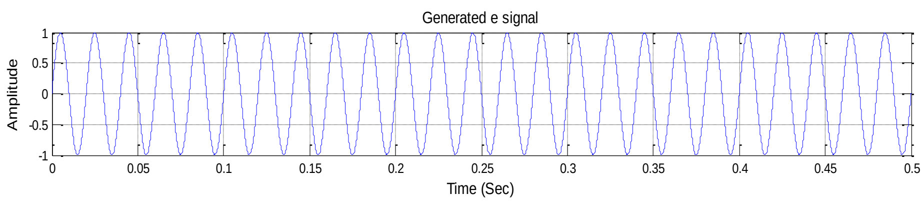

Figure 5. VSCon generated e signal having 50Hz frequency

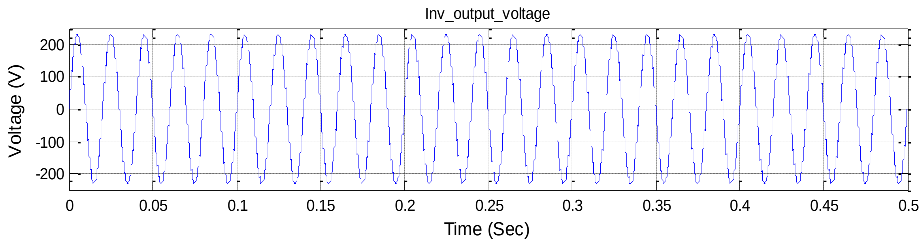

Figure 6. Inverter output

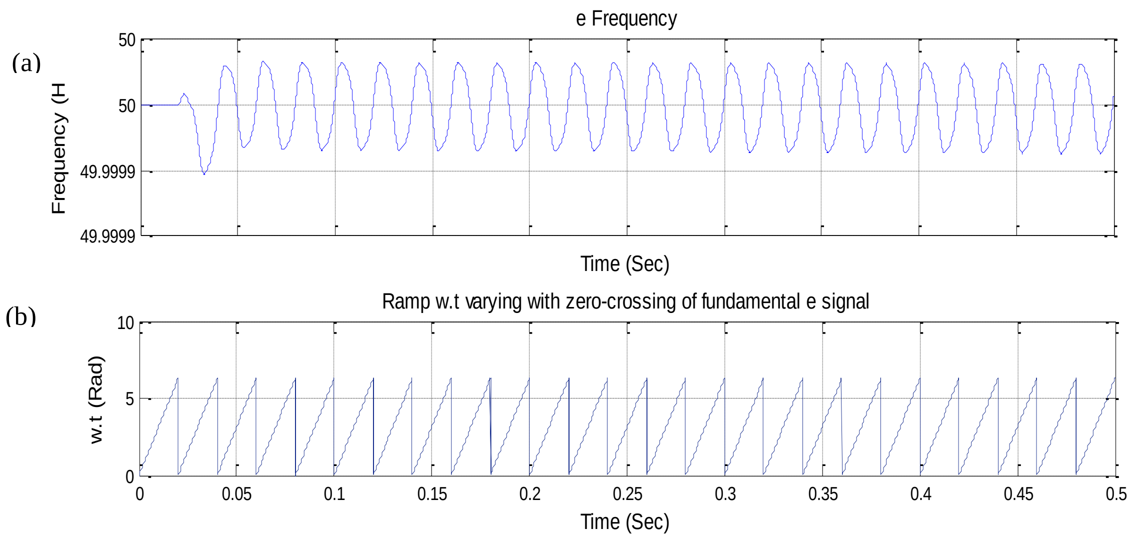

Figure 7. (a) Frequency of generating e signal on VSCon, (b) frequency ramp that contribute to the synchronization

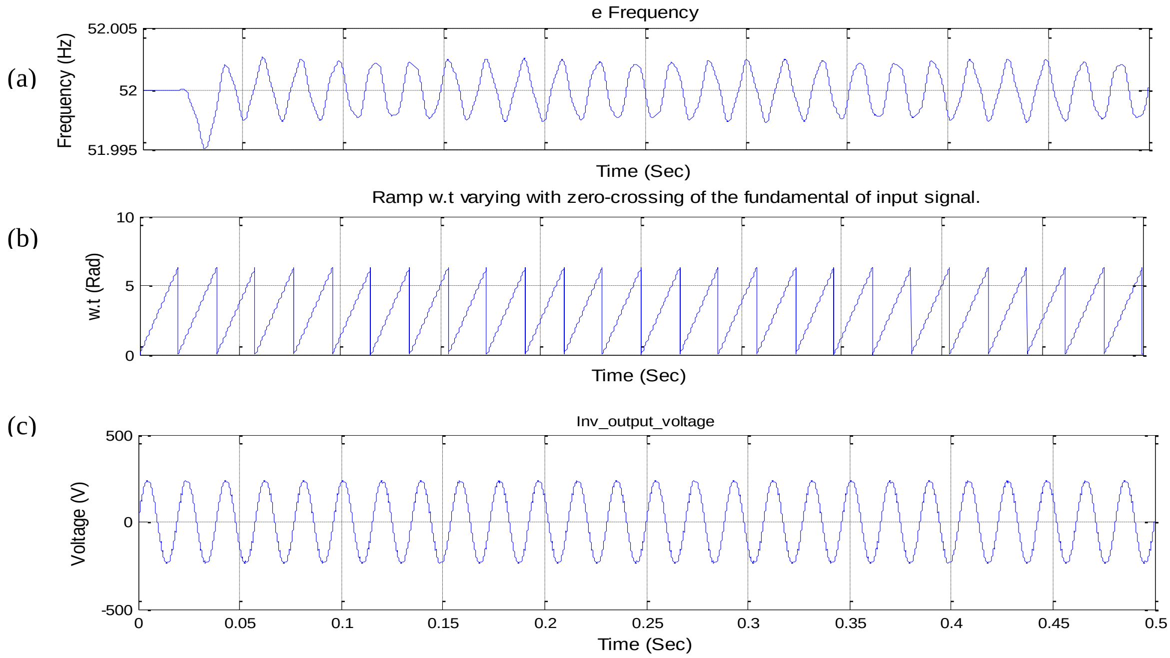

Figure 8. (a) VSCon generated e frequency signal, (b) frequency ramp that contribute to the synchronization, (c) inverter output respond when grid frequency at 52Hz

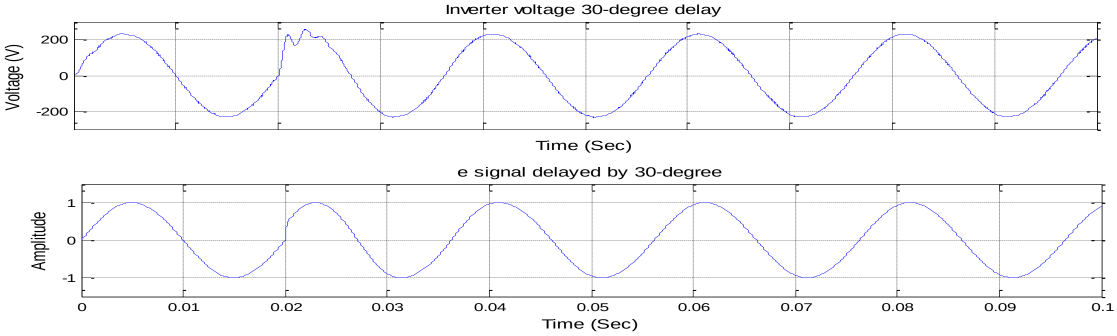

Figure 9. VSCon generated e signal tuned inverter output having 30-degree delay

For the second simulation test, the grid frequency has been changed to 52Hz. It has been conducted because; the authors would like to see the respond of the inverter output in order to maintain the synchronization. As the results, Figures 8(a), 8(b), 8(c) show that VSCon generates e signal that able to maintain the frequency and the ramp signal which are following the grid frequency. These results are generated becaused the PWM signal that been applied to the inverter is able to control the reference e signal with followed the frequency and amplitude as well as phase-angle that seeing from the grid. The frequency of VSCon that been produced here, is based on its zero-crossing of fundamental frequency which response to frequency during synchronous generator operation.

The variation of phase-angle and amplitude and its impact for e signal as well in inverter output as also been tested and the results are shown in Figure 9 where the grid voltage is having a 30^{o} phase delay. This has caused the inverter voltage to follow the delay after 0.02s when the grid has been connected. This VSCon has responded well to this delay angle which able to maintain the synchronization. While, the synchronous generator respond to the phase-angle can only be changed when the excitations and other external factors for which are the reactor bank as well as capacitor bank to control the angle between voltage and current. As from the results that have been collected, this VSCon which is based on mathematical equations of the synchronous generator can be applied to the inverter control in order to improve the performance of the inverter for self-synchronization without dedicated PLL.

5. CONCLUSION

As a conclusion and based on the simulation results, it has been proved that the synchronous generator characteristics can be implemented and used into the inverter control that will create a virtual angular speed which is based on the grid voltage input that will generate a signal that behave as grid signal for inverter operation. By having this advantage, the conventional PLL structure can be avoided in order to have self-synchronization mechanism. At the meantime, this inverter can be used to integrate the DERs into the conventional grid by injecting power without using dedicated PLL for better synchronize inverter-grid system. On the other hand, it also apply the ability to regulate a real power and reactive power and improves the power sharing among the parallel operation of distributed generation system.

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