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Fast Self-Synchronization between Low-Voltage Microgrid and Inverter using Virtual Synchronous Converter

In this paper, a fast self-synchronization known as virtual synchronous converter (VSCon) between single-phase microgrid and inverter in low-voltage microgrid, has been developed in Matlab/Simulink. The idea is to any phase locked loop (PLL) circuit for inverter-microgrid synchronization in order to improve the synchronization time. As known, it is difficult and lengthy process to tune the PLL gain parameters to reach suitable performance for synchronizing among the voltage, phase-angle and frequency between them. Due to this problem, a fast self synchronization technique is needed in order to minimize the time losses at the microgrid connection. Therefore, the VSCon has been developed which is based on the synchronous generator mathematical model but in virtual environment representation. It has been applied in the inverter control for generating switching pattern to the inverter switches in order to respond to the grid voltage for improve the synchronization. For a prove of concept, several simulation tests in MATLAB models have been conducted, in order to see the effectiveness of this VSCon. First test has been conducted, when a 240V, 50Hz frequency grid source is used for observing the self-synchronization the system with the power flows output. Furthermore, the next test is conducted when the grid frequency is changed from the rated frequency at 50Hz to 51Hz and the result shows the VSCon in inverter control takes nearly 40ms to synchronize to this new frequency value. The test on grid phase-angle delay also been tested when ac grid voltage has 15^0 phase delay. As from all the results, the improved inverter control with VSCon structure is able to have fast and self-synchronized between the inverter-grid connection before the power from the inverter can be transferred.

Keywords: Grid, Inverter, Phase-Locked-Loop; Synchronous Generator, Synchronization.

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1. Introduction

Nowadays, distributed energy resources (DERs) [1][2] have been a priority and an extra consideration in technological advancement due to increases in greenhouse gases emission and high maintenance operation in gas and oil energy production [3][4]. As an example in Malaysia, these DERs will be the main driven sources in order to generate about 2,080MW electricity energy by 2020, which will contribute about 7.8% of total energy capacity for Peninsular Malaysia and Sabah [5]. Therefore, this extra energy source should be controlled and monitored in order for the electrical network to be maintained and able to improve the stability of the system [6][7]. All of these can be achieved when an accurate/self synchronization between both side (DER and grid) has been achieved before the power can be delivered. Generally, two parts of power processing strategies are required in order to send the power from DERs to the grid. First, the harvest energy from the DERs is converted into constant electrical power by using DC power converters. For example, the non-conventional energy sources such as photovoltaic (PV) which offers a direct current/voltage to be stored in rechargeable battery bank and at the sametime a DC converter is needed to maintain the voltage level at the battery DC-link. Then, it will connect to the existing AC

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low-level grid network through an efficient power processing devices [8] such as the inverter. This DER topology is catching more room to be researched in order to export more power to the grid. In this point of view, smart and intelligent system at the point of common coupling (PCC) between grid and DGs are needed for quality power sharing without compromise on the synchronization event between inverter-grid. As a result, this research is necessary to be conducted in order to improve the synchronization time before the power can be transfer between DER-grid without using any PLL circuitry for self synchronization.

As usual, voltage source inverter (VSI) is used as a power processing converter for the inverter-grid connection. The advantages of VSI are where, it has ability to control the output voltage by applying a suitable control strategy [9] and also to maintain the synchronization condition [10] after it been connected. A good interaction at the PCC is needed in order not to burden the inverter control with an external references while to keep the inverter voltage synchronize with the grid voltage [11] even any changes on the frequency, phase and amplitude [12] at the grid side and also able to maintain the synchronization condition. The best power flows control is to use frequency droop and voltage droop where at the end it can perform an autonomous power flows to the microgrid [10]. Various power control methods focused aiming to transfer power into the microgrids from DERs such as in [13][14][15][16] are voltage source control, power-angle control, torque-angle control and current control were been explained. Fig. 1 shows the general synchronization and power control configuration for inverter-grid connection in low voltage microgrid network.

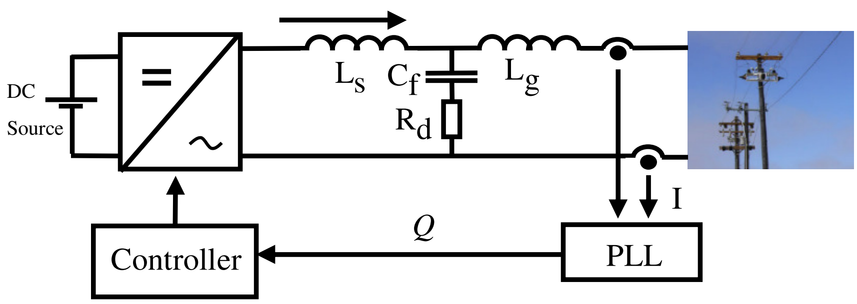

Fig. 1. PLL synchronization technique in low voltage-level microgrid- inverter.

Here, the PLL is used to deliver the information of grid voltage, frequency, amplitude, and phase-angle for calculating the reference phase *Q* which will be used in inverter control for generating a control carrier signal to the inverter. Therefore, to identify the frequency and phase-angle of grid voltage, a number of techniques can been employed which have been suggested in [17][18]. A PLL based methods are the well accepted ones due to its simplicity, robustness and effectiveness [19]. At the meantime, a improve PLL is considered several issues such as the stability margin and the transient response to the phase-jump parameters which has been presented in [20]. If these parameters are not taken in consideration, it will affect the overall control operations and increase the time of synchronization.

As known, when a synchronous generator (SG) connected to the grid, the synchronization and power delivering are happen when the generator operating at synchronous speed within the grid frequency and this speed can be changed according to the grid frequency by changing the mechanical characteristics to the generator. Because of this, the SG does not involve PLL methodology for synchronization between SG-grid before the power can be transferred to the electrical grid. This mechanism had triggered a concept of self-synchronization between inverter- grid synchronization as stated in [21] by changing the inverter control topology to a mimic of the SG operation. In this case, the frequency and amplitude of inverter voltage control are depended on angular speed of prime mover and field excitation of rotor coil.

Those parameters can be created in the inverter control model when the mathematical equations of the SG are been implemented to the inverter control. This technique is known as synchronverter that been proposed by [21][22][23] in 2008. Based from this concept, several improvements have been made in this paper, especially on the frequency and phase tracking mechanism on the inverter-grid in low voltage connection [24] which have not been discussed intensively in [21][22][23]. Therefore, this improved version of synchronverter can perform in grid-connected or stand-alone mode since it has capability to control the voltage phase-angle and the frequency of the inverter output [25]. Moreover, by maintaining the suitable synchronization control scheme on the voltage and frequency at inverter output, it will able to exchange the real and reactive power into the grid [26] but in faster time respond.

In this paper, a virtual synchronous converter (VSCon) which gives an improved version of synchronverter model without utilization of a dedicated PLL synchronization unit has been designed. However, the base mathematical model of VSCon has been realized, determined and used based on paper [24]. However, this improve VSCon has able to synchronize with-in, less than one cycle in 50Hz respond for all the cases that will be explained in this paper. It also improves the accuracy of synchronization and also reducing the time of synchronization by minimize the complexity of the overall inverter control structure.

2. Modelling of Virtual Synchronous Converter (VSCon)

The generator swing equations from [27] have been used for designing the improved VSCon, where the rotational inertia expression is defined the consequence of instability between the electromagnetic torque T_e and the mechanical torque T_m of the individual machines as shown in Fig. 2. Here, P_{in} and P_{out} are the input mechanical power and output electrical power respectively.

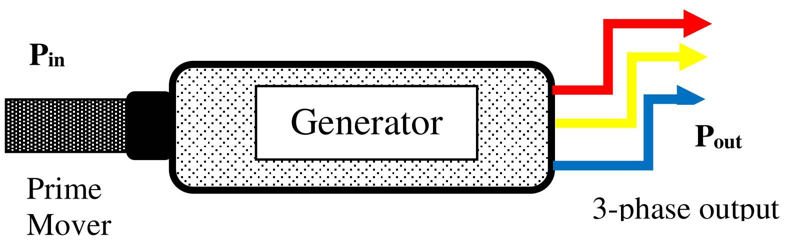

Fig. 2. Generator is connected to prime mover

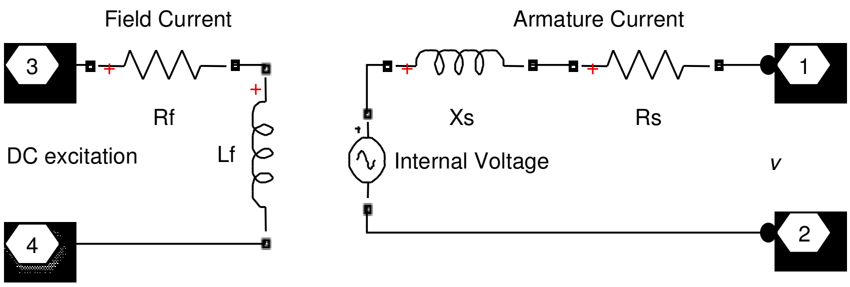

Fig. 3. Equivalent of Single-phase SG

The SG has been modeled based on Fig.3, by applying the mathematical model to equivalent SG model which is directly proportional with the virtual angular speed of rotor. By assuming SG torque is zero the equations are given in (1),(2) and (3). Meanwhile, the phase voltage *v* at terminal can be obtained below;

$$v = -R_S i - \frac{d\phi}{dt} = -R_S i - L_S \frac{di}{dt} + e \tag{1}$$

where ϕ is flux per-pole, L_S is self-inductance and R_s is stator coil resistance as shown in Fig 3. The internal generated voltage can be written as,

$$e = M_f i_f \dot{\theta} \langle \sin\delta \rangle - M_f \frac{di_f}{dt} \langle \cos\delta \rangle \tag{2}$$

Meanwhile, the torques equation can be written as,

$$\ddot{\theta} = \frac{1}{J}\left(T_m - T_e - D_p \dot{\theta}\right) \tag{3}$$

where θ, $\dot{\theta}$ and δ are rotor angular acceleration, rotor angular speed and rotor angle. Equation (3) shows the angular acceleration that been applied in single round-rotor machine where the stator inductance is anticipated to be constant which is based on the equivalent circuit of SG. As a result, (4) shows of electrical torque T_e which is proportional to the current grid *i* which can be collected from the grid as,

$$T_e = Z\left(\frac{P}{A}\right) M_f i_f \langle i, \sin\delta \rangle \tag{4}$$

By considering the structure of the SG, it contributes to the constant gain of the mutual current, the value of current carrying conductor in Z, while P define the pole machine number and A is number of current flowing in parallel paths are been included in (4). Equation 4 can be derived in another form, where the voltage is induced due to conductor reactance, which is then given in (5). Since, this SG is considered to be lap-wounded coil in stator and it has two-poles the equation can be normalized as,

$$T_e = K_f M_f i_f \langle E_r, \sin\delta \rangle \tag{5}$$

where, $K_f = Z\left(\frac{P}{A}\right)$ and $E_r = X_z i$ is emf induced in the machine under on-load condition and it also called as air-gap emf or internal induced emf or internal voltage of synchronous machines [28]. Equation (6) is the internal electrical component of synchronous generator that been described in [23] which be used for developing the VSCon. It can be written as,

$$e = \dot{\theta} M_f i_f \sin\delta \tag{6}$$

All of those stated formulas can be normalized into the inverter control with the grid information have been considered that will result to non-PLL structure to be applied to the system. Therefore, Fig. 4 shows the block diagrams of VSCon in inverter control interface without using PLL structure.

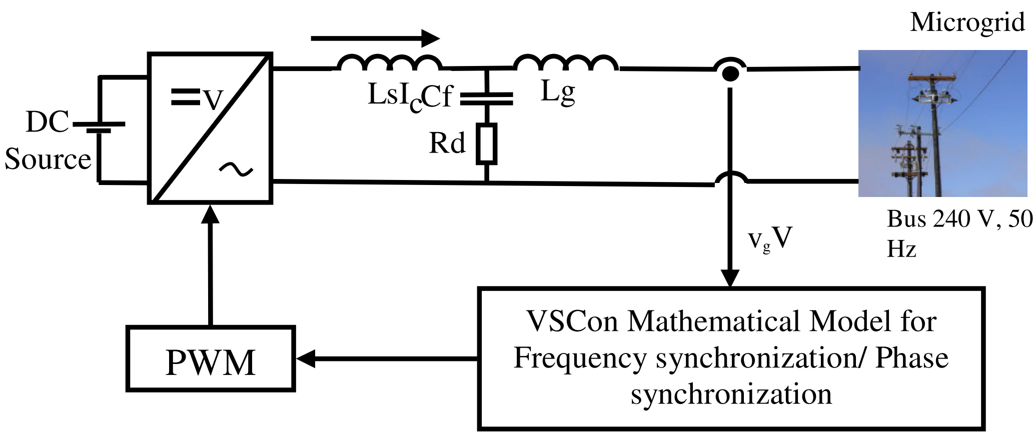

Fig. 4. Block diagram of VSCon without PLL structure.

2.1 Design of Virtual Synchronous Converter (VSCon)

As stated earlier, the VSCon is based on the SG mathematical equations model and then been added with the swing equation into the model. This virtual inertia of rotor is inserted with motor coefficient J in order to have small constant value of virtual acceleration θ that given in (7).

$$J\ddot{\theta} = T_e - T_m = \Delta T \tag{7}$$

Meanwhile, (8) and (9) are for speed and angular value of the SG in order to produce variable T_e in sinusoidal form and the grid voltage or current has to be directly feedback to VSCon,

$$\dot{\theta}(t) = {}^{1}\!/_{J} \int_{\dot{\theta}_{g\min}}^{\dot{\theta}_{g\max}} \ddot{\theta}\, dt \tag{8}$$

$$\delta(t) = \int_{0}^{\theta_{g_0}} \dot{\theta}\, dt \tag{9}$$

Therefore, the integration block is added in order to determine the virtual angular speed θ where it is used to limit the allowable grid frequency or real-time frequency between $\dot{\theta}_{g\max}$ and $\dot{\theta}_{g\min}$ as shown in equation (9). Similarly, phase-angle $\delta(t)$ can be determined by using (10) where θ_g is grid phase-angle voltage.

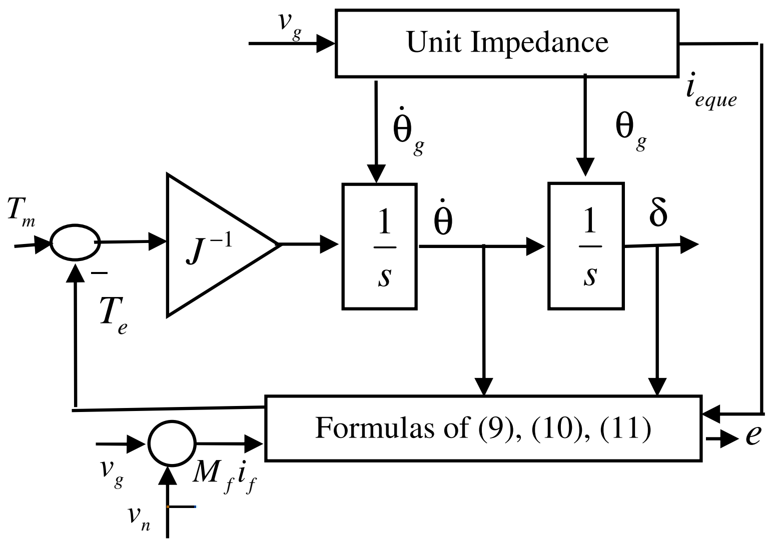

Fig. 5. The VSCon controller connecting microgrid voltage and frequency

Figure 5 shows the model structure of the VSCon that will be developed in the MATLAB in order to test the functionality of the model. It consists of grid voltage phase-angle θ_g while, e is the regulated signal generates from the VSCon which contain the grid voltage information for inverter switching operation. On the right side of Fig 5, the e signal is controlled by field excitation $M_f i_f$. The difference between grid voltage v_g and nominal voltage v_n is taken as for the summation function and then passed through to a constant gain $1/K$ in order to generate the value of $M_f i_f$. At the same time, it also can reduce a quick oscillation in inverter output voltage, which is caused by increasing the magnitude of e signal. By improving this value of the gain based on the voltage, frequency and phase of the grid, the final control equations of VSCon are expressed below,

$$M_f i_f = 1/K\left(v_n - v_g\right) = \frac{\Delta V}{K} \tag{10}$$

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

$$e\left(t\right) = \left(\Delta v\left(t\right)/K\right)\dot{\theta}\left(t\right)\,\sin\delta\left(t\right) \tag{11}$$

In this design, a round-rotor SG has been considered with the purpose of equally distributed inductance and all phases are assumed to be impedance balanced.

3. Results and discussion

The Matlab/Simulink software is used to develop and test the VSCon in order to be implemented in the inverter control for fast self-synchronization between inverter-grid network. Therefore, the mathematical modeling parts of the VSCon will be embedded to the inverter control based on the mathematical equations by following the block diagram given in Fig.5. Firstly, the VSCon has been tested on a rated value of grid voltage of 240V, 50Hz which is connected to an inverter with has a DC supply of 240V in order to see the accuracy of the proposed controller in terms of power transfers at PCC, synchronization time on different loads change. Next the VSCon also has been tested on the changes of the frequency and phase at the grid voltage. For the last simulation test, the nonlinear load has also been included in the system in order to determine the effectiveness of the improve VSCon during load changes.

The loads parameters are given in Table 1 have been set in the MATLAB and been connected to the grid system. The loads are from A.O. Smith Corporation, MegneTek Century Centurion and Hanning Elektro-Werke Morots. These loads are considered as full loaded conditions. These loads are used in order to see any a power flow among the inverter and grid during a change on the loads condition.

Table 1 System Parameters and Loads for power ratting for 240V in 50Hz microgrid

Parameters	Quantity
Ls	4 mH
Cf	7.5 μF
Lg	0.5 Ω
Rd	1.4 mH
Virtual Inertia (J)	0.693 Kg/m2
Nominal frequency	50 Hz
A.O. Smith Motor as Load 1	150 Ω and 1 mH
Hanning Elektro Motors as Load 2	100 Ω and 1.896 mH
MegneTek Motors as Load 3	100 Ω and 1.896 mH
Non-linear load as Load 4	50 Ω
dc-link	240 volts
Switching frequency	5 kHz
Power Converter	H-bridge single phase inverter

Figure 6 (a) shows the current contributed by the inverter when loads 1, 2 and 3 are been connected to the system. At time t=0.08s, load 1 is connected and it consumes nearly 1A current from the inverter. Then, load 2 with 550W and load 3 with 1200W power rating are connected to the grid at the PCC at t= 0.15s and at t=0.35s. As for the grid current flows, Fig.6 (b) shows the current been injected to the PCC when loads are increased. The total currents consumed by the three loads are shown in Fig. 6 (c). At the meantime, the real and reactive power that been injected from the inverter also been analyzed as shown in Figs. 7 (a) and 7 (b) respectively. It shows that, when all the loads are connected to the grid, the inverter injects approximately 1000W and 790VAR on real and reactive power after the synchronization has been established at t =0.08s.

(a)

(b)

(c)

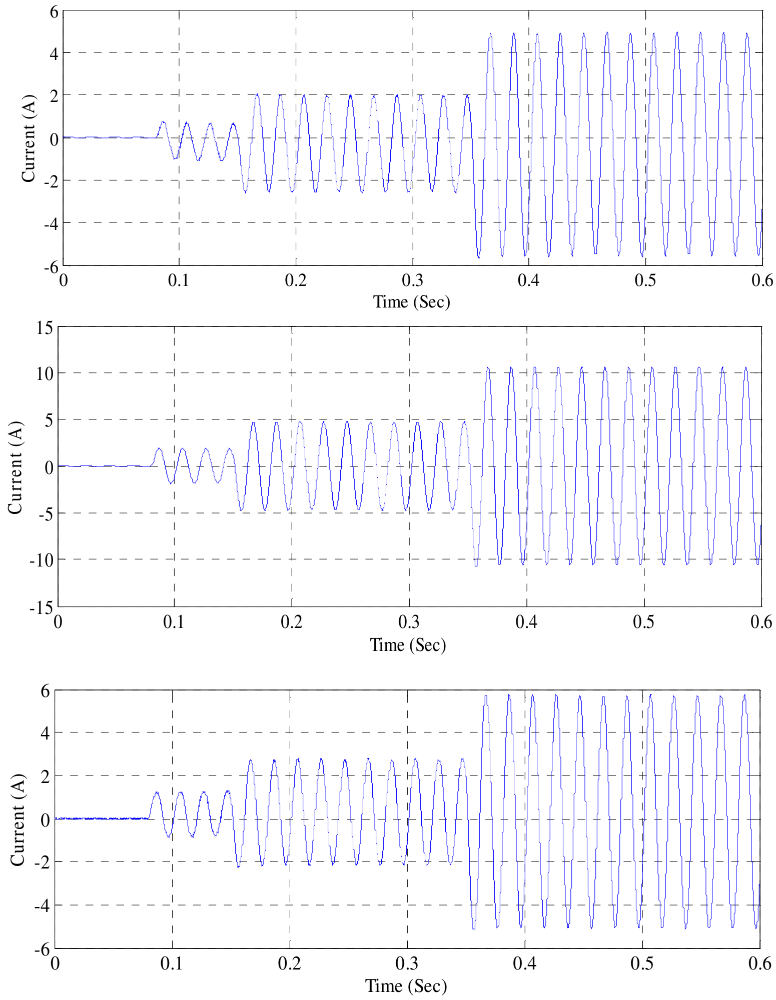

Fig. 6. (a) Current supply by the inverter to the loads, (b) grid current supplied to loads at PCC, (c) total current consumed by loads

(a)

(b)

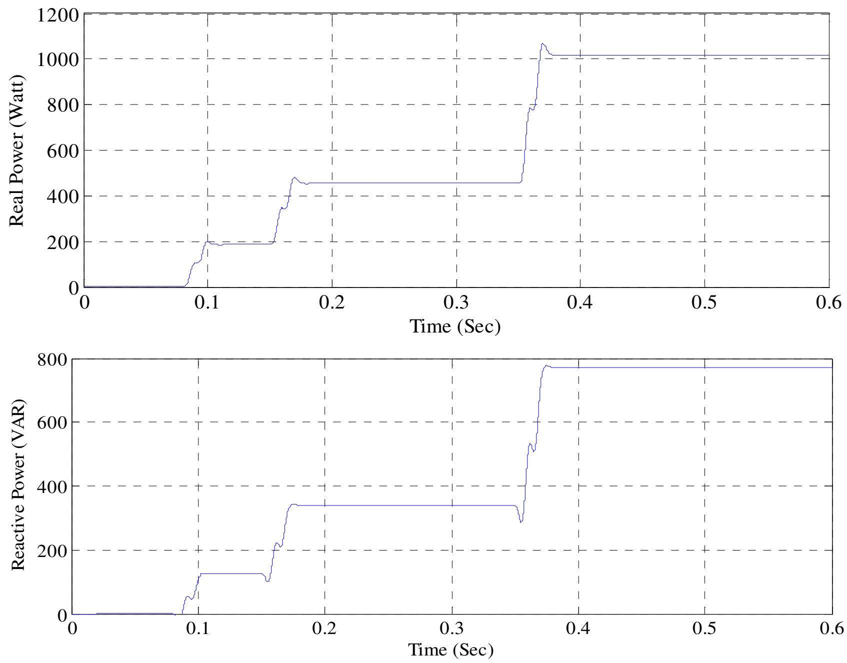

Fig. 7. (a) Real power to loads and (b) reactive power to loads from the inverter

4.1 Automatic Frequency and Phase Synchronization with VSCon

Synchronization is not just about to equal the magnitude between grid and inverter output voltage. It also requires to have phase and frequency tracking capability and at the same time to maintain the synchronization. Since, the VSCon controller signal controls the inverter switching pattern, therefore, the phase angle and grid frequency are also needed to be the input control parameters for VSCon for an accurate switching pattern rhythm that changes according to the changes of phase and frequency grid. This test, has been conducted when the grid frequency has been changed from 50 Hz to 51Hz. For the synchronization event, it has been set at 0.1s after the inverter and grid voltage have been connected. As the result, this VSCon is able to produce 51Hz frequency with an e signal for the inverter control process. Fig. 8 shows the e reference signal is connected at nearly 0.1s just after the connection has been established.

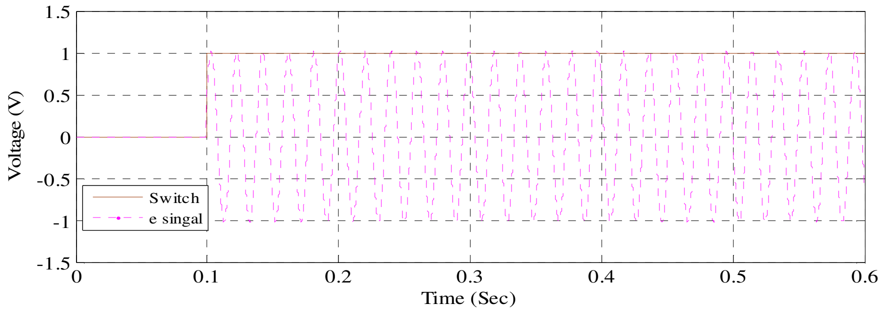

Fig. 8. The VSCon produced e signal is connected at 0.1s

Meanwhile, Fig. 9 shows the grid and inverter voltage before and after synchronization. At 0.1s the synchronization is happen after the circuit breaker has been closed in the simulation and the voltage grid frequency is set at 51Hz frequency. After 0.1s, it shows the inverter voltage is tried to follow the grid voltage but at the same time it creates a ripple signal for nearly half cycle from the grid frequency. This result shows that, the VSCon inverter control strategy is capable to have fast synchronized time. More focused on the synchronization period is shown in Fig. 10 for a period of 0.08s to 0.2s. It shows that, the inverter voltage is having a spike signal up to 300V just after it has been synchronized. This is because the e signal starts to respond to frequency grid. This condition can be improved when the switching pattern is embedded with zero crossing position or by determined the frequency bandwidth of the grid source that is not been discussed in this paper. For example, in Malaysia, TNB allowable frequency is rated at 50±1Hz [5].

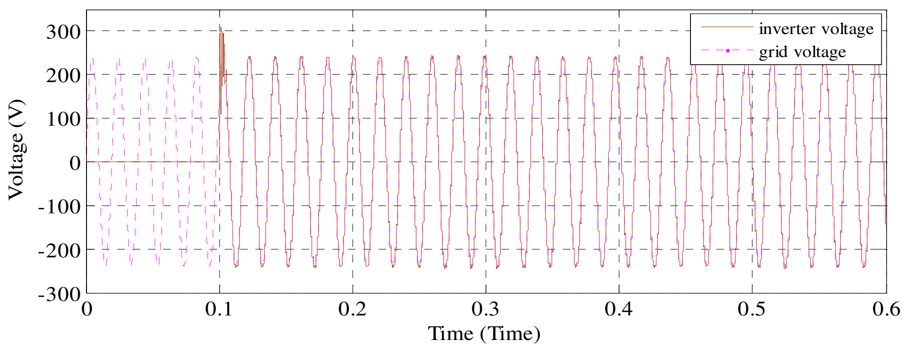

Fig. 9. The microgrid voltage and inverter voltage are synchronized at 0.1s

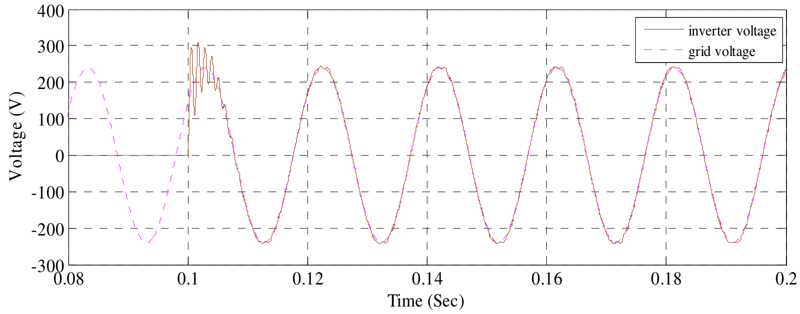

Fig. 10. Time interval of 0.08s to 0.2s is zoomed of Fig. 9.

The following simulation is when grid voltage is having phase delay and has been investigated in order to see the robustness of the VSCon. It is where the grid voltage is having 10^0 phase delay and with 240V, 51Hz frequency system. Fig. 11 shows, the grid voltage is shifted by 10^0 from the rated grid voltage. The same connection time between the inverter and grid at time 0.1s has been used for observing the phase tracking mechanism. When the inverter is being connected to the grid voltage at time 0.1s, the synchronization has immediately synchronized with a short period of time as shown in Fig. 12 where it justify the robustness of the improved VSCon.

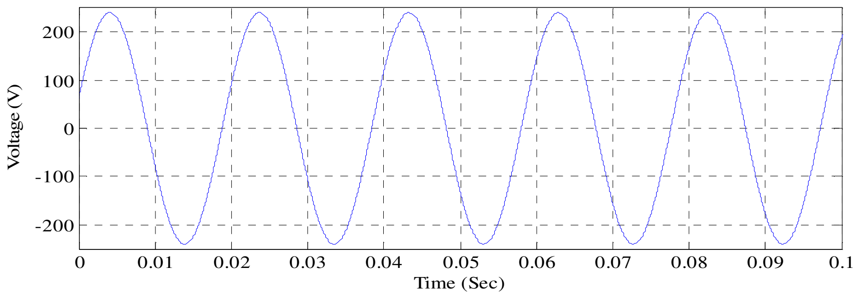

Fig. 11. The microgrid voltage phase is shifted by 10^0 at 51Hz.

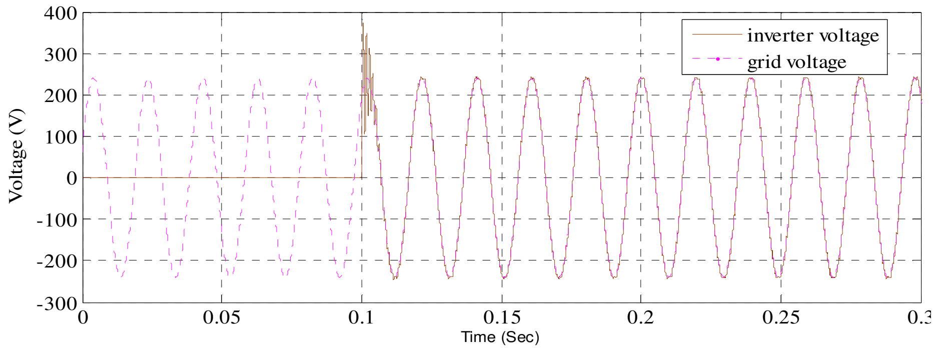

Fig. 12. The inverter and grid voltage are synchronized at 0.1s when voltage phase is shifted by 10^0 at 51Hz.

The loads changes test also has been conducted with the same the phase delay (10^0) and 51Hz frequency are being applied to the grid voltage. As a result, the VSCon inverter control is also able to keep the inverter voltage to be synchronized with the grid voltage.

The loads from Table I are been applied in this simulation test. Load 1 is connected at 0.02s which is drawn nearly 2A current. At the meantime, Load 2 and Load 3 are been connected with the grid at 0.15s and 0.22s respectively. When all three loads are connected with grid, it takes about 11A current to be delivered as shown in Fig. 13.

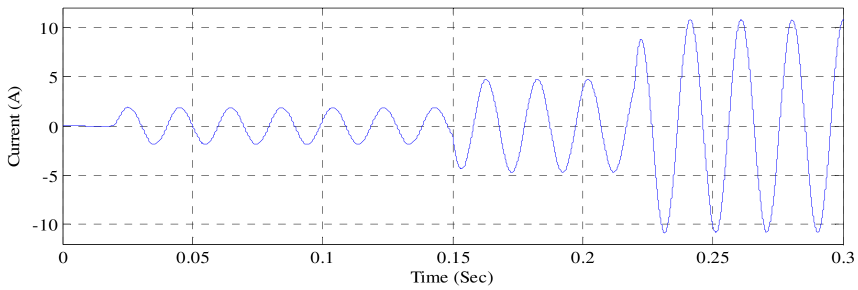

Fig. 13. Load current during loads connected.

Fig. 14 shows the inverter-grid synchronization is unchanged even after the loads are changed throughout the simulation. The synchronization is maintained when after Load 1, Load 2 and Load 3 are been connected with grids at 0.02s, 0.15s and 0.22s respectively. This condition shows that, the load changes are not affected to VSCon control but only to the different on phase, frequency and voltage at the grid.

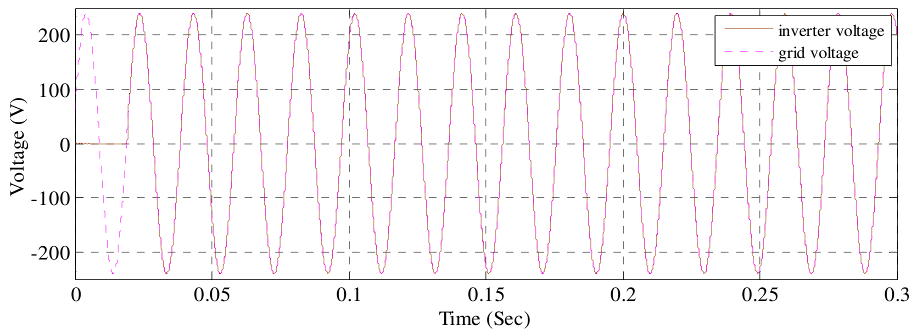

Fig. 14. Grid-inverter voltage respond when Load 1, Load 2 and Load 3 are been connected

Next, a test with a non-linear load has been conducted by introduces Load 4 as mentioned in Table 1. It consists of a 50Ω resistance with four thyristors as shown in Fig 15.

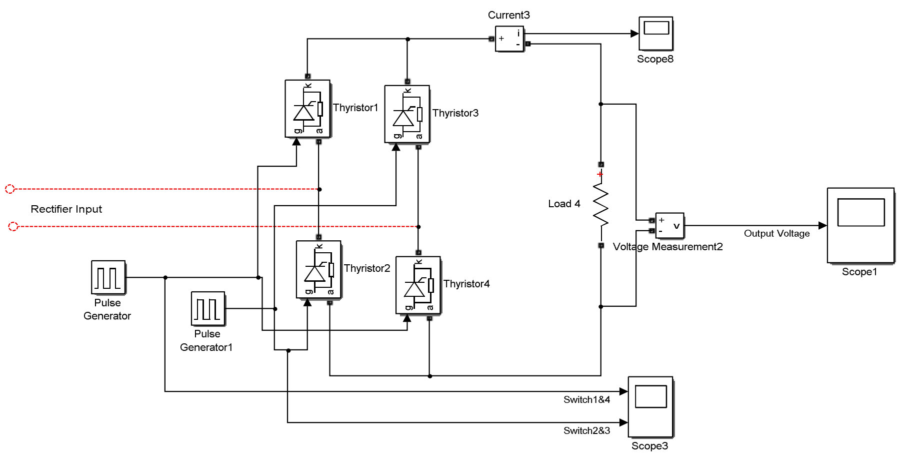

Fig. 15. Rectifier as a non-linear load.

The current consumed by this non-linear is shown in Fig. 16 where it is about 4.5A in discontinuous current mode to the load. Moreover, the voltage drop across the non-linear load is measured in Fig. 17.

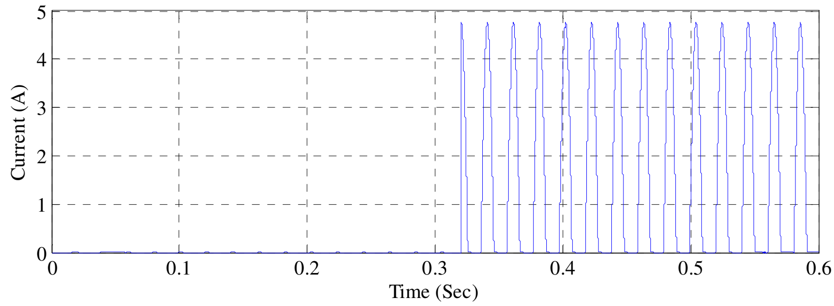

Fig. 16. Non-linear load current

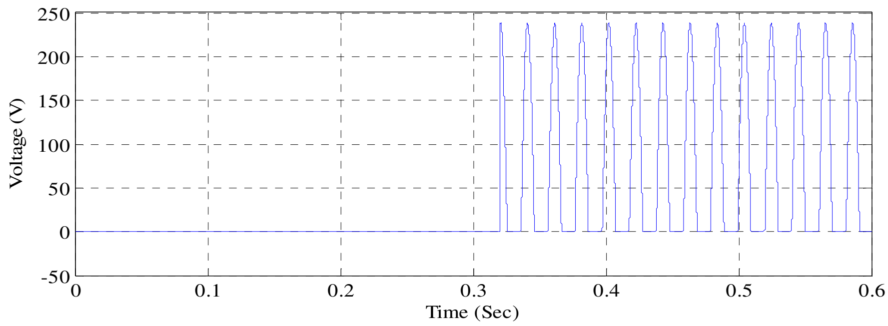

Fig. 17. Voltage drop across the non-linear load

This non-linear simulation test also has been conducted when the grid source is set at 240V, 49Hz frequency with 15^0 phase-angle delay. The result on this simulation is shown in Fig. 18. It indicates, the synchronization has been established at 0.02s without any ripple and it shows how fast the synchronization can happen. Along the simulation process, load 1, load 2, load 3 and Load 4, are been connected at time of 0.02s, 0.15s, 0.25s and 0.32s. It proves that, when connecting the non-linear load at the PCC grid, the synchronization for inverter-grid voltage has maintained/ unchanged and followed the given frequency and phase-angle changes at the time of 0.32s.

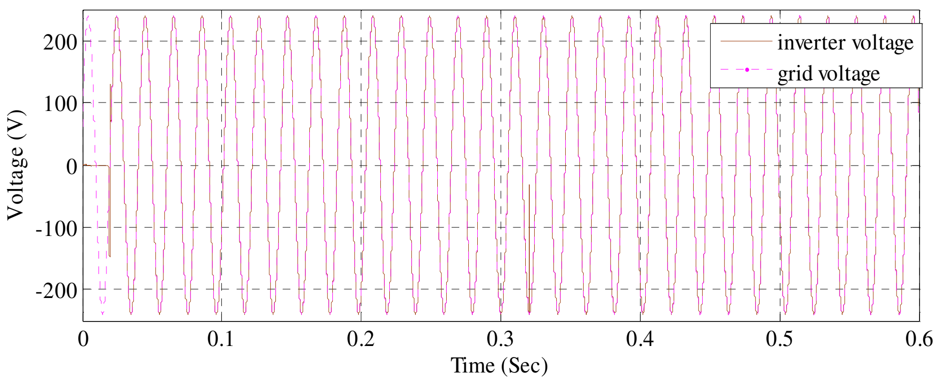

Fig. 18. Grid-inverter voltage while connecting non-linear load

4.2 Comparison of synchronization time between conventional PLL and VSCon

The last simulation test is conducted in order to see the comparison time response between the PLL and VSCon. This comparison has been done with the same structure and time connection in order to see the effectiveness of the VSCon with the PLL.

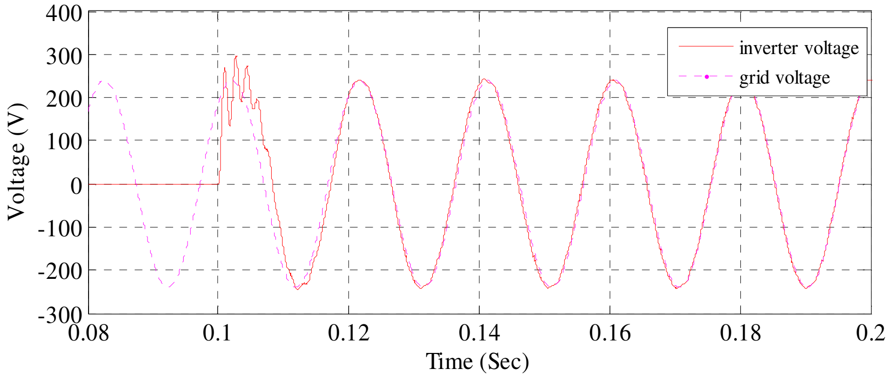

Fig. 19. The inverter is connected with microgrid of 240V at 51Hz at 0.1s and it is synchronized in nearly 0.18s using PLL

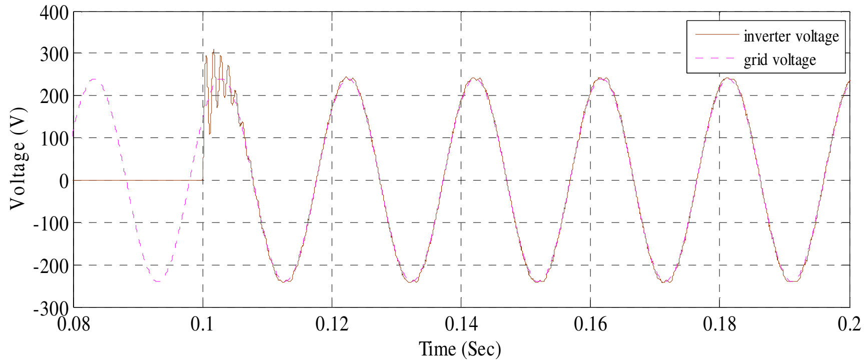

Fig. 20. The inverter is connected with microgrid of 240V at 51Hz at 0.1s and it is synchronized in nearly 0.12s using VSCon

Figs. 19 and 20 show the results on the synchronization time taken when the inverter control is applying the PLL structure and when the inverter control uses the VSCon topology. Both conditions are been tested when the grid frequency is been set at 51Hz. At time 0.1s the synchronization process is been took placed. Fig. 19 is been zoomed at interval 0.2s to 0.4s for clear visualization of both grid and inverter voltage condition in PLL mode. This condition shows that the PLL gives slow synchronize time for nearly about 5 cycles from the grid frequency before it can be maintained. The same interval shows in Fig. 20 when VSCon model has been applied to the inverter control which shows that, during 0.1s, the inverter voltage is trying to follow the grid voltage and creates a ripple signal for only about 1 cycle but then it is maintained the synchronization condition thought the simulation. This condition shows that, the proposed VSCon is able to give fast self-synchronization situation compared to the PLL that will be beneficial to the process of power flows between the inverter-grid at the PCC.

4. Conclusion

As a conclusion, this project shows, the SG model can be used as an inverter control strategy in order to have fast and self-synchronization for the DER source to the existing grid network. As in case, it also can avoid to use any PLL circuitry or other phase detections which requires a complex computational process for the controller design. In addition, if there is a suddenly load change, the VSCon is able to maintain the synchronization for the inverter-grid system. In other cases, when the grid frequency is changed from the rated value, the VSCon also can react quickly to achieve synchronization with minimum period of frequency adaptability by nearly 15ms or even after a non-linear load been connected to the network. Similar result also can be observed, when the grid phase-angle changes from the rated value, this VSCon has able to respond within 2-cycles of the rated grid frequency. However, as compared to the existing PLL based synchronization, it takes approximately 5-cycles for synchronization between inverter and grid. This technique manages to recover the inverter output system frequency to rated frequency level in just of 20ms when the input source phase is changed to 10^0 phase angle delay. Therefore, this improved VSCon which is based to SG can be an alternative method to achieve a fast and self synchronized between the inverter and grid before in order to improve the power flow from the DER to the existing electrical grid network.

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