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Integration of Photovoltaic Energy to the Grid, Using the Virtual Synchronous Generator Control Technique

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Abstract: Renewable energy is becoming more popular due to its benefits for both economic and environmental reasons. Therefore, having a fault free system will enhance efficiency and proper delivery of power. This paper presents the design, modelling and simulation of a Synchronverter, analyzing its fault and response of the system during integration. A synchronous frequency regulator for grid connection is proposed to improve quick recovery, power quality enhancement and good system performance after a fault occurrence. The swing equation provides the inertia and the damping for stability, swift system integration of photovoltaic energy to the grid and an overall effective performance. The effectiveness of the proposed model was simulated in MATLAB/Simulink to analyze the system's response during and after a fault occurrence and photovoltaic integration comparing load change at different times. Simulation results and analysis are presented to validate proposed controller.

Key words: Frequency regulator, inertia, swing equation, stability criterion, Synchronverter, VSG.

Nomenclature

BESS	Battery energy storage system
PV	Photo-voltaic
CB	Circuit breaker
DC	Direct current
AC	Alternating current
FRT	Fault-ride through
MPPT	Maximum power point tracking
VSG	Virtual synchronous generator
SOC	State of charge
THD	Total harmonic distortion
IGBT	Insulated gate bipolar transistor
SG	Synchronous generator
RE	Renewable energy
IEEE	Institute of Electrical and Electronics Engineers
VSM	Virtual synchronous machine
PI	Proportional integral
PWM	Pulse width modulation

1. Introduction

The installations of PVs in the smart grid have risen exponentially due to the impacts on the environment, availability, grid security enhancement, abundance and others making it more popular for economic and environmental reasons [1]. PV plays a key role in the future efficiency and zero emission society, as many countries have installed renewable energy capacity and distributed generator, making a high percentage of the total generation capacity [2]. Power electronic devices like the inverters are used to connect the distributed generators through a common bus.

One of the major problems of renewable energy is grid integration. During the integration of a micro grid to the grid, there arises the occurrence of differences in voltage, frequency and phase which poses so much instability to the system. Overtime a lot of techniques have been used to solve this problem and one of which is the use of the VSG. This control technique has proven to provide more stability and better integration effect due to its inertia and damping property embedded in its controller as compared to the conventional inverter.

In comparison of SG and the conventional power plants, the distributed generator has little, or no damping effect and rotor inertia embedded in it [3].

For energy integration grid tie inverters are used to maximize energy efficiently from the source to the

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supply however this method cannot be proven to be more efficient as it causes disturbance to the power system and not very reliable. There is need for a mutual balance between the supply and demand side of the renewable energy interconnected to the power system [4].

The proposed method by the authors addresses the methodology of the virtual synchronous generator which imitate the synchronous generator essentially adding inertia to the grid, which improves the stability of the power system [5]. First, we design a photovoltaic system and change the way it operates (mimic the synchronous generator) and secondly find a way to integrate these inverters to an already existing power system to act exactly like a large synchronous machine. The damping effect is also taken into consideration as this reduces hunting in the system. The Synchronverter comprises of the inverter which embedded in its controller is the inertia and damping properties also including the filter capacitors and inductors. The mechanical load of the Synchronverter is switched with the DC bus reintegrated with the power. The equations remain the same. We call such an inverter including the filter inductor and capacitors and the associated controller a Synchronverter.

A Synchronverter is equivalent to a SG stator terminal with a parallel connected capacitor bank. A Synchronverter has all the disadvantages and advantages of a synchronous generator. It is a nonlinear system with harmful phenomena such as instability because of under excitation and hunting (oscillation of the rotor about its final equilibrium position) which takes place in a Synchronverter.

One of the advantages is that the Synchronverter parameters can be chosen such as mutual inductance, inertia and friction coefficient. Energy is not also lost in the virtual mechanical friction. It is reverted to the DC common bus [6]. Also increasing and decreasing of the accelerating torque through the control of the mechanical prime mover is an important factor of transient stability enhancement.

IEEE explains a Synchronous Generator [7-11] as a self-commutated converter which functions to give a modified multiphase output voltage, for separately switching of regulated reactive and active power. This paper also considered the fault ride through for PV output power recovery which is 80% of the total power within 0.1 sec [12].

The rest of the paper is organized as follows: Section II gives a review of the DC/AC hybrid micro-grid model, which consists of the PV, with its MPPT, battery management system which is charged by the buck boost converter during low radiation of solar intensity and the boost converters which steps up input voltage from the PV. Section III explains how the inverter imitates the synchronous generator, the advantages as compared with a conventional inverter, implementation of the Synchronverter, principles and operation. Section IV presents the stability analysis criterion. Section V shows the simulation results with its different scenarios while Section VI gives the conclusion.

2. Review of the Hybrid DC/AC Microgrid Model Conversion

In photovoltaic energy systems to convey energy from the solar panels to the grid, power electronics devices are used as it ensures maximum power tracking of current and voltage. Therefore, utilizing this energy from the sun some converters and a battery management system was considered for optimal efficiency.

2.1 Photovoltaic System

Basic equations of the PV are used for modelling and simulation of the PV array on Simulink. The boost converter is connected to the PV to step-up and stabilize the input voltage from the PV. Although PV voltage range has impractical limited range, but the PV voltage variation value given as 350V - 370V in this paper is used for simulation. The step-up converter increases and maintains the voltage for the required input voltage needed for the inverter.

2.2 Storage Battery System

The lithium battery is connected to the bi-directional converter which allows for two-way charging of the lithium battery during high and low solar intensity respectively. The varying DC voltage V_{DC} is subdued by a droop control. The proportional integral generates the current command I_B which is used to set the state of charge for the battery [6].

The output active power of the PV is dependent on the solar radiation and temperature for power generation. The lithium battery is used for power compensation during low solar radiation. This in turn smoothen the real power output and minimizes adverse impact on the grid.

The controller for both the boost converter and bi-directional converter can be seen in Fig. 1 and Table 1 shows the given parameters of converters used for modelling. The transfer function of the two converters are attained to get the PI for the control of voltage and current as seen in Fig. 1, the boost converter is controlled by the voltage controller and the bi-directional converter is controlled by the current controller.

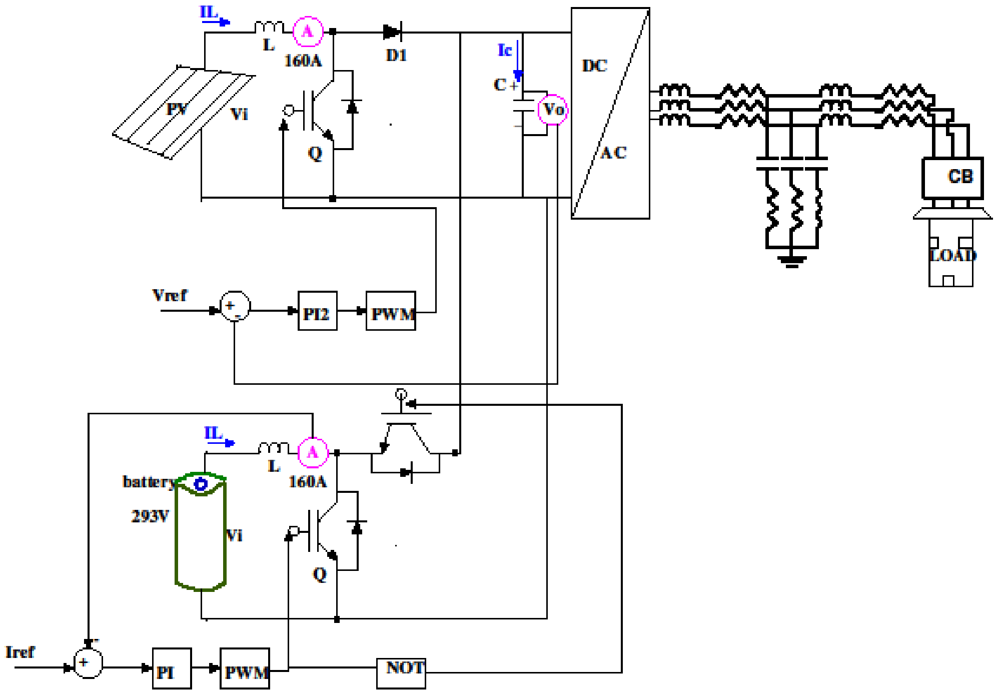

Fig. 1 A detailed model of the micro grid.

Table 1 Given parameters of converters.

Boost	Value	Buck boost	Values
Voltage output	400 V	Voltage output	400 V
Switching freq	10 kHz	Switching freq	10 kHz
Efficiency	0.9	Inductor	6 mH
Voltage min	330 V	Resistor	0.5 Ω
Voltage max	370 V	Capacitor	470 µF
Current output	160 A	Output current	160 A
Resistor	2.5 Ω	Duty cycle	0.3
Inductor	6 mH	Battery voltage	293 V
Capacitor	470 µF	Battery capacity	2.3 kWh
Duty cycle	0.7	Duty cycle	0.3

3. Synchronverters

Inverters that imitate the synchronous generator to add inertia in electrical power systems are called Synchronverters. Conventional inverters have little or no inertia which during sudden changes i.e. solar radiation variations or faults, follows changes quickly and sometimes results in a bad condition i.e. collapse of the micro-grid but the synchronous generator has much stability due to its inertia property. The synchronverter can emulate virtual inertia by using small amounts of stored energy controlled by a power electronics converter [13]. Inverters are used to integrate photovoltaic energy to the grid, but this could disturb the stability of the grid as the two systems have different characteristics, also the conventional inverter during low radiations shows great instability which is seen in the simulated results for the conventional inverter therefore using Synchronverters can help in modelling grid by changing the inverter model with the synchronous generator model [7].

3.1 Implementation of Synchronverter

Fig. 2 shows how to implement a Synchronverter. An inverter is used to convert DC to AC power. It includes six switching devices and an LCL filter to reduce voltage and current ripples caused by the switching of the IGBT. Although the LCL filter has an acceptable current ripple attenuation even with little inductance value, however it can cause instability to the system. So therefore, the LCL filter was designed to fit the Synchronverters parameter specification. Basically, the Synchronverter comprises of two main parts, the electronic part and the power part as shown below.

The preferred synchronous internal voltage V from the electronic part is the input of the power part. The inverter creates three phase voltage high switching signal [1] V_1, V_2, V_3. These switching voltages are furnished to the LCL filter as seen in Fig. 2. The LCL filter is considered in this paper as it reduces high ripple current and the losses are low.

Table 2 shows the parameters used to model the Synchronverter. A neutral line can be added if needed. The power segment of the Synchronverter is the left side which includes the three inductors and the capacitors. If the ripples of the power part are neglected, then the circuit will act like a synchronous generator connected in parallel with the capacitors. The characteristics of almost all the control components are non-linear. Therefore, for this analysis we approximate all component of the LCL filter to make it a single inductor component L_s and resistance R_s. It is important to note the three inductors play a vital role of acting as the stator coils in the synchronous generator. The main objective of the Synchronverter algorithm is to make the inverter act like a synchronous generator [1].

$$L_s = L_i + L_g \quad (1)$$

$$R_s = R_i + R_g \quad (2)$$

Fig. 3 shows the electronic part of the Synchronverter which is a digital implementation as it

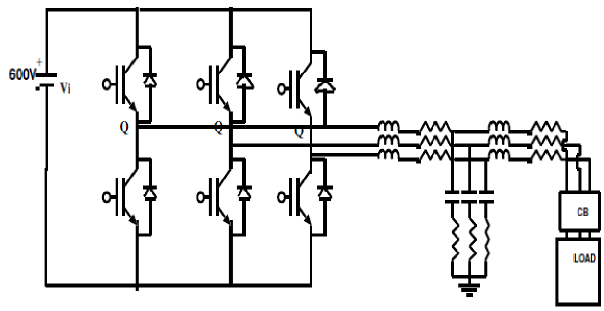

Fig. 2 Power segment of the Synchronverter [5].

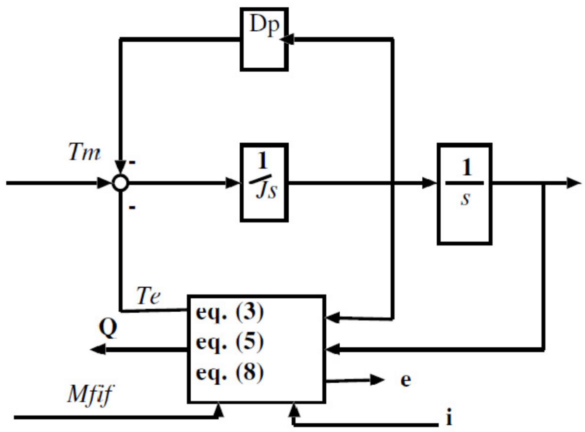

Fig. 3 Synchronverter electronic part segment.

decodes the equations of the synchronous generator model and generates the vector measurement v and i from P and Q which are the active and reactive power respectively for the reference signal. This aims to generate the voltage V with the given equations as seen in Fig. 3.

e can be expressed as thus:

$$e = M_f\, i_f\, \omega \sin\theta \quad (3)$$

The active and reactive power P and Q produces the internal synchronous generator voltage e is given as;

$$P = \theta\, M_f\, i_f \langle i_f \sin\theta \rangle \quad (4)$$

$$Q = -\theta\, M_f\, i_f \langle i_f \cos\theta \rangle \quad (5)$$

The real and reactive power which is expressed in d, q coordinates, corresponds with the conventional definition. The inductive load corresponds with the positive Q. It is important to note that if $I = i_0 \sin\varphi$ for the angle φ this would be a stable steady state operation with θ-φ [5] therefore the equation becomes

$$P = \theta\, M_f\, i_f \langle i_f \sin\theta \rangle = 3/2\, \theta\, M_f i_f\, i_0 \cos(\theta-\varphi) \quad (6)$$

$$Q = \theta\, M_f\, i_f \langle i_f \cos\theta \rangle = 3/2\, \theta\, M_f i_f\, i_0 \sin(\theta-\varphi) \quad (7)$$

When controlling the real and reactive power of the synchronous generator the above equation is used.

To carry out the frequency control in a Synchronverter, the swing equation is converter to:

$$J\theta = T_m - T_e - D_p\, (\theta-\theta r) \quad (8)$$

$$D_p = D_{p0} + D_{p1} \quad (9)$$

where D_{p0} is the damping effect factor and D_{p1} is the droop coefficient.

The controller for the virtual synchronous generator is seen in Fig. 4 with the given equation:

$$P_m = P_o + P_{ref} \quad (10)$$

$$P_o = K_p \cdot (\omega_{ref} - \omega) + K_I \cdot \int (\omega_{ref} - \omega) dt \quad (11)$$

the primer power and reference power of the virtual synchronous generator P_m and P_{ref} respectively. ω and ω_{ref} is the rotating speed of rotor and angular velocity which equates the electrical angular velocity in the case of a pole pair.

$$T_j \cdot d\omega/dt = P_m - P - K_d\, (\omega - \omega_{ref}) \quad (12)$$

where T_j is the inertia time constant, P is the output active power and K_d is the damping coefficient.

$$E = (Q_{ref} - Q) \cdot PI + (U_{ref} - U) \cdot K_{ev} \quad (13)$$

For Eq. (13), Q_{ref} and Q are the reference reactive power and output of the Synchronverter. The voltage regulation coefficient is given as K_{ev}. The swing equation to be the induced electromotive force of the virtual synchronous generator is given as phase θ copulated with E.

The equation for the stator voltage can be expressed as:

$$V_d = E_d - i_{od} R_v - L v_s i_{od} + \omega L v i_q \quad (14)$$

$$V_q = E_d - i_{od} R_v - L v_s i_{od} + \omega L v i_q \quad (15)$$

Fig. 4 shows the controller of the virtual synchronous generator which was implemented for the research. It comprises of three parts, the frequency regulator which covers the angular speed, velocity and primer power. The swing equation which covers the virtual rotatory aspect including the inertia and damping which are the key factors for the VSG stability and finally the stator voltage equation which is the conventional grid tie inverter equations.

For the conventional grid tie inverter, the control technique used is called the decouple control. This technique is such that the three-phase voltage on the load bus is calculated and converted into I_d and I_q [4]. Comparing the respective reference I_d and I_q with the d_q components, the given errors from the comparison are sent to the PI controller whose function is to adjust and produce the needed output voltage of the inverter.

Decoupling hinders unwanted energy transferred between electrical devices as seen in Fig. 5.

4. Stability Criterion

For the virtual synchronous generator, stability analysis is very important as it ensures constant efficient delivery of power. The transfer function of the system was used to obtain the bode plot and root locus stability analysis used in this paper.

For a system to be stable the gain margin should be greater than zero and the root locus shows the poles located on the left side of the Cartesian plane i.e. X-axis which shows stability of the system. For this system, the gain margin is infinity and the phase

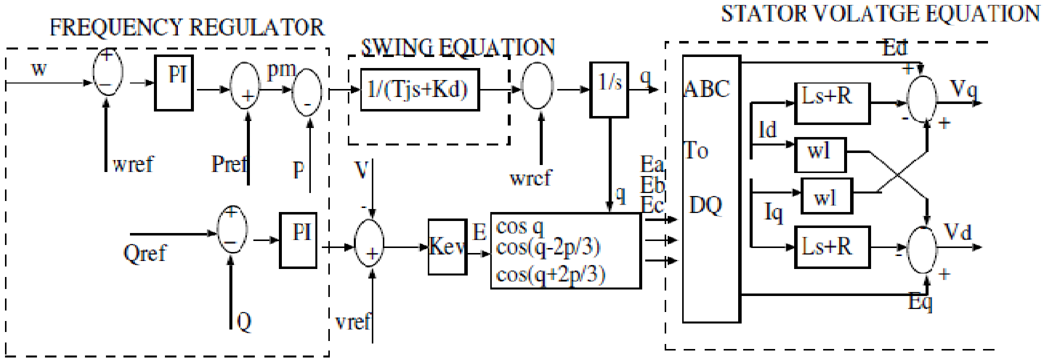

Fig. 4 VSM proposed voltage controller.

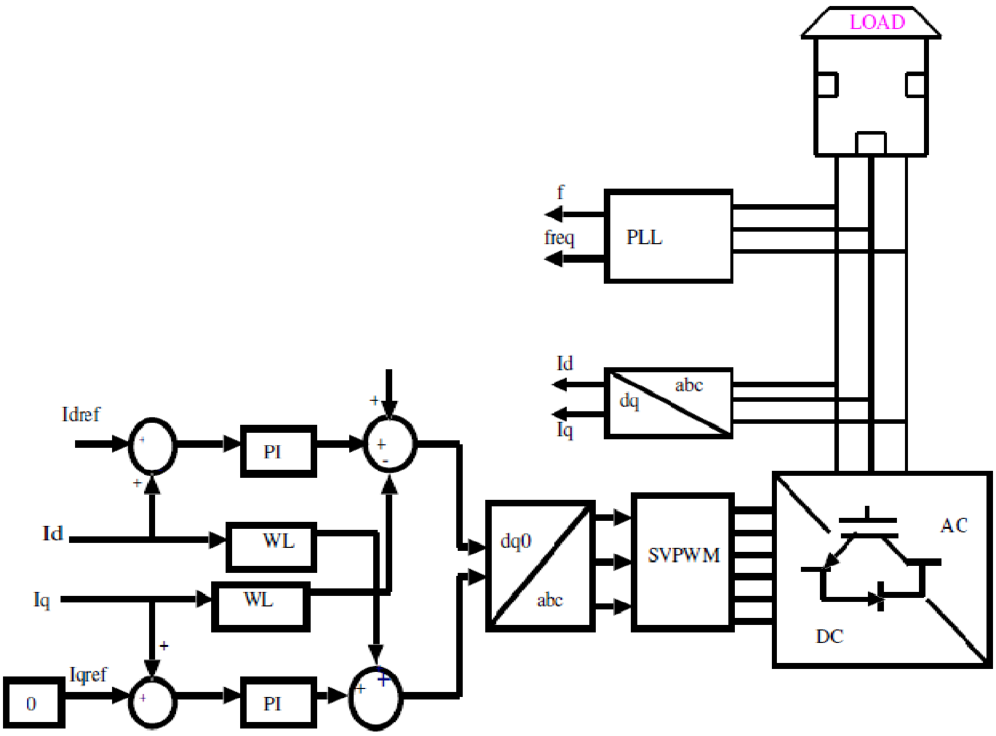

Fig. 5 Conventional grid-tie inverter controller.

margin is 82.7. As seen in Fig. 6, increase in gain does not affect stability of the system. The response of the control system depends on PI gains, using bode to analyze VSG stability the stable conditions are given as:

- For stability in a system the gain margin must be less than the phase margin or we can say the both margins should be positive;
- For a marginally stable system the gain margin must be equal to the phase margin or both margins should be zero;
- For unstable systems the gain margin should be greater than the phase margin.

5. Simulation Results

SCENARIOS 1-4, compare the integration effect and fault analysis of the conventional inverter and the Synchronverter at the same PV radiations and load change. It also shows the total harmonic distortion which represents power factor, peak current and efficiency in power systems and this was used to analyze the conventional inverter and Synchronverter respectively.

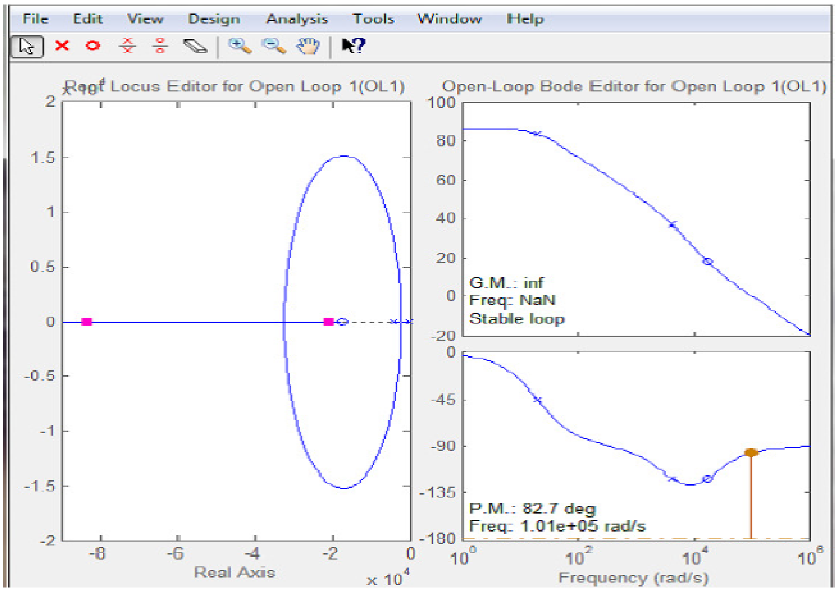

Fig. 6 Sisotool stability analysis.

Table 2 VSM parameters for the inverter.

Parameters	Symbols	Values
Inductance	L_s	2.2 mH
Resistance	R_s	0.075 Ω
Capacitance	C_s	20 µF
Damping coefficient	K_d	1.7
Inertia	T_j	0.2 kg/m^2
Pole pair	P	4
Frequency	F	50 Hz
Speed	N	1,500 rpm
Active power	P_m	90 kW
Reactive power	Q	40 kW
Voltage reg coefficient	K_{ev}	0.1759

SCENARIO 1: Integration effect and load increase of the conventional inverter.

Integrating two different systems with different characteristics causes great instability in the power system. In this analysis the inverter is integrated with the grid at varying loads both the conventional inverter and the Synchronverter have the same PV radiations and load change.

- The simulation starts with a load of 80 kW;
- At t = 0.5 s an additional load of 10 kW is added.

From the simulated result, integration of the inverter to the grid causes great instability effect to the entire system. Furthermore, the PV radiation varies during the day and night time from t = 0.2-0.4 s and this effect is seen to cause instability as seen in Figs. 7 and 8 which show the active and reactive power of the PV and grid. Solar panels will not produce reactive power being a DC generator, however, by using power converter and converting the same to AC power, reactive power was generated. The Synchronverter acts like a synchronous generator in which to convert electrical energy into rotational energy, magnetic field must be created in between the gaps of stator and rotor of the motor. Hence, some amount of energy must be used in creating magnetic field. The portion of power that contributes in creating magnetic field is known as

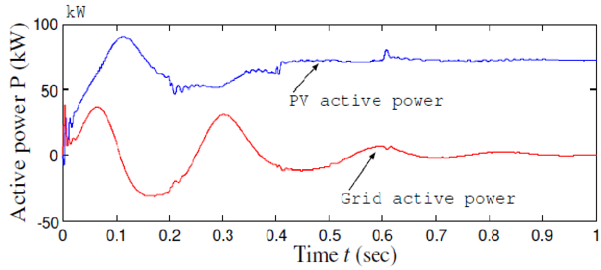

Fig. 7 Active power of PV and grid.

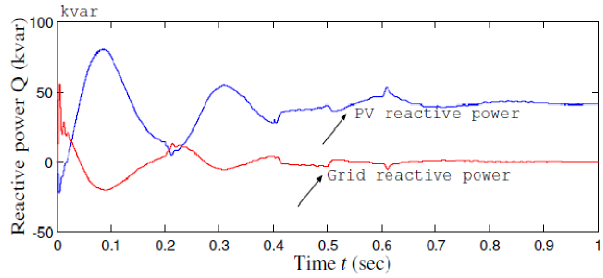

Fig. 8 Reactive power of PV and grid.

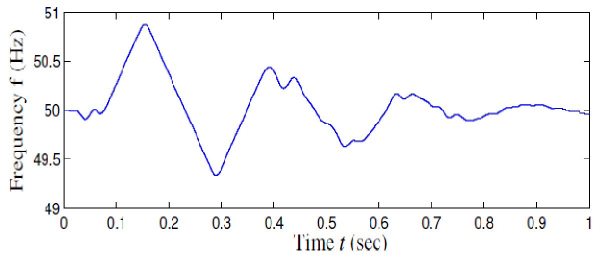

Fig. 9 Frequency.

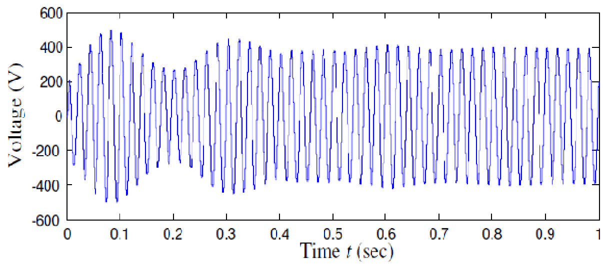

Fig. 10 Voltage.

reactive power. In Fig. 9, frequency varies rapidly which is due to the instability. Although the conventional inverter generates more power than the Synchronverter as there are no many losses that occur, the inverter gives a very high current output and a varying voltage as seen in Fig. 10 which is not good for electrical energy transmission.

SCENARIO 2: Integration effect and load increase of the Synchronverter.

Integration of the Synchronverter to the grid gives a better stability than the conventional inverter from the simulated results. Moreover, the varying radiation of the PV does not affect the stability of the Synchronverter due to its inertia property.

- The simulation starts with a load of 80 kW;
- At t = 0.5 s an additional load of 10 kW is added.

The DC bus supplies 600 V from the PV/Battery system, this acts as the mechanical prime mover. The Synchronverter operates at a constant load of 70 kW from t = 0-0.5 s at t = 0.5 s an additional load of 10 kW is added this caused a drop-in frequency and voltage for both the Synchronverter and grid at t = 0.5 s as seen in Figs. 11. Fig. 12 shows the reactive power of the PV and grid. Irrespective of the changes of both load and PV variations there is still great stability in the system as compared to the conventional inverter although more power is lost due to all the losses that occur in a synchronous generator. Increase in load demand decreases frequency of the Synchronverter which stabilizes because of the inertia property as seen Fig. 13. The relevance of speed measurement is important for this analysis as it guides on how much torque input into the generator from the prime mover, just like a synchronous generator when the speed at the rotor decreases due to load increase the mechanical power will automatically increase its speed to overcome the immediate power imbalance of demand and supply, and finally attain a constant speed in Fig. 14. This is due to the rotational inertia and droop speed control applied. Also, the line voltage of the Synchronverter is stable as seen in Fig. 15, which shows it is good for energy transmission compared to the conventional inverter.

SCENARIO 3: Fault analysis of the conventional inverter.

In this case we observe the behavior of the frequency, voltage and power at both the grid and PV when fault occurs, and the circuit breaker trips off at t = 0.7 s and the fault is rectified at t = 0.8 s also considering the fault ride through standards which

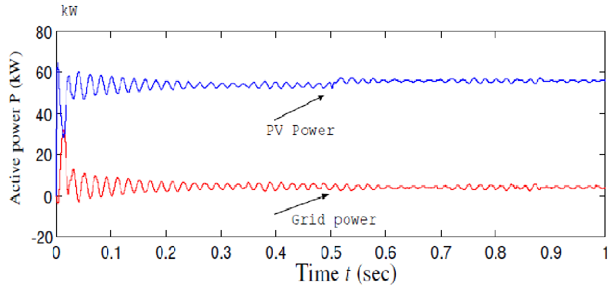

Fig.11 Active power of PV and grid.

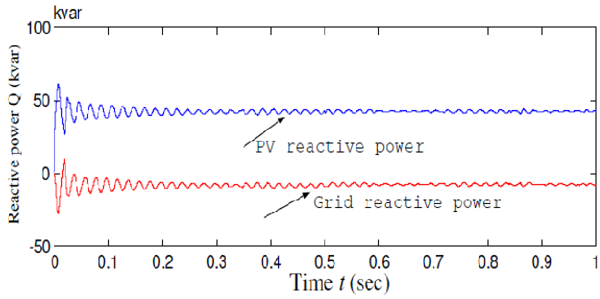

Fig. 12 Reactive power of the PV and grid.

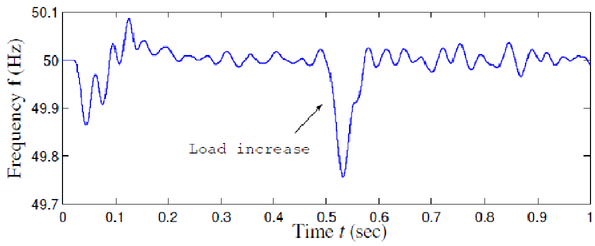

Fig. 13 Frequency of the Synchronverter.

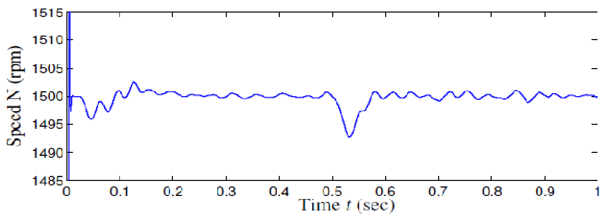

Fig. 14 Speed of the Synchronverter.

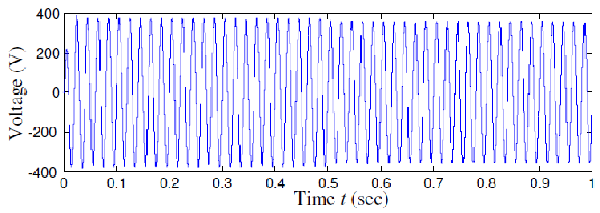

Fig. 15 Line voltage.

recovers output power being more than three-quarter of the total power within 0.1 sec:

- At t = 0.7 s fault occurs;
- At t = 0.8 s fault is rectified.

For Case 3, fault occurs at t = 0.7 s and is rectified at t = 0.8 s the fault ride through for Japan allows 80% of the total power within 0.1 sec. In Fig. 16 the active power of the PV during the fault cuts off from the grid acting as a standalone system and still supplies power to the load until the reconnection when it is integrated back to the grid. Figs. 17 and 18 show the frequency and voltage of the inverter respectively during the time of fault occurrence no variations on the line voltage. Fig. 19 shows the total harmonic distortion which is slightly close to the IEEE standards of 5% and its higher value is not good for the power system.

SCENARIO 4: Fault analysis for the Synchronverter.

In this case we observe the behavior of the frequency, voltage and power at both the grid and PV when fault occurs, and circuit breaker trips off at t = 0.7 s and the

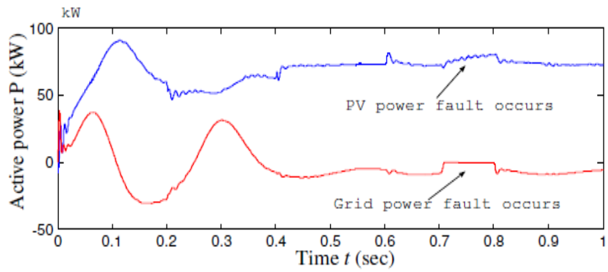

Fig. 16 Active power of the conventional inverter.

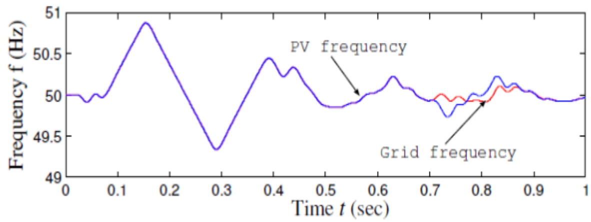

Fig. 17 Frequency of the inverter.

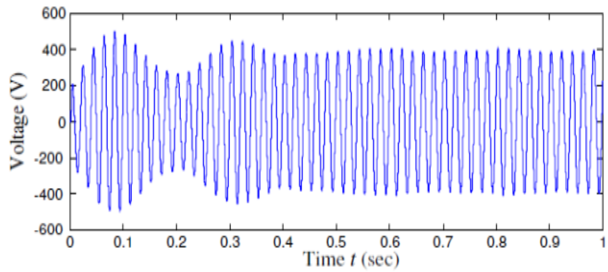

Fig. 18 Voltage.

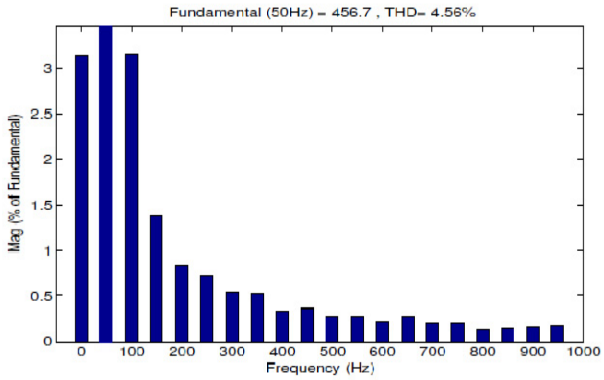

Fig. 19 Total harmonic distortion.

fault is rectified at $t = 0.8$ s considering the fault ride through standards which recovers output power being more than three-quarter of the total power within 0.1 sec.

- The simulation starts, and fault occurs at $t = 0.7$ s;
- At $t = 0.8$ s the fault is rectified.

In this case, fault occurs in the system at $t = 0.7$ s which trips off the circuit breaker and cuts off the Synchronverter from the grid. Fig. 20 shows no power flow from the Synchronverter to the grid. Fig. 21 shows the frequency of the both the grid and Synchronverter. The Synchronverter frequency goes below the minimum frequency range and causes collapse of the system, i.e. no power flow from the Synchronverter to the grid which causes a decrease in rotational speed in Fig. 22. The line voltage of the Grid increases during this time as the Synchronverter acts as a load to the grid. Figs. 23 and 24 show the Synchronverter line and phase voltage cut off. Fig. 25 shows a lower total harmonic distortion which means higher power factor, lower peak current and higher efficiency and it also corresponds with the IEEE standard of total harmonic distortion below 5%.

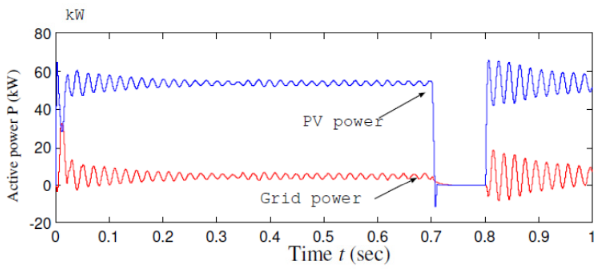

Fig. 20 Active power of the Synchronverter and grid.

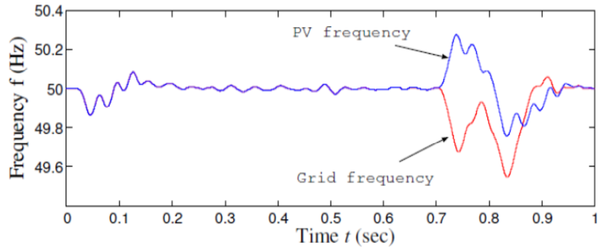

Fig. 21 Frequency of the Synchronverter.

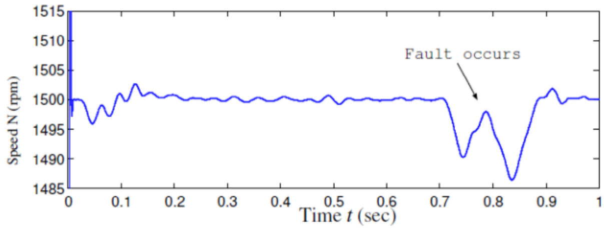

Fig. 22 Speed of the Synchronverter.

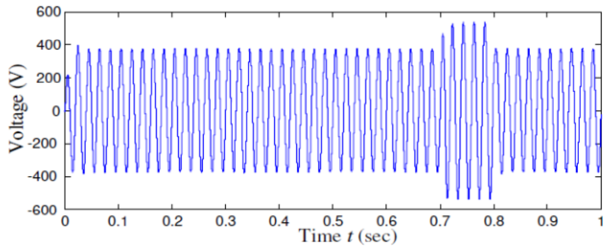

Fig. 23 Voltage of the Synchronverter.

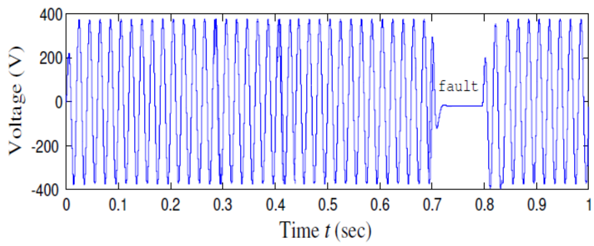

Fig. 24 Voltage of the grid.

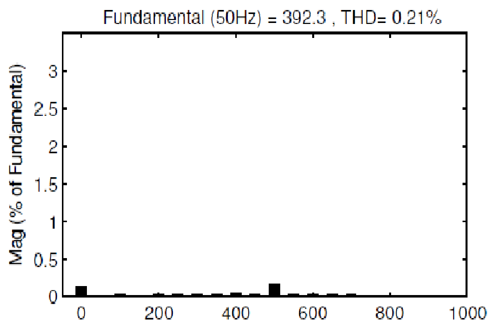

Fig. 25 Total harmonic distortion.

6. Conclusion

This paper addresses the use of the Synchronverter as a control technique for micro-grid integration. This control method realizes a friendly interaction between the microgrid and the main grid. It also provides a greater stability than the conventional voltage source inverter, considering the rotor inertia and damping properties embedded in the controller which are major properties of the synchronous generator for stability. The outcome of the simulation results shows a better stability and reliability of the synchronverter during integration and fault occurrence.

Although the conventional inverter provides a little more power than the Synchronverter, but it is more unstable and as such cause more disturbance to the grid during integration, However the synchronverter provides stability and reliability as it can quickly recovery from a fault and still attain stability.

The implementation and operation of the Synchronverter which includes integration effect, power regulation and fault analysis has been developed and described in detail, in this research.

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