AUTONOMOUS SOLAR PV-ARRAY FED INVERTER EXCITED WIND DRIVEN INDUCTION GENERATOR FOR OFF GRID APPLICATION

S.Sruthi[1]

[1]*Academic Consultant, Dept. Of EEE, SOE&T, SPMVV, Tirupati, AP, India*

Abstract - *Isolated renewable energy systems that is based fully on renewable resources but at the same time reliable is necessary for meeting the power demands of remote places where utility grid is not available and for which hybrid wind-solar systems plays a crucial role. In this paper, a simplified control scheme has been presented for a stand-alone hybrid PV array-excited wind driven induction generator considering a three phase variable load with or without unbalance. The proposed scheme exploits the ruggedness and cost-effective induction generator as a viable alternative for an expensive permanent magnet synchronous generator (PMSG) which is invariably used in stand-alone small wind turbines. Any stand-alone system employs a battery, however the system is suppose to deliver power even in the absence of battery and the battery less mode of operation is presented in this paper. The control scheme has been validated with simulation as well as hardware results. Extensive field test has been performed using a 2.4 kW PV panels, 2.2 kW Wind turbine emulator and weather stations for performance evaluation. The validation results have been presented which shows the proposed scheme is expected to be an attractive solution for remote application where utility grid is either not feasible or not economical.*

Key Words: Solar Energy, PV Array, Wind Energy, Wind Turbine, Inverter, wind driven Induction Generator, Off Grid.

1. INTRODUCTION

Over 400 million people in India, including 47.5% of those living in India's rural areas, still has no access to electricity. Because of the remoteness of much of India's un-electrified population, renewable energy can offer an economically viable means of providing connections to these groups. There is a strong need for off grid power generation, to cater those sectors, where either grid extension is either not feasible or not cost effective. Isolated renewable energy systems that is based fully on renewable resources and at the same time reliable is necessary for meeting the power demands of remote places where utility grid is not available. For which hybrid wind-solar systems play a crucial role. Since solar and wind have inherent complimentary profile, it becomes an attractive choice for a hybrid renewable energy scheme.

Normally in hybrid wind-solar schemes, PMSG (permanent magnet Synchronous generators), is invariably used as the wind driven generator especially for a standalone applications. In such hybrid schemes based on PV and wind driven PMSG, the varying amplitude varying frequency of the stator voltage of the PMSG and the variable dc voltage of the PV array have to be suitably conditioned using complex power-electronic interfaces. However, for any off-grid system, it is desirable to install components and their associated controls that are maintenance free and economical. In this context, hybrid system employing a dc-dc converter fed 3-phase Voltage Source inverter (VSI) as power interface stage, battery charged by solar photo voltaic cells (PV) and the PV excited Induction Generator (IG) driven by wind have been reported.

The three phase Load, output of IG and output of the VSI forms a Point of Common Coupling (PCC). This hybrid scheme can operate to supply the required load even in the absence of battery. However in this work, a fixed resistive load has been considered for the controller design as well as unbalance in load has not been considered. Further to this, hybrid scheme based on PV and IG reported need a utility grid for its operation. Most of them employ a doubly fed induction generator, which is once again expensive. It is attempted to develop a robust and reliable control scheme for autonomous hybrid system based on PV source and wind driven induction generator that can provide continuous regulated three phase output voltage for all types of load with or without unbalance.

In the present work, a simplified controller for with battery and battery less mode operations has been developed for a PV fed Boost Converter fed Inverter excited wind driven IG scheme (PVEWIG) to regulate the inverter DC link in the absence of battery. In this scheme, a three phase variable resistive as well as inductive load with or without unbalance has been considered. The proposed controller ensures voltage regulation of DC link and improves the power quality parameters at point of common coupling (PCC) under varying irradiation, temperature of PV array and wind speed variation in the wind generator. The proposed scheme has been implemented in hardware using a 2.4 kW PV array and a 2.25 kW Wind turbine emulator driven SCIG.

2. POWER CIRCUIT ARRANGEMENT OF THE PV ARRAY FED INVERTER EXCITED WIND DRIVEN IG

The PVEWIG system consists of PV array, dc-dc converter, battery, 3 leg inverter, wind driven three phase squirrel cage induction generator and a non-linear load. The PV array feeds a dc-dc boost converter. The voltage across the dc-dc boost converter is connected to a battery, which is inverted by a three phase inverter and the IG is integrated to the inverter output and is locked to inverter voltage and frequency. The IG would require reactive power which it would normally draw from a utility grid in a grid connected scheme. In the present scheme, the reactive power required by the induction machine is supplied by the PV array fed inverter.

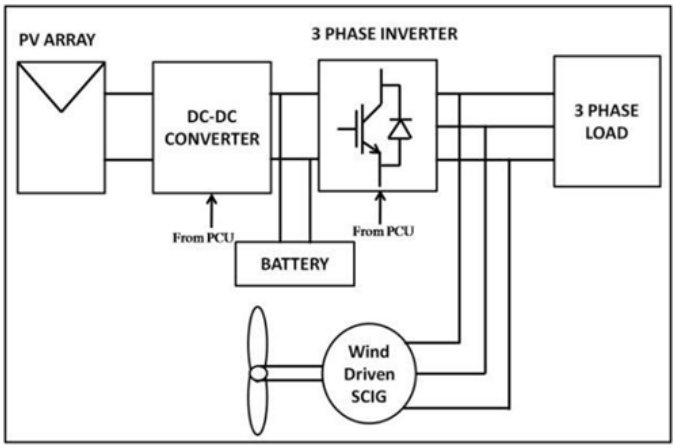


Fig-1: Block diagram of the Power Circuit for PVEWIG System with Battery

The output of the inverter acts as a virtual grid providing a constant voltage and frequency. The three-phase load is connected to inverter output and is supplied by PV-IG and battery or PV-IG, the load-sharing being dependent on irradiation and wind speed. The inverter output, IG output and load forms the point of common coupling (PCC). The block schematic of the entire PVEWIG scheme is shown in Fig. 1. One of the unique features of this hybrid scheme is that, this system employs an induction generator without a need of either utility grid or excitation capacitors, thereby avoiding all the disadvantages associated with it. In the absence of battery, the real power balance is such that the sum of PV array power and real power output of IG equals the inverter power output which is delivered to the load.

3. CONTROL SCHEME OF THE PV ARRAY FED INVERTER EXCITED WIND DRIVEN IG

In this paper, both with battery and battery less operations of the PVEWIG scheme has been considered. The system should continue to deliver power uninterrupted during the absence of battery, which might happen either due to deep discharge or fully charged condition of the battery. Also it might be necessary to remove the battery from the system for a brief duration for maintenance. In this mode, the boost converter will act in a voltage regulation mode and maintains constant DC link voltage under all conditions of weather and load changes. The Inverter is triggered by an open loop sinusoidal PWM controller. The control block diagram of the dc-dc boost converter used in this scheme is shown in Fig. 2.

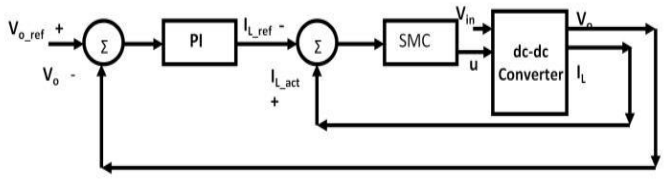


Fig-2: Block diagram of Cascaded PI-SMC controller for output voltage regulation of dc-dc boost converter

The V-I characteristics of PV array varies with irradiation and temperature and this shifts the operating point of the PV array. Further, the variation of wind speed alters the shaft torque to the induction generator. These varying parameters cause the input as well as load of the dc-dc converter to vary. In this event, the controller works in voltage regulation mode. The dc-link voltage is regulated using a cascaded PI-SMC control in which the outer loop consists of a PI regulator and the inner loop consists of a sliding mode current controller (SMC) as shown in Fig. 4.6. The outer PI controller generates a current reference from its input voltage error between reference (V_{o_ref}) and actual output voltage (V_o) of dc-dc converter. The error between reference (I_{L_ref}) and actual Inductor current (I_{L_act}) is given as input to SMC which generates the gate pulse for the boost converter IGBT. The basic principle of SMC involves design of a sliding surface in its control law which would direct the trajectory of the state variables towards a desired origin. Normally in a single switch dc–dc converter, the control law that adopts a switching function is given by

$$u = \frac{1}{2}(1 + sin(S))$$

Where, u is the switching function (logic state) of the converters power switch and the state variable is the inductor current.

Based on the general sliding mode control theory, the state variable error is defined as the difference between actual and reference value (of the inductor current), which forms the sliding function given by $S = i_{l\_actual} - i_{l\_ref}$.

3.1 Inverter Control of PVEWIG Scheme

When an IG is interfaced with the grid or in the proposed scheme with a "PV fed DC-DC converter fed inverter", initially there is a huge difference between the induced emf of the IG and the inverter voltage which causes a sudden inrush. The magnitude of this inrush depends on the initial speed of the rotor and the residual flux of the stator of the IG. If the rotor starts from zero speed then the magnitude of inrush is very severe, this is normally 5 to 6 times that of the rated current (which is the case of an induction motor). In this hybrid scheme, the IG is electrically integrated with the inverter output when the speed of the IG is slightly above the synchronous speed which corresponds to the cut in speed of the wind turbine. Therefore in such condition the magnitude and duration of the inrush is not much severe and could be withstood by the input dc source of the inverter. However, the output voltage of the inverter is gradually increased, by slowly increasing the modulation index of the sine PWM controller to totally eliminate any possibility of inrush current.

4. MODELING AND SIMULATION OF THE PVEWIG SYSTEM

The simulation is performed using the mathematical models of PV array, dc-dc boost converter, induction machine, voltage source inverter (VSI) and the load in order to reduce the memory size and computation time of the simulation, which would otherwise make the simulation more complex as the entire hybrid scheme with control consists of several subsystems. The block diagram of the entire hybrid scheme used for simulation is shown in Fig. 3. The mathematical equations governing the mathematical models of different subsystem shown in fig. 3 are illustrated in Table 1.

The PV model is expressed as given in (1.1) to (1.5) and the dc-dc boost converter model is given by (2.1) to (2.2). The classical dq model is used for representing induction generator. The inverter equations and load circuit are represented using (3) to (5). In this scheme, the total real power of the load is shared between inverter and IG. The reactive power of the load as well as the IG is met by the inverter. The real, reactive and apparent power distributions assuming the losses in the inverter and dc-dc converter are negligible, are given by (6) to (8).

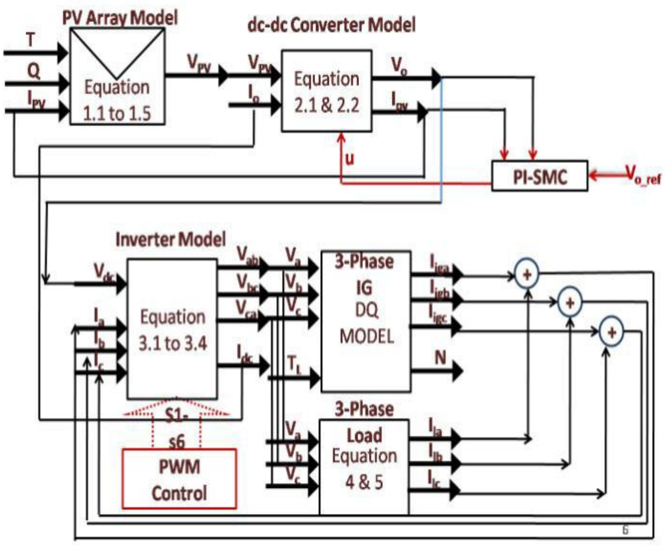
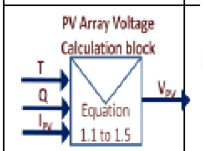
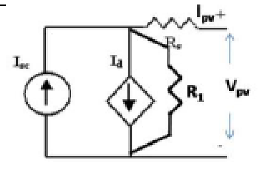
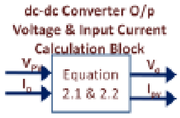
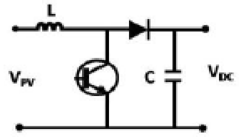
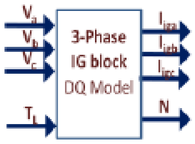
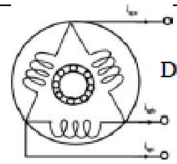
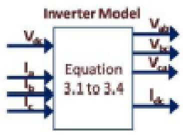
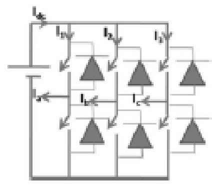
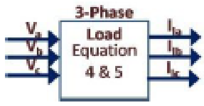
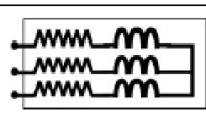
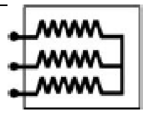


Fig-3: Block Diagram Representing the Mathematical Model of PVEWIG System

Table -1: Mathematical Models used for representing the PVEWIG system

Subsystem	Circuit Schematic
	
$I_{pv}=I_{sc}-I_d$ (1.1), $I_d \cong 10^{-9} I_{sc}\exp\frac{20.7}{V_{oc}}(V_{pv}+I_{pv}R_s)$ (1.2) $I_{sc}(Q,T)\cong I_{sc}Q(1+\alpha\,\Delta T)$ (1.3), $V_{pv}=(I_{sc}-I_d)R_1-I_{pv}R_s$ (1.4) $V_{oc}(Q,T)\cong V_{oc}(1-\gamma\Delta T)\ln(l+\beta\,\Delta Q)$ (1.5)	
	
$\frac{dI_L(t)}{dt}=\frac{E}{L}-\frac{V_o(t)}{L}(1-u)$ (2.1), $\frac{dV_o(t)}{dt}=\frac{I_L(t)}{C}(1-u)-\frac{I_o(t)}{C}u$ (2.2) $(i_{PV}=i_L)$, $(V_{DC}=V_o)$ u is the switching function	
	 Dq model of Induction machine is used
	
$I_{dc}=I_1+I_2+I_3$ $I_1=I_{S1}-I_{D1}$ (3.1) $I_2=I_{S3}-I_{D3}$ $I_3=I_{S5}-I_{D5}$ $v_a=(S1-S4)V_{dc}$ (3.2) $v_b=(S3-S6)V_{dc}$ $v_c=(S5-S2)V_{dc}$	$I_{S1}=I_a\times S1(for I_a>0)$ (3.3) $I_{S3}=I_b\times S3(for I_b>0)$ $I_{S5}=I_c\times S5(for I_c>0)$ $I_{D1}=-I_a\times S1(for I_a<0)$ (3.4) $I_{D3}=-I_b\times S3(for I_b<0)$ $I_{D5}=-I_c\times S5(for I_c<0)$ S1 to S6 are switching functions (Gate Pulses)
	  (Inductive Load) (Resistive Load)
$\frac{di_{la1}}{dt}=\frac{v_a-i_{la1}R_{a1}}{L_{load}}$ (4.1) $\frac{di_{lb1}}{dt}=\frac{v_b-i_{lb1}R_{b1}}{L_{load}}$ (4.2) $\frac{di_{lc1}}{dt}=\frac{v_c-i_{lc1}R_{c1}}{L_{load}}$ (4.3)	$i_{la2}=\frac{v_a}{R_{a2}}$ (5.1) $i_{lb2}=\frac{v_b}{R_{b2}}$ (5.2) $i_{lc2}=\frac{v_c}{R_{c2}}$ (5.3)

The instantaneous current distribution at the point of common coupling (PCC) is given by (9).

$$P_{Inverter} + P_{IG} = P_{load} \quad \ldots (6)$$

$$Q_{Inverter} = Q_{IG} + Q_{load} \quad \ldots (7)$$

$$S_{load} = S_{Inverter} + S_{IG} \quad \ldots (8)$$

$$i_{Inverter\_abc} + i_{IG\_abc} = i_{load\_abc} \quad \ldots (9)$$

Table-2: System Parameters of PVEWIG system Considered for Simulation and used for Hardware Implementation and Validation

S.no	Parameters	Symbol	Unit	Value
1.	Total Load Power	P_{load}	Watts	3450
2.	Rated Power of Resistive-Inductive load	P_{RL_load}	Watts	1350
3.	Rated Power of Lamp Load (Resistive load)	$P_{R\ load}$	Watts	2100
4.	Rated Power of Induction Generator	P_{IG}	Watts	2250
5.	Rated power of PV array at STC	P_{PV}	Watts	2400
6.	Rated AC RMS Line-Line Voltage of the System	V_{rms}	Volts	400
7.	Nominal DC Link Voltage of the Inverter	V_{DC}	Volts	570
8.	Open Circuit Voltage of PV Module	V_{oc}	Volts	19.5
9.	Short Circuit Current of PV Module	I_{sc}	Amps	3.3
10.	Number of PV Module in Series	N_{pv_s}	Nos	20
11	Number of PV Strings in Parallel	N_{pv_p}	Nos	2

Neglecting the losses in the inverter and boost converter, the real power output of inverter equals the real power output of PV array ($P_{Inverter}=P_{pv}$) in voltage regulation mode when the battery is isolated either due to deep discharge or fully charge condition. The different parameters considered for simulation is given Table II. Multiple loads have been considered for simulation which includes a lamp load (pure resistive) and a Resistive-inductive load.

The simulation block diagram of the entire hybrid scheme along with the controller implemented in MATLAB/SIMULINK is shown in Fig. 4. The starting response of the PVEWIG system is shown in Fig. 5. It could be observed the real power of load is shared between inverter and IG, while the reactive power of the load and IG is supplied by the inverter. During starting, the modulation index of the sine PWM inverter is gradually increased from its initial zero value, which facilitates integration of IG with the inverter without any inrush current as shown in figure 6. The steady state waveforms of voltage at PCC and current of PVEWIG system including load, IG and inverter are shown in Fig. 7. The distribution of real power among PV array and IG under disturbances in irradiation, wind turbine speed and load is shown in fig. 8. In this case the temperature is maintained constant at 35 deg Celsius. It can be observed the system rms voltage remains constant except for a short duration disturbance as shown in fig8. Also the real power balance is ensured among the two sources PV array and IG, providing a regulated output voltage to the load. The response of the system for a wind speed variation at a constant load and irradiation is shown in fig. 8. It can be observed, the controller ensures the power balance and maintaining constant DC link voltage. Further, in this case the power delivered by the IG increases with the wind speed while the PV power decreases accordingly, less than its available power for the given irradiation. However, the objective of the controller here is to regulate the DC link voltage in the battery less mode of operation.

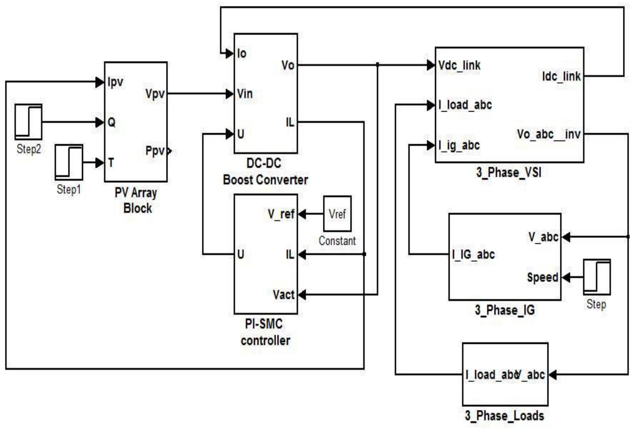


Fig-4: Simulation Block Diagram in MATLAB Representing the Mathematical Model of PVEWIG System

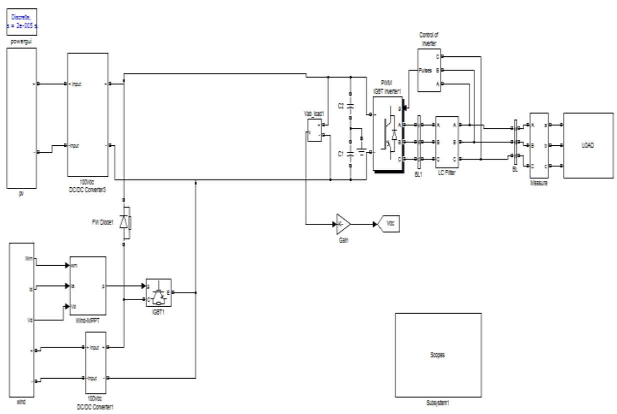


Fig-5: Simulation Circuit for Solar-Wind Hybrid Energy Systems without Battery

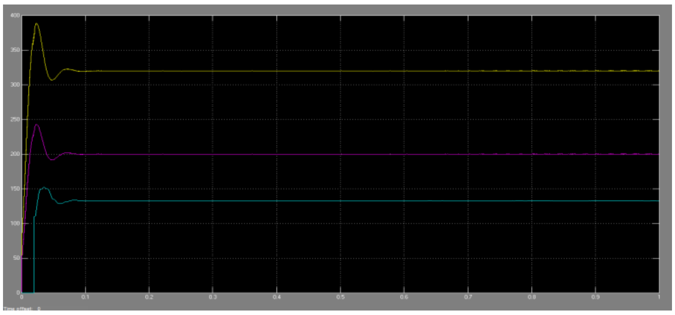


Fig-6: Simulation Result for V_{pv}, V_{dc}, V_{pcc_rms}

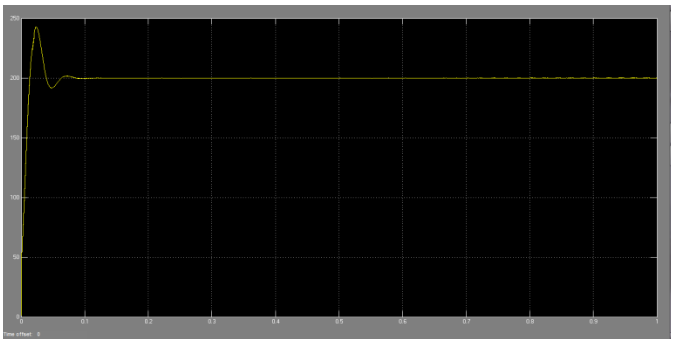


Fig-7: Simulation Results for Output Voltage Of DC-DC Converter V_{dc}

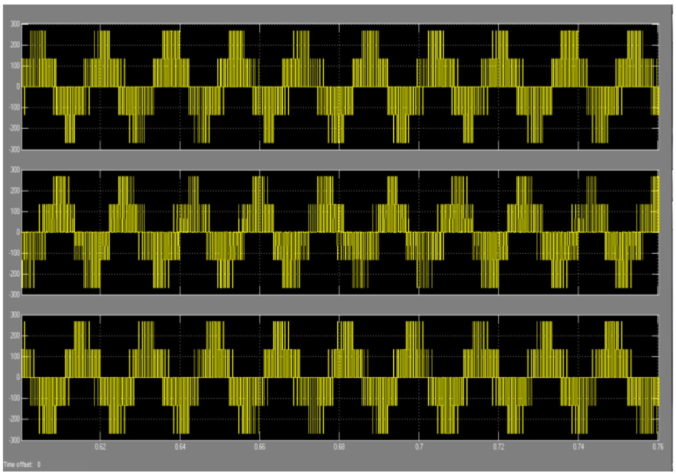


Fig-8: Simulation Results for Inverter Voltage V_{abc}

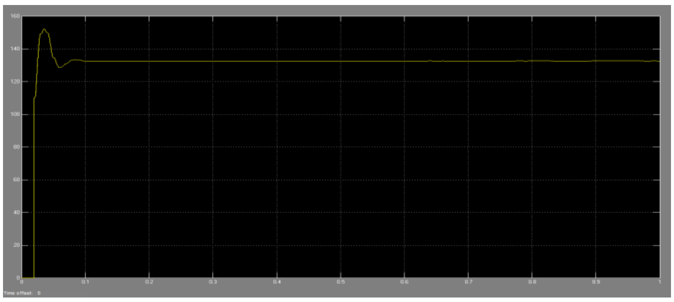


Fig-9: Simulation Result for Voltage V_{pcc}

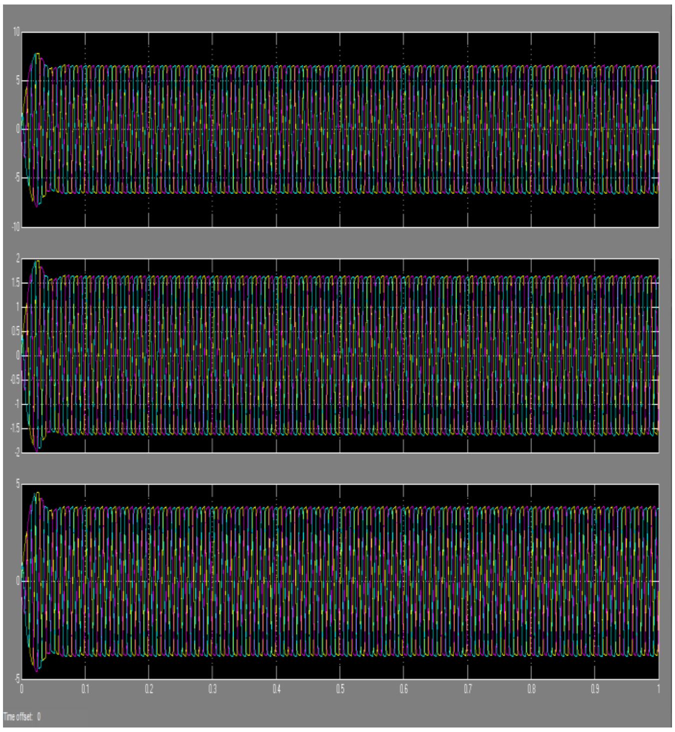


Fig-10: Simulation Results For Load Current I_{abc}, Inverter Current I_{abc_inv}, I_{abc}

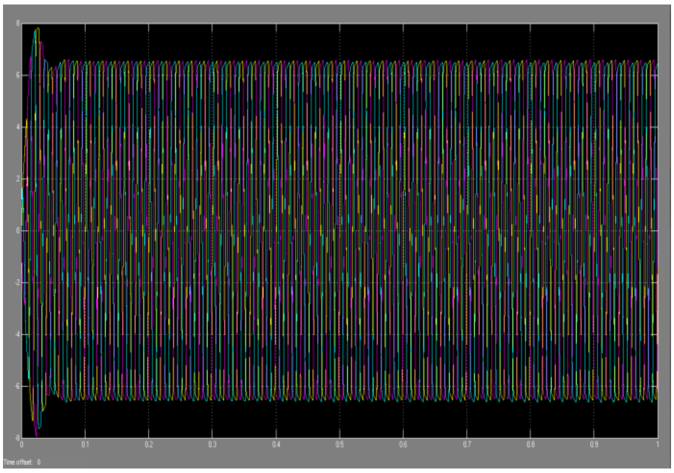


Fig-11: Simulation Result for Load Current I_{abc}

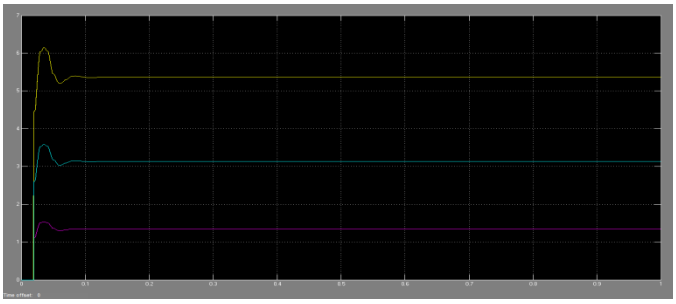


Fig-12: Simulation Results for I_{load_rms}, I_{ig_rms}, I_{inv_rms}

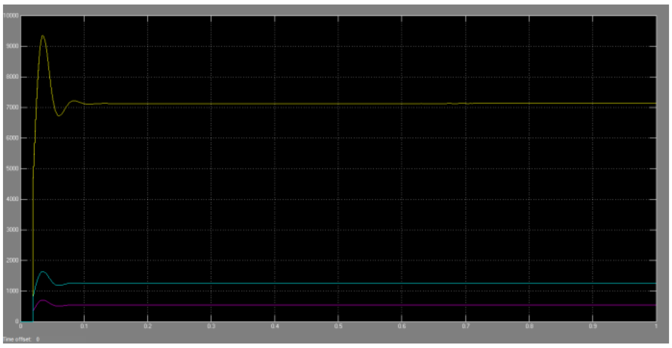


Fig-13: Simulation Results for Active Power P_{load}, P_{ig}, P_{inv}

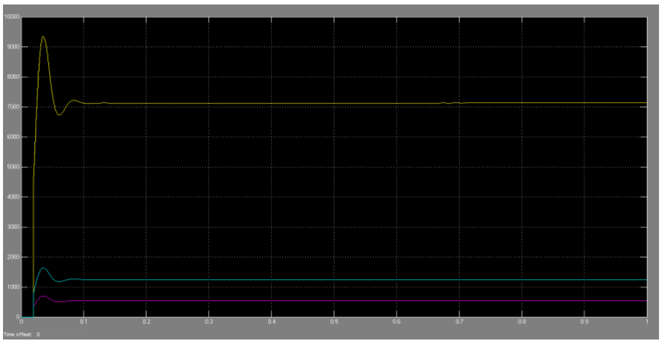


Fig-14: Simulation Results for Reactive Power Q_{load}, Q_{ig}, Q_{Inv}

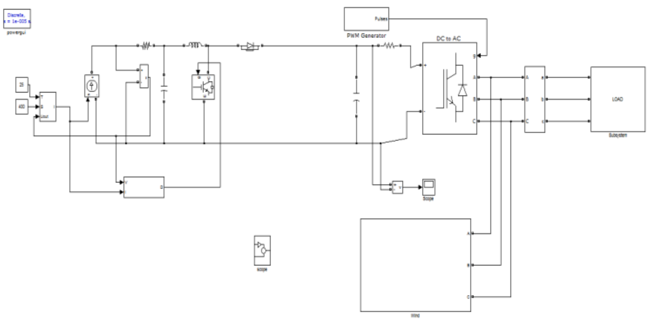


Fig-15: Simulation Circuit for Solar-Wind Hybrid Energy Systems with Battery

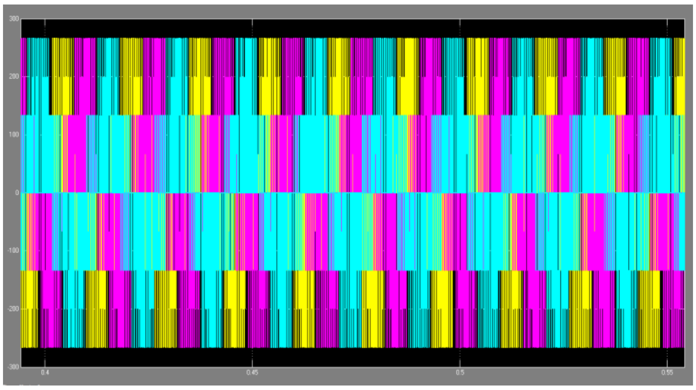


Fig-16: Simulation Results for Voltage V_{abc}

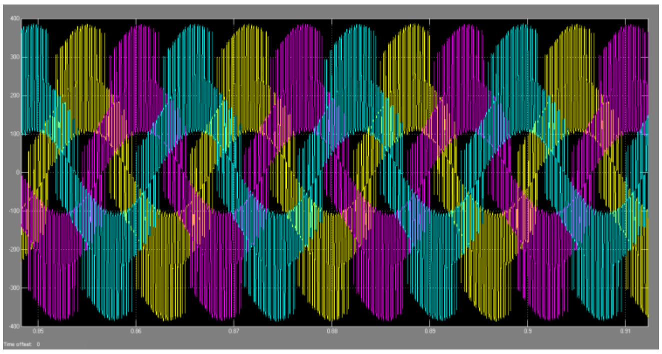


Fig-17: Simulation Results For Current Iabc

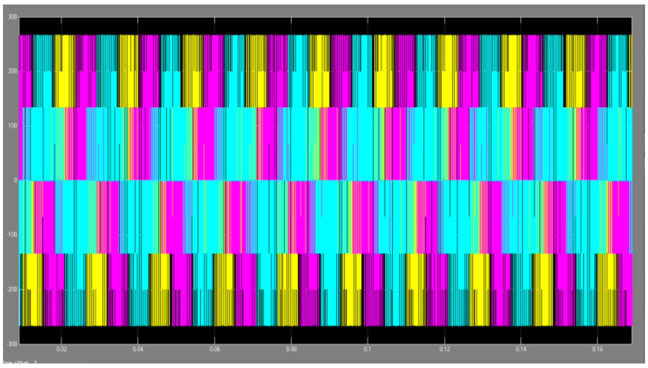


Fig-18: Simulation Result for Voltage V_{abc_wind}

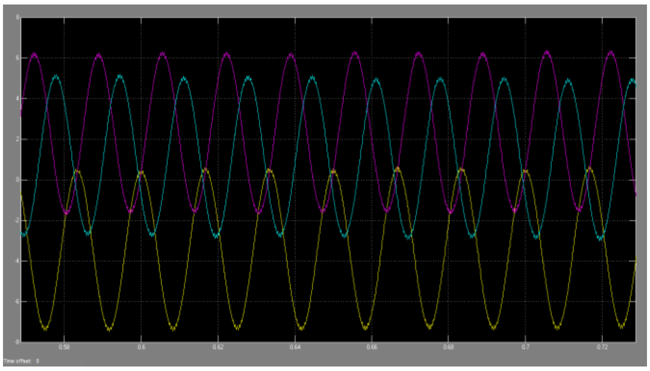


Fig-19: Simulation Result for Current I_{abc_wind}

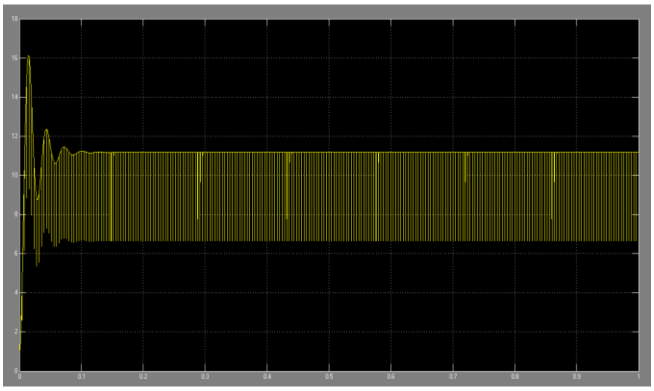


Fig-20: Simulation Result for DC-DC Converter V_{dc}

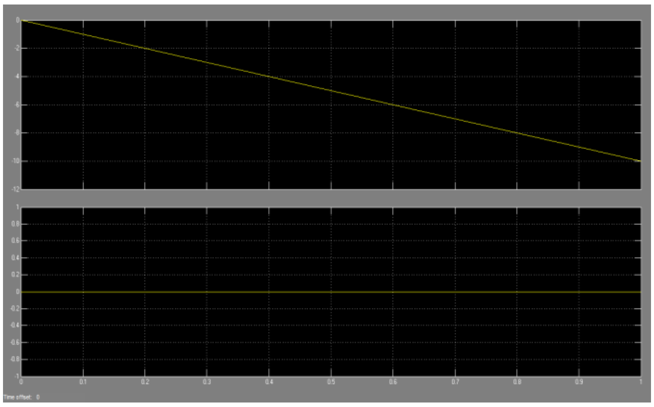


Fig-21: Simulation Results for Output Voltage

5. CONCLUSIONS

A cascaded PI-SMC control has been successfully implemented for a dc-dc boost converter interfaced between PV array and a three phase voltage source inverter of a PVEWIG system for regulating the inverter DC link voltage. The modeling and simulation results of with battery and battery less operation of PVEWIG scheme have been presented.

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