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MODELING, CONTROL DESIGN AND SIMULATION OFGRID CONNECTED SINGLE-PHASE SOLAR MICROINVERTER

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ABSTRACT

This paper represents the mathematical modeling, control design and simulation of grid connected single phase solar micro inverter. A system level approach is exploited to establish an upper-level block diagram that depicts the various blocks of the solar inverter. These blocks are PV panel, boost converter, inverter, ac grid and control system along with their coordination in power and signal flow. In mathematics modeling, complete state space model is developed, having three states of the system, magnetizing current, output voltage current and voltage. Photovoltaic voltage and duty ratio is taken as input to the state space model. A transfer function model between output ac voltage and input duty ratio is established and time domain analysis is conducted for its stability analysis. Frequency domain analysis is also carried out and a PI controller is designed to improve it relative stability. Feedback compensator and feed forward loop both are used to improve the system performance. The complete model along with its controller is developed in Simulink. Results of the model reveal the accurate operation of the inverter. DC rail output of the fly back converter produces 350V in steady state. In the startup phase of the inverter, it took 0.03 sec to synchronize the inverter output to the grid voltage. The peak voltage of the inverter is kept high than the grid voltage for the power injection to the grid. Safe mode operation of the inverter is tested by removing the grid intentionally and the inverter output voltage becomes zero.

Keywords: microinverter, modeling, control design, simulation.

1. INTRODUCTION

At present, major research activities are revolving around the sustainable solution of the energy crisis. Renewable energy resources have considerable importance in this aspect. Major concerns with conventional energy sources are fuel exhaustion and stringent environmental impacts. Among the renewable energy sources, solar and wind energy is widely studies for its harvesting and efficient conversion to the useable form [1].

Grid connected solar inverter is a special inverter which takes the power from solar panels and inject that power in existing grid system. Typically, grid connected solar inverters can not be used as stand-alone system in the absence of grid. At the time of overproduction, excess power is being routed to the grid [2].

The two major functions of the solar inverter system are: to harvest the maximum possible energy form the photovoltaic panels with minimum switching losses and second one is to convert the harvested energy in to sinusoidal current and inject into the grid. To harvest the maximum energy from the PV panels, maximum power point tracking (MPPT) module is required. Its output is the constant voltage DC and then it is converted to the AC current.

There are two typical configurations of grid connected solar inverters. These configurations are called single stage inverter and double stage inverter [3]. In single stage inverter configuration, input DC voltages are boosted up to peak value (as required by AC voltage) and then inverter converts the DC rail voltage to the output AC voltage.

On the other hand, two stage inverters involve two inverters. After the power conditioning of the PV output DC voltage, it is boosted up by the first inverter using high frequency transformer then second inverter is used to generate the final AC voltage to be fed into the grid. First inverter generates high frequency AC voltage to reduce the size of transformer and second inverter generates the AC voltages synchronized tothe grid voltage frequency. Single stage inverter is preferable because of itslow components involved as compared to double stage inverter, but its control design complexity is higher[4][5]. The “microinverter” term depicts an inverter (usually low power 200-400W) that is single stage in design and is installed with each PV panel. For a string of PV panels, the output of all inverters are connected each other for power collection and finally injected into the grid. Microinverter based PV systems are becoming popular due to its modular, scalable, easy to manage for installation and reduced maintenance cost. Other benefits of this system are enhanced system reliability, improved efficiency and reduced costs [6] [7].

2. DESIGN OF MICRO INVERTER

Grid connected solar micro inverter encompassed the main two parts, power processing part and the signal processing part. From the power section, DC power from the PV panel is converted into AC signal (rectified, one sided) by using the interleaved flyback converter. A full bridge converter is then used to convert the unidirectional AC power to the bidirectional AC power to be injected to the grid after its filtration. The signal processing side encompasses the measurement of several variables (grid voltage and its phase angle, PV panel voltage and current etc.) signal conditioning, gate drive circuits and heart of the processing is digital signal controller. A block diagram

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of the complete system is shown in the Figure-1 that indicates the power flow and signal flow of the microinverter system.

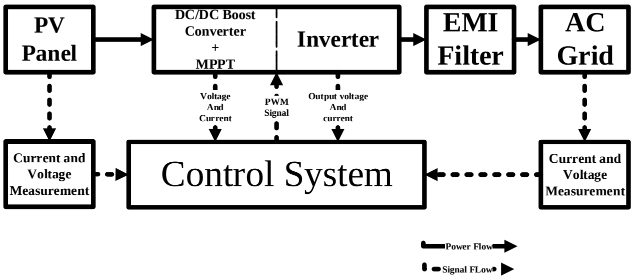

Figure-1. Upper-level block diagram of grid connected solar micro-inverter.

3. FLYBACK INTERLEAVE DC-DC BOOST CONVERTER

Power coming from the PV panel is fed to the flyback interleave converter, that boosts the DC voltage by considering the MPPT algorithm into account. Interleaving operation is accomplished if more than one converter is operated [8]. In this design two fly-back converters are operating at 180 degree out of phase in order to accomplish the interleaving operations [6]. Implementation of Fly-back Interleave Converter is shown in Figure-2.

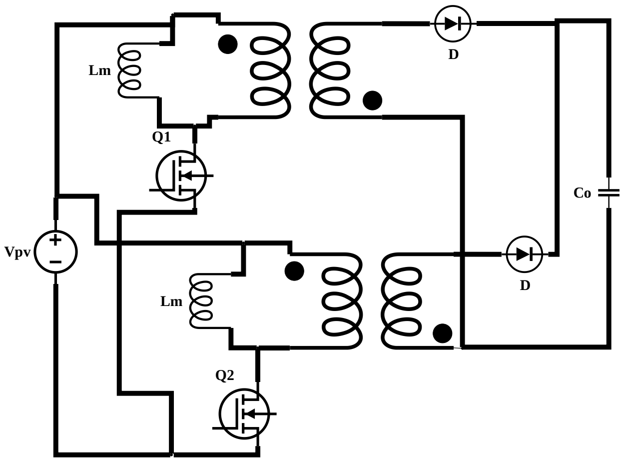

Figure-2. Implementation of fly-back interleave converter.

Interleave fly-back converter is preferable, because it has certain benefits over signal stage fly-back converter. Benefits of interleave fly-back converter are listed below:

a) It reduces the peak and RMS currents experienced by transformers and semiconductor devices i.e. MOSFETS and diodes.

b) It reduces RMS current in input and output capacitor.

c) EMI energy is reduced because of low peak currents.

d) It distributes the load of heat generating elements.

There are some disadvantages of fly back interleave converter:

a) It needs more components than signal stage fly-back converter

b) It needs more area for fabrication.

c) Control system design for interleave fly-back converter is more complex than single stage fly-back converter.

To develop an adequate understanding of process mathematical model is required to design the control system for fly back converter in order to get desired output [9]. To develop the model non-ideal fly-back model is shown in Figure-3.

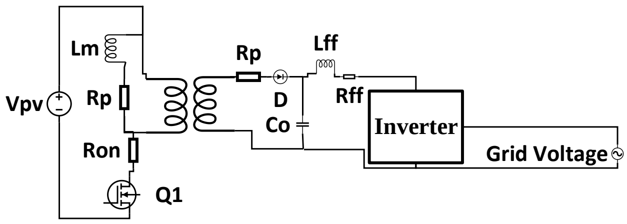

Figure-3. Non ideal fly back converter.

Fly back converter has three state variables depending upon the energy storing elements in it. State variables are described in following Table-1.

Table-1. State variables of fly-back converter.

S. No	State Variable	Symbol
1	Current through Magnetizing Inductor of transformer	i_m
2	Voltage across output capacitor	V_c
3	Current through output filter's inductor.	i_f

When the switch is on, the diode on secondary side will be in open state so that the voltages at magnetizing inductor will be

$$V_{LM(on)} = V_{PV} - i_m(R_p + R_{on}) \quad (1)$$

Similarly, when the switch is off, the diode on secondary side will be in closed state and the voltages at magnetizing inductor will be

$$V_{LM(off)} = -\left(\frac{V_c + i_m R_s}{N}\right) \quad (2)$$

The equation of average magnetizing inductor will be

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$$V_{LM} = DV_{LM(on)} + D'V_{LM(off)} \quad (3)$$

Where D depicts the on time of the switch and D' depicts the off time of the switch

Inserting the values in equation (3) from equations (1) and (2), equation (3) become

$$V_{LM} = D\left(V_{PV} - i_m\left(R_p + R_{on}\right)\right) - D'\left(\frac{V_c + i_m R_S}{N}\right) \quad (4)$$

When the switch is in on state the current at secondary side will be zero because diode will act as open circuit. On the other hand, when the switch is in open state, current will flow at secondary side because of current stored in magnetizing inductor of transformer. Current at secondary side is denoted as i_s

$$i_{s(on)} = 0 \quad (5)$$

$$i_{s(off)} = \frac{i_m}{N} \quad (6)$$

The equation for average secondary current will be

$$i_s = Di_{s(on)} + D'i_{s(off)} \quad (7)$$

After inserting the values of $i_{s(on)}$ and $i_{s(off)}$ in equation (7) from equations (5) and (6) equation (7) become

$$i_s = D'\frac{i_m}{N} \quad (8)$$

Current through output capacitor of the fly-back converter is represented as i_c and can be modeled as

$$i_c = i_s - i_f \quad (9)$$

All equations are averaged over a signal time period. These equations are obtained from large scale analysis of the system and these equations represent the exact non linearity of the system. Since the converter is operating at unity power factor which implies that there will be resistive load of the converter. The operating point for linearization will be the RMS value of grid voltages. Input matrix for the system is

$$u = \begin{bmatrix} D \\ V_{pv} \end{bmatrix} \quad (10)$$

Considering all equations, state equations of the system will become

$$\frac{d(i_m)}{dt} = -\frac{R_{eq}}{L_m} i_m - \frac{D'}{L_m N} V_c + \frac{V_{eq}}{L_m} D \quad (11)$$

$$\frac{d(i_f)}{dt} = -\frac{R_{ff}}{L_{ff}} i_f + \frac{1}{L_{ff}} V_c \quad (12)$$

$$\frac{d(v_c)}{dt} = \frac{D'}{NC_o} i_m - \frac{1}{C_o} i_f - \frac{i_m}{NC_o} D \quad (13)$$

Where

$$R_{eq} = D\left(R_{on} + R_p\right) + D'\frac{R_S}{N} \quad (14)$$

$$V_{eq} = v_{pv} - I_m\left(R_{on} + R_p\right) + \frac{I_m R_S}{N} + \frac{v_f}{N} \quad (15)$$

State space representation of this system is shown below:

$$\begin{bmatrix} \frac{d(i_m)}{dt} \\ \frac{d(i_f)}{dt} \\ \frac{d(v_c)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_{eq}}{L_m} & 0 & -\frac{D'}{L_m N} \\ 0 & -\frac{R_{ff}}{L_{ff}} & \frac{1}{L_{ff}} \\ \frac{D'}{NC_o} & -\frac{1}{C_o} & 0 \end{bmatrix} \begin{bmatrix} i_m \\ i_f \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{V_{eq}}{L_m} & 0 \\ 0 & \frac{1}{L_{ff}} \\ -\frac{i_m}{NC_o} & 0 \end{bmatrix} \begin{bmatrix} D \\ V_{pv} \end{bmatrix}$$

$$i_f = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_m \\ i_f \\ v_c \end{bmatrix}$$

This state space model has three state and two input variables (Duty cycle and PV voltage). Out of three state variables anyone may be selected to be considered as output variable. For our work, we intend to have out voltage, so v_c is considered as output variable and output equation is written. State matrix, input matrix and output matrix are also shown in parametric form in this developed state equation. Typical values of component properties are enumerated in the following table for simulation purpose. These values are assumed to remain as constant during the operation of the microinverter, so this model is considered to be time invariant model.

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Table-2. Values of components.

S. No	Component	Symbol	Value
1.	Transformer primary winding resistance	R_p	0.028Ω
2.	Transformer Secondary winding resistance	R_s	1. Ω
3.	Filter Inductance	L_{ff}	300uH
4.	Filter resistance	R_{ff}	Ω
5.	Magnetizing inductance	L_m	55uH
6.	Output Capacitor	C_0	0.245uF
7.	Turn ratio	N	7
8.	MOSFET Turn on Resistance	R_{on}	0.012Ω

4. CONTROL DESIGN

The developed model is scripted in Matlab, and a transfer function of system is obtained, having the voltage as output and duty cycle as an input. Thisobtained transfer function is written below:

$$G(s) = \frac{-1.210 * 10^{10}s + 1.3 * 10^{10}}{s^3 + 8.23 * 10^5 s^2 + 1.542 * 10^{10}s + 3.636 * 10^{14}}$$

From stability analysis of the system, poles and zeros of this transfer function is plotted in the s-plane. Roots of the denominator are the zeros, whereas the roots of the denominator are the poles of the transfer function. For system analysis the depiction of poles and zeros are evident in Figure-4.

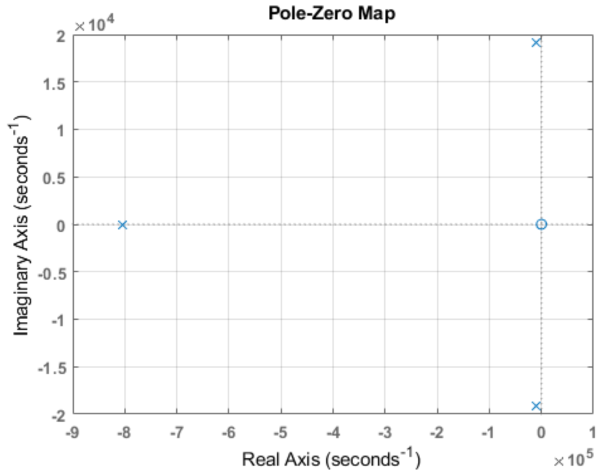

Figure-4. Pole zero plot of the system.

The system has one zero having the value of 1.0744, and is located in right half of the s-plane, which is typical for the buck-boost power converter topologies. The system transfer function has three poles, one is located at real axis (having imaginary part zero) and other two are complex conjugate pairs and are located in left half plane near to imaginary axis. This indicates that the system is at the verge of marginally stable condition. To keep the system in stable condition, feed back loop mandatory. For the frequency domain analysis of the system, open loop bode plot is developed and shown in Figure-5.

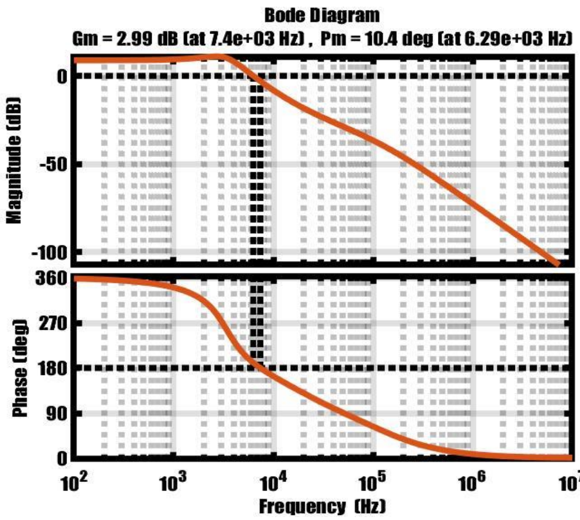

Figure-5. Bode plot of uuncompensatedssystem.

Bode plot of the system reveals that system has verylow gain margin (2.99dB) and phase margin (10.4 deg) that implies system has poor relative stability. This should be enhanced so that system shouldn't get unstable at any its operating point [9]. Therefore, the control design criteria are as following:

a) Gain margin of the compensated system should be greater than or equal to +10db

b) Phase margin of the compensated system should be greater than or equal to 45 degree

c) Gain at operating frequency should be +15db

The PI (Proportional and integral) controller is designed by using control toolbox in Matlab to obtain the required stability margins (gain and phase) and band width. By resolving the control objectives into controller gains, the designed controller transfer function is as follows.

$$G_c(s) = \frac{0.17s + 1200}{s}$$

After the incorporation of feedback and controller block, close loop transfer function is computed and its Bode plot is developed and shown in Figure-6. The diagram indicates that system has completely met the criteria of control design. Compensated system has 10.4 dB gain margin and 104-degree phase margin. It shows that system is behaving as desired with more relative stable state.

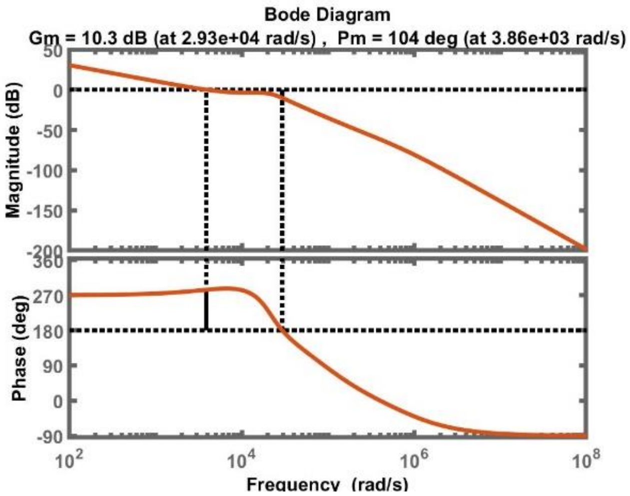

Figure-6. Bode diagram of compensated system.

MPPT generates the reference signal for PI controller. By considering the information about reference signal and feedback signal, system generates an error signal. PI controller produces duty cycle proportional to error signal. This duty cycle is considered as dynamic duty cycle, because it keeps changing with respect to the output current of the fly back converter. Base or static duty cycle will be provided by feed forward controller. Feed forwarded controller is ratio between PV voltages and output voltages of fly back converter. Feed forward gain (FFG) is given below.

$$\mathrm{FFG} = \frac{\mathrm{V_{fly-back}}}{\mathrm{V_{fly-back}} + \mathrm{nV_{pv}}} \tag{16}$$

Where n is turn ratio of fly back transformer. It is noted that $V_{fly-back}$ should be equal to nV_{pv}. When $V_{fly-back} = nV_{pv}$ then feed forward controller will provide a static duty cycle ratio of 50%.Complete block diagram of system along with feedback and feed forward loops is Figure-10.

5. SIMULATION OF MICRO SOLAR INVERTER

Simulation of Micro inverter is developed in Simulink and is shows in Figure-71. The major blocks of the model are, grid input, PLL, PV array, control system, flyback convertor and final state inverter. Input arguments of PV array are the temperature and solar irradiation, and output is current and voltage, which are fed to the flyback convertor block. Input signals to the convertor block are the PWM driving signal, that is generated by control system block that encompasses the MPPT block, feedforward compensator, PI controller, summing point, saturation block and PWM generator. The generated output of the flyback convertor is fixed DC voltage and it is taken as input to the inverter block that produces the grid interfaceable ac voltage for power injection. The control system block diagram with its various blocks is shown in Figure-.

6. RESULTS

The whole model developed in Simulink is run for various time scales to observe its behavior and outputs. Solver and time stepping is configured in the model. Input argument (temperature and radiation) are assigned and PV output is harvested by MPPT algorithm. This DC voltage is boosted by interleave converter and a DC rail of 350V is achieved and is shown in Figure-7. From the start of the simulation, output voltage of flyback converter starts increasing and attained the steady state value of 350V in 0.03ses.

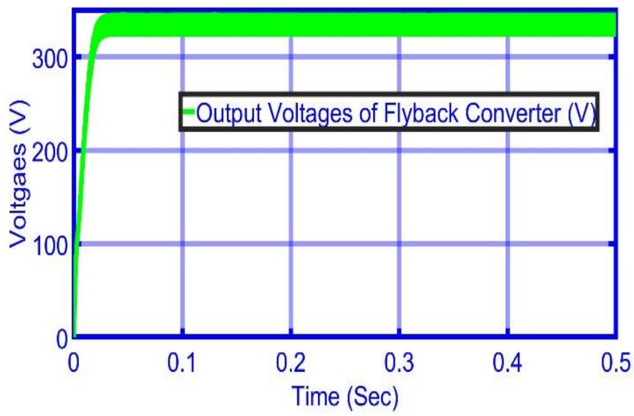

Figure-7. Flyback converter output voltages (V).

The DC rail generated by interleave convertor is the input to the invertor. Main purpose of grid connected solar inverter is to convert DC Power into the AC power and synchronize it to the grid voltages in order to inject the sinusoidal current into the grid. For this purpose, it is necessary that instantaneous voltages of generated AC waveform should be greater than grid voltages so, that current can move from high potential to low potential.PWM signals generated by control system is driving the flyback converter and inverter.

The sinusoidal voltage generated by the inverter block grid voltageis shown in the Figure-8. It is evident that, at start output waveform doesn't match the frequency and amplitude with grid voltage waveform and the system is in transient phase. After 0.02 sec, the transient phase is diminished and output voltages have synchronized with grid voltages and output voltage achieved steady state condition. In the third cycle of the generated voltage, peak

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voltage of the generated ac voltage is higher than the grid voltage and the active power flow to the grid is established. Inverter took 0.03 sec to settle its output for power sharing and this is because of the charging of capacitor at output of fly back interleave converter. This can also be seen in the state space model of the system that D matrix of the system is null matrix which implies that there is not feed forward path for the energy to be delivered at output without any delay. Frequencies of both wave forms are same (50 Hz), but there is difference in the instantaneous and peak voltages for the active power injection to the grid.

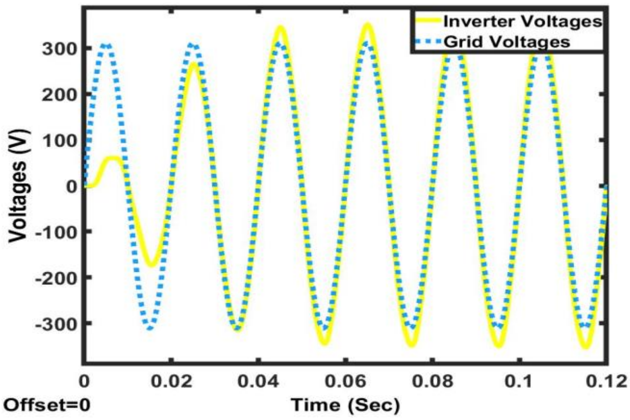

Figure-8. Inverter output and grid voltage.

A safety feature of the inverter operation when the grid in removed intentionally or during the black, is also incorporated in the control section of the system. Figure-9 depicts this safety feature when the grid is failed at 0.08 sec. The controller responds quickly and shut down all the control signals to the converter and inverter for its safety and the inverter output voltage is suppressed to zero.

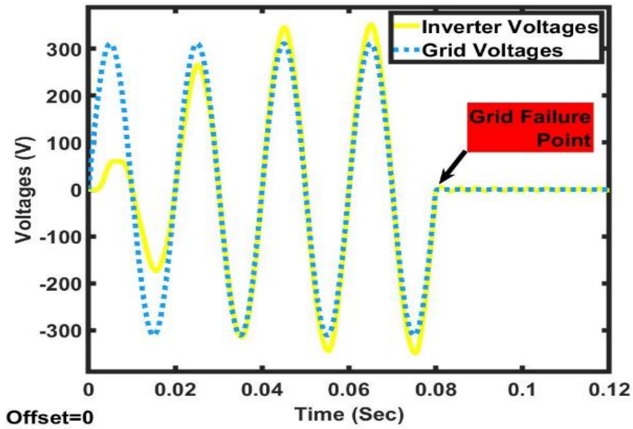

Figure-9. Grid failure mode operation.

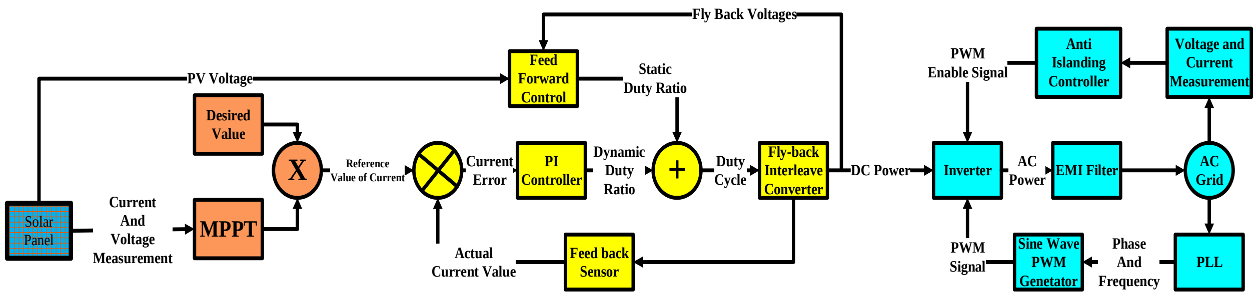

Figure-10. Complete block diagram of the system.

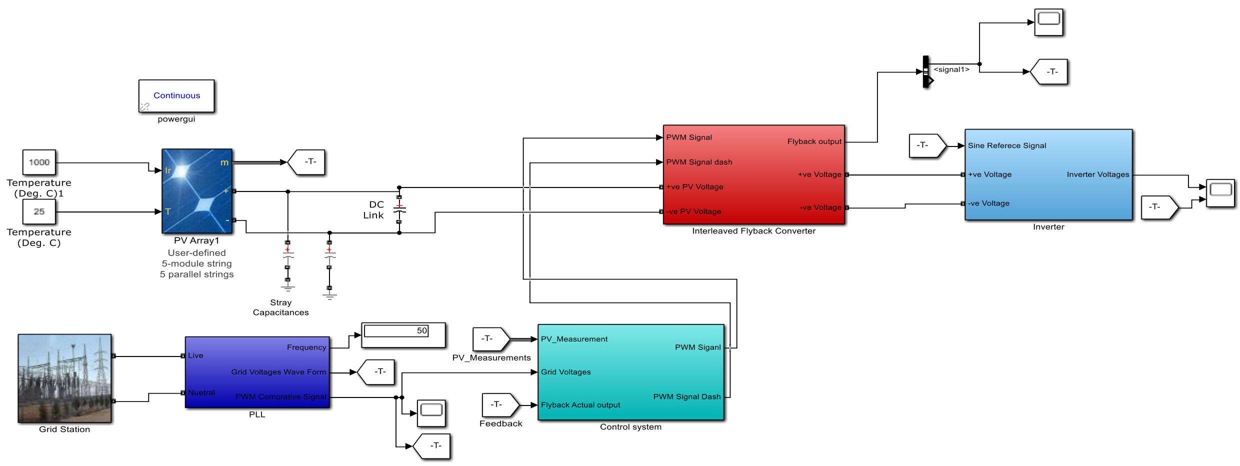

Figure-71. Complete system model.

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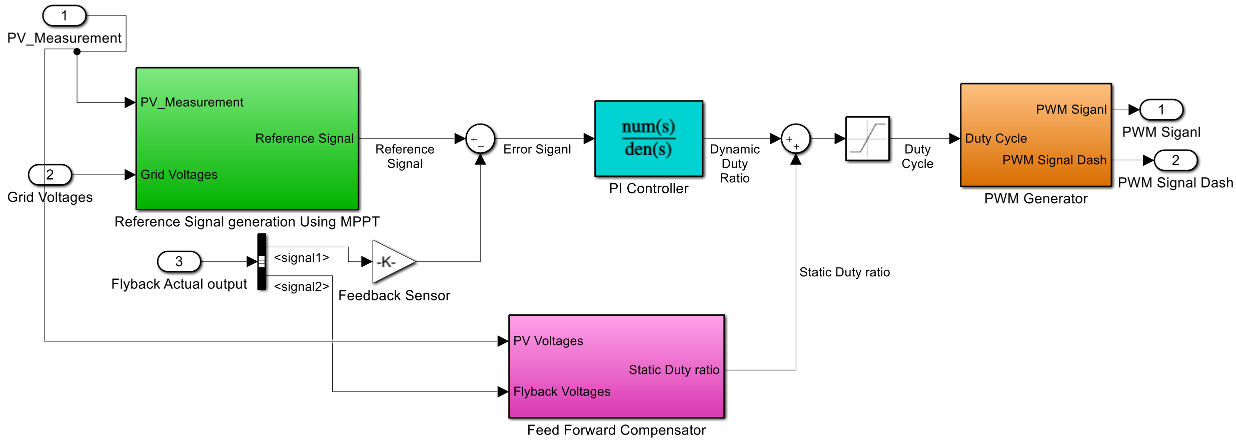

Figure-12. Control System.

7. CONCLUSIONS

This document depicts the design, simulation and analysis of grid connected solar microinverter. Critical stage of microinverter is design of interleave fly back converter. Dynamics of the fly back converter reveals that it's a marginally stable system, to compensate this system PI controller was designed. This controller inserted high frequency zeros into left half plane, which attracted the closed loop poles in left half plane and made the system stable. MPPT provided that maximum power point of solar panel and PLL provided the information about the grid voltage frequency and phase, so that solar microinverter extracted maximum power from solar panel and produced a sinusoidal voltage waveform which is synchronized to the grid voltages. Results showed that inverter output waveform followed the trend of grid voltages effectively and power injection to gird is ensure.

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