Design of Control Systems for Grid Interconnection and Power Control of a Grid Tie Inverter for Micro-grid Application

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ABSTRACT: *COEP-Microgrid, a project by the students of College of Engineering Pune aims at establishing a microgrid in the college campus serving as a living laboratory for research and development of novel grid technologies. Proposed microgrid has an AC-bus and DC-bus, interconnected together with a tie line DC -AC converter. In grid connected mode AC bus of microgrid is synchronized with utility grid. Synchronization with utility grid requires grid and AC bus to have synchronism in frequency, phase sequence and voltage. Power flow requires phase difference between grid and AC bus. Control System is required to effectively regulate power flow between the grid and AC bus. The grid synchronizing control system is composed of frequency and phase control for regulated power flow and voltage control system for reduction of reactive power flow. The control system involves automatic active power flow control. It takes the feedback of DC link Capacitor and changes the power angle accordingly. Control system incorporating voltage, phase and power control was developed for grid-tie inverter. This paper discusses the design, simulation and practical implementation of control system described in various microgrid scenarios.*

Keywords: Microgrid, Grid-tie Inverter, Voltage Control, Automatic Power Control

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1. Introduction

MICROGRIDS are the networks comprising of various generators, storage devices, and controllable loads that can operate either grid connected or islanded mode as a controlled entity. Suitable micro-grid control strategy design is the key for stability of the microgrid under different operation mode, especially when changing from the grid connected operation to the islanding operation. Operation of micro-grid in grid connected mode demands control of power flow from micro-grid to utility grid.

Synchronisation of microgrids AC bus with utility grid requires frequency and voltage of grid to be equal to the frequency and voltage that of the inverter.

This paper describes design, simulation and practical implementation of the control strategy for grid tie based AC bus for MicroGrid applications. Voltage, frequency and phase control formulate the control system. Voltage source inverter is synchronized using frequency and voltage control and power control is achieved by phase control.

2. Grid Tie-inverter Control Problem

Synchronization of inverter with grid requires inverter frequency to be equal to that of grid. Grid has almost constant frequency, however difference in frequency of inverter output and grid results in high power imbalance. Phase difference is key factor which determines the active and reactive power flow to and from grid [1]. A varying phase difference can cause varying power flow in the circuit. With inverter frequency at 49 Hz and grid frequency at 50 Hz the variations in power flow can be seen in figure 1.[6]

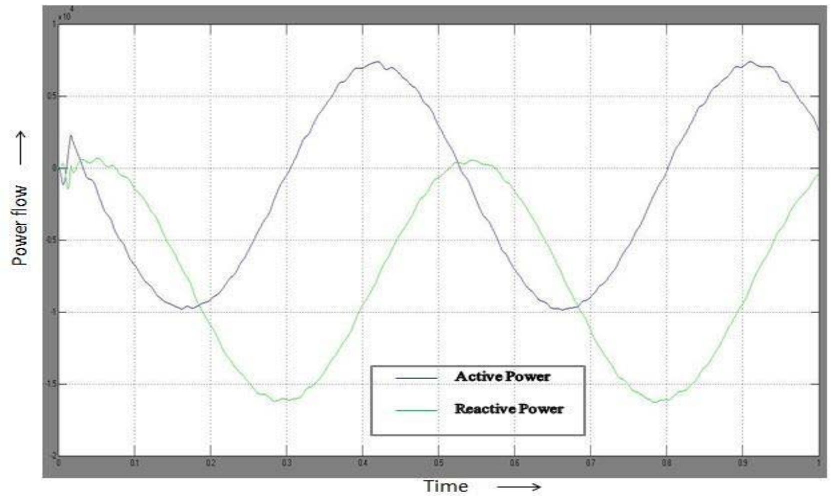

Figure 1. Power flow due to frequency variations

Voltage of inverter governs the reactive power flow and needs to be regulated. Difference in inverter terminal voltage and grid voltage results in reactive power flow[1]. Control System is required to maintain required voltage and frequency in islanded condition. Control System needs to be robust and have quick response time. Delays in response time can lead to failure of synchronization of inverter with grid and lead to varying power flow and can damage inverter power circuit[2].

3. Proposed Solution

To deal with the problem statement mentioned above, various control strategies are incorporated.

3.1 Power Control System

Constant power throw into the grid requires the capacitor voltage to be constant. As the power generated on DC bus increases capacitor gets over-charged. Voltage of capacitor is compared with a reference value and using PID control system the power angle of inverter is changed to control the power flow into the grid. The capacitor voltage is maintained at such a value so as to reduce reactive power demand of inverter.

Discrete PID control is applied for active and reactive power control. PID control is implemented to maintain the voltage of capacitor same as that of reference voltage. The power transfer from DC side to AC side is governed by phase angle (power angle), given by equation, $P_{active} = \frac{EV\sin(\delta)}{X}$ [6].

As the Capacitor voltage increases phase angle is increased to alter the alter the power flow from Inverter to Grid.

3.2 Frequency Control System

The feedback obtained from the grid is stepped down to 5 Volts. The grid waveform is converted to square wave using sine to square wave converter. Obtained square wave is used to measure frequency of the grid. The square wave acts as input to external interrupt hardware of micro-controller which measures the frequency of interrupts received. The frequency of inverter output is related to frequency of SPWM used to drive inverter bridges. Thus the frequency of inverter can be changed to frequency of grid measured using external interrupt hardware and frequency of grid is synchronized with frequency of inverter. Frequency control system has improved response time due to analog external interrupt hardware

3.3 Phase Control System

Phase control system maintains the phase difference between inverter generated wave and grid voltage wave constant. The

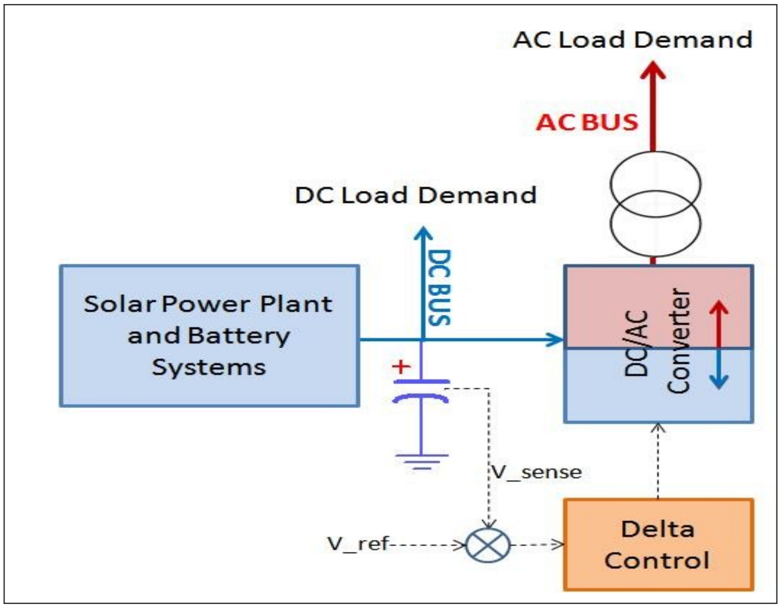

Figure 2. Control System for Power flow

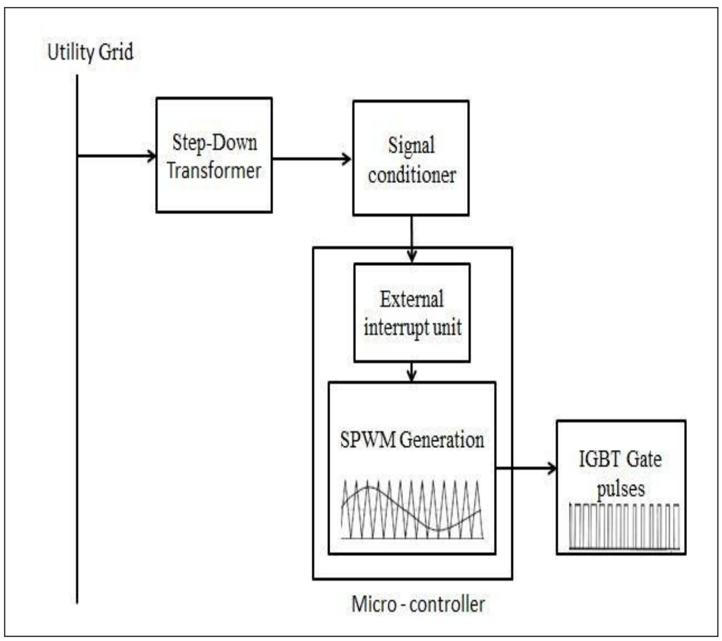

Figure 3. Proposed Frequency Control System

sinusoidal wave of grid is stepped down using a transformer and converted to corresponding square wave. Square wave acts as an external interrupt to processor / microcontroller generating SPWM. Phase of generated SPWM can be adjusted according to the external interrupt received and power angle predefined as per power flow required. PID controller is used to give perfect matching of phase angle after the filter and phase angle of grid wave. The PID controller is necessary because the filter gives some additional phase shift to inverter generated voltage wave.

3.4 Voltage Control System

Micro-Grid has limited generation and in islanded mode as the load on inverter increases the voltage regulation of inverter increases. The Voltage of inverter falls below rated terminal voltage. Voltage Control System involves regulation of terminal voltage. It involves feedback from inverter terminal which is given to PID control which changes the modulation index of SPWM waveforms and alters the terminal voltage of inverter.

1) Design of Discrete PID Controller: The Transfer func- tion of discrete PID Controller is shown in figure 4.

$$U[z]\ Ts\ [z+1]\ [z-1] = kp + Ki^* \quad (1)$$

$$Kp + Ki^*\frac{TS}{2} + \frac{Kd}{TS})\ Z2 + \frac{((-Kp + Ki * TS + Kd)\ Z + Kd}{(z_2 - z) \qquad (z1z)} \quad (2)$$

$$U[z] = z^{-1}\ U[z] + aE[z] + bz^{-1}\ E[z] + cz^{-2}\ E[z] \quad (3)$$

$$u[k] = u[k-1] + ae[k] + be[k-1] + ce[k-2] \quad (4)$$

$$a = Kp + K_1 * \frac{TS}{2} + \frac{K\,d}{s} \quad (5)$$

$$b = -Kp + K_1 * \frac{TS}{2} - \frac{2K\,d}{s} \quad (6)$$

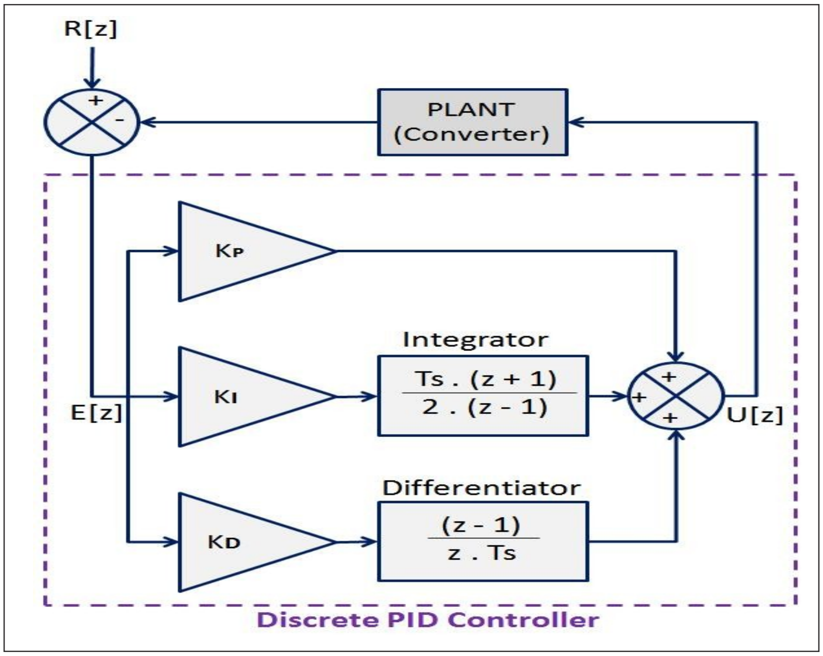

Figure 4. PID Control System for Power Angle Control

$$c = \frac{K\,d}{T\,s} \quad (7)$$

Ts = Sampling time of the discrete system
Kp = Proportional gain
KI = Integral gain
KD = Differential gain
U [*z*] = Input to the plant
R [*z*] = Reference to controller
E [*z*] = Error sequence [4]

Trade-off between overshoot and settling time is achieved by proper tuning of *Kp*, *Ki*, *Kd* values used above. Discrete PID controller developed maintains the capacitor voltage to the reference value and controls the reactive power flow from the inverter by variations in power angle of inverter.

Active Power is proportional to sine of the power angle. PID controller works best in linear range. Therefore saturation block is introduced after the PID controller to limit the output from $-\pi / 2$ to $\pi / 2$. The DC Bus voltage of microgrid is 48V which is reference voltage for PID

4. Simulations

The Grid-tie inverter was simulated in MATLAB. The SPWM generator block has input of phase angle (power angle) and modulation index for the SPWM waves. The terminals DC4 and DC4 are connected to PV system. The terminals AC1, AC3,AC5 are AC output terminals. The LCL filter is connected between inverter and power measurement unit. The LCL filter filters the output voltage waveform of inverter and gives THD less than 2% [4].The PID controller is discrete type, and controls the phase angle so as to maintain DC link voltage constant. The model is simulated in discrete mode. Ode 45 equation solver is used and the sampling time is of 5e-6 sec.

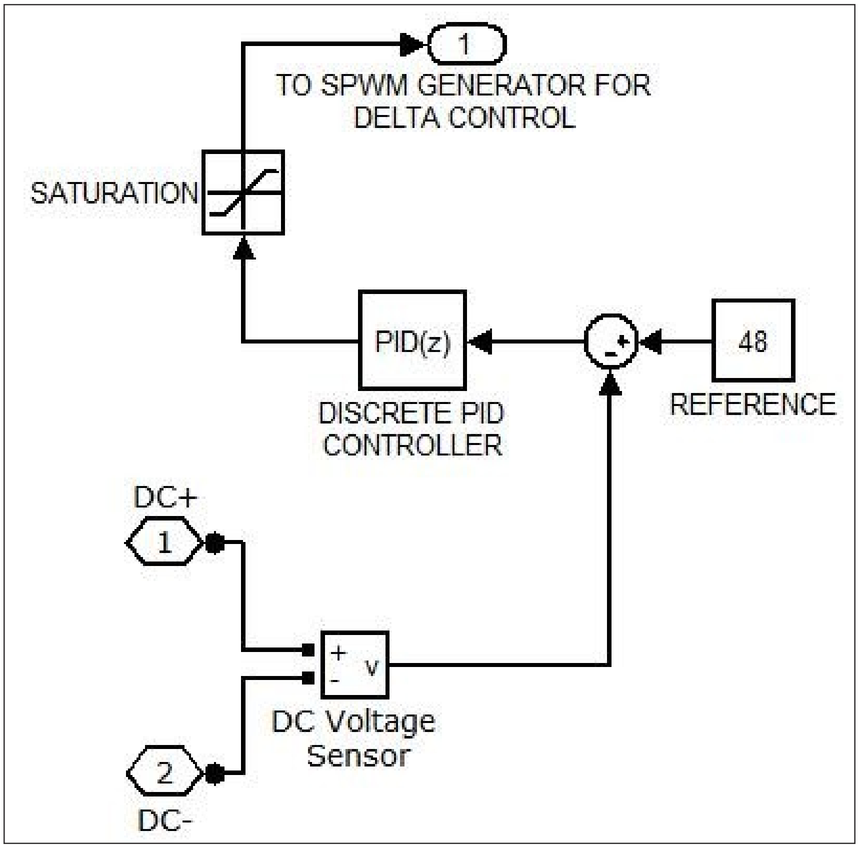

Figure 5. Simulated Discrete PID control

5. Practical Implementation

The Grid tie inverter is made using IG- BTs(FGA25N120NTD), the gating pulses to the inverter IGBT's are provided by a gate driver circuit which forms the interface between control circuit and power circuit. The inverter is connected to grid via LCL filter and sinusoidal wave of THD less than 2% in voltage is obtained at its terminal[4]. The feedback obtained from the grid is given to step down transformer. Square wave corresponding to grid's sine wave is obtained by sine to square wave converter. This square wave is fed to external interrupt circuitry of microcontroller. As the frequency of grid changes the frequency of external interrupts to the controller changes, thus facilitating measurement of frequency. The controller varies the frequency of generated SPWM signals driving the gate pulses of IGBT bridges. Thus ensuring variable frequency and grid synchronised operation of inverter

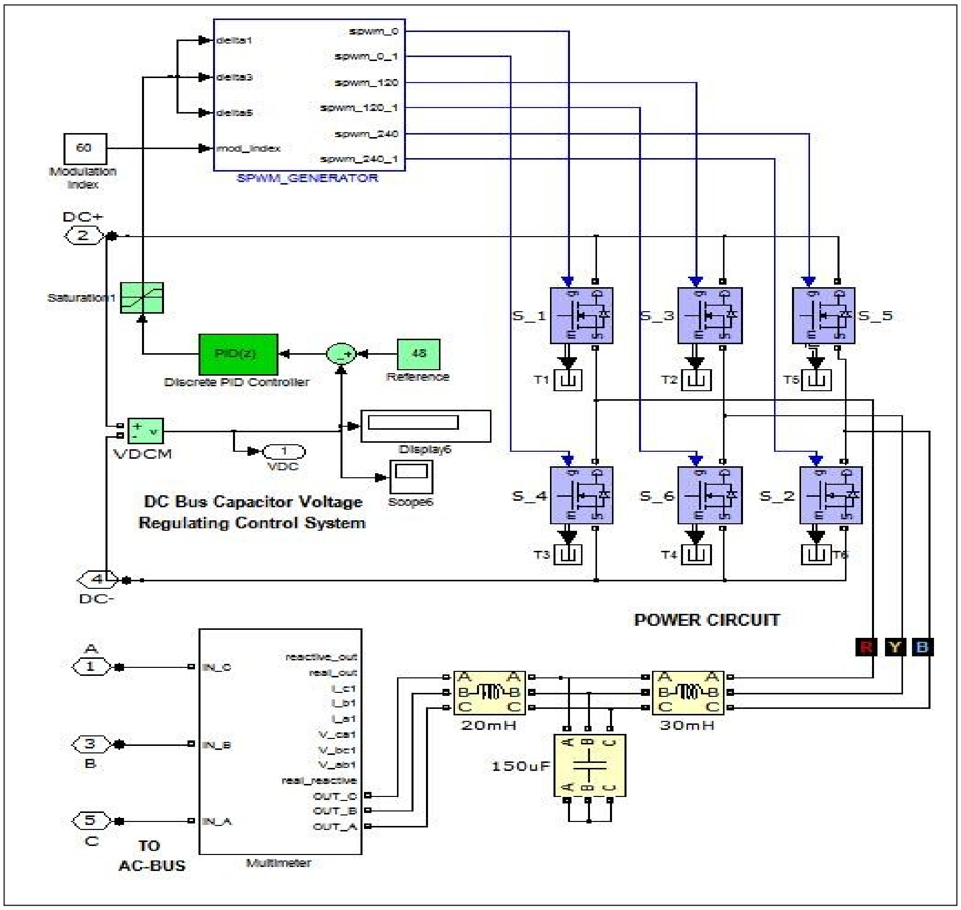

Figure 6. Simulated Control System for Grid Connected DC-AC Converter

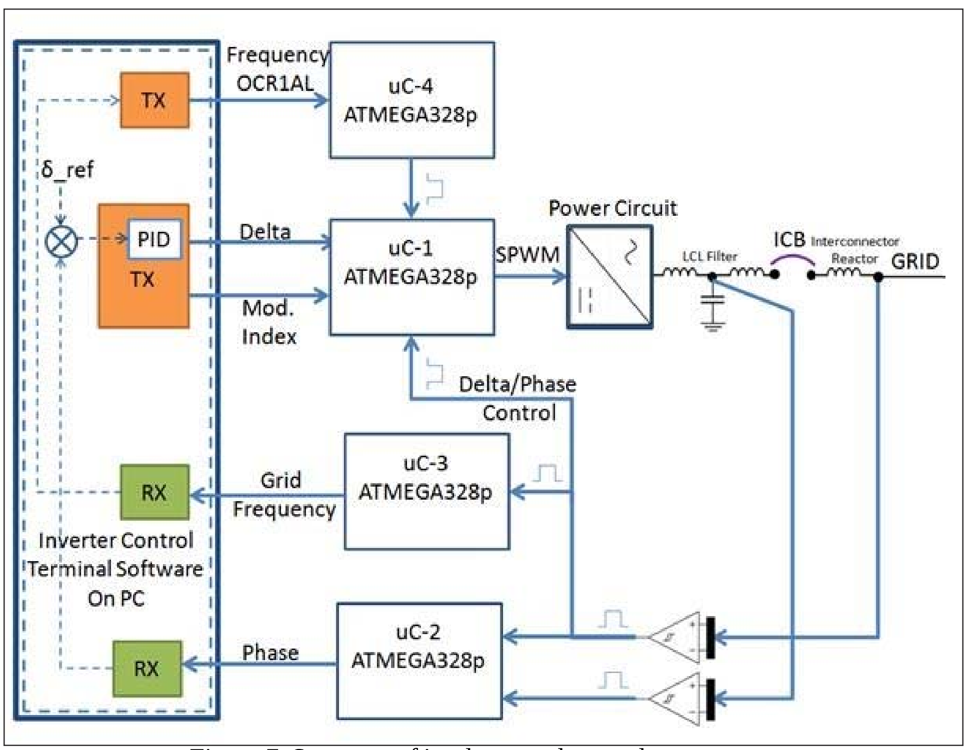

Figure 7. Structure of implemented control systems

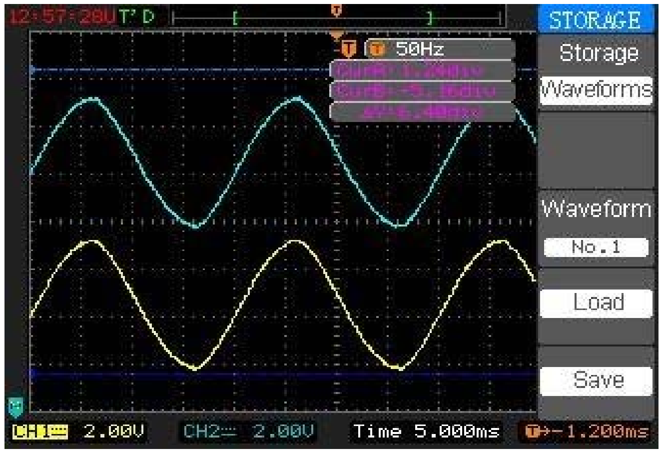

Figure 8. Frequency synchronisation(stepped down waveforms)

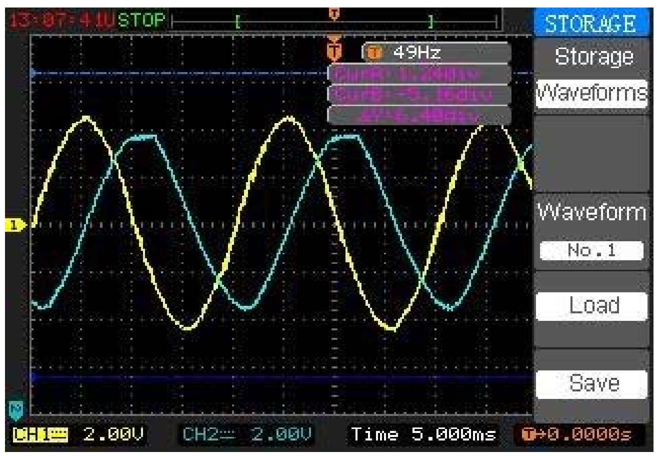

Figure 9. Phase offset given to inverter w.r.t grid (stepped down waveform)

After frequency matching the phase angles of grid voltage wave and inverter wave are matched using phase control system. This ensures the smooth synchronisation of inverter to grid. The controller used for control of frequency and phase angle is Atmega328P, having clock frequency of 8 MHz. The ADC conversion time is of 8 clock cycles. So the response time of phase control system for correction of phase is 1-2 microseconds.(time to be written with calculations).Here two controllers are used separately one for generating external interrupts from sine wave and other for generating SPWM for IGBT bridges. The phase angle control is used for power control of inverter. The desirable phase angle is achieved by introducing offset in SPWM waves given to inverter. In figure 9 below phase angle of 30 degrees lead is given to inverter waveform with respect to grid waveform.

To maintain equilibrium between generated DC power and power thrown into grid (AC power), the DC link capacitor voltage must be maintained constant. This is known as voltage control method for power transfer. To control the power of grid tie inverter PID controller is used, PID controller is needed as LCL filter can cause a phase shift in generated sine wave of inverter [4]. PID controller adjusts the power angle (delta) to its required value. The difference between Voltage reference and capacitor voltage is fed to this PID controller as manipulating variable. At output this PID controller manipulates phase angle of inverter so as to control the power of inverter. The PID controller used is digital type. The output of this PID is given to controller which generates SPWM of IGBT bridges. By proper tuning of PID smooth control over power of inverter is obtained.

6. Results

The Control System was implemented on inverter along with LCL filter interfaced to utility grid. The control systems synchronized the frequency of inverter (fig 8) with grid and maintained a constant phase difference with grid waveform (fig 9). The response of control systems was within expected limits.

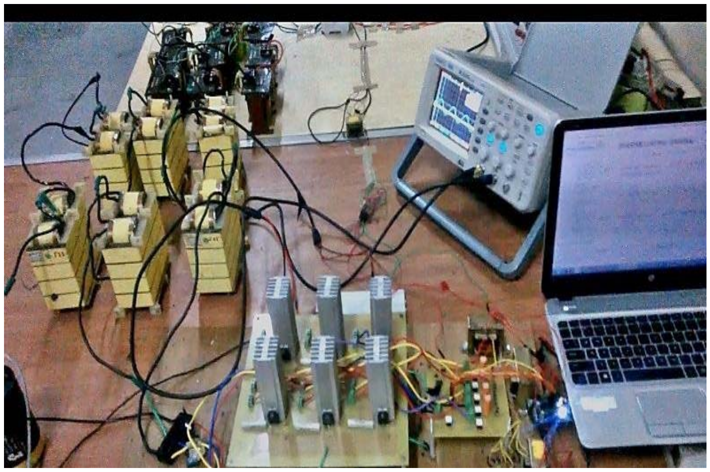

Figure 10. Practically implemented inverter

Power flow was regulated through power angle control. Power flow to utility grid could also be manually controlled by changing power angle through central interface of control system.

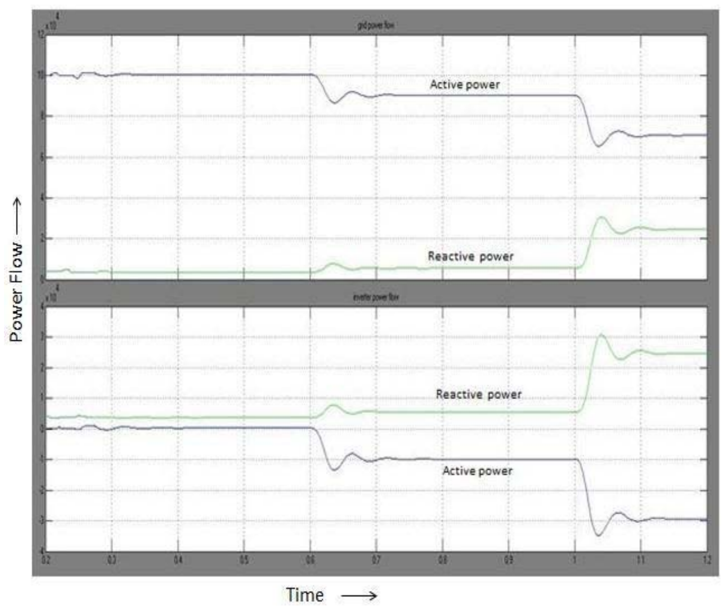

Figure 11. Manual control of active power transfer

Figure 11 shows the active and reactive power flow through simulation. The grid tie inverter is feeding a load of 10 *kW*. At the time instant t = 0.6sec, the power angle of inverter is increased to 10 degree and there is corresponding increase in the active power supplied by the inverter. Further increase in the power angle to 20° at time instant t = 1 sec. Further when power generated from PV system is increased, the power angle is adjusted by PID controller such that to throw additional generated power into the grid and maintain the DC link voltage constant.

Figure 12 shows the increase in generation on DC bus, corresponding DC link voltage and control efforts taken by PID controller to maintain the DC link voltage.

Conclusion

This paper gives description about implementation of control system for grid-tie inverter. The control system developed has better response time due to use of digital control systems with external interrupt hardware even in worst case scenario. The frequency control system and phase control system keep the inverter in exact synchronization and provide desirable phase

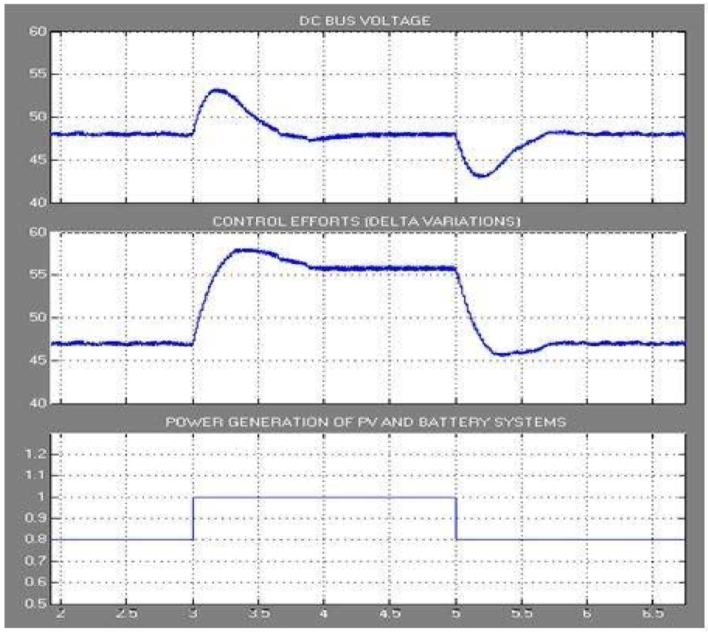

Figure 12. Automatic control of active power and DC link voltage

angle between inverter voltage wave and grid voltage wave. Control system is able to regulate the maximum power flow into grid for instantaneous generation capacity of DC bus and maintain the DC link voltage constant through control action. Power flow variations due to increase in generation on DC bus causes fluctuations in DC link capacitor which cannot be restricted beyond certain extent due to limitations of PID control implemented.

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