Real Time Hardware in Loop Testing of Single Phase Grid Connected PV System

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***Abstract*—This paper demonstrates the validation and performance testing of a decoupled controller for a single phase single stage rooftop PV by its hardware in loop (HIL) implementation. The designed controller was programmed in a digital signal controller. The rest of the system placed in real time simulator i.e. OP5600 HIL box from OPAL-RT. By the help of asynchronous communication between the plant in HIL box and controller in the microcontroller the whole system was implemented. For various operating conditions the system results are studied and reported in this paper. The effect of grid conditions on the controller behavior also analyzed.**

***Keywords*—Hardware in loop; real time simulation; microcontroller; Incremental conductance.**

Abbreviations:

HIL- Hardware in loop implementation,

P&O- Perturb and observe,

DSPIC- Digital signal peripheral interface controller,

UART- Universal asynchronous transmitter and receiver,

DSO- Digital signal oscilloscope,

FPGA- Field programming gate array.

I. Introduction

THE change in perception of civilization toward abandoning the use of electricity generated from fossil fuel has created a lot of buzz in the market for the usage of clean energy. Photovoltaic (PV) modules for generation of electricity is the most popularly accepted clean energy source. Roof top PV's are helpful in alleviating the dependability of the local loads on the grid. Furthermore the excess power generated during the peak generating time i.e. mostly 10 AM to 4 PM can be injected into the grid. This scheduled variation in power injection affects the voltage regulation at the load end. By changing the tap setting of the distribution transformer and the use of compensating devices like capacitor, the voltage profile can be regulated [1]. The reactive power support can also be provided with the help of the local single phase inverter. This has certain disadvantages like increasing the MVA rating of the inverter. Still this method is preferable owing to the fact of variable reactive power supply.

Multiple types of inverter topologies are provided in the literature [2-3]. The four switch H bridge inverter is mostly used in the single phase application due to their simplicity in design and implementation. PV modules can be of single stage or double stage [4]. Maximum power tracking and the gate pulse control of the inverter are carried out in two different stages for a double stage inverter i.e. a dc-dc boost converter and inverter. The single stage inverter topology removes the usage of two stages unlike double stage inverter. The reference for the dc link voltage is generated by the maximum power point tracking (MPPT) [5] algorithms such as perturb and observe (P&O), incremental conductance (INC) based, adaptive fuzzy based etc. The P&O works on the perturbation of the dc link voltage continuously until the maximum power point is reached. Perturbation size affects the steady state stability of the system and the convergence of the steady state voltage. Incremental conductance algorithm is much faster than the other methods as it searches for the point on the system where the incremental conductance equals the conductance of the system. This paper implements the INC based MPPT method.

The inverter is driven by a gate signal from a controller. The main functions of the controller are to maintain the dc link voltage constant, active and reactive power supplied by the inverter. Different control schemes for single phase inverter are reported in the literature. The resonant control with harmonics compensators [6] are suitable for single phase application. But the difficulty in deciding the resonant controller gains make it less favorable for practical use in single phase inverters. Synchronous voltage control or decoupled control for an inverter [7] widely used in the three phase domain. This control has the advantage of decoupling the real and reactive power control for any system. This control philosophy can easily implemented for single phase inverters [8]. In this control scheme the active power controlled by maintaining the dc link voltage constant through direct axis current and the reactive power by controlling the quadratic axis current. Reactive power supply by the inverter maintained for various purposes i.e. for regulating voltage profile at the load end and improving power factor.

The experimental validation helps in examining the performance of the developed control algorithm. Real time hardware in loop simulation (HIL) [9] of a system provides optimum test bed for this type of experimentation. With this platform controller stability at worst operating condition conditions can be examined. OP5600 HIL box [10] is a real time simulator from OPAL-RT, has the provision for hardware connection and monitoring. The developed control algorithm can be implemented with the help of different

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digital signal controllers or microcontrollers i.e. DSPIC, Arduino, C2000 from TI. The programmed microcontroller receives analog signal from the plant and after processing the signals it generates digital gate pulse for driving the inverter.

This paper demonstrates the modeling of a single stage single phase PV generator with synchronous voltage control. The synchronous voltage control algorithm was programmed in a digital signal peripheral interface controller (DSPIC) i.e. 33fj128MC802 [11]. Rest of the system was real time simulated using the OP5600 HIL box. A synchronous communication between the digital controller and the HIL box initiated. For different operating conditions the system behavior was studied and reported.

Single phase single stage grid connected PV modeling was reported in the section II. Section III describes the decoupled control algorithm development. The Real time HIL of the system was carried out in section IV. Simulation results were discussed for different operating scenario in the section V. Then conclusion derived from the experimentation was reported.

II. System Modeling

A. Photovoltaic panel

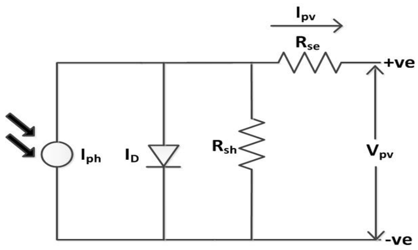


Fig. 1 Equivalent circuit of the PV cell

The PV panel consist of a 3 KW PV module with 15 number of series and 1 parallel PV cell. The PV cell specifications are reported in the appendix section. Modelling of the PV cell was carried out using the basic single diode model as shown in the fig. 1. Here the basic assumption is that the performance of the PV panel does not degrades with life. The current source represents the photon currents generated when the light source falls on the panel. The diode connected across the current source is for showing the effect of charge diffusion in the semiconductor. Series resistance is to show the resistance offered in the flow of photon current and parallel resistance shows the effect of leakage current in the cell. For N_s series cells and N_p parallel cells the total pv current is given by,

$$I_{pv} = N_p \beta \left[I_{sc} + K_i \left(T_{ref} - T_{op} \right) \right] - N_p I_{rs} \left(e^{\left(\frac{q V_{dc}}{K T_c A N_s} \right)} - 1 \right) \tag{1}$$

Where I_{ph} is the photon current, I_{rs} is the reverse saturation current, V_{dc} is dc link voltage, K_i is the cell short circuit constant, T_{ref} is the reference temperature (300^o K), T_{op} is the operating temperature of the panel, I_{sc} is the cell short circuit current, q is the charge of electron (1.602e-19 C), A is PN junction ideality factor (1.92), and β is solar irradiation in watt/m^2.

B. Inverter with grid

A single phase inverter consist of four MOSFET switches. Simpler design, cheaper cost and higher switching frequency of MOSFET based inverter makes it favorable for single phase inverter application. The switching frequency of the system decides the amount of ripple in the injected grid current by the distributed generator. Interfacing inductor and filter capacitor acts as high frequency filter for the invert circuit. LC filter oscillates at the switching frequency of the pulse width modulation (PWM) carrier signal. Design of this LC filter is done to cancel out the ripples in the inverted ac signal so as to get a pure sine wave voltage at the inverter terminal. Inductor current determines the amount of ripple current in the injected grid current. The allowable THD should be less than 5 % according to the IEEE standards [1]. And capacitor determines the amount of ripple in the voltage at the PCC. PCC is assumed to be at the grid side of the interfacing inductor as shown in fig. 2.

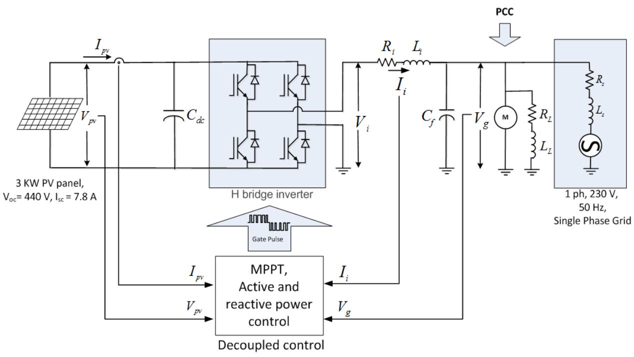


Fig. 2 PV module connected with grid

This Inverted voltage connected with single phase supply i.e. one of the phases and neutral in secondary side of a d-y11 distribution transformer. dy11 transformer vector group corresponds to the delta connected primary and star connected secondary winding and 30 degree of phase difference between them. To realize the effect of the distribution transformer and the feeder, supply is modelled as a sinusoidal supply with inherent internal resistance and inductance. Owing to the high R/X ratio i.e. 5-10 [2] of the distribution system, the inductance and the resistance of the supply is taken. The system frequency is assumed to be at 50 Hz. Fig. 2 shows the PV module connected with grid through a single phase inverter.

III. Control Schematic

The functions of the inverter module in the above described model are controlled DC to AC inversion, maintaining DC link voltage as per the MPPT algorithm, as there are no other active power sources the dc link voltage may collapse when the solar insolation level is low and control of active and reactive power supplied by the inverter into the grid. The above objectives can be achieved by controlling the gate pulse given to the MOSFETs of the inverter. The decoupled or vector control is very much popular for the three phase devices like motor, inverter, Statcom etc. This control can easily be implemented in single phase devices by making small adjustment in the control schematic.

Decoupled control philosophy works on the signals which are in the dq domain. So the primal motive is to convert the single phase voltage and current signal into dq signals.

Park's transformation [3] matrix transforms signals from stationary reference frame to rotating reference frame i.e. dq domain. Hence by converting the signals from single phase domain to stationary reference domain and then applying Park's transformation helps in getting the dq quantities.

From the fig. 2 the basic equations describing the behavior of the system is given by (2),

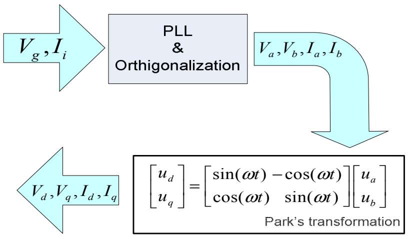


Fig 3. DQ transformation

$$V_i - V_g = I_i R_i + L\frac{dI_i}{dt} \quad (2)$$

Now orthogonalizing grid voltage V_g and current I_i with the help of a second order generalized integrator (SOGI) [4] circuit. The frequency and angle information can also be obtained from the SOGI circuit. (3) shows the orthogonal zed signals generated.

$$V_\alpha = V_g = V_m \sin(\omega t) \text{ and } V_\beta = V_m \cos(\omega t) \quad (3)$$

Similarly orthogonal signals from for grid current can be obtained. Now the Park's transformation for both of current and voltage signals is applied to get the dq domain signals. Now writing the equation (2) in dq domain as showed in (4)

$$\begin{aligned} L_i\frac{dI_d}{dt} &= -R_i I_d + L_i\omega I_q + \frac{V_{dc}}{2} m_d - V_{gd} \\ L_i\frac{dI_q}{dt} &= -R_i I_q - L_i\omega I_d + \frac{V_{dc}}{2} m_q - V_{gq} \end{aligned} \quad (4)$$

Where m_d and m_q are the direct axis and quadrature axis modulation index. Now these signals need to be converted in to sinusoidal domain for production of pulses in sinusoidal pulse width modulation (SPWM) technique. So an inverse Park's transformation matrix is used. From the generated two sinusoidal signals, only one will be used for generating PWM pulse.

The control schematic is as shown in the fig. 4. For an inverter constancy of dc link voltage ensures the total power transfer from the dc side to ac side. Hence by maintaining the dc link voltage as per the reference quantity will make the total active power generated by PV module to pass it to grid side. Incremental conductance (INC) [5] based maximum power tracking algorithm calculates the reference voltage for variable insolation operating condition. The INC based algorithm searches for the operating voltage point of a PV module where the total power generated will be maximum. The power generated by PV module will be maximum when the (5) is achieved.

$$\frac{dP_{pv}}{dV_{dc}} = 0 \Rightarrow \frac{d\left(V_{dc}I_{dc}\right)}{dV_{dc}} = 0 \Rightarrow \frac{I_{dc}}{V_{dc}} = \frac{dI_{dc}}{dV_{dc}} \quad (5)$$

From the decoupling principle [6] it can be seen that the control signals for controlling active and reactive power are I_d and I_q respectively. DC link controller provides reference quantity for the inner current loop i.e. I_d control loop. Similarly another PI controller maintains the reactive power to be supplied by the inverter at its terminal. This controller generates a reference quantity for the I_q control loop.

A. Feed forward compensation

From the fig. 4 it can be observed that current I_d is responsible for controlling the active power delivered by the inverter. But during initial condition when the dc link capacitor is not charged or during switching on of the inverter the voltage buildup at the dc link end may take ample time. So in order to compensate this delay in time a feed forward compensation loop is provided at the inner I_d current loop. (6) depicts the compensation amount is found from the power balance condition on the ac and dc side, i.e.

$$P_{dc} = P_{ac} \Rightarrow V_{dc}I_{dc} = \frac{3}{2}(V_d I_d + V_q I_q) \quad (6)$$

For single phase system it will always be balanced so V_q component will always be zero. So a component corresponding to the I_d can be found from equation (6). This component is responsible for removing the initial delay due to the discharged dc link capacitor during start up.

IV. Hardware In Loop Implementation

HIL of a control algorithm helps in validating the performance and veracity of the implemented algorithm. This also helps in removing the shortcoming of a designed algorithm. In this paper the HIL of the discussed decoupled control algorithm is implemented with the help of a digital signal programmable interface controller (DSPIC). This

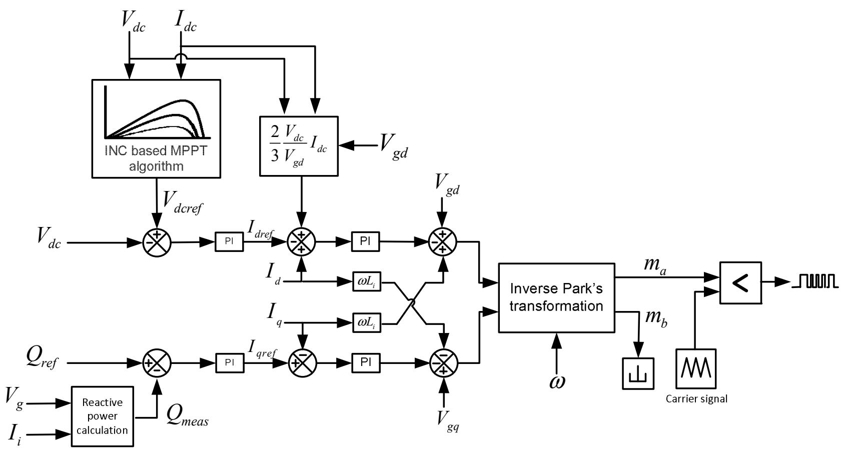


Fig 4. Control schematic

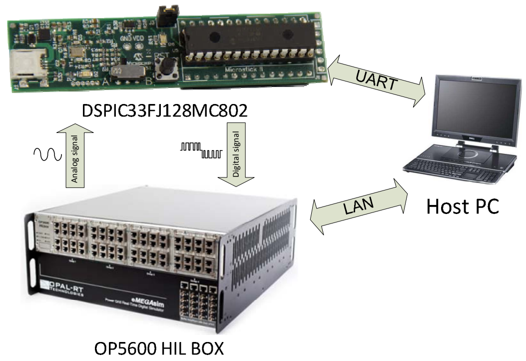


Fig. 5 HIL implementation

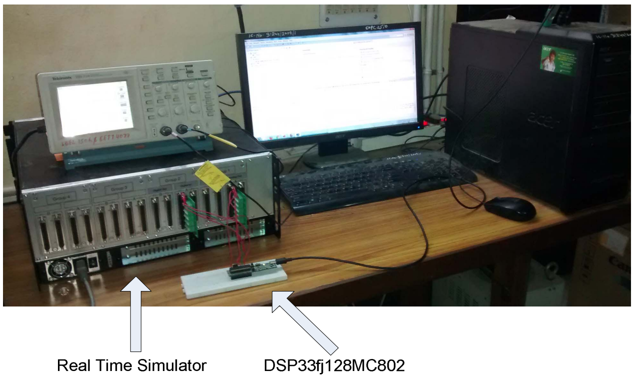


Fig. 6 Hardware in loop setup

DSPIC is then tested with the help of multi core OP5600 HIL box from OPAL-RT. The implementation of the system in HIL is as shown in fig. 5. The whole system is divided into two parts i.e. plant and controller. The two different Matlab models were formed for the two parts. Plant contains the PV module connected with inverter to grid and some residential loads i.e. SPIM and lighting loads. This model is made to be placed in the OP5600 HIL box.

The sensed analog signals in the model pass through signal conditioning process before made available at the analog out ports of the HIL box. The discussed decoupled controller for single phase inverter is placed inside the controller model. This model is then programmed in a DSP33fj128MC802 microcontroller. Now the communication between the two modules i.e. HIL box and the DSPIC is done in the actual analog and digital signals. Microcontroller generates digital pulses after proper signal reconditioning and processing the analog outputs from the HIL box. So a synchronous communication is initiated between them. The sampling rate for the both of the system are different and to be chosen carefully.

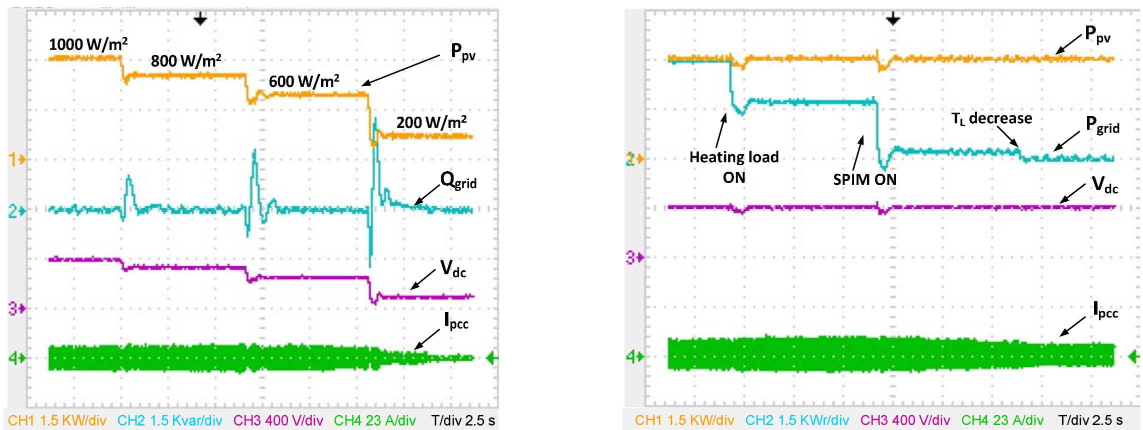
A. DSPIC 33fj128MC802

This is a high performance programmable 16 bit digital signal controller with 35 programmable digital I/O pins and 4 analog in pins. It has 128 KB flash programmable memory and 3.3 V (±10%) operating voltage. This is suitable for compact mechatronics applications. The MP-LAB IDE software was used for programming the device. The C programs and along with some header files are written into the programmable space in the DSPIC. This device is not suitable for larger control algorithms. The Analog to Digital Converter Interrupts are used for this DSPIC. A/D Converter takes some time to complete its operation. So the CPU can either wait for it to complete or set up an AD conversion complete interrupt. In the latter case CPU can do other tasks while A/D converter converts the input. As soon as A/D converter completes its job it will inform CPU to read the value from its buffer.

C codes and the header files are generated in MATLAB/Simulink® compatible libraries for Microchip. The specification of analog input and digital output are defined in the Matlab model of the controller. The clock frequency at which the system will operate, number of instruction per second in term of millions (MIPS), sampling time of the model are specified in the model before generating the C codes from the MATLAB model. The generated codes are now written into the DSPIC programmable memory with the help of MP-LAB integrated development environment software. The communication between the host computer and the DSPIC is carried out using the universal asynchronous receiver/transmitter (UART) communication through USB cable. Internal oscillator frequency of the DSPIC kit is very less. So a crystal oscillator of frequency 11.0592 MHz is used as to generate higher switching frequency. The sampling time of the signal is taken in the range of milliseconds. This time step to be chosen by considering the synchronous communication between the HIL box and DSPIC.

B. OP5600 HIL box

HIL simulator suitable for simulating an environment for testing and verifying a hardware module. It is a real time



(a) (b)

Fig. 6. PV module power (P_{pv}), Reactive power supplied by inverter (Q_{grid}), DC link voltage (V_{dc}), current at the PCC (I_{pcc}) for (a) Variable insolation, (b) Switching ON of local load

simulator box with multiple high frequency processor cores (about 3.3 GHz). Multiple cores in the simulator helps in running a large system without any delay in processing. It has equipped with field programming gate array (FPGA) for analog and digital I/O communication with other or peripherals. Total 128 number of digital, analog or 256 number of mixed signals can be accommodated at a time and at the same time those signals can be monitored through digital storage oscilloscope (DSO). This system runs in Linux/Redhat platform. RT-Lab software is the GUI (graphic user interface) for handling the operation of the HIL box.

Developed models in the Matlab/Simulink domain are used for real time simulation. The plant model is made to run in the RT-LAB software. After defining the proper configuration files the sensed voltage and current signals are made available at the FPGA I/O pins. Similarly for detection of digital signals. The sampling time of the system was taken as 20 microseconds. From the I/O monitoring ports the required signal are monitored using 4 channel DSO.

V. Real Time Simulation And Results

For various operating condition the single stage grid connected system was studied and the results reported in the following section. Fig. 6 shows the total power 3 KW at 230 V, 50 Hz supplied by the PV module to grid. The dc operating voltage corresponding to the maximum power point at the nominal insolation condition i.e. 1000 w/m^2 is 400 V. The switching frequency of the inverter is taken as 2000 KHz. A 1.2 HP single phase capacitor start and run induction machine and heating load of total 1000 w was considered as residential load connected at the PCC.

A. *Variable insolation*

In this case the insolation level on the PV panel was varied as shown in the fig. 6. For different insolation level the active power, reactive power injected, dc link voltage and current fed to the grid by the inverter is shown in fig. 6 (a). The MPPT algorithm tracks the maximum power point on the P vs. V curve. The THD (Total harmonics distortion) level of the current is found to be below 5 %. Here the reactive power is maintained at zero level in order to ensure the unity power factor operation. In the need of voltage regulation at the terminal of the inverter the reactive power injected by the system can be adjusted using the described decoupled control philosophy.

B. *Variable loading*

Fig 6 (b). Shows the response of the decoupled controller for various change in loading at the inverter terminal. Here two kind of loads i.e. heating and motor load used as the peculiar residential load. The PV power, active power, line current injected into the grid and dc link voltage for different loading condition is as shown in Fig. 6 (b) and 7 (a) & (b). It can be observed that the dc link voltage variation for sudden loading change at the terminal is minimum.

C. *Grid voltage variation*

For grid voltage variation i.e. voltage dip and surge the controller performance was tested and plotted in the fig. 7 (c) & (d). The sudden dip in voltage causes the large drawl of reactive power from the nearby grid. During this time the decoupled controller can also supply the reactive power with proper regulation. This can be done by setting the reference reactive power for the control using the proportionate quantity of the deviation of supply voltage. For different grid condition i.e. strong (large X/R ratio) and weak grid condition (small X/R ratio) the system performance was plotted.

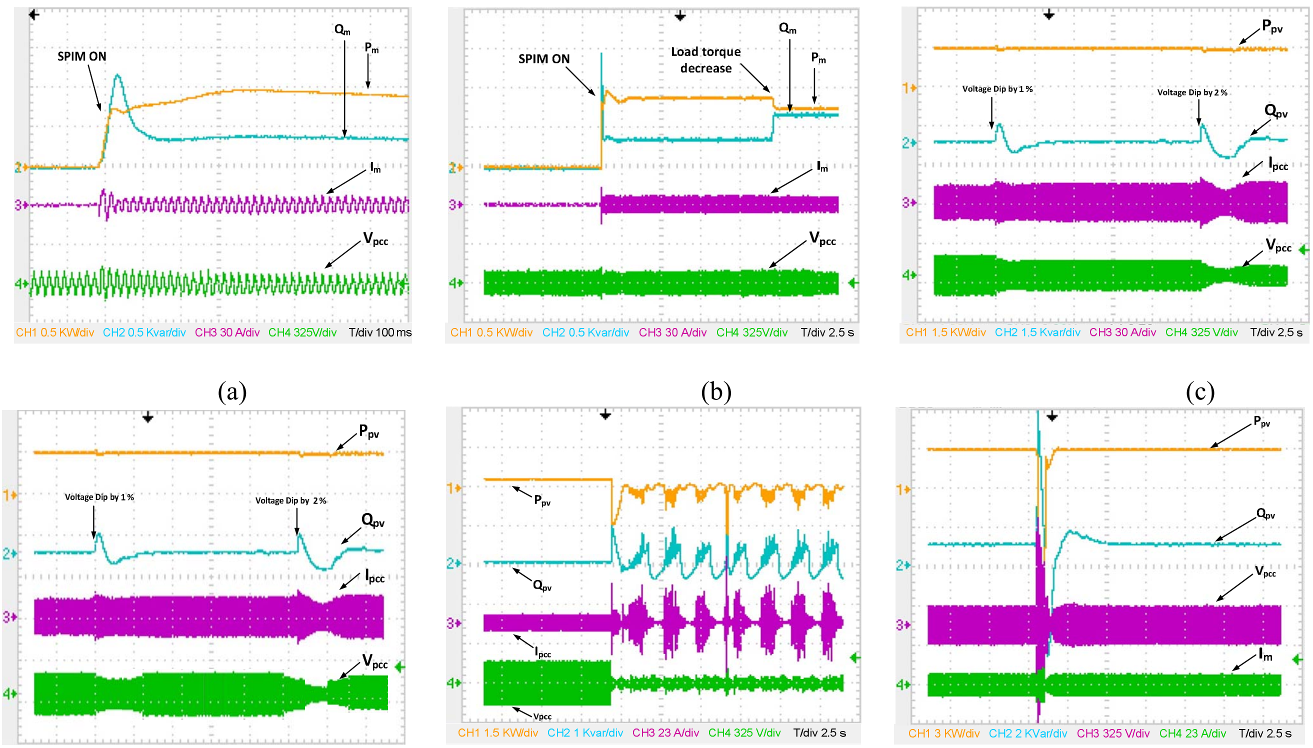


Fig. 7. (a)-(b) Induction motor real (P_m), reactive power (Q_m), current drawn (I_m) and terminal voltage(V_{pcc}); Real (P_{pv})and reactive power (Q_{pv}) injected by the inverter, terminal voltage (V_{pcc}) and current injected(I_{pcc}) for grid voltage variation at (c) strong grid condition , (d) weak grid condition and for frequency variation (e) strong grid, (f) weak grid condition.

D. Grid Frequency variation

For different grid condition the controller performance at frequency deviation from nominal plotted in fig 7 (d) & (f). It can be observed that the system for a strong grid system the performance of the controller is much better and faster as compared to that for a weak grid system.

VI. CONCLUSION

This paper discusses the implementation of designed decoupled control algorithm for single phase grid connected photovoltaic generating system for house hold. The validation of control algorithm was carried out using the digital signal processor. This controller can be used in the hardware module as its real time testing was done using the real time simulator. The future work may to carry out the stability analysis of the proposed control algorithm. The developed control algorithm can be used to control the active and reactive power in a distribution system for maintaining the voltage profile.

VII. APPENDIX

Parameter	*Specification*
PV Cell	V_{oc}= 37.3 A, I_{sc}=8.2 A, V_m=30.3, I_m=7.5 A, Ns= 15, Np=1,
PV power	*3 KW*
DC link voltage	*400 V*
DC link capacitor (C_{dc})	*2000 µf*
Grid Voltage	*230 V, 50 Hz*
Filter Inductor(R_i, L_i)	*0.03Ω, 3mH*
Filter capacitor(R_f, C_f)	*0.01Ω, 110µ f*
Grid inductance(L_g)	*3mH, 0.55 Ω*
Current controller	K_p=0.6, K_r=6
DSPIC specification	*Model no- 33fj128MC802, 128 KB flash rom, 7 I/O' and sampling time, Ts=1e-3 sec.*

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