Microgrid Design and Control Using a Discrete Proportional Resonant Controller

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Abstract- This paper presents a Proportional Resonant (PR) controller design in discrete domain for regulating the active and reactive power output for a three-phase AC Micro-Grid system. The PR controller reduces the steady state error and help in synchronous d-q transformation in three phase system. It employs a Voltage Sourced Converter (VSC) which is configured to operate as a current source through an interface L-filter. The power is controlled indirectly by controlling the inverter's output current. This paper also presents a comparison of THD between Proportional Integral (PI) and Proportional Resonant (PR) controllers and indicates that the THD using Proportional Resonant (PR) controller is less than the Proportional Integral (PI) controller by more than 2%. The complete work is designed and implemented in MATLAB/SIMULINK.

Keywords- Microgrid, microsource, Proportional Resonant, Proportional Integral, controller, THD

1. Introduction

The global call to reduce CO2 emissions in the generation of electricity, re-organising the electrical market and the advancement of technology in the development of micro-generation lead to the growing interest in the use of microgeneration. The main attributes of Microgrid are generation sources, loads and energy storages. It is a collective work of a small generation system, a low voltage distribution network and fast acting power switches and devices for connecting the load. Microgrids are designed and developed for some special functions. They are mostly used for small urban areas or in small industries for meeting the electricity requirements. Various microgrids generate power ranging from 25 to 100 kW [1]. There are also systems which are used widely having lower and upper power levels. Some of the energy sources that are used in micro-grid for electricity generation are diesel, gas, fuel cells and renewable sources like wind, solar etc…

The microgrids generate power at lower cost and emit less amount of gases when compared with traditional power sources. Since the generating units are small in size, they can be placed very conveniently for cooling, distribution and maintainance of the installation. There is an enormous increase in small scale generation. There is a need of connecting the loads to these small scale generating units together with the utility [2]. The inverters play the role of connecting the generating units to the distribution network. Microgrids can work in offgrid mode and grid connected mode. In off-grid mode, the generated power is stored without the help from the main grid. These type of grids are equipped with batteries and nearby loads connected to one or multiple energy sources. In grid connected mode, the microgrid is connected to the main grid using power electronic devices to synchronise with the main grid [3]. This connection called grid-connected mode, is the main operating mode. The microgrid then can be used as back-up system which can store the power using batteries or as an assistance to the main utility system when the power demand is high on main grid . There is another mode of microgrid operation called emergency mode, in which the local loads are fed using microgrid alone when the main grid fails under some circumstances.Under grid connected mode, the microgrid is connected to the main grid using a power source and a large battery. The excess of the energy generated is stored in the batteries or super capacitors and support the main grid when the load demand on it increases. The size and type of the batteries depend on the system's configuaration. When the main grid is in normal operating state , the microgrid charges the battery bank to full charged condition so that the batteries can be used during emergency mode. When the demand is more on main grid, then the microgrid operates along with utility system when feeding the local loads. When the generated power from the microgrid is greater than the demanded power level, extra generated energy is sent to the main grid. In the other way, if the energy generated from microgrid is not sufficient to supply its local loads, the main grid helps in compensating the deficient energy. Most of the loads operate on AC power and this requires the inverters to invert the DC energy generated from the sources. The battery inverters are required to invert and also control the energy flow [4].

The microgrid system components are identified based on their function. Units like grid forming units, grid supporting units and grid parallel units are present[5]. Grid formimg units are used for controlling the voltage and frequency of grid by stabilizing the loads and sources. Diesel generators and battery inverters are some of the grid forming units. The other unit i.e. the grid supporting unit is very simple unit which is used for grid control. The active and reactive power of these units depend on the connected system's voltage and frequency. The grid parallel units comprises of loads, renewable energy source generators like wind energy converters and photovoltaic systems. These units are required to generate the maximum power from the available sources [6]. The impact of microgrid on environment is very less when compared to thermal or hydro stations. The use of microgids reduces the gas ejections into the environment and helps in forming a green eco-system. According to the report "Microgrids-the Future of Small Grids" [7] decentralizing of power production reduces the consumption of fossil sources than the present consumption . The most positive features of microgrids are the location of the plant being close to the load and having low generation and distribution voltage level. Because of these, the electricity supplied is more secure and relaible besides having low power loss in network. Also, it reduces the cost of transmission and distribution of electrcial energy [8]. There wont be any need to invest in transmission and large scale generation. This drops down electricity prices because of more extensive use of transmission and distribution networks.

All the controlleres so far designed in the literature are analog controllers. But in future, the whole worls power system will be changed to smart grid in which the digital circuits plays the key role in controlling and monitoring the micro-grids. This has broughht the idea of designing the discrete controlleres for the operation of micro-grid. This paper presents a microgrid model of 100 Kw. The MG components which have been studied are the Photovoltaic Array, MPPT control of boost converter, current controlled VSC, Proportional resonant controller. The discrete Proportional Integral (PI) and Proportional Resonant (PR) current controllers are used for controlling the microgrid and then compared.

2. System Description

2.1. Photovoltaic Array

Photovoltaic generation is a technique which converts the heat energy of sunlight to electrical energy. PV technology is well established and is widely used to supply electrical energy for the remote areas from the distribution network. The inverter consists of a Maximum power point tracking (MPPT) circuit for getting the maximum power from solar panel, Energy storage element, like a capacitor or battery , DC-DC converter for boosting the PV output voltage, DC-AC inverter , Isolation transformer to stop the injection of DC into the network, Filter circuit to filter out the harmonic currents of network.

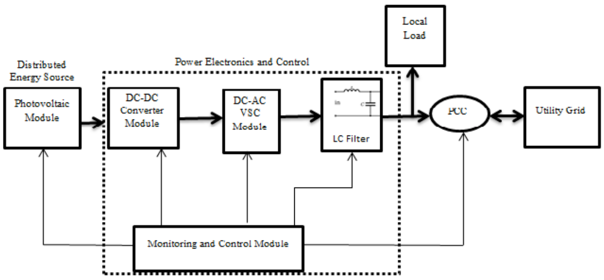


Fig 2.1. Basic Microgrid.

2.2. MPPT Controller

The MPPT controller make use of "Incremental Conductance + Integral Regulator" technique to optimize the switching duty cycle [9]. In figure 2.1, the DC/DC boost converter is the power electronic interface. The duty ratio for the converter is obtained from the MPPT controller. Incremental Conductance(INC) method is used for better result. An incremental algorithm principle helps in decreasing and increasing the control variable appropriately by associating the PV module conductance (I/V) to its augmenting conductance (dI/dV). Maximum power point is obtained when the photovoltaic (PV) generation.

$$\frac{dP}{dV} = 0 \; where \; \mathrm{P} = \mathrm{V} * \mathrm{I} \tag{2.1}$$

$$\text{substituting } \mathrm{P} = \mathrm{V} * \mathrm{I} \text{ in } (1)$$

$$\frac{d(\mathrm{V} * \mathrm{I})}{dV} = I + V * \frac{dI}{dV} = 0 \tag{2.2}$$

$$\frac{dI}{dV} = -\frac{I}{V} \tag{2.3}$$

The integral regulator minimizes the error (dI/dV + I/V)INC has higher tracking performance compared to perturb and observe (P&O) algorithm. The transient of the output is better with INC MPPT when the irradiance and cell temperature are constant [9]. The tracking efficiency result is 99.73% with step size 0.02% when a step change of irradiance and temperature are applied. The output current has low frequency ripple content depending on the rate of the dc link capacitance alone with the size of the step that is utilized in alteringthe duty cycle converter.The step size of the MPP in the PV array is adjusted automatically using the variable step size INC. This improves the MPPT speed and accuracy together [9].

2.3. DC/DC converter stage

The boost converter [10] is used to increase the output power of the PV array. The design of this circuit is simple. Any algorithm of maximum power point can be used to implement with software and hardware. The boost converter circuit is shown in figure 2.3. Boost converter can operate in continuous and discontinuous conduction mode. The conduction mode depends on the amount of energy that can be stored with the relative switching time frame. The output voltage varies with the duty cycle which in turn is adjusted by using the maximum power point controller. The boost converter designed in [11] has all possible duty cycles and works for all changes in the irradiations of the PV array.

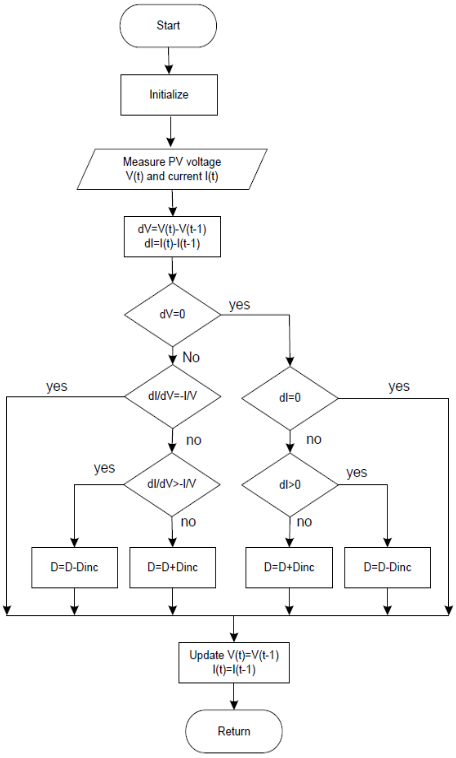


Fig2.2: Flowchart of Incremental conductance method [9]

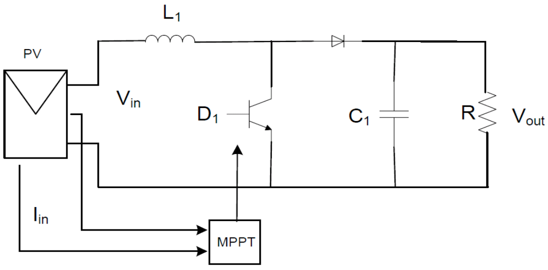


Fig 2.3: Dc/Dc converter

2.4. DC/DC converter stage

It should change the DC current to a sinusoidal waveform with a lower amount of harmonics. The PV array has to finally provide a AC power to the grid. The topology of the inverter to be chosen depends on the application like standalone PV system or grid connected. The other factors that decide the topology are the power output of the PV, the current harmonics and the cost. When the PV panel is connected to the grid, the inverters should have island detection, power quality within the standards, grounding, etc.

The DC/AC inverter has some many topologies in literature like frequency-commutated current source inverter (CSI), a full-bridge multilevel inverter like diode clamped three-level VSI, etc. The line commutated inverters are proved to be robust, cheap and have more efficiency but has a low power factor from 0.6 to 0.7. The self-commutated inverters are more popular as they are capable of high switching frequency, cheap and robust. But, due to high switching frequency, it gives more losses in semiconductor. The line frequency-commutated inverter uses a sinusoidal signal to give an AC output. The drawback of this are the harmonics which can cause series resonance with the capacitors present in the system. The full-bridge inverter is widely used in PV system. Figure 2.4 is the three-phase full bridge inverter. The command of the switch depends on the modulation schemes to obtain the sinusoidal output.

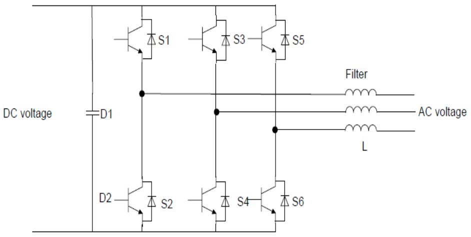


Fig 2.4: Dc/Dc converter

3. Current Control for VSC

3.1. Conventional PI Controller

A conventional PI controller is defined by the transfer function

$$G_{pi} = K_P + \frac{K_I}{S} \qquad 3.1$$

where kP and kI are the proportional and integral gains, respectively.A controller conventional form can be implemented in each of the two SRF axes to achieve zero steady-state error. The synchronous frequency ωo for the Park transformation should be adjusted to coincide with the frequency of the harmonic order h to control, that is, ωo = hω1, with ω1 being the fundamental frequency. For negative-sequence components, ωo = −hω1 should be considered. The PI controllers for each harmonic order h can be tuned with independent proportional and integral gains (kPh and kIh, respectively):

3.2. *DC/DC converter stage*

The equivalent transfer function in stationary frame of a PI controller implemented in a positive seuence SRF can be obtained by application of a frequency shift of –hw1 at all frequencies that is, by substitution of s → s - jhω1 in 2.1.

$$G^{+}_{PI_h} = G_{pi_h}(S - jh_{\omega 1}) = K_{P_h} + \frac{K_{Ih}}{S - jh_{\omega 1}} \qquad 3.2$$

On the other hand, the substitution s → s + jhω1 , when ωo=-hω1 should be applied in order to obtain the transfer function in stationary frame of a PI controller implemented in a negative-sequence SRF

$$G^{-}_{PI_h} = G_{pi_h}(S + jh_{\omega 1}) = K_{P_h} + \frac{K_{Ih}}{S + jh_{\omega 1}} \qquad 3.3$$

Addition of 3.2 and 3.3 leads to

$$G_{PR_h} = G^{-}_{PI_h} + G^{+}_{PI_h} = K_{P_h} + \frac{K_{Ih}}{S^2 + h^2{}_{\omega 1^2}} \qquad 3.4$$

which is the transfer function of a PR controller. GPRh(s) provides infinite gain in open loop at the resonant frequency hω1, so that unity gain and zero phase shift in closed loop (zero steady state error) is achieved at the frequency. It should be remarked that to implement with additional damping terms should be avoided. The resonant term R1(S) is the part of a GPRh(s) controller that provided infinite gain at the resonant frequency. R1h(s) is preferred as a Laplace transform of a cosine function than a sine function as it provides better stability.

3.3. *Discretisation of PR Controller*

Most studies devoted to resonant controllers have been carried out in the continuous domain [12] [13]. However their observations and conclusions cannot be directly applied to digital devices in the discrete time domain. So, performance of PR controller is analysed in discrete domain forward and backward are used for discretisation of PR controller. Forward and Bacyward Euler discretisation implies

$$S = \frac{1 - Z^{-1}}{Z^{-1}T_s}$$

$$S = \frac{1 - Z^{-1}}{T_s}$$

$$\begin{aligned} G^{f\&b}_{PR_h} &= K_{P_h} + \frac{K_{Ih}\dfrac{z^{-1}T_s}{1 - z^{-1}}}{1 + h^2 w_1^2 \dfrac{T_s}{1 - z^{-1}} \dfrac{z^{-1}T_s}{1 - z^{-1}}} \\ &= K_{P_h} + \frac{K_{Ih}T_s z^{-1}(1 - z^{-1})}{(1 - z^{-1})^2 + z^{-1}h^2 w_1^2 {T_s}^2} \\ &= K_{P_h} + \frac{K_{Ih}T_s(z^{-1} - z^{-2})}{1 + z^{-1}(h^2 w_1^2 {T_s}^2 - 2) + z^{-2}} \qquad 3.5 \end{aligned}$$

3.4. *Advantages of PR controller over PI controller*

Grid connected PV Inverter systems have become more popular in the modern power system and the number of such systems connected to the main grid are increasing from time to time.Hence, the harmonics generated by these systems through the power electronic devices are to be reduced which can reduce the quality of the power. PI controller cannot be used for this as it can not go along with the reference of a sinusoidal wave without having steady state error due to the changes in the integral term. This necessiates the use of the grid voltage as a feed-forward term which helps the controller to try the steady state at fast rate and obtain a good dynamic response. This drawback leads to development of PR controller.

4. Results

A microgrid of 100 KW consisting of photovoltaic generation connected to the grid is developed as shown in the figure 4.1. and simulated in MATLAB/Simulink development software. The PR controller and PI controller compensator are implemented for the inverters output current regulation. The parameters used for the simulation are shown in table 4.2.

The THD is less for for the current and voltage waveforms using the propotional resonant controller than the propotional integrator controller.The power, current and voltage waveforms obtained using PR and PI controllers from the utility grid, solat and at load are as shown below. In the figures 4.2 to 4.10, PR is for Proportional Resonant Controller and PI is for proportional Integrator Controller. The microgrid is simulated for different types of loads like a pure resistive load and also for reactive loads with resistive load. In all the results of figures 4.2 to 4.10 , it observed that the propotional resonant controller performs better than the propotional integrator controller to fulfil the load requirements. For example from the figure 4.10 , which are the results simulated for the load of 100 KW + 75 KVAR, the propotional resonant controller meet the exact lood of 100 KW and 75 KVAR in the figure 4.10 where as the propotinal integrator controller just meets the load of 90 KW and 71 KVAR at the load terminals. This behaviour is observed for other load conditions also which can be sseen in the figures 4.2 to 4.10.

The solar irradiance for solar power generation is considered as 1000 w/m2 upto 0.7 sec and then reduces to

550 w/m2 from 0.7 sec to 1 second. Accodingly, the output power from the solar grid changes i.e. the current from the solar grid comes down at 0.7 seconnds and inturn the power also reduced from 0.7 seconds. This decrease in current and power from solar grid to the load is compensated from the utility grid and at last the load requirement is met with the co-ordination of both solar grid and utility grid. For exaple, in the figure 4.9, the current from the solar grid reduces from 450 A to 350 A starting frm 0.7 sec to 1 second and this reduction ofcurrent is compensated with the increase in current from utility grid from 800 A to 1000A to meet the load requirements. The results obtained for different load variations are as shown below from the figures 4.2 to 4.10. Also, The the current, voltage and the power signal comes to steady stare value in less time using propotional resonant contrller than the PI controller. From the figure 4.10, it can be observed that the real power and reactive power at load settles to constant value at 0.1 second using propotinal resonant controller where as it takes more than 0.2 seconds using the propotional integrator controller and also the output using proportional integrator controller is in oscillation mode till the last moment of time.

Table 4.1 Comparison between THD values

S.no	THD	PI controller	PR controller
1	Current	0.0845	0.064
2	Voltage	0.0643	0.0438

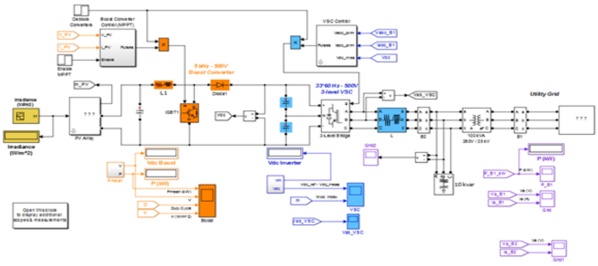


Fig 4.1: Simulink model of 100 KW microgrid

For load = 100 KW

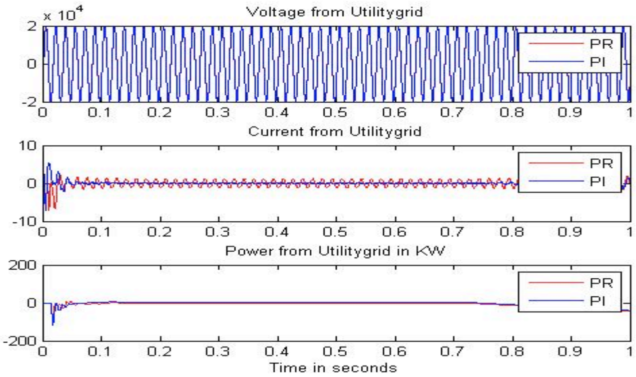


Fig 4.2: Voltage, Current and Power from Utility to Load

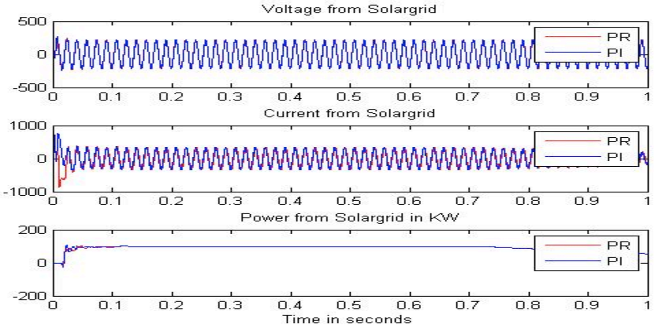


Fig 4.3: Voltage, Current and Power from Solar grid to Load

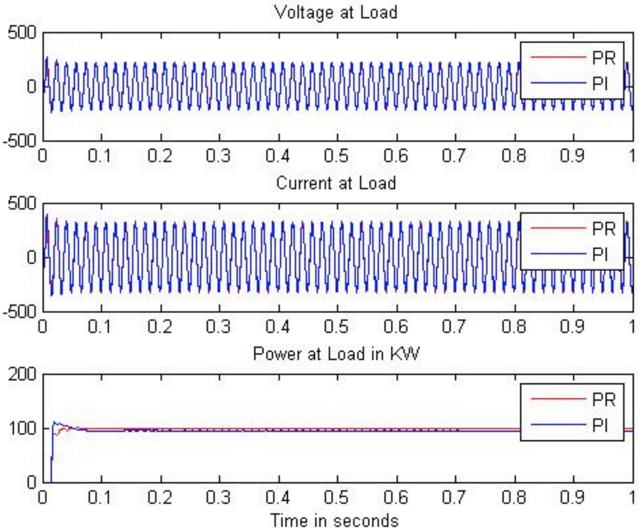


Fig 4.4: Voltage, Current and Real Power at Load

For load = 100 KW and 5 KVAR

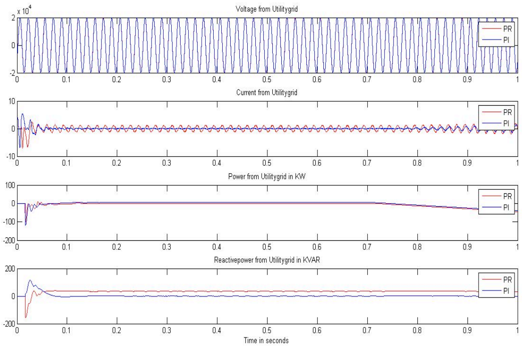


Fig 4.5: Voltage, Current , Real Power and Reactive Power from Utility to Load

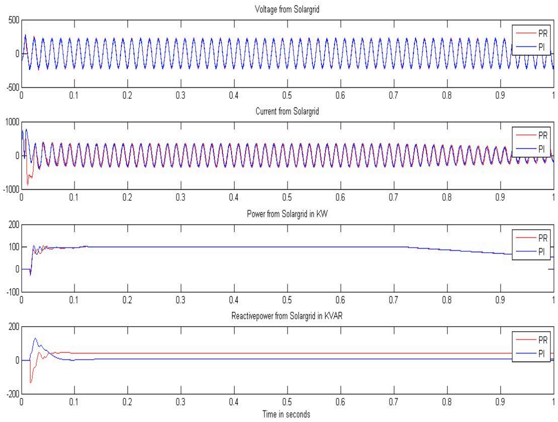


Fig 4.6: Voltage, Current , Real Power and Reactive Power from Solar grid to load

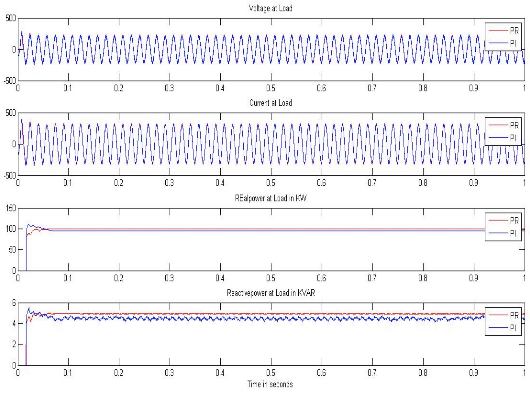


Fig 4.7: Voltage, Current , Real Power and Reactive Power at load

For load = 100 KW and 75 KVAR

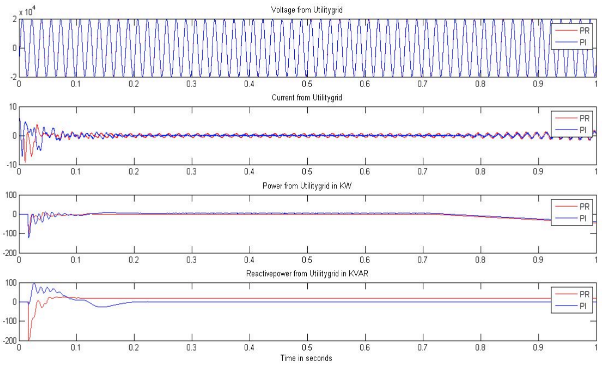


Fig 4.8: Voltage, Current , Real Power and Reactive Power from Utility grid to Load

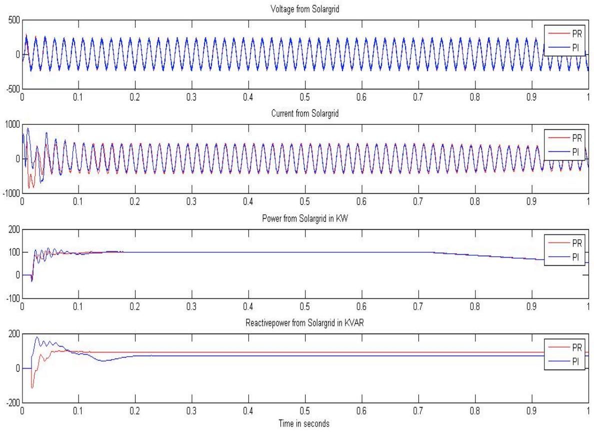


Fig 4.9: Voltage, Current , Real Power and Reactive Power from Solar grid to Load

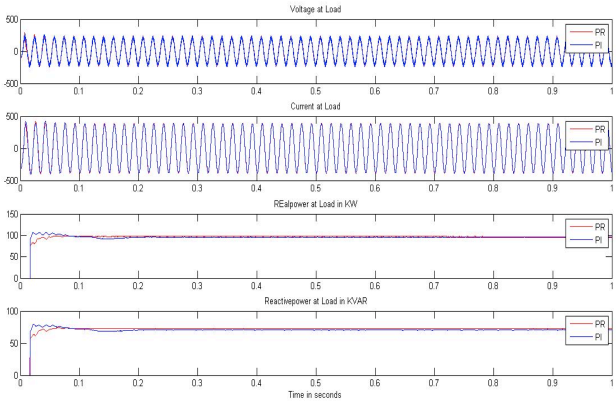
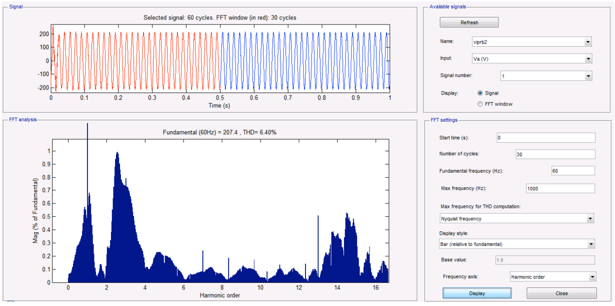
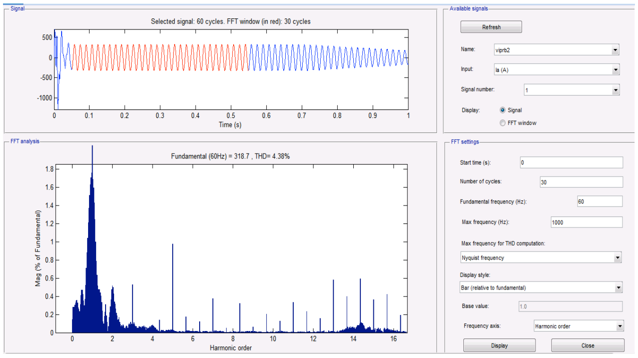


Fig 4.10: Voltage, Current , Real Power and reactive Power at Load



Name: viprb2
Input: Va (V)
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0
Number of cycles: 30
Fundamental frequency (Hz): 60
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig 4.11: FFT analysis of Phase A Microgrid voltage(VaMicrogrid) using PI controller



Name: viprb2
Input: Ia (A)
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0
Number of cycles: 30
Fundamental frequency (Hz): 60
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig 4.12: FFT analysis of Phase A Microgrid Voltage (VaMicrogrid) using PR controller

5. Conclusion

In this paper, the photovoltaic system is developed and an incremental conductance with integral regulator is used to track maximum power from it. Then, the design of the boost converter, PR current controller for DC-AC Converter is designed. When the irradiance varies, the PV models output current change. The complete system simulations of the whole system with maximum power point, boost converter and VSC were performed by varying the Local load, the irradiance and the temperature. This paper has presented the effectiveness of using the Proportional Resonant (PR) control strategy to control active and/or reactive power transfer between the Micro-Grid and the transmission grid system. The THD value of the current and voltage in the grid using PR controller are 6.4% and 4.38% respectively and are less by 2% than the PI controller current and voltage THD. The PR controller tracks stationary frame reference currents calculated from the active (PC(t)) and reactive (QC(t)) PI controller actuating power outputs using d-q frame power equations. Consequently this improves the performance of the control loop as opposed to reference currents calculated directly from αβ frame power equations. The PR controller tracks reference currents with a very small steady-state error and reduced Total harmonic distortion. Model development and simulations were done using the MATLAB/Simulink software environment.

Table 4.2 :Parameters used for microgrid simulation.

Solar Panel Parameters	
Series connected modules=5	Series Resistance =0.037998
Parallel Strings = 66	Parallel Resistance =1.175 e-08 Ω /module
Voc = 64.2 V/module	Isat = 5.9602 A/module
Isc =5.96 A/module	Qd=1.3
Boost Converter	
R = 0.005 Ω	L=5e-3 H, C= 12000e-06 F
RL Filter	
R= 2e-3 Ω	L= 250e-6 H
Vdc regulator Gains	
Kp= 7	Ki=800
Current Regulator gains	
Kp = 0.3	Ki = 100

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