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A Novel Control Strategy for a PV Grid Connected Voltage VAR Compensation using PI and PI Fuzzy Controller

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Abstract: Three-phase grid-connected converters are widely used in renewable and electric power system applications. Traditionally, grid-connected converters are controlled with standard decoupled d-q vector control mechanisms. However, recent studies indicate that such mechanisms show limitations in their applicability to dynamic systems. This thesis investigates how to mitigate such restrictions using a Fuzzy-PI to control a grid-connected rectifier/inverter. The Fuzzy-PI implements a dynamic rule book and fuzzy rules. To enhance performance and stability under disturbance, additional strategies are adopted, including the use of integrals of error signals to the network inputs and the introduction of grid disturbance voltage to the outputs of a fuzzy system. The performance of the Fuzzy PI controller is studied under typical vector control conditions and compared against conventional vector control methods, which demonstrates that the neural vector control strategy proposed in this paper is effective. Even in dynamic and power converter switching environments, the fuzzy vector controller shows strong ability to trace rapidly changing reference commands, tolerate system disturbances, and satisfy control requirements for a faulted power system.
Keywords: PI Controller, D-Q axis parameter, grid connected converter, decouple vector control

I. INTRODUCTION

The Environmental friendly renewable energy technologies such as solar energy and wind energy based systems are among the fleet of new generating technologies driving the need for distributed generation of electricity. Power Electronics has ignited the next technical revolution and enables the connection of distributed generation (DG) systems to the power system. Hence the increasing power demand will be met by Distributed Generation (DG) system which is founded on renewable energy sources such as wind power, solar power and small hydro power etc. [1] -[2]. In order to ensure sinusoidal current injection into the grid, these systems need to be controlled. Simply, their intermittent characteristics give them poor controllability [3]. Grid connected inverter plays a critical part in maintaining voltage at the point of common coupling (PCC) constant. The grid code requirements such as grid stability, fault ride through, force control and grid synchronization, and so forth should be touched by the power plant operator for the dependable performance of utility grid based on DG system. The synchronization with utility voltage vector is the major event associated with the DG system [4]. The information about the phase angle of utility voltage is tracked accurately to control the flow of active and reactive power and to move around on and off power devices.

A form of solar energy is wind. The wind flow patterns are modified due to the bodies of water and vegetation, uneven heating of the air by the sun, wind flow, the earth terrains. Wind turbine converts the kinetic energy in the wind into mechanical then to electrical by

Hence the role of the hybrid generation system is better than individual wind or individual PV generation system [6]. It overcomes the demerits of individual system. The system reliability can be increased by the grid interface of the hybrid generation system.

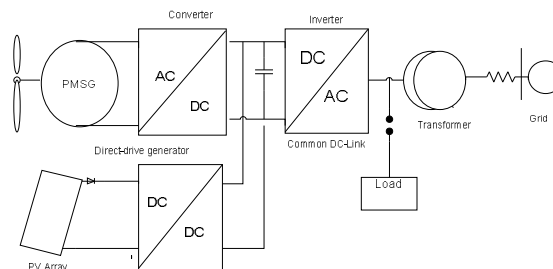


Fig. 1.1 System represents Grid-connected hybrid wind/PV

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In this system, there is a wind turbine, the output of the wind turbine is fed to the permanent magnet synchronous generator. The production of the wind system is in AC so we need AC to DC convertor to change the AC output into DC. Similarly, on the PV side the output of the PV array is connected to a DC-DC boost converter to produce the output voltage up to a desired point. And the yield of PV and wind are connected to a common DC link voltage. The common DC link voltage will be connected to the DC to AC converter and the yield of the inverter is synchronizing with grid. This inverter converts DC power from the PV array and the wind turbine into AC power and it maintains the potential difference and frequency equal to the grid voltage and frequency. Renewable energy sources are playing an intense role in the today power scenario; due to rapid development of future energy demand and depletion of fossil fuels. Renewable energy sources include wave energy, small hydro, wind power, PV system, biomass, etc. Wind energy system is the most promising beginning of energy among all renewable energy sources due to economic viability [11]. Distributed generation (DG) based on renewable energy sources is mostly small scale power generation units (typically ranges from 20 kilowatt to 20 MW) and they are sited at the user end without the use long distance transmission line. As a result of this, the transportation cost of generation is cut down and consumption levels are tight to each other. It is practicable to implement interfaces which have the power to be operated in isolation called micro grids or grid connected [12].

A. Small Signal Model of 1- Φ Inverter

The primary aim of studying small signal model is to predict low frequency component present in the output voltage [6]. The magnitude and form of this component depend not merely on the duty cycle variation, but besides the frequency response of the convertor. It is obtained by applying a deliberate perturbation around the operating level and then linearizing it at that level. The 1- Φ full bridge VSI system is illustrated in Fig.4.1.

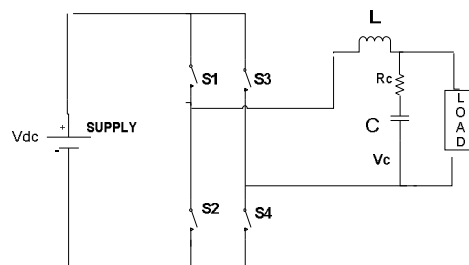


Fig.1.1 Schematic diagram of 1- Φ inverter to be modeled

The inverter in the above figure is being modeled and analyzed with an LC filter on the load side which considers R as load. Let us consider L is filter inductance R_c is damping resistor, C is filtered capacitor, or is loaded resistance, S_1, S_2, S_3, S_4 Are switches and V_{dc}

The main purpose of using the damping resistor is to damp out the oscillations occurring due to the use of LC filter resonance.

Case 1: When switches S_1 and S_2 are ON, then circuit is shown in Fig.1.2.

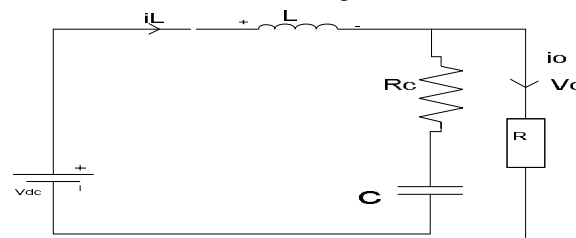


Fig 1.2 Equivalent circuit when switches S_1 and S_2 are ON

Applying KVL in Fig 2.2

$$L \frac{di_L}{dt} = V_o - V_{dc} \quad (1.1)$$

$$i_c = i_L - i_o$$

$$C \frac{dV_c}{dt} = i_L - \frac{V_o}{R} \quad (1.2)$$

Case 2: When switches S_3 and S_4 are ON, the resultant circuit will be as shown in Fig.4.3.

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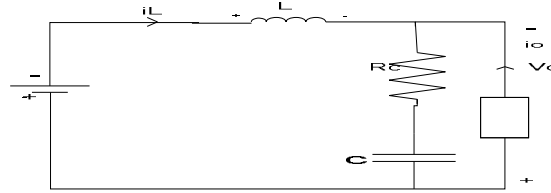


Fig 4.3 Equivalent circuit when switches S_3 and S_4 are ON

$$L \frac{di_L}{dt} = V_o - V_{dc} \quad (1.3)$$

$$i_c = -i_L - i_o$$

$$C \frac{dV_c}{dt} = -i_L - \frac{V_o}{R} \quad (1.4)$$

Let us consider the average value of the inductor current and capacitor voltage, over a switching period T_s

$$\Rightarrow L \frac{d\langle i_L \rangle_{T_s}}{dt} = d \langle V_{dc} - V_o \rangle T_s + d' \langle V_o - V_{dc} \rangle T_s \quad (1.5)$$

Where d = duty cycle and $d' = 1-d$

$$\text{And } C \frac{d\langle V_c \rangle_{T_s}}{dt} = d \langle i_L - \frac{V_o}{R} \rangle T_s + d' \langle -i_L - \frac{V_o}{R} \rangle T_s \quad (1.6)$$

Let us define an operating point as follows

- Duty cycle = D
- Input Voltage = V_{dc}
- Output Voltage = V_o
- Capacitor Voltage = V_c
- Inductor Current = i_L
- Source Current = i_s

In order to design a small signal model we will have to consider a small perturbation along with its steady state values.

- $\langle V_{dc} \rangle T_s = V_{dc} + \widehat{v}_{dc}$
- $\langle V_o \rangle T_s = V_o + \widehat{v}_o$
- $\langle D \rangle T_s = D + \widehat{d}$
- $\langle i_L \rangle T_s = I_L + \widehat{i}_L$
- $\langle V_c \rangle T_s = V_c + \widehat{v}_c$

Put above values in equation (1.5) and (1.6). On simplification the equation gives rise to a multiplication of steady state value terms along with linear and nonlinear terms. Multiplication of perturbation terms can be neglected as its results are very small. And then the resulting expression would be

$$L \frac{d\widehat{i}_L}{dt} = (D - D') \widehat{v}_{dc} - (D - D') \widehat{v}_o + 2 V_o \widehat{d}$$

$$L \frac{d\widehat{i}_L}{dt} = (2D - 1) \widehat{v}_{dc} - (2D - 1) \widehat{v}_o + 2 V_{dc} \widehat{d} \quad (1.7)$$

Similarly

$$C \frac{d\widehat{v}_c}{dt} = (2D - 1) \widehat{i}_L - \frac{\widehat{v}_o}{R} + 2 I_L \widehat{d} \quad (1.8)$$

From the equations (4.7) & (4.8) small signal model of the inverter is derived and is depicted in Fig.4.3.

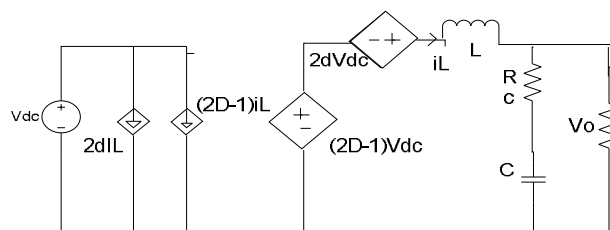


Fig 1.3 Small signal model of 1-Φ inverter

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From Fig 1.3 it can be observed that a small signal ac current I_L is drawn by the inverter out of the input voltage source V_{dc} . As the concerned VSI of bridge type configuration the duty cycle is $(2D-1)$. The term $(2D-1)\hat{I}_L$ is dependent on the inductor current variation \hat{I}_L and is represented by a subordinate source. The term $2\hat{d}I_L$ is driven by the control variations and is modeled by an independent source. This is an equivalent circuit that models the low frequency small signal variations in the inverter waveforms and it can be worked out for using conventional analog circuit analysis techniques to get the inverter transfer functions.

B. Control Strategy for 1- Φ Inverter

A control strategy is to be used to produce the output potential of the inverter being sinusoidal and hence to reduce THD in it. In this work an ACC [7] has been enforced to control the inductor current and PI controller or Resonant controller for controlling output voltage.

1) *Proportional Resonant (PR) controller:* In order to alleviate the shortcomings associated with conventional PI controller a novel controller proportional resonant controller [PR] is introduced recently.

PR controllers are equivalent to conventional PI controller implemented in two synchronous rotating frame (positive sequence and negative sequence) and thus able to track sinusoidal references with variable frequency of both positive and negative sequences with zero steady state error. The transport office of PR controller can be gained by applying an internal control model with modified state transformation or frequency domain approach. [16]

As d-q transformation cannot be given to single phase system directly, a new method is adopted by multiplying the sine and cosine functions resulting from phase locked loop with the feedback error signal $e(t)$ as indicated in Fig. 1.4.

This accomplishes the same matter of translating the component at a chosen frequency to DC quantity leaving others to use quantities. Let us assume the feedback error signal contains a fundamental component along with the fifth harmonic component which is expressed by the equation (3.1)

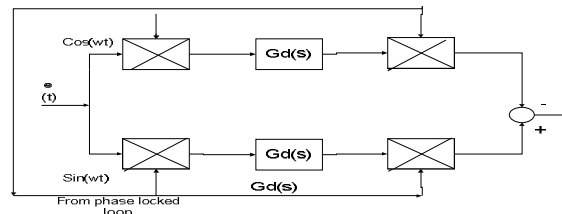


Fig. 1.4 Single phase equivalent presentation of PR controller

This achieves the same issue of translating the component at a chosen frequency to DC quantity leaving others to use quantities. Let us accept the feedback error signal contains a fundamental component along with the fifth harmonic component which is shown by equation (1.9)

$$e(t) = E_1 \cos(\omega t + \phi_1) + E_5 \cos(5\omega t + \phi_5) \quad (1.9)$$

Where ω , ϕ_1 , ϕ_5 are the fundamental angular frequency, fundamental and fifth harmonic phase shifts respectively.

Multiplying equation (1.9) by $\sin(\omega t)$ and $\cos(\omega t)$ respectively equations (1.10) and (1.11) are derived

$$e(t) \cos(\omega t) = \frac{E_1}{2} \{ \cos(\phi_1) + \cos(2\omega t + \phi_1) \} + \frac{E_5}{2} \{ \cos(6\omega t + \phi_5) + \cos(4\omega t + \phi_5) \} \quad (1.10)$$

$$e(t) \sin(\omega t) = \frac{E_1}{2} \{ \sin(-\phi_1) + \sin(2\omega t + \phi_1) \} + \frac{E_5}{2} \{ \sin(6\omega t + \phi_5) + \sin(-4\omega t - \phi_5) \} \quad (1.11)$$

From equations (1.10) and (1.11) it is observed that the fundamental component of the feedback error signal is a constant as it is a function of phase shift ϕ_1 only. The only complication with this equivalent single-form conversion is that the chosen frequency component not only appears as a dark quantity in the synchronous form, it also leads to harmonic terms at a frequency of 2ω , unlike three phase synchronous d-q conversion. Still, passing equations (1.10) & (1.11) through integral blocks would still push the fundamental error amplitude E_1 to zero, caused by the infinite gain of the integral blocks.

Instead of transforming the feedback error to the equivalent synchronous frame for processing, an alternative approach of

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transforming the controller $G_d(s)$ from the synchronous to the stationary frame is also possible. The as quantity which includes the DC controller $G_d(s)$ can be expressed by equation (1.12) after taking positive and negative sequence components into consideration.

$$G_a(s) = G_d(s) (s + j\omega) - G_d(s) (s - j\omega) \quad (1.12)$$

Where, $G_a(s)$ is the equivalent stationary frame transfer function.

For ideal Integrator $G_d(s) = \frac{K_i}{s}$ and by substituting in equation (1.12) $G_a(s)$ can be derived as follows

$$G_a(s) = \frac{Y(s)}{E(s)} = \frac{2K_i s}{s^2 + \omega^2} \quad (1.13)$$

For non-ideal Integrator, $G_d(s) = \frac{K_i s}{1 + \frac{s}{\omega_c}}$ and by substituting in equation (3.4)

$G_a(s)$ can be derived as follows

$$G_a(s) = \frac{Y(s)}{E(s)} = \frac{2K_i \omega_c s}{s^2 + 2\omega_c s + \omega^2} \quad (1.14)$$

Where, K_i and ω_c are the integral controller gain and cutoff frequency respectively.

Equation (1.13) when grouped with a proportional term K_p gives the ideal PR controller with an infinite gain at the ac frequency ω (Fig.4.5), and no phase shift and gain at other frequencies. For K_p , it is tuned in the same way as for a PI controller, and it basically determines the dynamics of the system in terms of bandwidth, phase and gain margin.

An interesting feature of the PR controller as harmonic eliminator is that it does not affect the dynamics of the fundamental PR controller, as it compensates only for frequencies that are very close to the selected resonant frequencies.

Current Control Scheme: An ACC is having an advantage over a peak current controller of adding a high increase in the forward control path and thus reduces the steady state error [7]. Here the inductor current has been averaged over a shift point. And digital implementation of the current controller introduces a sampling delay. This delay yields 10 phase lag at the half of switching frequency. So, digital delay of one switching period is introduced in the current loop whose transfer function is given by Eq (1.15) based on Paddes expansion.

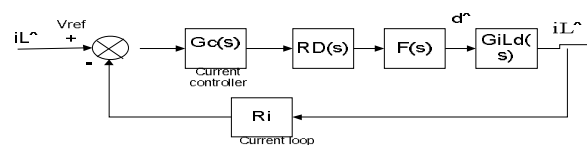


Fig.1.5 Control loop for ACC strategy

The reference value of inductor current is generated from the output of voltage control loop discussed in the next section. A current sensor is being used to sense inductor current and its gain R_i is considered for controller design. In this research work its value is taken as 0.2. The transfer function of the design of the current loop is the ratio between duty cycle to output current $G_{iLd}(s)$ and is given by equation (1.11) which has been deduced from small signal model of inverter (Fig.1.4)

by keeping $\widehat{v_{dc}} = 0$.

$$G_{iLd}(s) = \frac{2V_{dc}}{Z + sL} \quad (1.15)$$

Where Z = load impedance is given by equation $Z = \frac{(R_c C s + 1) R}{C s (R_c + R) + 1}$

$$(1.16)$$

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As shown in the bode plot of $G_{iLd}(s)$ phase cross over frequency is 10kHz which gives flatter response to inductor current which is due to implementation of ACC.

For the current loop a proportional and resonant controller has been chosen. An ideal resonant controller adds an infinity gain to the control loop so as to reduce the steady state error. The transfer function of choosing proportional and resonant control is given by equation (4.17)

$$G_c(s) = K_p + \frac{K_1 B_1 s}{s^2 + B_1 s + \omega_s^2} \quad (1.17)$$

For this application gain $K_1=100$, bandwidth $B_1=2\pi$ rad and the resonant angular frequency $\omega_1=2\pi \cdot 50$ rad/sec. It can be observed from Fig.3.3 that at resonant frequency (i.e 50Hz) a high gain is being added to loop and there is a phase drop simultaneously. The current loop is having a phase margin of 0 and gain crossover frequency is 1.9 kHz. The value of K_p has been chosen as 0.3859.

Voltage Control Scheme: The voltage controller is meant for controlling the output voltage of the inverter and it generates a reference current for the current controller (ACC). In this research work with two types of controllers for voltage control have been implemented and compared.

$$G_{v0-vc} = \frac{\hat{v}_0}{\hat{v}_c} \quad (1.18)$$

PI Voltage Controller: The PI controller produces a system response with minimized steady state error in the output. The integral action reduces the error produced by the proportional action. The control scheme of the inverter including voltage control. Like current sensor, a voltage sensor of gain β is used to sense the output voltage of the inverter. In this work the gain of the voltage sensor is assumed as 0.006.

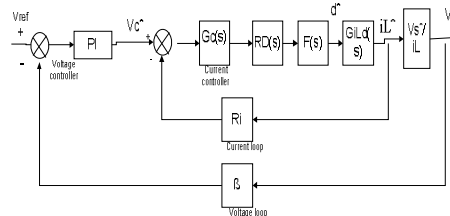


Fig.1.5. ACC with PI controller

The value of the gain of the PI controller has been derived from the step response of the plant transfer function and is given by equation (1.19) and the bode plot of the voltage loop with PI controller is given in the Fig.1.3.

$$PI(s) = 0.20448 \cdot \frac{s+4270}{s} \quad (1.19)$$

The transfer function of the voltage loop with PI controller is given by equation (4.20) which has been deduced from Fig.4.11 From Fig 4.11 it was found that the gain crossover frequency of the voltage loop is 0 Hz and the phase margin is 1.

$$T_g = G_{v0-vc}(s) \cdot \beta \cdot PI(s) \quad (1.20)$$

Resonant Voltage Controller: In this work a proportional and resonant controller was implemented along with the ACC so as to reduce THD in grid voltage. This controller is meant for improving the reference tracking and the attenuation of multiple fundamental spectral components.

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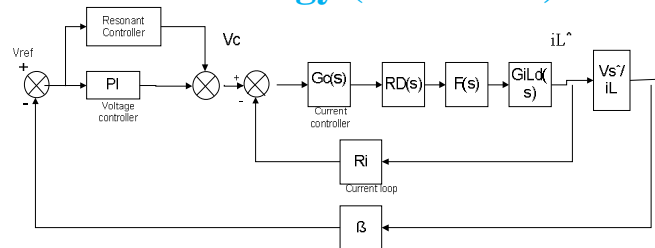


Fig.1.6 ACC with P+Resonant controller

The values of the gains of odd harmonics and their bandwidths have been given in the Table 1.1 [14].

Harmonics	Gains	Bandwidth
1	28	Π
3	5	3π
5	8	5π
7	6	7π
9	4	9π

From the bode plot of the voltage loop with proportion and resonant controller as shown in Fig.4.14 it can be observed that the phase is zero at the harmonic frequencies, this means that the controller has a resistive behavior. The decreasing value at high frequencies allows a reduction in the harmonic voltage and hence reduction in voltage THD.

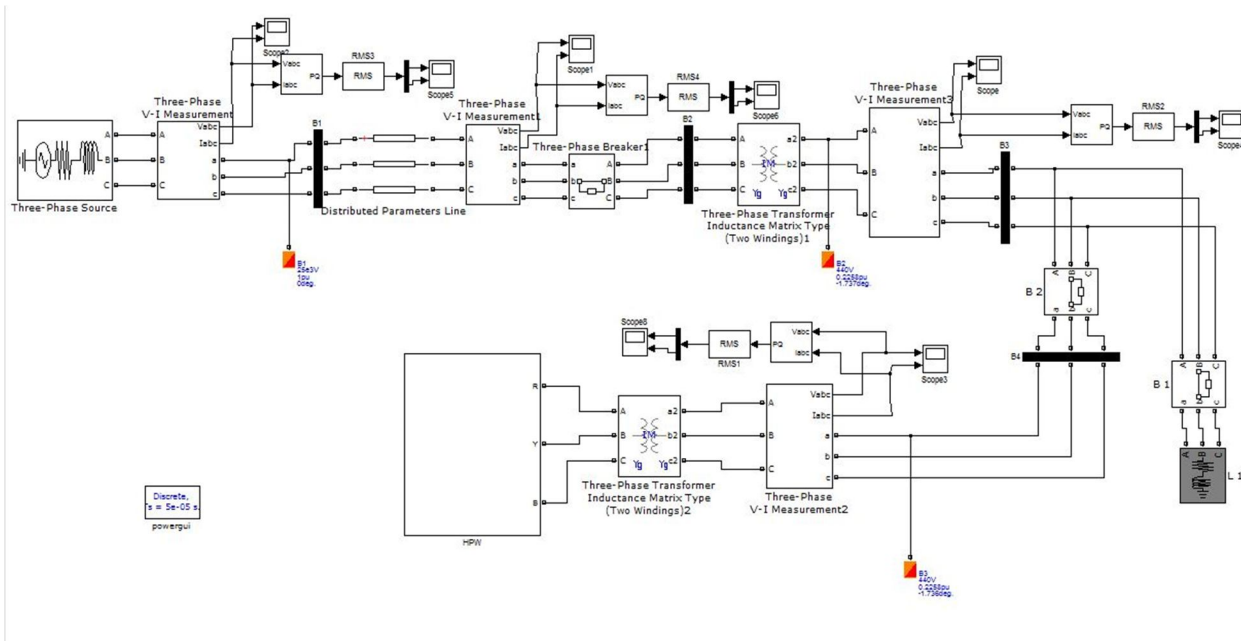
From the bode plot, the gain crossover frequency is found to be 10 kHz and the phase margin is 80° . The system parameters of the concerned 1- Φ inverter are given in Table.1.2.

S. No	Parameter	Value
1	DC link voltage (Vdc)	400 V
2	Inverter Output Voltage (V0)	230 Vrms
3	Inverter Output Frequency (f)	50 Hz
4	Filter Inductance (L)	5.46 mH
5	Filter Capacitance (C)	4.7 μ F
6	Damping Resistance (RC)	5 Ω
7	Inverter Switching Frequency (fs)	16 kHz
8	Load Resistance (Rload)	17.16 Ω

Boost Converter: DC-DC Converter is advisable that accepts a DC input voltage and produce a desired DC output voltage. The output produced is at a different voltage level, then the input. There are three types of DC-DC converters that are buck, boost and buck-boost Converter and hear in this Boost converter is used to step up the PV output. Also DC-DC converters are used to provide noise isolation and power bus regulation.

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Model of PV and Wind Energy Connected Grid



PV and Wind Energy Connected Grid

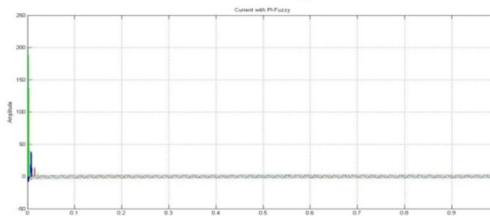
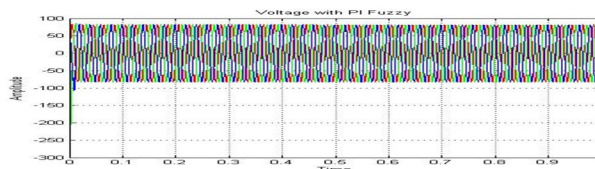


Fig 5.14 Voltage and Current at Load Side using PI



II. RESULTS

3-phase grid-connected rectifier/inverters are used widely in renewable, micro grid and electric power system applications. PV and Wind Energy connected to power system controlled with Voltage source converter. This project investigates conventional vector control approaches for the power system-connected converters and analyzes the limitations associated with conventional vector control methods. And so, a Fuzzy-based PI vector control method is introduced. One of the main effects is that the associated low harmonics in current and voltage in Fuzzy PI as compared to PI.

III. CONCLUSION AND FUTURE SCOPE

In this thesis, we have studied PV and Wind Energy connected to power system controlled with VSC. VSC is connected with PI and PI-Fuzzy to reduce the harmonics in current and potential difference. And it is found that Fuzzy PI is best for reducing harmonics. In time to come, it can be more rectified using ANFIS. Grid connected hybrid wind-solar generation system is unitary of the burning research fields today. The challenge to go through the project and the new research arena of study were the motivations of the task. The combination of solar and wind power source provide a prudent sort of force generation. Wind energy is the most

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inexpensive variety of renewable energy and PV offers an added advantage over other renewable source because they produces no disturbance and require least maintenance. The combination of solar and wind power source provide a prudent sort of force generation.

IV. ACKNOWLEDGMENT

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