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A Novel Voltage Regulation Technique using Fractional Order PI Controller for A Three Phase Grid Connected Photovoltaic System

M.Vinay Kumar, U.Salma

***Abstract** - The integration of distributed generations (DG's) to the grid has led to number of challenges apart from the advantages, one of the challenge associated is the voltage regulation. Photovoltaic (PV) system as a DG is considered as it has a better edge when compared to the other DG's. The application of PV system to the grid requires extra compensating devices to mitigate the voltage regulation issues. A novel voltage regulation strategy for three phase grid connected PV system using fractional order proportional plus integral (FOPI) controller is proposed in this paper. The modelling&analysis of FOPI controller along with the integer orderproportional plus integral (IOPI) controlleris presented in this paper. FOPI controllers are designed in Matlab using FOMCON toolbox (Fractional order Modeling and Control).The simulation is consequently carried out in the Matlab/Simulink environment for both the controllers with resistive loads, resistive & inductive loadsand resistive, inductive & capacitive loads.The FOPI controller outperforms IOPI controller, results of simulation reflectthat controller using FOPI gives better performancewhen compared with the IOPI controller. The effectiveness ofthe FOPI controller confirms the authentication and the simulation results are deliberated for all the different loads.*

***Keywords** – Photovoltaic (PV) System, Distributed Generation (DG), Insolation, DC Link Voltage, Integer Order Proportional plus Integral (IOPI) controller, Fractional Order Proportional Integral (FOPI) controller, Voltage Regulation, Matlab/ SIMULINK.*

I. INTRODUCTION

A sthe demand for electrical energy is increasing all through the globe, more and more fossil fuels i.e., non-renewable energy sources (NRES) have to be consumed to bridge the gap between the demand and the supply. There is a fast depletion of NRES and also it leads to huge pollution. To save the environment and keep the reserves of NRES for the future generation alternate energy sources are replaced which are advantageous over NRES.

The renewable energy sources (RES) are inexhaustible in nature and do not produce any harmful gases thus protects the environment [1]. Thevarious available RES are solar energy, wind energy, tidal energy, bio mass energy, biomass energy, geothermal energy,nuclear energy, hydel energy, etc., among them solar energy is widely used as it is abundant in nature, available free of cost, etc., the only problem is, it is intermittent in nature.

The photovoltaic (PV) cell converts the incident solar radiation into electrical energy. The PV cells are the basic elements of the PV system. The output of each PV cell is around 0.5V and 28mA/m2. For obtaining higher voltages and currents these cells should be connected in series/parallel respectively[2-3]. The PV system has two modes of operation standalone mode and grid connected mode. The PV system is operated at standalone mode when the load center is far away from the utility grid, at the places where lying of distribution lines is difficult and at the far hilly areas [4need to attach paper]. The PV system supplies excess generated power to the grid after supplying its loads and during deficiency of power generation, it draws power from the grid, this is the operation of the grid connected PV system, this system is widely used [5-7]. The block diagram of grid connected PV system is shown in Fig.1.

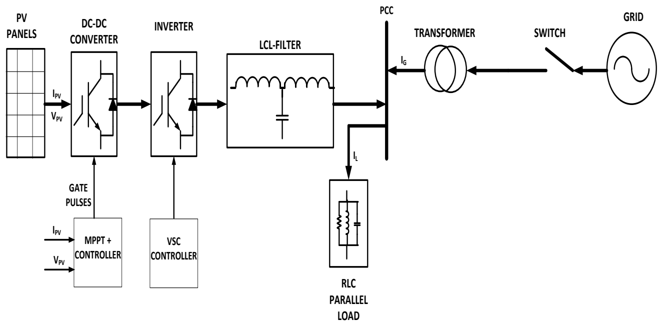

Fig.1. Block diagram of grid connected PV system

The grid connected PV systemhas a few challenges; one of them is voltage regulation [8]. For various reasons like change in irradiance, temperature and load the voltage across the load should be maintained within the limits as per standards.

A mathematical topic named fractional calculus is in usage since 250 years, researchers now days are working towards application of fractional calculus to their areas of work. The basic descriptions of fractional calculus and fractional order controls are discussed [9].

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* Correspondence Author
M.Vinay Kumar, Asst. Prof, EEE Dept, GMRIT, Rajam
U.Salma, Assoc. Prof, EECE Dept, GIT, GITAM University, Visakapatnam

The fractional order controllers have a prospective of improvement in performance of the system [10-11].The fractional order proportional integral (FOPI) controller contains non integer term sλ, where λ belongs to a set of real numbers. When compared with IOPI, a FOPI controller has one more parameter named λ, by tuning it properly; this controller works effectively than IOPI controller [12-13].

To authenticate the effectiveness of the fractional order proportional integral (FOPI) controller over the integral order proportional integral (IOPI) controller, the IOPI controller is simulated for the same PV system with the same PI controller parameters. The Matlab toolbox named FOMCON (Fractional order Modeling and Control), contains required tools to simulate fractional order models. A number of graphical user interfaces are available with necessary comments. The MATLAB/ Simulink software having the FOMCON toolbox for fractional-order PI controller design is presented [14-15].

The rest of the paper is arranged in the following way, Section II describesgrid connected PV system,Section III explains the proposed voltage regulation methodologyand the simulation results are deliberated in section IV andSection V closes the paper.

II. GRID CONNECTED PHOTOVOLTAICSYSTEM

The grid connected PV system broadly constitutes of a PV array, a MPPT controller, a DC-DC converter, a DC-AC converter, load connected at point of common coupling (PCC), atransformer, a static switch and the electric utility grid [5-7]. The modelling of each element is presented below.

A. Photovoltaic Cell

Photovoltaic (PV) cell is a basic building element of a PV system. It converts the incident solar radiation to electrical energy using photovoltaic effect, it generates 0.5 V, 28m A/m2 and a power of 1-2 W. A number of PV cells are connected in series/parallel for higher voltages and currents respectively form a module. Numbers of such modules are connected in series or parallelto form a PV panel. Numbers of such panels are connected in series or parallel to form a PV array [2-3].

Different circuits for PV cell have been proposed in the literature, most generally used model is single-diode circuit, the equivalent circuit of an ideal PV cell and a practical PV cell is shown in Fig.2 below.

The mathematical equations of a PV cell are given below, using Kirchhoff's current law,

$$I_{PV} = I_{Ph} - I_d - I_{sh} \tag{1}$$

Where $I_{PV}$the load is current, I_{Ph} is the photon generated current (function of insolation and cell temperature), I_d is the diode current, I_{sh} is the shunt current.The photon generated current I_{Ph} is given as

$$I_{Ph} = [I_{scr} + K_i(T_c - T_r)]\frac{S}{1000} \tag{2}$$

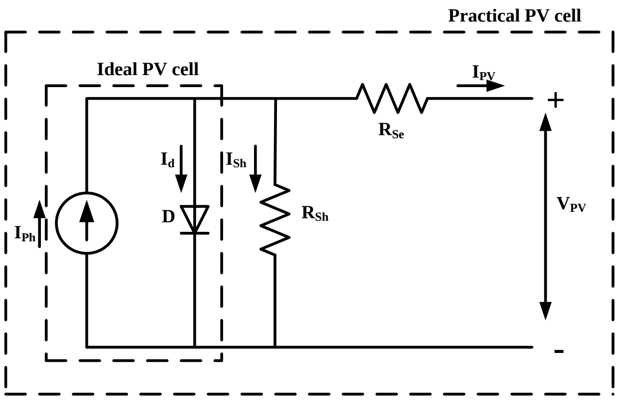

Fig 2. Equivalent circuit of an ideal PV cell and a practical PV cell

The load current I_{PV} is given as

$$I_{PV} = I_{Ph} - I_O\left[\exp\left(\frac{V_{PV}+I_{PV}R_{Se}}{aV_t}\right) - 1\right] - \left(\frac{V_{PV}+I_{PV}R_{Se}}{R_{Sh}}\right) \tag{3}$$

$I_o$is the reverse saturation current, R_{se} is the series resistance (PV cell structural resistance), R_{sh} is the shunt resistance, V_{PV} is the terminal voltage, V_t is the thermal voltage, a is the diode ideality factor.The I-V (current-voltage) characteristics and P-V (power-voltage) characteristics of a PV cell is non-linear, this indicates that there exists a unique point where maximum power can be drawn from the PV module, this unique point is a function of solar radiation and cell temperature.

The load current $I_{PV}$for the PV array is given as

$$I_{PV} = N_P I_{Ph} - N_P I_{RS}\left[\exp\left(\frac{q}{kT_c a} * \frac{V_{PV}}{N_S}\right) - 1\right] \tag{4}$$

Where k is the Boltzman's constant and it is 1.38 X 10-23 J/K, T_c is cell operating temperature, N_P is number of cells connected in parallel, N_S is number of cells connected in series. $I_{RS}$is the reverse saturation current and is given as

$$I_{RS} = I_{RR}\left[\frac{T_C}{T_{Ref}}\right]^3 \exp\left(\frac{qE_g}{ka}\left[\frac{1}{T_{Ref}} - \frac{1}{T_C}\right]\right) \tag{5}$$

The cell reference temperature is T_{Ref}, The reverse saturation current is I_{RR} at T_{Ref}. The cell band gap energy isE_g.

B. Power Electronic Converters

Depending upon number of stages for a PV system, the system will be having a DC-DC converter or DC-AC converter. In a single stage grid connected PV system, the output of PV arrays is connected to the DC link to maintain constant DC voltage and this is converted to AC using anDC-AC converter, i.e.,inverter. In a double stage grid connected PV system, the output of PV arrays is connected to the DC-DC converter and its output is connected to a DC-AC converter, i.e.,inverter. A double stage grid connected PV system shown in Fig.3 below.

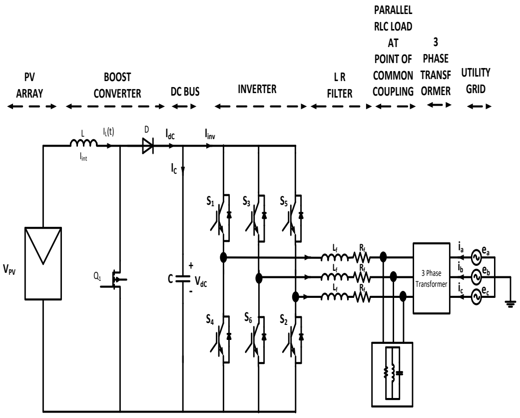

Fig.3. A double stage grid connected PV system

i. DC-DC Converter

These converters vary the properties of the DC voltage; are of different types like buck, boost buck-boost, cuk, full converter type. Among these converters buck and boost converters are the basic ones, other converters are derivative of these converters [16]. The output voltage of PV array is unregulated DC voltage which is due to varying solar insolation and temperature, a boost converter is usedto regulate this unregulated PV array output DC voltage and it also steps up the input DC voltage.The main components of a boost converter are diode, inductor and a high frequency switch. The Fig.4 below shows a boost converter, the magnitude of the output voltage cane be controlled by the adjusting the switching period.

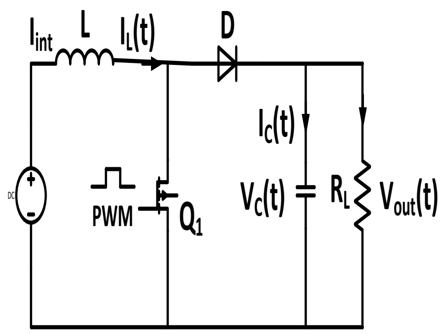

Fig.4. A boost converter

There are two modes of operation namely discontinuous conduction mode and discontinuous conduction mode, it depends upon the energy absorption and release with respect to switching period.

The duty cycle (D) is given as

$$D = 1 - \frac{V_o}{V_i}$$

(6)

WhereV_o is output voltage and V_i is the input voltage.

The value of inductance, capacitance for the boost converter to operate in continuous conduction mode is

$$L_{min} = \frac{(1-D)^2 * D * R}{2 * f} \quad (7)$$

$$C_{min} = \frac{D}{2 * f * V_r} \quad (8)$$

Where D is the duty cycle, R is the boost converter output resistance, $V_r$is the ripple voltage andf is the switching frequency.

ii. DC-AC Converter

The DC-AC converter, i.e., an inverter converts the DC input voltage to output AC voltage. The schematic of a three phase inverter is shown below in Fig.5.

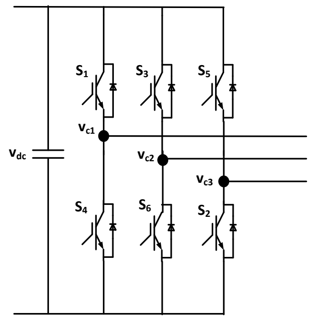

Fig.5.Threephase inverter

It consists of total number of six switches,S_1, S_2, S_3, S_4, S_5 and S_6, for the three arms, with two switches in each arm. The two switches in same arm should never be turned 'ON' simultaneously as it would lead to short circuiting of the voltage source.The DC link capacitor connects the DC-DC converters output DC power to the inverter [17-18]. A high capacitance value of DC link capacitor is selected to stabilize the DC voltage. The output current, phase, frequency and voltage of the inverter can be controlled.

III. VOLTAGE REGULATION

The grid connectedPV system comes across number of challenges and one of the challengesis voltage regulation. The inverter output voltage has to be maintained within the prescribed limits [19-21].

A grid connected PV system shown in Fig.6 below.

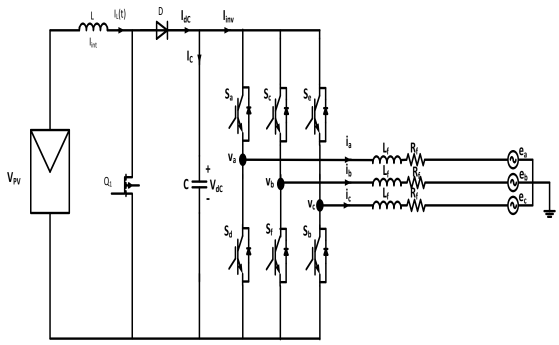

Fig.6. Grid connected PV system

The state-space model for the VSI in abc frame is given as

$$\begin{cases} \dot{i}_a = -\frac{R}{L}i_a - \frac{1}{L}e_a + \frac{V_{dc}}{3L}(2S_a - S_b - S_c) + \Delta f_1 \\ \dot{i}_b = -\frac{R}{L}i_b - \frac{1}{L}e_b + \frac{V_{dc}}{3L}(-S_a + 2S_b - S_c) + \Delta f_2 \\ \dot{i}_c = -\frac{R}{L}i_c - \frac{1}{L}e_c + \frac{V_{dc}}{3L}(S_a - S_b + 2S_c) + \Delta f_3 \\ \dot{V}_{dc} = \frac{1}{C}i_{dc} - \frac{1}{C}(i_a S_a - i_b S_b - i_c S_c) + \Delta f_4 \end{cases}$$

(8)

The switch S in the three arms of the inverter can take two values, i.e., 1 for the conduction and 0 for the blocking state.

$$S_i = \begin{cases} 1 & \forall \text{ ON} \\ 0 & \forall \text{ OFF} \end{cases} \quad (9)$$

The transformation matrix T is given as

$$T_{dq0}^{abc} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - 120^0) & \cos(\theta + 120^0) \\ \sin(\theta) & \sin(\theta - 120^0) & \sin(\theta + 120^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}$$

(10)

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The dynamic model developed from the above equations can be written as

$$\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & \frac{S_d}{L} \\ -\omega & -\frac{R}{L} & \frac{S_q}{L} \\ -\frac{S_d}{C} & -\frac{S_q}{C} & 0 \end{bmatrix} + \begin{bmatrix} -\frac{1}{L} & 0 & 0 \\ 0 & -\frac{1}{L} & 0 \\ 0 & 0 & \frac{1}{C} \end{bmatrix} \begin{bmatrix} e_d \\ e_q \\ i_{dc} \end{bmatrix} + \begin{bmatrix} \Delta f_d \\ \Delta f_q \\ \Delta f_4 \end{bmatrix} \quad (11)$$

where,

$$i_{dq} = T_{dq0}^{abc}.\, i_{abc}, e_{dq} = T_{dq0}^{abc}.\, e_{abc}$$
$$\Delta f_{dq} = T_{dq0}^{abc}.\, \Delta f_{abc}, S_{dq} = T_{dq0}^{abc}.\, S_{abc}$$

(12)

Using Clarke's transformation, the above equations can be changed to two phase stationary frame

$$T_{\alpha\beta}^{abc} = \frac{2}{3}\begin{bmatrix} 0 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

(13)

The total active power and reactive power fed to the grid at any instant is given as

$$S = P + jQ$$

(14)

Where the active power P and the reactive power Q is given as

$$\begin{cases} P = \frac{3}{2}\left(e_d i_d + e_q i_q\right) \\ Q = \frac{3}{2}\left(e_q i_d - e_d i_q\right) \end{cases}$$

(15)

for the synchronous rotating d-q frame $e_q = 0$,

here the active power P and the reactive power Q becomes

$$\begin{cases} P = \frac{3}{2}\left(e_d i_d\right) \\ Q = \frac{3}{2}\left(e_q i_d\right) \end{cases}$$

(16)

The power relationship between input power and output power of the inverter is given as

$$v_{dc} i_{dc} = \frac{3}{2} e_d i_d \quad (17)$$

It is for an ideal inverter assuming zero power loss

A. Voltage Regulation using Integer Order PI controller

The control approachfor the inverter has two loops; one isthe internal current loop which is used for grid synchronizationand the other is the external voltage loop which is used for regulating the DC bus voltage [22].The controller controls DC bus voltage to 800V. The functional diagram for voltage regulation using integral PI controller is shown in Fig.7 below.

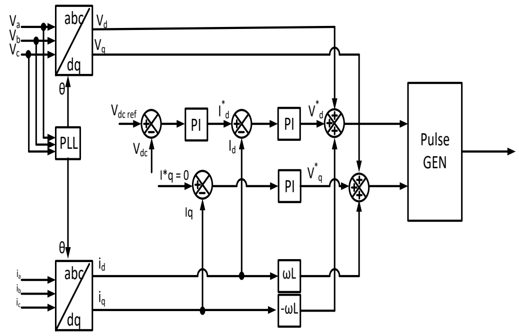

Fig.7. PI control of three phase grid connected PV system

The relation between inverter voltage and the grid voltage for the grid connected system shown in figure.6 above can be written as

$$v_a = R_f i_a + L_f \frac{di_a}{dt} + e_a \quad (18)$$
$$v_b = R_f i_b + L_f \frac{di_b}{dt} + e_b \quad (19)$$
$$v_c = R_f i_c + L_f \frac{di_c}{dt} + e_c \quad (20)$$

Where, e_a,$e_b$and e_c are the respective grid phase voltages, v_a, v_b and v_c are the respective inverter output phase voltages,i_a, $i_b$and i_c are the respective inverter grid currents,R_f and L_f are the filter resistance and inductance respectively. The block diagram of d-q transformation is shown in above Fig.7.

Synchronous reference control convertsabc to dqtransformation of the grid voltage, the current to areference frame rotating synchronously alongwith the grid voltage. It is simpler to model and use the controller and the filter as the variables become DC values, when synchronous reference frame is used. To synchronize the inverter current with the grid voltage, the phase angle of the grid voltage has to be extracted using abc to dq transformation.

The extraction of the grid voltage phase angle is done using the phase-locked loop (PLL) technique [22].The DC link voltage controller generates reference active current Id, for obtaining unity power factor at the inverter, the reference reactive current Iqis set to zero in the synchronous reference frame.

After applying Park's transform to equations (18)-(20) we get

$$v_d = R_f i_d + L_f \frac{di_d}{dt} - \omega L_f i_q + e_d \quad (21)$$
$$v_q = R_f i_q + L_f \frac{di_q}{dt} + \omega L_f i_d + e_q \quad (22)$$

where v_d, $v_q$are the inverter voltages in d-q coordinates,

e_d, $e_q$are the utility grid voltages in d-q coordinatesand ω is the grid voltage angular frequency.

Assuming L_f>>R_f, and approximating to L_f, the above equations can be rewritten as

$$v_d = L_f \frac{di_d}{dt} - \omega L_f i_q + e_d$$

(23)

$$v_q = L_f \frac{di_q}{dt} + \omega L_f i_d + e_q$$

(24)

The conventional proportional integral (PI) controllers are used as their implementation is easy and can regulate the DC variables effectively.

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The controller output voltage is then given to pulse generator.

B. Synchronisation

Phase locked loop (PLL) is used for synchronizing the PV system with the utility grid, the block diagram of PLL is shown in Fig. 6 below.

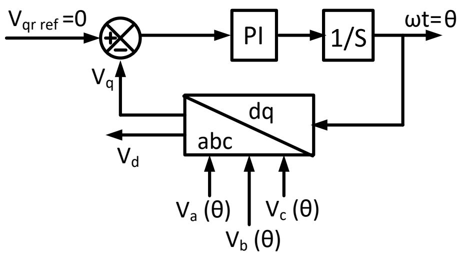

Fig.8. Block diagram of PLL

It determines the direct component of the grid current by applying reverse Parke's transformation to the grid voltage. The q axis component of the grid voltage produced by this transformation is made to zero to produce the synchronisation angle θ, the PLL becomes active when the difference between the phase angle of the grid and the inverter becomes zero.

IV. PROPOSED METHODOLOGY

According to fractional order calculus, ' ${}_aD_t^\rho$' represents a fractional differential operator, it is defined as

$$ {}_aD_t^\rho = \begin{cases} \frac{d^\rho}{dt^\rho} & \rho > 1 \\ 1 & \rho = 1 \\ \int_\rho^t (d\tau)^{-\rho} & \rho < 0 \end{cases} \qquad (25) $$

The upper and lower limits of the operator are 'a' and 't', the operator range is 'ρ'.

The definitions commonly used for fractional differentiation and integration are Riemann-Liouville (R-L) & Grunwald-Letnikov (G-L), R-L defined FOPI in continuous models whereas G-L defined FOPI in discrete model,

The G-L is defined as

$$ {}_aD_t^\rho f(t) = \lim_{h\to 0}\frac{1}{h^\rho}\sum_{j=0}^{\frac{t-a}{h}}(-1)^j\frac{\Gamma(\rho-1)}{\Gamma(j+1)\Gamma(\rho-j+1)f(t-jh)} \qquad (26) $$

The R-L is defined as

$$ {}_aD_t^\rho f(t) = \frac{1}{\Gamma(n-k)}\frac{d^\rho}{dt^\rho}\int_a^t \frac{f(\tau)}{(t-\tau)^{q-\rho+1}}d\tau $$

(27)

Where, integration limit is 'a', step size is 'h', degree of integration/differentiation is 'ρ', gamma function is 'Γ' and is given as

$$ \Gamma(t) = \frac{1}{t}\prod_{n=1}^{\infty}\frac{\left(1+\frac{1}{n}\right)^t}{1+\frac{1}{t}} \qquad (28) $$

The fractional order proportional integral derivative(FOPID) controller was proposed by podlunby [23]. The differential equation for FOPID controller is given as

$$ u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{-\mu} e(t) \quad (29) $$

Where, K_p is the proportional constant, K_i is the integral constant, K_d is the derivative constant, e(t) is the input, u(t) is the output, λ is the order of the integral, μ is the order of the differential. $1/S^\mu$

The transfer function for FOPID controller is given as

$$ C(s) = \frac{U(s)}{E(s)} = K_p + K_i S^{-\lambda} + K_d D^{-\mu} $$

(30)

The block diagram for FOPID controller is shown in Fig. 9 below

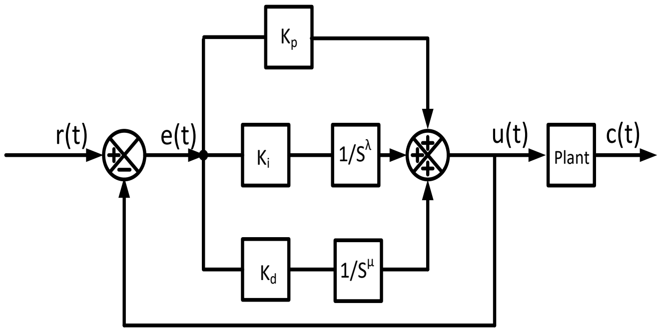

Fig 9. Block diagram for FOPID controller

Depending upon the values of λ and μ, different fractional order controllers can be obtained and for λ = μ = 1, an IOPID controller is obtained, for μ = 0, [24] a FOPI controller is obtained.

In this work the fractional order proportional integral (FOPI) controller is proposed for the voltage regulation of the grid connected PV system.

The FOPI controller is similar to an integer order proportional integral (IOPI) controller but has one extra element, the power of s in integral is (-λ), λ is a positive real numbers that can have any value from 0 to 2.The parameters of FOPI controller are K_p, K_i, and λ. FOPI controller is more effective when compared to the IOPI controllercontrol strategy as it has three parameters to be tuned.

The differential equation for FOPI controller is given as

$$ u(t) = K_p e(t) + K_i D^{-\lambda} e(t) $$

(31)

The transfer function for FOPI controller is given as

$$ C(s) = \frac{U(s)}{E(s)} = K_p + K_i S^{-\lambda} \qquad (32) $$

The block diagram for FOPI controller is shown in Fig. 10 below

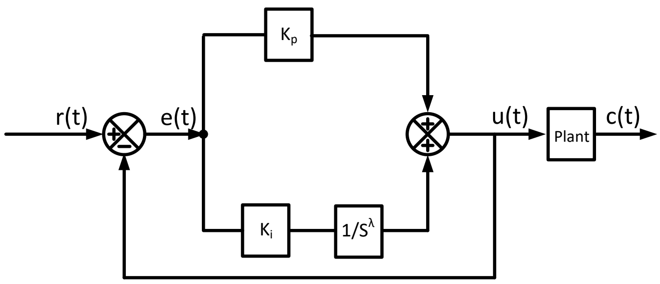

Fig 10. Block diagram for FOPI controller

The MATLAB toolbox function 'FOMCON' (Fractional-order Modeling and Control) is used to find the FOPI controller parameters namely K_p proportional gain, K_i integral gain and integral power λ [25].

V. SIMULATION RESULTS

The grid connected PV system was simulated with an IOPIcontroller and also for the proposedFOPI controller separately, for three different cases namely, resistive load, resistive load& inductive load and resistiveload& capacitiveload. Resistive load alone of power 1 kW was simulated for a time period of 15s from 1s to 15s, resistive load& inductive load of power of (1 kW + 1kVAR) was simulated for a time period of 5s from 15s to 20s and resistive & capacitive loading of power (1 kW - 1kVAR) was simulated for a time period of 5s from 20s to 25s respectively.The simulation results reveal that control action of the FOPI controller is much quicker and better than that of the IOPI controller.

Case – i: The PV system operated at a temperature of 25^0C and irradiance of 500 W/m^2withResistive loading of 1 kW.

The time domain characteristics of the DC link voltage generated using IOPI controller and then the proposed FOPI controller obtained by simulating the PV system is shown in Fig. 11 below.

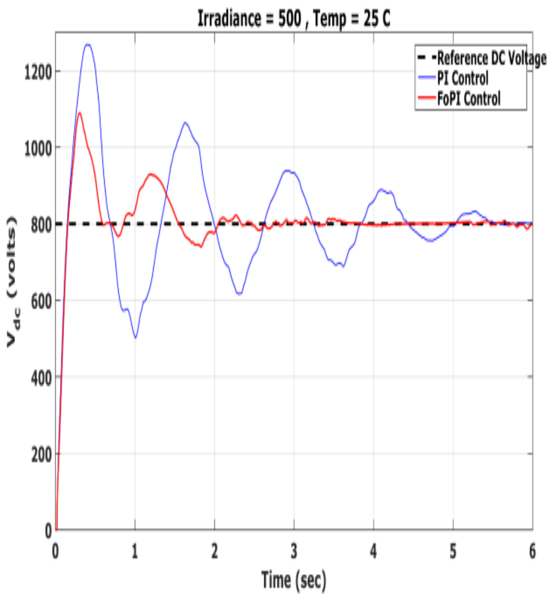

Fig.11. DC link voltage generated using IOPI controller andthe proposed FOPI controller

The rise time, settling time and peak overshoot for the DC link voltage using FOPI controller is less when compared to the IOPI controller.

The time domain characteristics of the active power generated using IOPI controller and then the proposed FOPI controller obtained by simulating the PV system is shown in Fig. 12 below

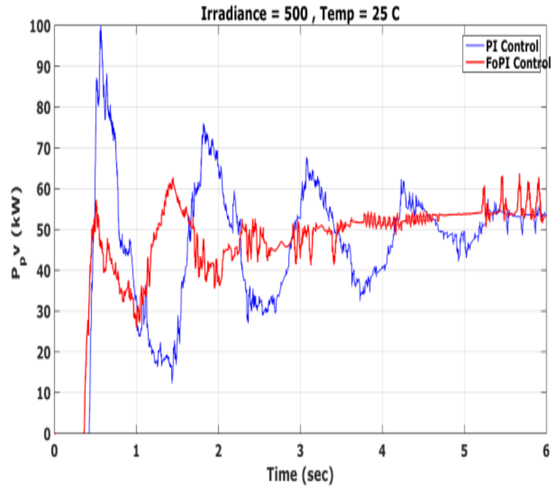

Fig.12.Active power generated using IOPI controller and the proposed FOPI controller

The rise time, settling time and peak overshoot for active power generated using FOPI controller is less when compared to the IOPI controller.

Case – ii: The PV system operated at a temperature of 25^0C and irradiance of 500 W/$m^2$with Inductive loading of 100 kVAR

The time domain characteristics of the DC link voltage generated using IOPI controller and then the proposed FOPI controller obtained by simulating the PV system is shown in Fig. 13 below.

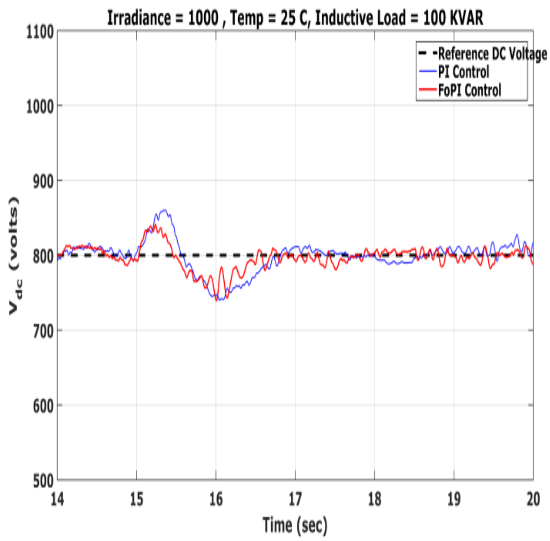

Fig 13. DC link voltage generated using IOPI controller and the proposed FOPI controller

The rise time, settling time and peak overshoot for the DC link voltage using FOPI controller is less when compared to the IOPI controller.

The time domain characteristics of the active power generated using IOPI controller and then the proposed FOPI controller obtained by simulating for the PV system is shown in Fig. 14

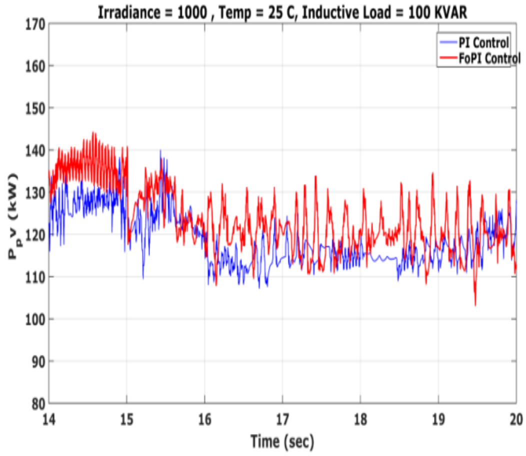

Fig.14. Active power generated using IOPI controller and the proposed FOPI controller

The rise time, settling time and peak overshoot for active power generated using FOPI controller is less when compared to the IOPI controller.

Case – iii: The PV system operated at a temperature of 25^{0}C and irradiance of 500 W/m^2 with Capacitive loading of 1000 kVAR.

The time domain characteristics of the DC link voltage generated using IOPI controller and then the proposed FOPI controller obtained by simulating the PV system is shown in Fig. 15 below.

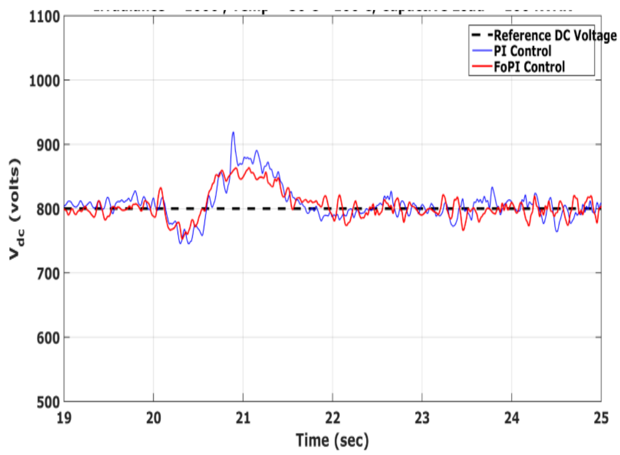

Fig 15. DC link voltage generated using IOPI controller and the proposed FOPI controller

The rise time, settling time and peak overshoot for the DC link voltage using FOPI controller is less when compared to the IOPI controller.

The time domain characteristics of the active power generated using IOPI controller and then the proposed FOPI controller obtained by simulating the PV system is shown in Fig. 16below.

The rise time, settling time and peak overshoot for active power generated using FOPI controller is less when compared to the IOPI controller.

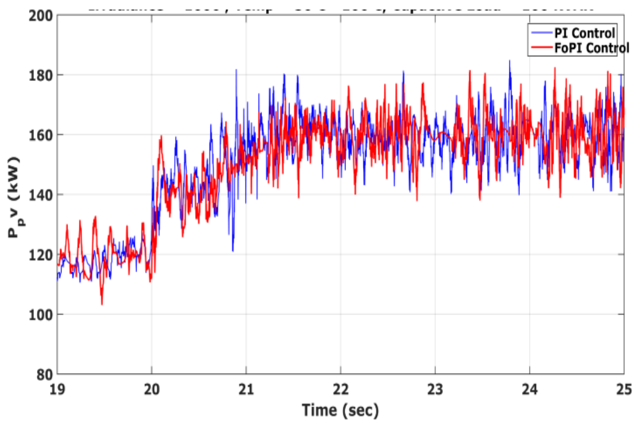

Figure 16. Active power generated using IOPI controller and the proposed FOPI controller

VI. CONCLUSION

A novel fractional Order PI (FOPI) controller was presented to improve the voltage regulation of a grid connected PV system. The performance of this controller was tested in grid connected mode by introducing sag and swells and simulated accordingly. The proposed FOPI controller'sperformance was much effective for mitigating sag and swells, in turn improvedthe voltage regulation. The proposed FOPI controller deals effectively in improving voltage regulation compared to IOPI, the simulation results of this controller proves by observing time domain parameters such as overshoot and settling time.

VII. FUTURE SCOPE OF WORK

As the demand for electrical energy is ever increasing, the distributed generations (DG) with renewable energy sources are as a substitute energy source connected to the grid are also increasing. In this paper a novel controller methodology using fractional order proportional plus integral is presented and it has outperformed the integer order proportional plus integral controller. The author wish to test the performance of voltage regulation with few more fractional order controllers for the grid connected photovoltaic system.

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AUTHORS PROFILE

M. Vinay Kumar, is currently working as Asst. Prof in EEE Dept, **GMRInstitute of Technology, Rajam,**completedB. Tech degree in Electrical andElectronics Engineering from JNTUniversity, Hyderabad affiliated college, and M.Tech from Baharat Institute of Higher Education and Research, Deemed University, Chennai. Presently he is pursuing Ph.D, under the guidance of Dr. U.Salma,Associate Professor, department of Electrical and Electronics Engineering,GITAM Institute ofTechnology, GITAM University, Visakhapatnam. His research interests include power electronics application to power systems, HVDC transmission.

U. Salma, completed B. Tech and M.Tech degrees in Electrical andElectronics Engineering from JNTUniversity, Hyderabad, India. Received her Doctoral degree, Ph. D in Electrical andElectronics Engineering from JNTUniversity, Kakinada, India. Currently she is working as an AssociateProfessor in the department of Electrical andElectronics Engineering, GITAM Institute ofTechnology, GITAM University, Visakhapatnam,AP, India. Her research interests include Applicationof model order reduction techniques to powersystems