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Fractional Order Controller for Non-linear Current Control Technique

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Abstract*: *linear and Non-Linear controller shows their best performance under different power quality conditions. However, under sub transient condition these controller shows sluggish performance. This paper introduces the application of Fractional order [FO] controller in real world power system phenomena. FO-controller based on proportional integral control action was used here for grid interconnection of inverter. Different power quality issues such as Real & Reactive Power exchange between renewable source and grid have been presented here. Matlab Simulink model was developed for a real-world grid connected model in order to check the robustness of the controller. A comparison between the PI controller and FO-PI controller was presented in this paper.

Keywords* : *Linear controller, Non-linear controller, Fractional order controller, Current control techniques

I. INTRODUCTION

In recent digital world, fractional order calculus has many applications and are quite common in the modelling of Electrical and Mechanical system. FO is more flexible to real world system as because most of the classical phenomena possess some degree of fractionality in their characteristics. But in most of the classical phenomena, fractionality present in their behavior does not changes the characteristics because of small degree of fractionality. Hence fractional order derivative and integer is applied in the system to change its characteristics. There are many definitions for fractional order controller however Grunwald-Letnikov, Cauchy Integral Formula, Caputo and Riemann-Liouville are more commonly used definitions.

Fractional integer and derivatives are the special function of integer order controller which is generally described by a set of fractional order equations. These equations when used in real world, electrical problem such as dynamic disturbance and sub transient disturbances can be suppressed. In the present work a fractional order system with higher order fractionally is used for the modelling of equations and thereby implementing a second order system in the design criteria.

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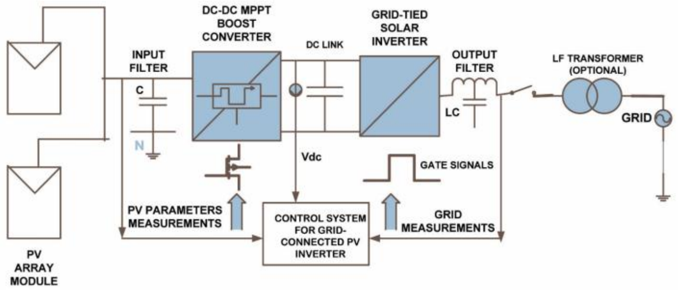

Figure.1. Grid Connected Solar Photovoltaic system with Controller

Figure-1. Shows the grid connected solar photovoltaic system with controller connected in between solar PV module and grid tied inverter. Basically two types of controllers are used one for current control and other for voltage control. Voltage controller takes its input from solar PV module and reference and there by forming the outer voltage control loop. Similar to voltage control loop, current control loop can be formed by taking reference from grid transformed parameters. Two techniques either FO controller or PI controller or FO-PI can be implemented in the outer voltage control loop and inner current control loop for grid interconnection of solar PV module.

Stability analysis of the solar photovoltaic grid connected system can be analyzed by considering the following factor as invariant, they are (i) Temperature of the system (ii) resistance and magnetizing current of transformer are remain un altered (iii) valves used for the converter are loss less (iv) DC component at the output AC is zero. Over the last two decades PI-controller has been used for analyzing the performance of controller, this is because of its simplicity and cost effective. However, with linear controller the analysis of transient and sub transient performance of SPV grid connected system becomes more difficult as compared to Fractional order controller. A comparison between linear controller and nonlinear controller is presented here for checking the robustness of the controller. Structure of the paper is as follows, Section-I presents a brief introduction to PI and FO-PI controller. Section-II presents modelling of solar photovoltaic system, Section-III shows the modelling of linear controller followed by section-IV presenting modelling of fractional order-PI controller. Section-V describing the conclusion of the paper.

II. SOLAR CELL & PERFORMANCE ANALYSIS

Solar photovoltaic produces energy at its output upon receiving solar energy. This is due to the presence of activated solar cell in the solar module.

Photon present in the solar radiation when passes through the solar cell activates the inner layer and there by activating the outer cell to allow the flow of electron in the outer circuit to which the device is connected. This phenomenon is implemented in the MATLAB by varying the solar insolation and temperature as its parameters. Further from the literature it can be found that there are three types of solar modelling such as one diode modelling, two diode modelling and three diode modelling. It is clear from literature that increasing the number of diode in the modelling increases the chances to observe the exact loss occurring in the system. However, in the complexity present in the higher order of modelling does not suit its MATLAB implementation. Therefore, in the present research MATLAB modelling based on the single diode model is presented.

Some of the basic equation involved in the single diode modelling of the solar cell is as follows.

$$i_0 = \left(i_{0,STC} + k_T.(T_0 - T_{0,cell})\right).\frac{P_0}{P_{0,STC}} \quad (1)$$

Where i_0 represents the photo generated current produced by the solar cell upon the absorption of photon present in the solar insolation. Not all the photons present in the solar insolation will be absorbed but those photons whose energy is greater than the band gap energy of the solar cell is absorbed. From equation (1) one can easily found that increase in the solar insolation increases the photo generated current. Hence it is a good practice to keep the solar insolation at 1000W/m^2 for MATLAB environment for the better result. Single diode model of the solar PV system is shown in figure-2. The Shockley diode presented in the figure represents the internal junction present in the solar cell which forbids the reverse saturation current to flow back into the cell performance. Rs and Rsh represents the series and parallel resistance. It is an usual practice to keep Rsh as much high as possible so as to produce large amount of voltage at the output. On the other hand, Rs is kept small for increasing the current carrying capacity. Model parameters can be evaluated either by analytical method or by using iteration methods. In this paper, all the parameters are calculated using iteration methods, which starts with some initial guess.

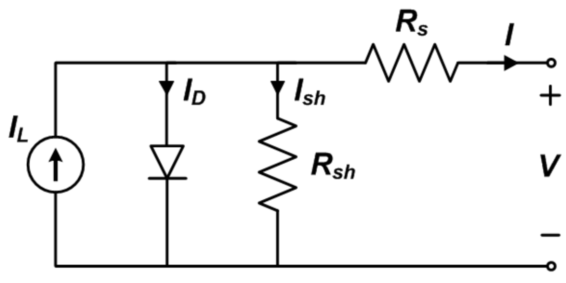

Figure.2. One Diode model of Solar Cell

$$C = \varepsilon_0.\varepsilon_r.\frac{A}{d} \quad (2)$$

Equation (2) shows the parasitic capacitance present at the junction level of the solar cell. Here ε_0, represents the permittivity of free space having dielectric constant of 8.85 X 10^{-12} F/m and ε_r, represents the relative permittivity of the solar cell. For silicon based wafer relative permittivity is approximately 11.7.

$$R_{sh} = \frac{V_{mp}}{I_{sc} - I_{mp}} - \frac{V_{oc} - V_{mp}}{I_{mp}} \quad (3)$$

Here Rsh represents the parallel resistance of the diode model. V_{mp} represents the peak voltage at the point of MPP and that of V_{oc} represents the open circuit voltage of the solar cell. Typical performance of different materials used in the solar cell manufacturing are shown in table-1

Table.1. Band Gap Energy and Ideality Factor of Different Technologies

Sl. No.	Materials	Ideality Factor	Band Gap
01	Si-Poly	1.3	1.12
02	Si-Mono	1.2	1.1
03	CdTe	1.5	1.5
04	Cigs	1.24	1.15
05	A-Si	1.8	1.7

A typical laboratory test for different materials has been carried out with solar simulators. The simulator uses a solar radiation of 1000W/m^2, with variable temperature condition for calculating the amount of power loss occurring in the solar cell. Different test such as Insulation test, Humidity freeze test, Damp heat test. From all these tests, it can be found that Monocrystalline test shows highest performance in terms of efficiency. However, from economic point of view multi crystalline solar cell shows better performance.

Table.2. Module performance at STC for Different Technologies

Technologies	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	Module Eff. %	Cell Eff.
Multi Crystalline Si	104.5	22.40	6.36	13.5	15.5
Mono Crystalline Si	82.4	22.46	4.794	14.1	17.4
CIGS	106.3	58.9	3.145	9.81	11.0
CdTe	49.6	92.1	1.087	6.89	7.36
A-Si	99.8	97.6	1.502	6.85	7.18

Table.3. Insulation test result for Different Technologies

Technologies	Test Voltage(V)	Insulation Resistance(GΩ)	Leakage Current(nA)
Si-Mono	1000	20.6	48.54
Si-Poly	1000	583MΩ	1.715μA
CIGS	1000	1.70	588.23
CdTe	1000	11.7	85.47
A-Si	1000	3.49	286.5

Table.4. Humidity Freeze test result for Different Technologies

Technology	Temp & Humidity	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	Module Eff. %	Cell Eff.
Si-Mono	200hr	82.7	22.51	4.759	14.5	17.4
Si-Poly	200hr	105	22.0	6.37	13.5	15.6
CdTe	200hr	50.9	93.6	1.079	7.06	7.55
CIGS	200hr	110	59.8	3.117	10.2	11.4
A-Si	200hr	96.9	99.4	1.493	6.66	6.97

Table-2. Shows the performance analysis of different technology under standard temperature condition (STC), where it is found that monocrystalline solar cell has better performance in terms of efficiency (17.4 %) conversion. In contradiction, amorophus silicon shows least performance with an efficiency of 7.18 % only. Similarly Table-3 & 4 shows the test result for Insulation test and Humidity Freeze test. During insulation test polycrystalline solar cell shows lowest leakage current of 1.715μA as compared to other materials and technology.

III. RESULT ANALYSIS

Transfer function for a renewable grid interconnected solar photovoltaic system current controller can be represented as

$$G(s) = \frac{a_1 S^{\alpha 1n} + a_0}{b_2 S^{\alpha 2n-2} + b_1 S^{\alpha 2n-1} + b_0} \qquad (4)$$

here a_1,a_0 and b_2,b_1,b_0 represents the coefficients for the transfer function as shown in equation (4) . The fractional order equation as shown in (4) is similar to the time domain presentation of PI controller as used for current controller. Corresponding differential equation to equation (4) can be written as

$$b_1 y^{\alpha 2n2}(t) + b_2 y^{\alpha 2n}(t) + b_0 y(t) = u(t) \qquad (5)$$

The validity of equation (5) can be evaluated by setting all the initial conditions to zero i.e.

$$Y(0)=0,\ Y'(0)=0 \text{ and } Y''(0)=0 \qquad (6)$$

Unit step response of equation (6) can be written as

$$y(t) = \frac{1}{b_2}\sum_{k=0}^{\infty}\frac{(-1)^K}{k}\left(\frac{b_0}{b_1}\right)^{k-2}\left(\frac{b_1}{b_2}\right)^{k-1}\varepsilon_{k-2} + \frac{1}{b_1}\sum_{k=0}^{n-1}\frac{(-1)^K}{k}\left(\frac{b_0}{b_1}\right)^{k}\varepsilon_{k-1} \qquad (7)$$

Real time transfer function for PI-controller as described in section-II can be written as

$$G(s) = \frac{0.001093s - 1.264e-06}{s^2 + 0.001376s + 4.945e-07} \qquad (8)$$

Controlling parameters as shown in equation (8) can be evaluated by using frequency domain. Frequency domain plot such as Bode plot for equation (8) is shown in figure.15. Parameters extracted from bode plot for stability analysis is shown in table-5

Table.5. Stability Criterion Parameters

Sl. No.	Parameter	Magnitude
01	Proportional Gain (K_P)	-0.10717
02	Integral Gain (K_i)	-0.0019911
03	Rise Time	2.35e03sec
04	Settling Time	4.31e04sec
05	Over Shoot	5.81%
06	Gain Margin	4.47dB@ 0.00597 rad/sec
07	Phase Margin	22^0 @ 0.00417 rad/sec
08	Closed loop Stability	Stable

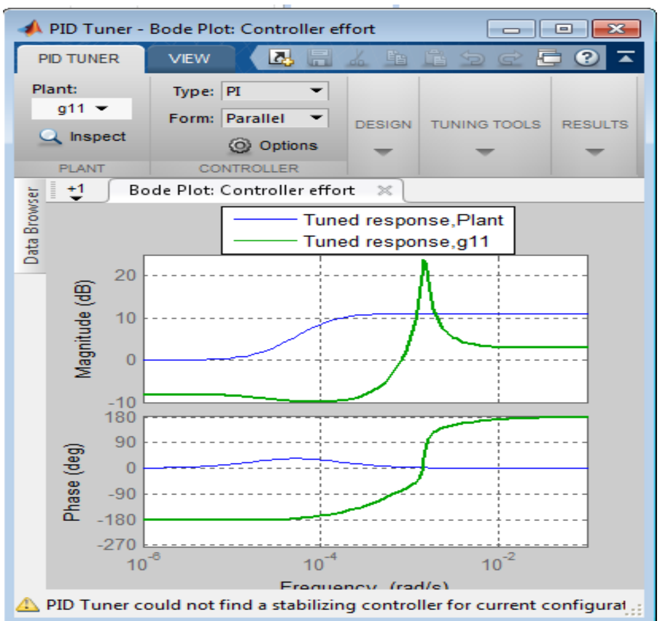

Figure.3. Bode plot analysis of current controller

From the transfer function and it's bode plot analysis it is clear that the cross over frequency for current controller is maintained at 1000rad/sec at λ=0.637. Using auto tuner, the fractionalised open loop transfer function becomes

$$G(s) = \frac{1}{0.01S + 1} \qquad (9)$$

Fractional order transfer function after pass-1 becomes

G(s)=
0.0049956s^{2.63}+3.9948e-05s^{2}+0.00019982 s^{1.63}+1.5979e-06s+1.9982e-06s^{0.63}+1.5979e-08
----
s^{3.5}+s^{3}+0.0049956s^{2.63}+s^{2.5}+s^{2}+0.00019982s^{1.63}+s^{1.5}+s+1.9982e-06s^{0.63}+1.5979e-08

(10)

Stability parameters for Fractional order transfer function (10) is shown in table

Table.6. Stability parameters for Fraction order transfer function

Sl. No.	Parameter	Magnitude
01	Proportional Gain (K_P)	-0.10717
02	Integral Gain (K_i)	-0.0019911
03	Rise Time	2.35e03sec
04	Settling Time	4.31e04sec
05	Over Shoot	5.81%
06	Gain Margin	4.47dB@ 0.00597 rad/sec
07	Phase Margin	22^0 @ 0.00417 rad/sec
08	Closed loop Stability	Stable

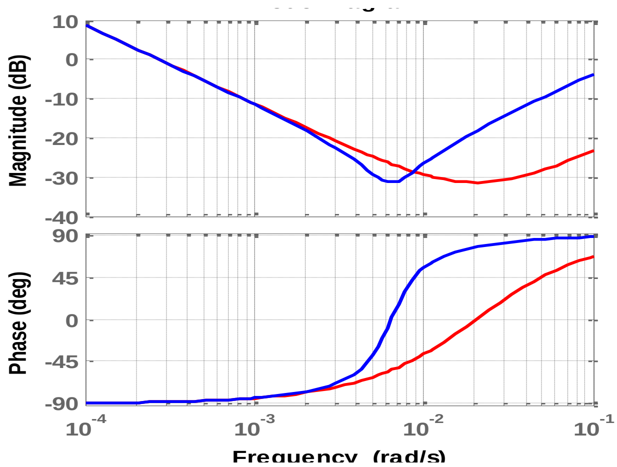

Figure.5. Comparative analysis of FO-PI with PI Controller

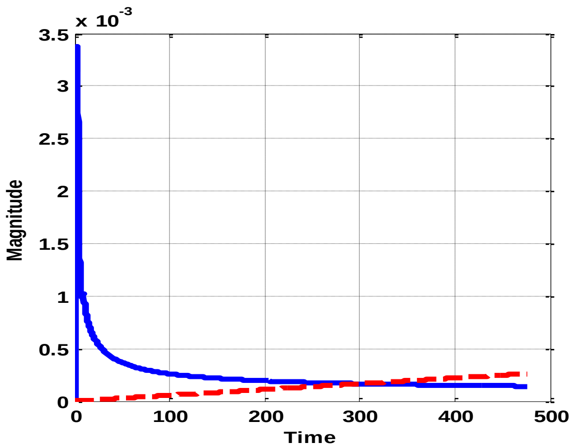

Figure.4. Graphical method for evaluation of FO-PI controller

After applying the auto tuner for Pass-2 with q=0.0047

$$G(s) = \frac{0.004856s^{2.63}+3.4983e\text{-}05s^{2.501}+0.00025794s^{1.63}+1.7824e\text{-}06s+2.7419e\text{-}06s^{0.839}+1.78209e\text{-}11}{s^{2.395}+s^{3.1104}+0.0049978s^{1.92}+s^{2.7}+0.00139578s^{2.49}+s^{1.28}+s+1.0183e\text{-}03s^{0.47}+1.569e\text{-}11} \quad (11)$$

The solver have reached a local minimum, but cannot be certain because the first-order optimality measure is not less than the Tol Fun tolerance (1e-4*TolFun for the Levenberg-Marquardt algorithm).

Table.7. Iteration Function Parameters

Iteration No.	Function Count	F(x)	Norm of Step	1st Order Optimality
00	4	4.821e11	0	9.64e09
01	8	3.05e11	10	7.56e09
02	12	1.744e10	20	3.72e09
03	16	0.0066017	20.82	74.6
04	20	0.006183	3.91	4.33
05	24	0.005965	7.89	34.4
06	28	00005919	1.31	1.16
07	32	0.005911	1.07	0.626
08	36	0.005910	0.9807	0.622387
09	40	0.005908	0.9784	0.6214
10	44	0.005908	0.9781	0.6214

For tuning the Current controller with fractional order controller Result obtained from equation (11) is plotted with integer order controller. Intersection of these two plots will clearly determine the order and gain of the current controller.

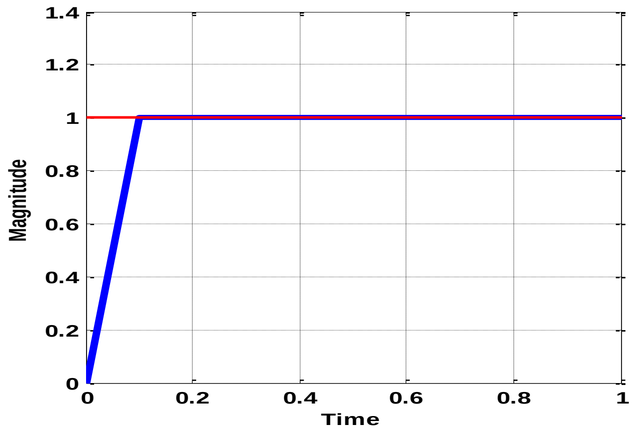

Figure.6. Time domain analysis of FO-PI controller

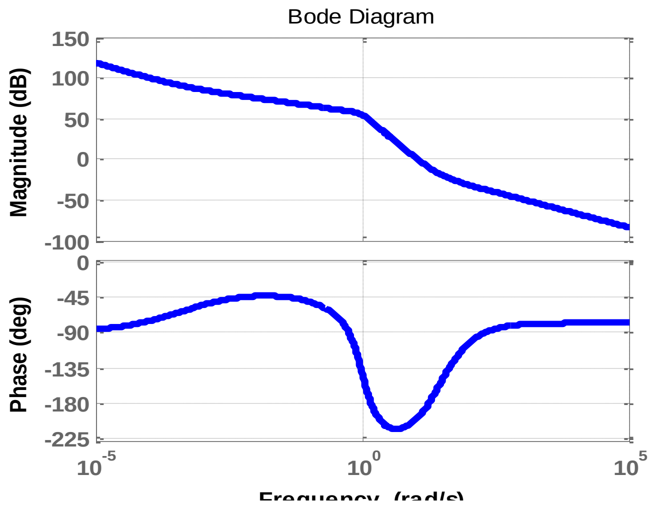

Figure.7. Bode Plot response for FO-PI Identified model Parameters

Figure.7. Bode Plot response for FO-PI Identified model Parameters extracted from figure.5 &6 using stability tuner is summarized in table.8.

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Table.8. Stability parameters for Fraction order transfer function

Sl. No.	Parameter	Magnitude
01	Proportional Gain (K_P)	-1.386
02	Integral Gain (K_i)	-3.84e-05
03	Rise Time	1.19e03
04	Settling Time	1.29e-05
05	Over Shoot	9.99%
06	Gain Margin	1.17dB@ 0.0756 rad/sec
07	Phase Margin	51.3^0 @ 0.0692 rad/sec
08	Closed loop Stability	Marginally Stable

IV. CONCLUSION

Fractional order controller has been presented in this paper. Linear PI-controller is easy to implement as compared to fractional order controller. PI controller requires some sophisticated control techniques such as Phase locked loop and abc to dq conversion for control of inner current control loop and outer voltage control loop. Synchronisation time in case of linear PI- current controller is much larger as compared to fractional order PI- controller. Successful convergence in case of fractional order linear controller depends upon the initial guess. Instead of a number of advantages and disadvantages fractional order controller shows superior performance as compared to linear PI-controller during transient and sub transient operation analysis..

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