Design of PI Controller for Grid-connected DG unit using Root Locus Technique

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***Abstract*— Increase in awareness on global warming has led to a new trend of power generation using Distributed Generation (DG). The DG is connected to the low voltage network through power electronic converters. Normally, it operates in grid connected mode and supplies a rated power to the main grid. The safe operation of the DG system is essential to avoid damage to the system. The performance of the system depends on design of proper controller. This paper proposes a method to the design PI controller for Grid-connected DG using Root Locus technique. A MATLAB control system tool box is used to estimate the gain of the controller based on system requirements. To show the effectiveness of the design, MATLAB simulation is carried out to implement the complete power system with DG connected to the grid. A comparison of performance of the system is also analysed by considering L and LC filter.**

Keywords— Distributed Generation, grid connected mode, PI controller, Root locus technique.

I. INTRODUCTION

Recently, the energy demand has increased due to rise in population and economic development. Today, most of the energy is produced by centralized power plants using conventional energy sources. The main drawbacks of such system are environmental pollution, transmission losses and continuous upgradation of transmission and distribution facilities to cope with increasing demand. Depletion of fossil fuel resources and more strict environmental regulations have encouraged small scale (1 kW to 10 MW) power generation at distribution voltage level using non-conventional energy sources called Distributed Generation (DG) [1]. As the power produced by most of renewable energy sources is DC, they require power electronic converters to interface with low voltage distribution networks. They have become more popular in the recent years due to increase in technological advances in power electronics and energy storage devices. The DGs provide many other advantages like increase in reliability, flexibility, efficiency and power quality. However, they increase the complexity of the distribution system [2-3].

Under abnormal condition in the main grid, the distributed generation is disconnected from the power system, to avoid islanded operation as per standards like IEEE 929, IEEE 1547, IEC 61727 and VDE 0126-1-1 [4-7]. In this mode, the DG inverter detects islanding situation and isolates itself from to power system. Various control strategies have been proposed in literature for grid connected and islanded mode of operation of DG system. A new voltage control strategy which is used provide a smooth transition from grid-connected to islanded mode for DG units with inverter is presented in [8]. *Fang Gao et al*., introduced the control strategy based on the concept of voltage-controlled Voltage Source Converter (VSC) rather than the conventional current-controlled VSC. A small-signal analysis is performed on the system to show the behavior of the proposed control system. A new control strategy is proposed by Irvin J. Balaguer et. al [9] to implement grid-connected and intentional islanding operation for a single DG unit. It uses feed forward voltages for good dynamic response.

Design of controller plays an important role in stable operation of a close loop system. An unstable system can cause damage to the system, to adjacent property, or to human life. Hence, designing a proper controller is essential. The various techniques like Routh-Hurwitz criterion, Root Locus technique, Nyquist criterion, Bode plot etc are used for designing a controller for close loop system. The Root locus technique is a graphical method of designing and analyzing a control system. This method is widely used in evaluating the stability of the control system. The stability of control strategies in grid-connected and intentional islanding operation for a single DG unit [9] is analyzed using bode plot technique. A buck and boost converter design using the root locus method is performed and the system performance is compared with the frequency response techniques in [10]. An adaptive droop controller is used to achieve quick steady state in islanded mode in micro-grid with two DG sources [11]. It provides an accurate load sharing among DGs with high gain values but it leads to control system instability.

This paper presents design of PI controller for a grid connected DG using Root locus technique. It is observed that the system performance improves using the estimated gain values. The comparison of performance is analysed with L and LC filter. The rest of this paper is arranged as follows: Section II explains basic structure and operation of DG system, Section III presents transfer function of Grid connected DG system Section IV describes Root locus technique for designing PI controller, Section V discusses simulation results for DG in grid connected mode of operation and Section VI the conclusion.

II. BASIC STRUCTURE AND OPERATION OF DG SYSTEM

The DG unit is normally connected to AC grid through voltage source inverter (VSI) as shown in Fig 1.

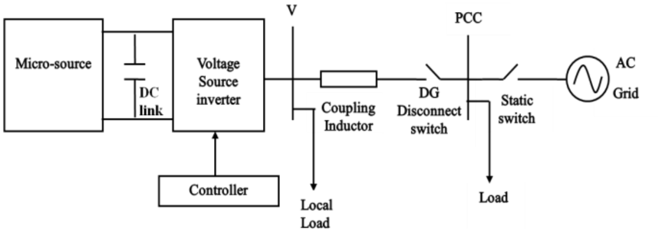


Fig 1. Basic structure of grid connected DG system

The micro-source is a renewable source like solar, fuel cell etc. An inductor acts as filter and supplies rated current to the grid. In grid connected mode, DG is connected in parallel to the grid and supplies rated power to it. The voltage and frequency at Point of Common Coupling (PCC) is controlled by grid. The DG operates in synchronism with the utility and injects power at voltage and frequency specified by the standards. The transfer function of DG in grid connected mode is discussed briefly in next section.

III. TRANSFER FUNCTION OF DG IN GRID CONNECTED MODE

Fig 2 shows the block diagram of close-loop control of DG in grid connected mode. In this mode, DG injects only active power into the grid. The DG output currents are transformed to *d-q* reference frame [12]. The reactive component of current (I_q) is set to zero [8]. The active component of DG output current (I_d) is compared with reference current (I_{dref}) to get the error signal and the error is reduced to zero using PI controller.

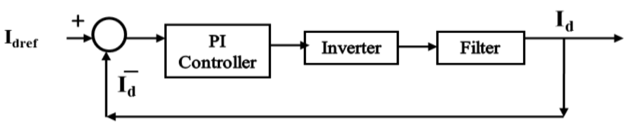


Fig 2. Block diagram of close-loop control system of DG

The transfer function of DG in grid connected mode is derived from block diagram of the close loop control system shown above. The filter at the output of DG helps to reduce harmonics injected into the grid. The L and LC filters are widely used in the power system hence this paper is intended to study the effect of these two filters on the performance of the close loop system. The transfer function of the system is derived considering different types of filters:

Case (i) L-filter

Case (ii) LC-filter

Case (i) L-filter:

The transfer function of PI controller is given by equation (1)

$$G_1(s) = k_P + \frac{k_I}{s} \quad (1)$$

where k_p is the proportional gain and k_I is the integral gain of PI controller. The inverter is assumed with ideal gain of $G_2(s)$ =1. The filter consists of inductor and the load considered is resistive. The transfer function of filter circuit is given by equation (2).

$$G_3(s) = \frac{1}{L_f s + R} \quad (2)$$

where R is load resistance and L_f is filter inductor. The close-loop transfer function of the current control system with L-filter is given by equation (3).

$$T(s) = \frac{k_p s + k_I}{L_f s^2 + (k_p + R)s + k_I} \quad (3)$$

Case (ii) LC-filter:

The transfer function of the LC-filter is given by equation (4).

$$G_3(s) = \frac{C}{s^2 RCL_f + sCL_f + RC} \quad (4)$$

The close-loop transfer function of the close loop control system with LC-filter is is given by equation (5).

$$T(s) = \frac{k_p s + k_I}{L_f Rs^3 + L_f s^2 + (k_p + R)s + k_I} \quad (5)$$

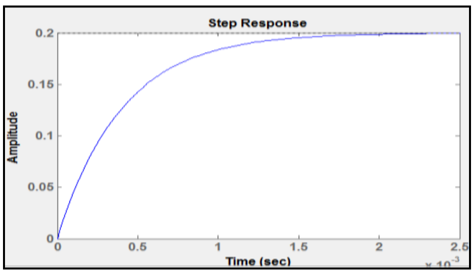
The PI controller gains k_p and k_I are obtained by the location of close loop poles in s-plane. For stable system, all the poles of close-loop transfer function should lie on left half of s-plane. The Root Locus Technique is used to obtain the position of poles. The SISO GUI tool in Matlab is used to verify the results of simulation for the control system. The Step response plot and Root Locus plots are discussed briefly for grid connected in the next section.

IV. ROOT LOCUS TECHNIQUE TO FIND CONTROLLER GAIN

The transfer functions of the DG system with L-filter and LC-filter given by (3) and (5) respectively are simulated in MATLAB control system tool box with the values of R=4Ω, L=2mH and C=30μF.

Case (i) L-filter:

The step response plot and Root Locus plots without controller are obtained as shown in Fig 3.



(a)

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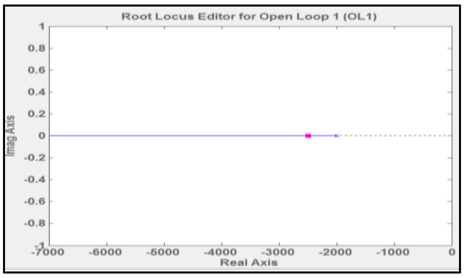
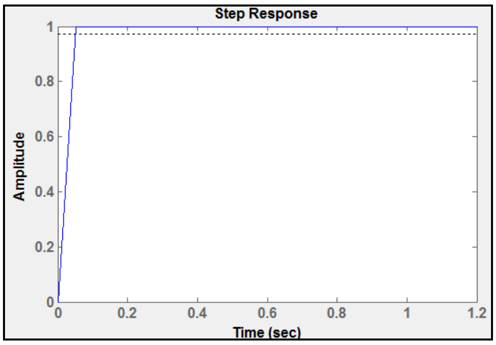


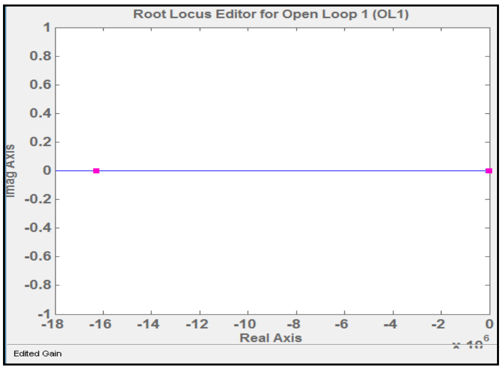
(b)

Fig 3. (a) Step response (b) Root Locus plot without PI regulator

It is observed from Fig. 3 (a) that there is a high steady state error as the final value is 0.2. From Fig 3 (b) it is seen that the system is stable with the close loop pole on left half of s-plane. However, to reach a final value of 1, the PI controller is added into the close loop system by adding a pole close to origin s=-0.01 and one zero is placed away from origin at s=-10 in s-plane. The gain K_p is increased by moving the pole in the root locus plot and the step response is observed. At K_p =180 and K_I =18, the steady state error reduces to minimum value. The step response plot and Root Locus plots with controller are obtained as shown in Fig 4.



(a)



(b)

Fig 4. (a) Step response (b) Root Locus plot with PI regulator

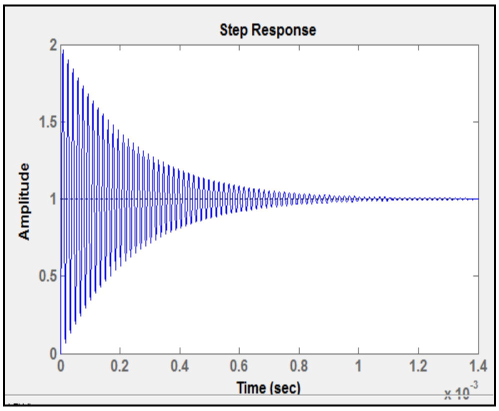
From Fig 4 (a) we observe that the steady state error is reduced and settling time is increased. Fig 4(b) shows that the system is stable with the close loop pole on left half of s-plane. The results of the step response plot and Root Locus plot with and without PI controller are tabulated in Table I.

TABLE I. RESULTS OF ROOT LOCUS PLOT FOR L-FILTER IN GRID CONNECTED MODE

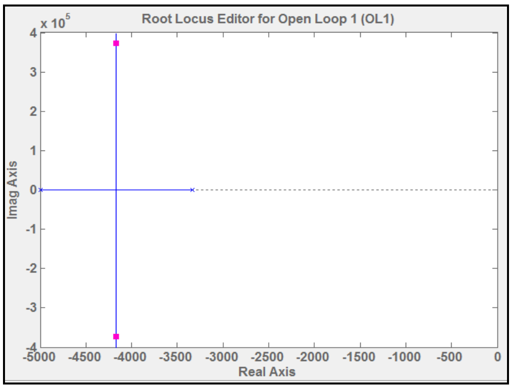
Parameter	Without Compensator	With compensator
Final Value	0.2	0.978
Steady-state error	0.8	0.022
Settling Time(sec)	1.56e-3	0.1
Close-loop poles	-2.5e3	-16e6 and -0.01

Case (ii) LC-filter:

The transfer function given by equation (5) is simulated in MATLAB. The step response plot and Root Locus plots without controller with an LC-filter are obtained as shown in Fig 5.



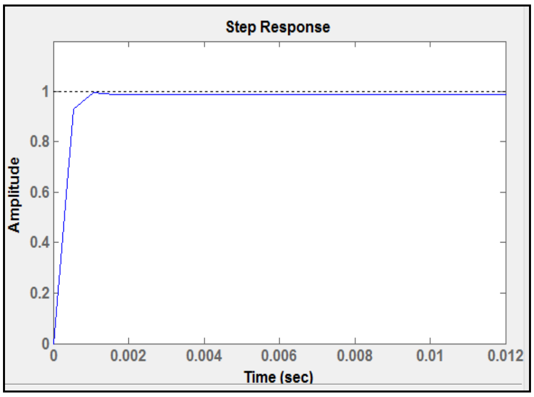
(a)



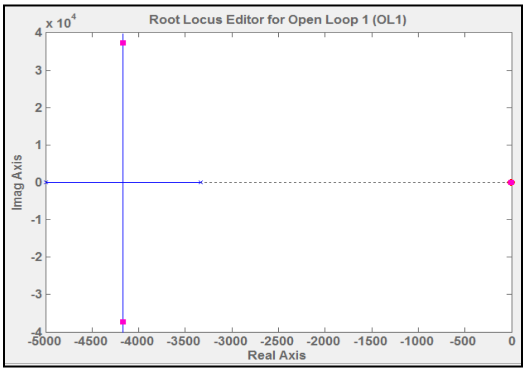
(b)

Fig 5 (a) Step response (b) Root Locus plot without PI regulator

It is observed from Fig. 5 (a) that without PI controller, the system has high oscillations (100% overshoot) before settling to final value is 1.0. From Fig 5 (b) it is seen that the system is stable. However, to reduce the % overshoot, the PI controller is added into the close loop system with one pole placed close to origin s=-0.01 and one zero placed away from origin at s=-10 in s-plane. The gain K_p is increased by moving the pole step by step and step response is observed. At K_p =150 and K_I =15, the steady state value is reached without any oscillations. The step response plot and Root Locus plots with controller are obtained as shown in Fig 6.



(a)



(b)

Fig 6. (a) Step response (b) Root Locus plot with PI regulator

The results of the step response plot and Root Locus plot with and without PI controller are tabulated in Table II.

TABLE II. RESULTS OF ROOT LOCUS PLOT FOR LC-FILTER IN GRID CONNECTED MODE

Parameter	Without Compensator	With compensator
Final Value	0.99	0.985
Steady-state error	0.01	0.015
Settling Time(sec)	1.0e-3	1.0e-3
Close-loop pole	-4.17e3±3.73e5	-4.17e3±3.73e4 and -0.01

It is observed that the system is stable with designed gain values of PI controller. The comparison of L and LC filter is summarized in Table III.

TABLE III. COMPARISON OF L AND LC-FILTER WITH PI CONTROLLER

Parameter	L-filter	LC-filter
Final Value	0.978	0.985
Steady-state error	0.022	0.015
Settling Time(sec)	0.1	1.0e-3
Close-loop pole	-16e6 and -0.01	-4.17e3±3.73e4 and -0.01

From the Table III it can be concluded that LC filter with designed values of PI controller gives better performance compared to L filter.

V. SIMULATION RESULTS

The matlab simulink model of the grid connected DG in Fig. 1 is as shown in Fig 7. A 3-Φ power system is developed with DG supplying rated power to the grid at load terminals. A passive load that consumes only active power is considered for simulation purpose. The DG supplies rated current to the grid in grid connected mode. To inject the desired currents into the grid, the inverter switches are operated using Sine PWM technique. The DG output currents are obtained from the rating from equation (6).

$$I_{(L-L)} = \frac{P_{dg}}{(\sqrt{3} * V_{(L-L)})} \tag{6}$$

where $I_{(L-L)}$ is the rms value of current, $V_{(L-L)}$ is the rms value of voltage and P_{dg} is the DG rating.

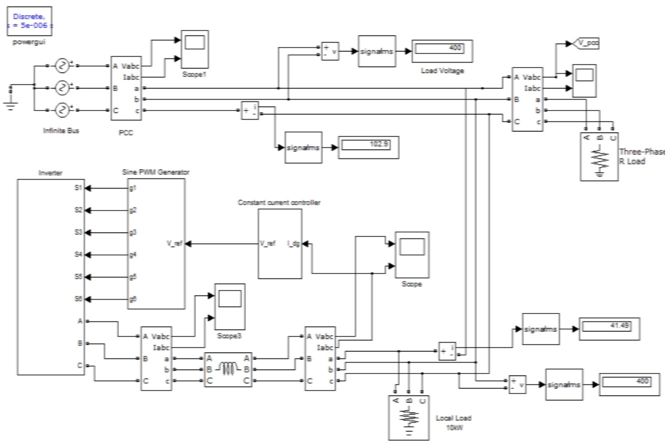


Fig 7. Simulink model of Grid connected DG

The details of the system parameters used for simulation are given in Table III.

TABLE IV. POWER SYSTEM PARAMETERS

Grid Parameters	
Line Voltage (rms)	400 V
Frequency	50 Hz
Load	100 kW
Inverter Parameters	
Line Voltage (rms)	400 V
Frequency	50 Hz
Inverter switching frequency	10 kHz
DC link voltage	840 V
DG capacity	40 kW
Filter Inductor	2 mH

The waveforms of DG output currents without proper design of PI regulator are as shown in Fig 8. It is known that for a power of 40 kW, the rms value of current should be 57.73A.

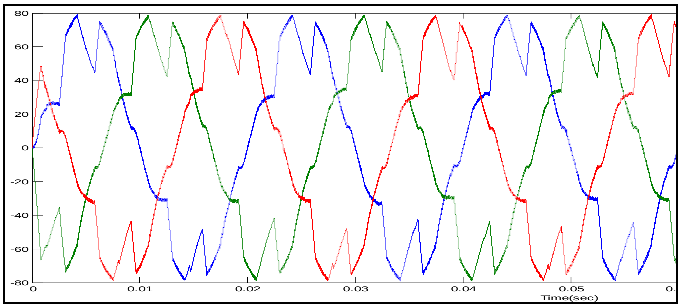


Fig 8. Waveforms of DG output currents without proper design

It is observed from the waveform that it is distorted. Hence, to get desired currents, the PI controller gains are found using Root Locus technique as mentioned in section IV. The waveforms of DG output currents with the predetermined values of gains are as shown in Fig 9. It is observed that the DG output currents are of required magnitude and frequency.

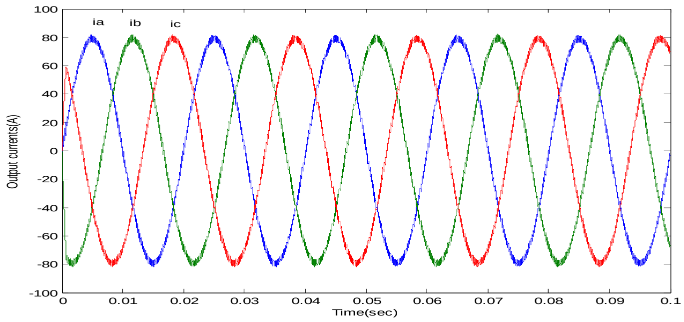


Fig 9. Waveforms of DG output currents with proper design

VI. CONCLUSION

Proper design of PI controller plays an important role in stable operation of DG system. This paper presents the design of PI controller for Grid-connected DG unit using Root Locus technique. The system performance is analysed with and without controller. It is observed that the DG with controller injects currents of improved power quality. The performance also depends on filter used. A comparison of L and LC filter shows that LC filter gives better results. The MATLAB simulation of DG system gives satisfactory results. Advantage of the method is that the same technique can also be used for the stable operation of DG unit in islanded mode of operation.

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