

# State space modelling, analysis and optimization of microgrid droop controller

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**Abstract**—The concept of microgrid has become more relevant due to the increase in the use of distributed energy resources. However, the important factors which are to be considered are their ability to control the power flow and stability of the system. Droop control strategy requires no communication system and realizes the “plug and play” function between source and load. In this paper a state space model of such a system is developed based on small signal disturbances. Eigenvalue analysis of the system is also done and the parameters which determine the stability of the system are identified. The optimum values of these parameters are found out by increasing the stability of the system using particle swarm optimization (PSO) technique. The simulation is done by MATLAB coding and the results show that the values of the optimized parameters will improve the stability of the system by shifting the eigenvalues away from the imaginary axis as far as possible on the left half of s plane.

**Keywords**—Droop controller, microgrid, eigenvalue analysis, particle swarm optimization

## I. INTRODUCTION

The concept of distribution generation is highly promoted and has become more relevant due to environmental considerations and as an alternative to fossil fuels [1], [2]. The generation which are not centrally dispatched and controlled can be considered as distribution generation which are usually connected to the distribution part of the power system. The development of distributed generation leads to the concept of microgrid [3]. The multiple distributed resources in a microgrid operates in parallel and power converters associated will have different control objectives as in [4], [5], [6].

Different control strategies like multi agent control, master slave control and droop control are proposed in the literature [7] and [8]. Among these, the droop control method has been identified as the popular method for controlling the operation of different DG units within the microgrid. The droop control method mimics the operation of conventional droop characteristics of alternator in which real and reactive power sharing is done by varying the magnitude of operating voltage and frequency. The significance to know the response of the system to various disturbances leads to the widespread use of small signal model [9], [10].

In this paper, a detailed model of inverter based microgrid is presented. Each DG inverter will have an outer power control loop based on droop control and inner voltage and current control loop. A small-signal state-space model is constructed on a synchronous reference frame whose rotation frequency is set by the power controller of individual inverter as in [11].

The analysis of eigenvalues can be done after obtaining the state space model of the microgrid from which the stability and dynamic performance is analyzed. The variation of eigenvalues with respect to the variation of different parameters in the control loops is also analyzed. After identifying the main parameters which will affect the stability and performance, these parameters are optimized. In [12], parameters are optimized based on the genetic algorithm by minimizing the difference between measured and reference values of active and reactive power in which adequacy is the main control objective. The stability analysis of the system by varying the position of eigenvalue is not done in this method. In this paper, the optimization is done by PSO taking the objective function as the shifting of the extreme right eigenvalue to as much left as possible and thus stability of the system is improved.

## II. MICROGRID SYSTEM

Fig. 1 shows the single-line diagram of the study system. It contains two DGs which are connected to its local loads through inverter, LC filter and coupling inductor. A common load is also connected through a line. When microgrid is operated in the autonomous mode, apart from meeting the load requirement, it has to maintain the voltage and frequency within the allowable limits.

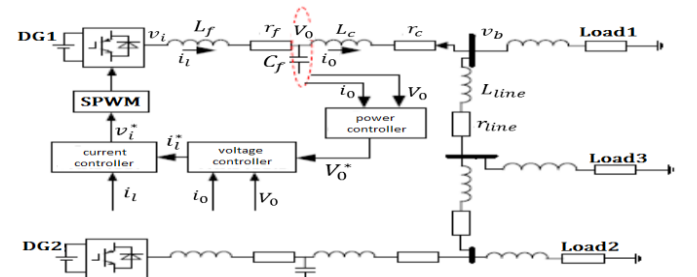


Fig. 1. Microgrid study system

### III. MICROGRID SMALL SIGNAL MODEL

The model presented in this paper consists of three submodules which are inverter model, line model and load model. Each inverter is modelled in its individual reference frame and then transferred into a common reference frame.

#### A. Inverter Model

The droop controller of a VSI consists of power sharing controller, voltage controller and current controller as in Fig 2.

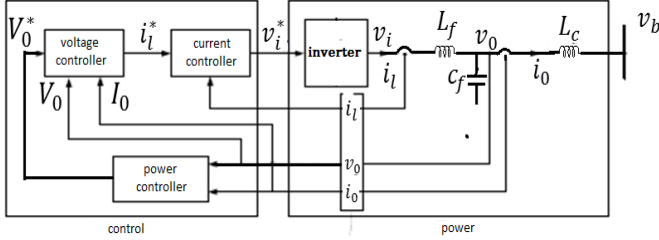


Fig. 2. Inverter model

The reference values of voltage and frequency are set by the power sharing controller given in Fig. 3 according to the desired values of real and reactive power.

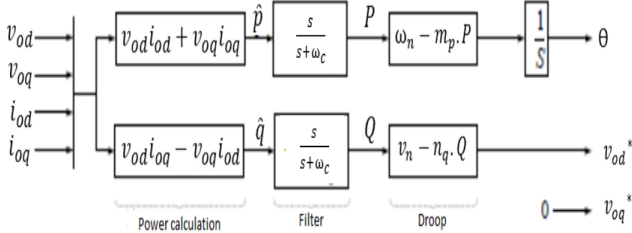


Fig. 3. Power sharing controller

The corresponding equations are:

$$P = \frac{s}{s+\omega_c} (v_{od}i_{od} + v_{oq}i_{oq}) \quad (1)$$

$$Q = \frac{s}{s+\omega_c} (v_{od}i_{oq} - v_{oq}i_{od}) \quad (2)$$

$$\omega = \omega_n - k_p P, \quad \dot{\theta} = \omega \quad (3)$$

$$v_{od}^* = v_n - k_q Q, \quad v_{oq}^* = 0 \quad (4)$$

$$\theta = \omega_n t + \delta \quad (5)$$

where,

- $P$  : Fundamental component of real power,
- $Q$  : Fundamental component of reactive power,
- $v_o$  : LC filter output voltage,
- $i_o$  : LC filter output current,
- $v_0^*$  : Reference output voltage of power controller
- $\omega_c$  : Cut off frequency of Low pass filter,
- $\delta$  : Angle of inverter reference frame with respect to the common reference frame

From equations(3) and (5),

$$\dot{\delta} = -k_p P \quad (6)$$

Linearizing the above equations for small perturbation and rearranging, small signal model of power sharing controller is obtained as

$$\begin{bmatrix} \Delta\delta \\ \Delta P \\ \Delta Q \end{bmatrix} = A_1 \begin{bmatrix} \Delta\delta \\ \Delta P \\ \Delta Q \end{bmatrix} + A_2 \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} \Delta\omega \\ \Delta v_0^* \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta P \\ \Delta Q \end{bmatrix} \quad (8)$$

where,

$$\Delta v_0^* = \begin{bmatrix} \Delta v_{od}^* \\ \Delta v_{oq}^* \end{bmatrix}, \Delta V_0 = \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix}, \Delta i_l = \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix}, \Delta i_o = \begin{bmatrix} \Delta i_{od} \\ \Delta i_{oq} \end{bmatrix}$$

In output voltage control loop, the output voltage is compared with the reference given by the power sharing controller and a feed forward gain is obtained to compensate for output current disturbances and generate the reference current vector as shown in Fig. 4.

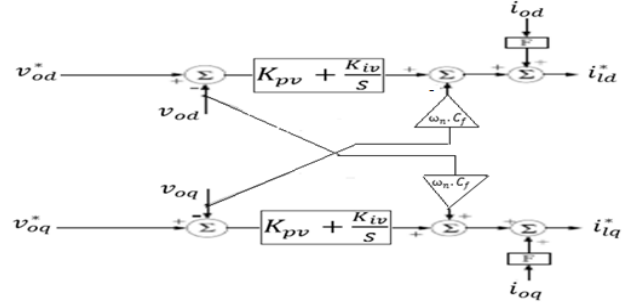


Fig. 4. Voltage controller

Let time derivative of  $\phi$  be defined as

$$\frac{d\phi_d}{dt} = v_{od}^* - v_{od} \quad (9)$$

$$\frac{d\phi_q}{dt} = v_{oq}^* - v_{oq} \quad (10)$$

Corresponding state equations are

$$\dot{i}_{ld}^* = F i_{ld} - \omega_n C_f v_{oq} + K_{pv}(v_{od}^* - v_{od}) + K_{iv}\phi_d \quad (11)$$

$$\dot{i}_{lq}^* = F i_{lq} + \omega_n C_f v_{od} + K_{pv}(v_{oq}^* - v_{oq}) + K_{iv}\phi_q \quad (12)$$

where,

- $C_f$  : filter capacitance
- $K_{pv}$  : proportional constant of PI controller
- $K_{iv}$  : integral constant of PI controller

Linearizing the above equations, we get

$$\Delta\dot{\phi} = [0][\Delta\phi] + C_1[\Delta V_0^*] + C_2 \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} \quad (13)$$

$$[\Delta i_l^*] = C[\Delta\phi] + C_3[\Delta V_0^*] + C_4 \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} \quad (14)$$

where  $\Delta\phi = \begin{bmatrix} \Delta\phi_d \\ \Delta\phi_q \end{bmatrix}$

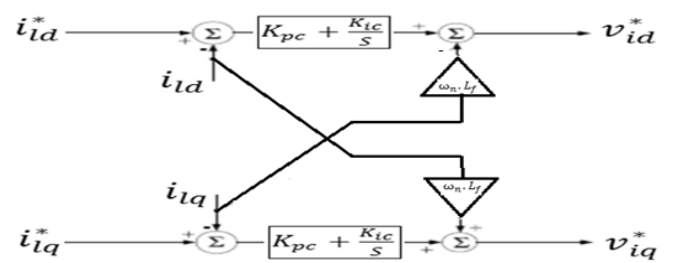


Fig. 5. Current controller

Similar to voltage controller, current control loop uses a PI controller to compare the output filter current and reference

value given by the voltage controller as shown in Fig. 5 and generate reference voltage for the pulse generator. Let time derivative of  $\gamma$  be defined as

$$\frac{d\gamma_d}{dt} = i_{ld}^* - i_{ld} \quad (15)$$

$$\frac{d\gamma_q}{dt} = i_{lq}^* - i_{lq} \quad (16)$$

Corresponding state equations are

$$v_{ld}^* = -\omega_n L_f i_{lq} + K_{pc}(i_{ld}^* - i_{ld}) + K_{ic}\gamma_d \quad (17)$$

$$v_{lq}^* = \omega_n L_f i_{ld} + K_{pc}(i_{lq}^* - i_{lq}) + K_{ic}\gamma_q \quad (18)$$

where,  $L_f$  : filter inductance  
 $K_{pc}$  : proportional constant of PI controller  
 $K_{ic}$  : integral constant of PI controller

Linearizing the above equations, we get

$$\Delta\dot{\gamma} = [0][\Delta\gamma] + D_1[\Delta i_l^*] + D_2 \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} \quad (19)$$

$$[\Delta v_i^*] = D[\Delta\gamma] + D_3[\Delta i_l^*] + D_4 \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} \quad (20)$$

$$\text{where } \Delta\gamma = \begin{bmatrix} \Delta\gamma_d \\ \Delta\gamma_q \end{bmatrix}$$

The voltage and current equations corresponding to the LC filter and coupling inductance can be represented as

$$v_i - v_o = r_f i_l + L_f \frac{di_l}{dt} \quad (21)$$

$$i_l - i_o = c_f \frac{dv_o}{dt} \quad (22)$$

$$v_o - v_b = r_c i_o + L_c \frac{di_o}{dt} \quad (23)$$

where  $v_b$  : bus voltage  
 $L_c$  : coupling inductance

Linearizing and rearranging the above equations after DQ transformation we get,

$$\begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} = E \begin{bmatrix} \Delta i_l \\ \Delta v_o \\ \Delta i_o \end{bmatrix} + E_1[\Delta v_i] + E_2[\Delta v_{bdq}] + E_3[\Delta\omega] \quad (24)$$

Output variables of each inverter are required to be converted into common reference frame for connecting it to the rest of the system. Corresponding equations are:

$$i_{oD} = i_{od} \cos\delta - i_{oq} \sin\delta \quad (25)$$

$$i_{oQ} = i_{od} \sin\delta + i_{oq} \cos\delta \quad (26)$$

where,  $i_{oD}$ : Direct axis component of current in common reference frame,

$i_{oQ}$ : Quadrature axis component of current in common reference frame

Linearizing the above equations, we get

$$[\Delta i_{oDQ}] = T_s[\Delta i_o] + T_c[\Delta\delta] \quad (27)$$

where,

$$T_s = \begin{bmatrix} \cos\delta_0 & -\sin\delta_0 \\ \sin\delta_0 & \cos\delta_0 \end{bmatrix}, T_c = \begin{bmatrix} -I_{od} \sin\delta_0 - I_{oq} \cos\delta_0 \\ I_{od} \cos\delta_0 - I_{oq} \sin\delta_0 \end{bmatrix}$$

Similarly bus voltage on individual inverter reference frame can be represented using reverse transformation as

$$[\Delta v_{bdq}] = [T_s^{-1}] [\Delta v_{bdQ}] + [T_v^{-1}] [\Delta\delta] \quad (28)$$

where,

$$T_v^{-1} = \begin{bmatrix} -V_{bD} \sin\delta_0 + V_{bQ} \cos\delta_0 \\ -V_{bD} \cos\delta_0 - V_{bQ} \sin\delta_0 \end{bmatrix}$$

$V_{bD}$  is the direct axis component of voltage in common reference frame and  $V_{bQ}$  is the quadrature axis component of voltage in common reference frame

From equations (7), (8), (13), (14), (19), (20), (24), (27) and (28),

$$[\Delta x_{inv i}] = G_{1i} [\Delta x_{inv i}] + G_{2i} [\Delta v_{bdQ i}] \quad (29)$$

$$\begin{bmatrix} \Delta\omega_i \\ [\Delta i_{oDQ i}] \end{bmatrix} = \begin{bmatrix} G_{3i} \\ G_{4i} \end{bmatrix} [\Delta x_{inv i}] \quad (30)$$

where,

$$[\Delta x_{inv i}] = [\Delta\delta_i \ \Delta P_i \ \Delta Q_i \ \Delta\phi_i \ \Delta\gamma_i \ \Delta i_{li} \ \Delta v_{oi} \ \Delta i_{oi}]$$

Since there are two inverters in the microgrid system,

$$[\Delta x_{inv}] = [\Delta x_{inv1} \ \Delta x_{inv2}]^T$$

### B. Network Model

The voltage difference between adjacent buses  $j$  and  $k$  as shown in Fig. 6 is given by

$$v_{bj} - v_{bk} = i_{line i} r_{line i} + L_{line i} \frac{di_{line i}}{dt} \quad (31)$$

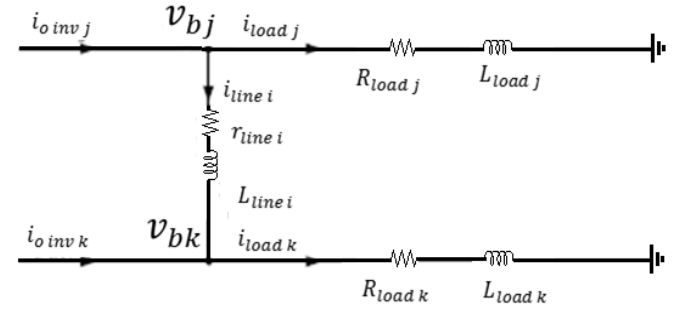


Fig. 6. Network and load model

Taking DQ transformation and linearization,

$$\Delta i_{line i} = H_{1i} [\Delta i_{line i}] + H_{2i} [\Delta v_{bdQ i}] + H_{3i} \Delta\omega \quad (32)$$

For given network with 2 lines and 3 nodes, equation become,

$$\Delta i_{line} = H_1 [\Delta i_{line}] + H_2 [\Delta v_{bdQ}] + H_3 \Delta\omega \quad (33)$$

where,

$$[\Delta i_{line}] = [\Delta i_{line1} \ \Delta i_{line2}]^T$$

$$[\Delta v_{bdQ}] = [\Delta v_{bdQ1} \ \Delta v_{bdQ2} \ \Delta v_{bdQ3}]^T$$

### C. Load model

Equation of RL load connected at  $i^{th}$  node is,

$$v_{bj} = i_{load i} R_{load i} + L_{load i} \frac{di_{load i}}{dt} \quad (34)$$

Taking DQ transformation and linearization,

$$\Delta i_{load} = L_1 [\Delta i_{load}] + L_2 [\Delta v_{bdQ}] + L_3 \Delta\omega \quad (35)$$

where  $[\Delta i_{load}] = [\Delta i_{load1} \ \Delta i_{load2} \ \Delta i_{load3}]^T$

### D. Complete microgrid model

Considering the model equations (29), (30), (33) and (35) we get overall state space model as

$$\begin{bmatrix} \Delta \dot{x}_{inv} \\ \Delta \dot{i}_{line} \\ \Delta \dot{i}_{load} \end{bmatrix} = A_m \begin{bmatrix} \Delta x_{inv} \\ \Delta i_{line} \\ \Delta i_{load} \end{bmatrix} + \begin{bmatrix} G_2 \\ H_2 \\ L_2 \end{bmatrix} [\Delta v_{bdQ}] \quad (36)$$

$$\text{where, } A_m = \begin{bmatrix} G_1 & 0 & 0 \\ H_3 G_3 & H_1 & 0 \\ L_3 G_3 & 0 & L_1 \end{bmatrix}$$

To establish the node voltage, a virtual resistor  $r_N$  is assumed at each node of the network. Hence, the voltage of  $i^{th}$  node is given by

$$V_{bi} = r_N(i_{oi} - i_{load i} + i_{line i}) \quad (37)$$

For the selected network with two nodes,

$$[\Delta v_{bDQ}] = R_N(M_1[\Delta i_{oDQ}] + M_2[\Delta i_{loadDQ}] + M_3[\Delta i_{line}]) \quad (38)$$

where, matrix  $R_N$  is of size  $6 \times 6$ , whose diagonal elements are equal to  $r_N$ . The matrix  $M_1$  is of size  $4 \times 2$ s, which maps the inverter connection points onto network nodes. Similarly,  $M_2$  of size  $6 \times 4$  maps load connection points onto the network nodes. Matrix  $M_3$  of size  $6 \times 4$  maps the connecting lines onto the network nodes.

Based on equation (35) and (37), 36 order state space model is obtained as

$$\begin{bmatrix} \Delta \dot{x}_{inv} \\ \Delta \dot{i}_{line} \\ \Delta \dot{i}_{load} \end{bmatrix} = A_{mg} \begin{bmatrix} \Delta x_{inv} \\ \Delta i_{line} \\ \Delta i_{load} \end{bmatrix} \quad (39)$$

#### IV. EIGEN VALUE ANALYSIS

The complete eigenvalue spectrum of the linearized small signal model can be calculated under the initial condition given in Table 1. The parameters of the system are given in Table 2. From the eigenvalue plot shown in Fig. 7, it is observed that the eigenvalues are distributed in three different region and stability is determined by the low frequency eigenvalues near the imaginary axis. The number of eigenvalues in each region is also given in the plot.

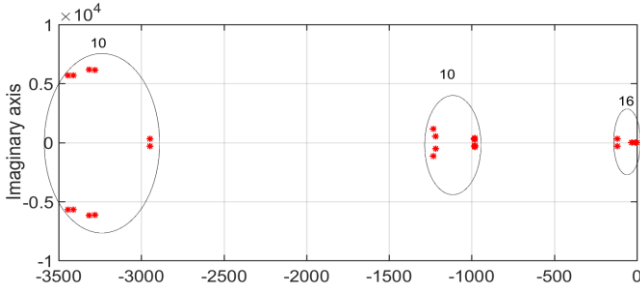


Fig.7 Eigenvalue spectrum in S plane

In order to find out the effect on stability due to the variation of control parameters  $k_p, k_q, k_{pv}, k_{pc}, k_{iv}$  and  $k_{ic}$ , eigenvalue spectrum is plotted by varying each of these parameters and keeping others constant. From Fig. 8 it can be concluded that as the value of  $k_p$  increases, the dominant eigenvalues move away from the real axis and closer to the imaginary axis which decreases the stability.

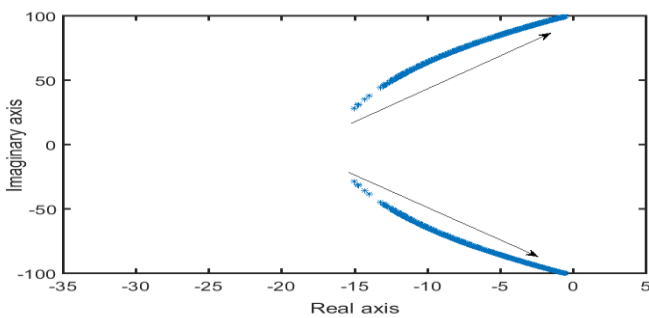


Fig.8 Variation of eigenvalues with  $k_p$  in S plane

TABLE 1  
INITIAL OPERATING VALUES

parameter	values	parameter	values
$V_{od}$	[311.2 311.6] V	$I_{line d1}$	-7.8A
$V_{oq}$	[0 0]V	$I_{line q1}$	1.4A
$I_{od}$	[21.2 21.2]A	$I_{line dz}$	-5.3A
$I_{oq}$	[-.34 -1.05]A	$I_{line q2}$	0.7A
$I_{ld}$	[21.2 21.2]A	$v_{bd}$	[308.7 308.5 308]V
$I_{lq}$	[-14.3 -11.3]A	$v_{bq}$	[-2.8 -1.3 -1.5]V
$\delta_0$	[-14.3 -11.3]A	$\omega_0$	314rad/s

TABLE 2  
SYSTEM PARAMETERS OF MICROGRID

parameter	values	parameter	values
$L_f$	1.5mH	$k_p$	1.03 e-5
$R_f$	0.15Ω	$k_q$	2.95 e-4
$C_f$	1500μF	$K_{pv}$	10.11
$L_c$	0.15mH	$K_{iv}$	100
$R_c$	0.05Ω	$K_{pc}$	10
$R_{line1}$	0.147Ω	$K_{ic}$	0.12
$L_{line1}$	1.63mH	F	0.7
$R_{line2}$	0.11Ω	$\omega_c$	31.4rad/s
$L_{line2}$	1.25mH		

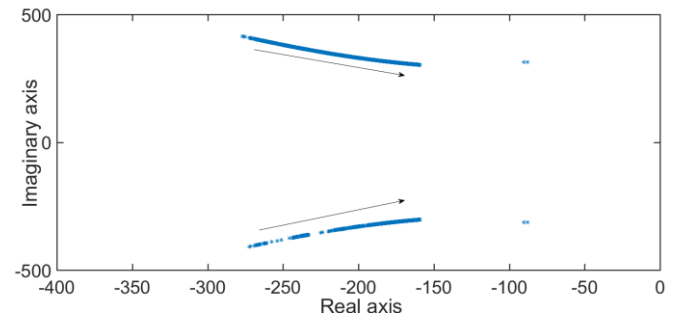


Fig. 9 Variation of eigenvalues with  $k_q$  in S plane

Similarly as  $k_q$  increases, dominant eigenvalues move towards unstable region as shown in Fig. 9. Similar but nonuniform variation is obtained when  $k_{pv}$  and  $k_{ic}$  are changed as shown in Fig. 10 and Fig. 11 and the variation is less when  $k_{pc}$  and  $k_{iv}$  are changed. So it can be concluded that the main parameters which determine the stability of the system are  $k_p, k_q, k_{pv}$  and  $k_{ic}$ .

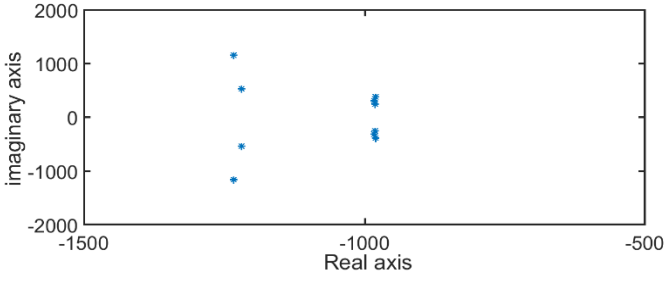


Fig. 10 Variation of eigenvalues with  $k_{ic}$  in S plane

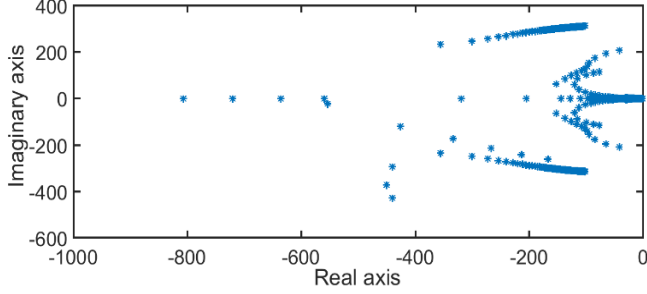


Fig. 11 Variation of eigenvalues with  $k_{pv}$  in S plane

## V. DROOP CONTROL OPTIMIZATION USING PSO

From the analysis given in Section IV, it is clear that the values of the parameters  $k_p, k_q, k_{pv}$  and  $k_{ic}$  decide the stability of the system. Hence the optimum values of the parameters are to be sought so that the system is stable. The objective of the optimization problem is to improve the stability of the system by controlling the position of eigenvalues. System will become stable when the eigenvalues are on the left side of imaginary axis and stability increases as the distance from imaginary axis increases.

Let eigenvalues be represented as  $\lambda_i = Re_i + j Im_i$ , where  $Re_i$  is the real part and  $Im_i$  is the imaginary part of the  $i^{th}$  eigenvalue. So the objective function is

Min  $J = \text{maximum of } (Re_i) \text{ such that } k_p, k_q, k_{pv} \text{ and } k_{ic} \text{ are within the limit.}$

In PSO, each particle is a real valued vector with dimension equal to the number of parameters to be optimized. Each particle is a solution to the optimization problem and such P particles will be there where P is the size of the population. Initially a random solution is taken within the parameter limit which is nothing but position in the search space. The position of each particle is updated based on its inertia, personal best and group best according to the equation given below

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (40)$$

$$v_i(k+1) = wv_i(k) + r_1 C_1 [P_i(k) - x_i(k)] + r_2 C_2 [g(k) - x_i(k)] \quad (41)$$

where,

$x_i(k)$  : position of  $i^{th}$  particle in  $k^{th}$  iteration

$v_i(k)$  : velocity of  $i^{th}$  particle in  $k^{th}$  iteration

w : inertia coefficient

$C_1, C_2$  : acceleration coefficient

$P_i(k)$  : local best position of  $i^{th}$  particle in  $k^{th}$  iteration

$g(k)$  : global best position among particles in  $k^{th}$  iteration

TABLE 3  
PARAMETERS OF PSO

Parameter	Values
Number of iteration	100
Population size	50
Inertia coefficient	1
Damping ratio of inertia coefficient,	0.99
Individual acceleration coefficient, $C_1$	2
Global acceleration coefficient, $C_2$	2
Unknown variables	$[k_p, k_q, k_{pv}, k_{ic}]$
Lower limit of unknown variables	$[1e-7, 1e-7, 0, 0]$
Upper limit of unknown variables	$[0.1, 0.1, 500, 500]$

By conducting this updating process for velocity and position, at the end of a few iterations the optimum value is obtained. For the optimization problem discussed earlier, the parameters are given in Table 3.

By varying the microgrid control parameters  $X = [k_p, k_q, k_{pv}, k_{ic}]$ , the solution is obtained as  $X = [2.87e-4, 1e-7, 5.98, 129.56]$  and  $J = -11.7123$ . The convergence curve of objective function is given in Fig. 12.

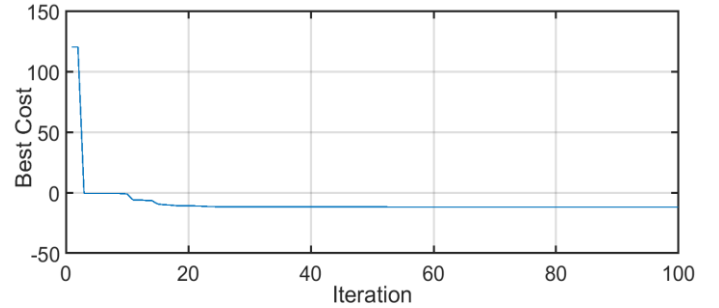


Fig. 12 Convergence curve of objective function

The variations of dominant eigenvalues before and after optimization are given in Fig. 13 and Fig. 14. In Fig. 13, the real part of extreme right eigenvalue is at -0.012 and it is shifted to -11.7123 after optimization as in Fig. 14. Therefore, stability can be improved by the optimal setting of control parameters  $k_p, k_q, k_{pv}$  and  $k_{ic}$ .

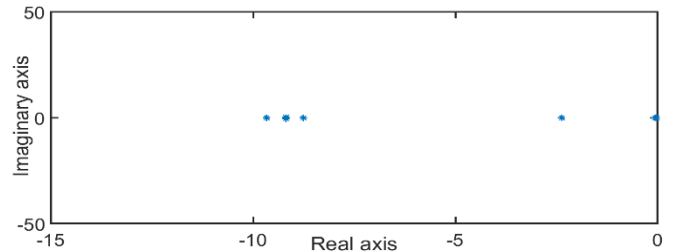


Fig. 13 Dominant eigenvalues before optimization in S plane

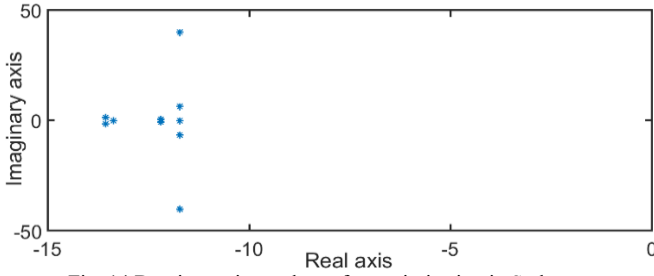


Fig. 14 Dominant eigenvalues after optimization in S plane

## VI. RESPONSE OF THE SYSTEM FOR SMALL DISTURBANCES

In order to validate the effectiveness of optimized system, a change of 1A (0.4pu) is applied for load 2. The variation of states  $\Delta\delta_1$  and  $\Delta\delta_2$  before and after optimization is given in Fig. 15. Before optimization the states were not converging to zero even after one second, whereas it tends to approaching zero approximately at 0.4 second after optimization.

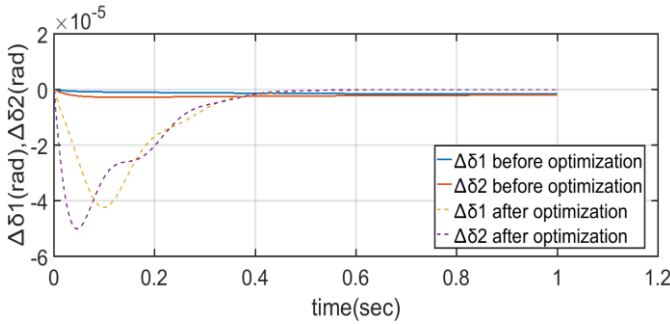


Fig. 15 variation of  $\Delta\delta_1$  and  $\Delta\delta_2$  before and after optimization

Similar variation for  $\Delta P_1, \Delta Q_1$  and  $\Delta P_2, \Delta Q_2$  are given in Fig. 16 and Fig. 17 respectively. In these cases, the states were not converging to zero before optimization and it goes to zero at 0.5 second when the parameters are optimized.

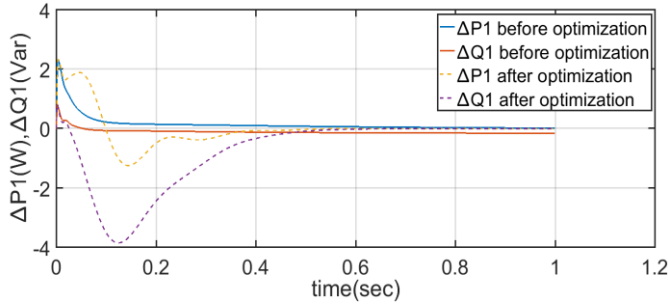


Fig. 16 variation of  $\Delta P_1$  and  $\Delta Q_1$  before and after optimization

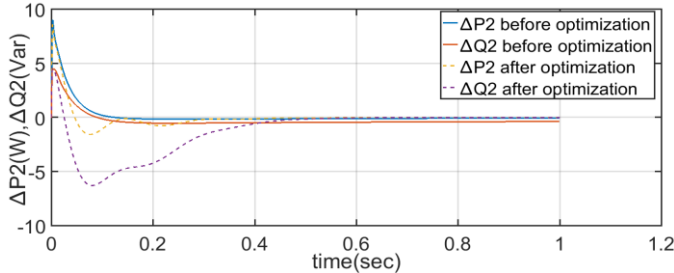


Fig. 17 variation of  $\Delta P_2$  and  $\Delta Q_2$  before and after optimization

## VII. CONCLUSION

The small signal based state space model is used for analyzing the stability and dynamic performance of the microgrid system. From the eigenvalue analysis, it is observed that as  $k_p$  increases, the dominant eigenvalues move away from the real axis improving system performance while move closer to the imaginary axis deteriorating the stability.  $k_q$  has little influence on the dynamic performance of the system, but when the value is too large, the dominant roots move towards unstable region. The proportional parameter of voltage loop,  $k_{pv}$  and integral parameter of current loop,  $k_{ic}$  also have a great influence on the dominant eigenvalues whereas the integral parameters of voltage loop,  $k_{iv}$  and proportional parameter of current loop,  $k_{pc}$  do not affect the dominant roots significantly. Therefore the key parameters affecting the microgrid stability and dynamic performance are  $k_p, k_q, k_{pv}$  and  $k_{ic}$ . By performing the particle swarm optimization, the optimum values of these parameters are found.

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