International Journal on
“Technical and Physical Problems of Engineering”
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2013 Issue 15 Volume 5 Number 2 Pages 118-122

ANALYSIS OF POWER SHARING BASED ON SMALL SIGNAL STABILITY IN A DC MICROGRID

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Abstract- Control techniques are wildly used and popular method to improve operational performance of microgrid. Control techniques are divided into two groups: centralized and decentralized that also known as droops controlled. In this paper, droop based decentralized control of a microgrid is studied for power sharing. In order to analysis stability, state space equation is derived. Dynamic model of each component is extracted individually and used for microgrid stability analysis. Eigen values of system indicate that variation of PI controller results in changing the location of system poles. Results show that system stability depends on system and PI controller parameters.

Keywords: DC Microgrid, Small Signal Analysis, Voltage Source Inverter (VSI), Stability.

I. INTRODUCTION

Recent innovations in small scale distributed power generation systems combined with technological advancements in power electronic systems led to concepts of future network technologies such as microgrids. These small autonomous regions of power systems can offer increased reliability and efficiency and can help integrate renewable energy and other forms of distributed generation (DG) [1]. Nowadays, DGs are widely used in the power systems to improve the overall conditions of the network. Less environmental impact, high electric efficiency, low variable maintenance cost, quick start up, low installation cost and many other benefits, encourage the system manager to utilize this type of generation in the network [2].

Many forms of distributed generation such as fuel cells, photovoltaic and micro-turbines are interfaced to the network through power electronic converters [2-3]. These interface devices make the sources more flexible in their operation and control compared to the conventional electrical machines. However, due to their negligible physical inertia they also make the system potentially susceptible to oscillation resulting from network disturbances.

The high penetration of Distributed generations DGs in nowadays distribution networks, islanding and microgrid operation of them is attracting attentions. Microgrids development will help more reliable power delivery, loss reduction and voltage profile enhancement. Supply reliability is increased by standalone operation of microgrids during contingency in main and upstream network.

Microgrids are facing some issues. Proper operation of microgrid requires new control, protection and communication infrastructure developments. Microgrids stability must be achieved by subjecting novel control methods. With the development of distributed generation resources and the increase of energy generation technologies, the operation of power systems faced with new complexities.

Due to rapid development of the power electronics industry, an increasing number of high power semiconductor devices are available for power system applications [18]. DC nature of home, domestic and commercial loads is ranked DC over AC distribution networks. DC distributed energy resources supports this fact. Studies are under taken that efficiency of DC microgrid is 10-22% more [4, 16]. However in protection, DC microgrid faces issues because of no zero crossing of waveforms [5].

DC microgrid consists of different sources and loads connected together. An appropriate load sharing algorithms is required. Load sharing algorithms divided into two categories. (i) Master slave controller: this method needs fast communication between converters and any failure in communication will lead in load sharing failure. System reliability is also reduced by introducing communication circuits and master controller [6]. (ii) Droop controller: no communication is need and voltage and currents play communication channel. It is most suitable for vast microgrids. Droop controller is implemented in each source [7].

Droop controller stability and analysis is reported in several papers. Some modifications are also made to achieve more stable and fast response [8-15]. Success of droop controller in ac microgrids makes it a candidate for implementation in DC microgrids. In this paper droop control based a DC microgrid is studied. Small signal model and state space of equation is derived. Stability of microgrid and load sharing is analyzed by system poles analysis and their movement in s-plane.

Next section models typical DC microgrid components for small signal and stability analysis. In third section, case study microgrid is presented. Respective state space equations are derived and system eigenvalues is obtained. Finally the controller parameters effect on poles location and system stability is studied.

II. DYNAMIC MODELING OF MICROGRID COMPONENTS

DC microgrid consists of three sub circuits. VSI interfacing sources provide electrical power for microgrid like wind turbines and PVs. Distribution network performs task of delivering power from sources to load. Loads are the final part of microgrid.

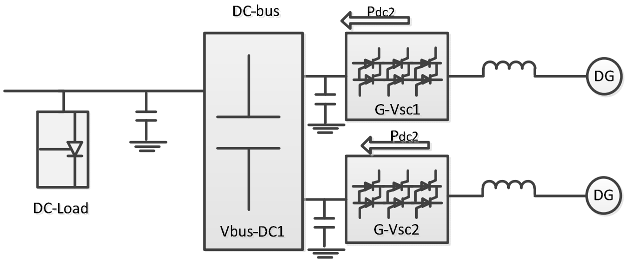

Figure 1. Schematic of DC microgrid [3]

Transient stability analysis of DC microgrid involves extracting small signal model of each part. Dynamic modeling of microgrid parts is presented as follows.

Voltage source inverters are a main component in microgrid power control and maintain microgrid voltage. VSI small signal model represents for power control loop, filter and voltage and current controller dynamic. Generator and sources dynamic is much slower than VSI dynamic and generator dynamic is neglected. Generator bus voltage is considered constant and dynamic behind it is not modeled.

A. Voltage Source Inverter

VSI is interface between distributed generation and network. Complete block diagram model of VSI is shown in Figure 2. Because of high frequency switching its dynamic is negligible. First block of inverter controls inverter output power based on inverter droop. Each inverter participates in dc microgrid voltage adjusting by injecting appropriate power. Inverter droop determines each source participation level.

Second and third block of inverter controls voltage and current to achieve desirable power injection by building reference signals feeding to switching block. Most control laws such as PID, do not explicitly consider the future implication of current control actions [17]. In this block the proportional and integral parameters should be adjusted to set the error on zero point. Voltage and current control is designed in such way to eliminate high frequency transients.

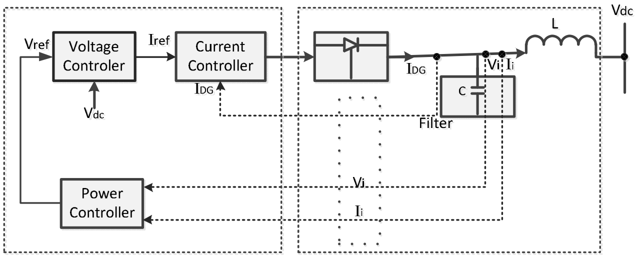

Figure 2. Block diagram model of VSI [8]

Droop control concept is similar to classic synchronous generator drop frequency control. In traditional power systems, governor responds to loading variation on the basis of its drop frequency characteristics. VSI control blocks perform governor action to maintain microgrid voltage.

As seen in Figure 2, instant power is evaluated by sampling output voltage and current. Power signal is filtered by a low pass filter. Low pass filtering eliminates harmonics in order to fundamental component power is considered. Filtering dynamic is formulated in (1).

$$P = \frac{\omega_c}{s+\omega_c}\tilde{P} \tag{1}$$

where, ω_c is cut off frequency of filter. Power dispatching between sources is performed by drop introduction to inverter. A virtual loop of inverters voltages is defined. Reference DC voltage is calculated according to droop gain, represented in (2).

$$V_{dc}^{*} = V_n - P \times m_P \tag{2}$$

where m_p is calculated by (3).

$$m_p = \frac{V_{dc,\max} - V_{dc,\min}}{P_{\max}} \tag{3}$$

where, m_P is Coefficient Droop and V_n is nominal voltage. Power signal in DC microgrid is calculated by voltage and current multiplying. Reference voltage signal is produced by

$$V_i^{*} = V_n - m_{P1}\frac{\omega_c}{s+\omega_c} \times \tilde{P}_i \tag{4}$$

Equation (1) can be written versus output voltage and currents.

$$P_i = \frac{\omega_c}{s+\omega_c} V_i I_i \tag{5}$$

$$\dot{P}_i = \omega_c V_i I_i - \omega_c P_i \tag{6}$$

where V_i, I_i and P_i are respectively output voltage and output current and output power VSI of bus *i*. In order to small signal stability, a linearization approximation around operating point, shown in (7- 9) is done.

$$P = f(V, I) \tag{7}$$

$$\Delta P = \left.\frac{\partial f}{\partial V}\right|_{(V_0,I_0)} \Delta V + \left.\frac{\partial f}{\partial I}\right|_{(V_0,I_0)} \Delta I \tag{8}$$

$$\Delta\dot{P}_i = -\omega_c \Delta P_i + (\omega_c I_{i_0})\Delta V_i + (\omega_c V_{i_0})\Delta I_i \tag{9}$$

where, ΔP_i and ΔV_i are state variables, V_{i_0} and I_{i_0} are the inverter operation point output voltage and current. Power control block calculates reference voltage sent to voltage control block. Output voltage control is obtained by an ideal PI controller.

A conceptual flux is considered to reflect voltage control loop and treated as a state variable. Related equations are shown in (10, 11).

$$\frac{d\varphi_i}{dt} = V_i^* - V_i \tag{10}$$

$$\Delta I_i^* = k_{I_i}\Delta\varphi_i + k_{P_i}(-m_{P_i}\Delta P_i - \Delta V_i^*) \tag{11}$$

Voltage control block output is current reference signal which is sent to switching unit to control switching to reach desire current and power for each inverter considering its droop. Because of fast switching dynamic of hysteresis switching it is meaningful to ignore switching dynamics and reaching to (12).

$$\Delta I_i^* = \Delta I_i \tag{12}$$

By substituting (11) in (9), Equation (13) is derived.

$$\begin{aligned}\Delta\dot{P}_i &= -\omega_c(1+k_{P_i}m_{P_i}V_{i_0})\Delta P_i + (k_{I_i}\omega_c V_{i_0})\Delta\varphi_i + \\ &+\omega_c(I_{i_0} - k_{P_i}V_{i_0})\Delta V_i\end{aligned} \tag{13}$$

where k_{P_i} and k_{I_i} are the proportional and integral gains, respectively.

B. Filters

When low pass filter in each inverter output is utilized to reduce harmonics and THD and (14, 15) represent behavior of circuit.

$$\Delta\dot{V}_i = \frac{-\Delta I_{Line}}{C_{filter}} + \frac{1}{C_{filter}}\Delta I_i \tag{14}$$

$$\Delta\dot{I}_{equal} = \frac{1}{L_{equal}}(\Delta V_i - R_{line}\,\Delta I_{line} - \Delta V_{DC}) \tag{15}$$

where C_{filter} is the capacitance of filter output of Voltage source inverter and ΔP_i is derived before in (13). Rewriting and expanding (10) other equation is reached (16).

$$\Delta\dot{\varphi}_i = \Delta V_i^* - \Delta V_i = -m_{P_i}\Delta P_i - \Delta V_i \tag{16}$$

Combining (11, 14) produces state equation describing ΔV_i variable, shown in (17).

$$\begin{aligned}\Delta\dot{V}_i &= -\frac{k_{P_i}m_{P_i}}{C_{filter}}\Delta P_i + \frac{k_{I_i}}{C_{filter}}\Delta\varphi_i + \\ &-\frac{k_{P_i}}{C_{filter}}\Delta V_i - \frac{1}{C_{filter}}\Delta I_{filter,i}\end{aligned} \tag{17}$$

A state space model is extracted by ΔP and $\Delta\varphi$ as state variables. Below set of equation is representing state space model of inverter.

$$\begin{cases}\Delta\dot{P}_i = -\omega_c(1+k_{P_i}m_{P_i}V_{i_0})\Delta P_i + (k_{I_i}\omega_c V_{i_0})\Delta\varphi_i \\ +\omega_c(I_{i_0} - k_{P_i}V_{i_0})\Delta V_i \\ \Delta\dot{\varphi}_i = -m_{P_i}\Delta P_i - \Delta V_i\end{cases} \tag{18}$$

State equation for inverter currents can be extracted from (15) where ΔV_{dc} is expanded based on inverter voltages, currents and line impedances.

C. Network and Load

Loads are modeled as constant current load for small signal stability. Lines inductances can be dealt easily in achieving whole system state space equations.

III. CASE STUDY MICROGRID

Case study DC microgrid is shown in Figure 3. Microgrid is supplied by two inverter interfaced DGs and loads considered constant current. Network specification is shown in Table 1. Droop based control shares loads between inverters. Initial operating point of microgrid is addressed in Table 2.

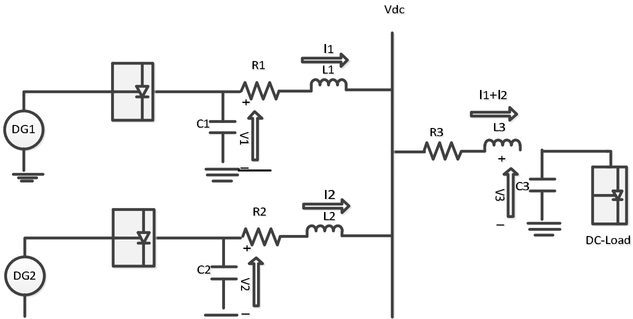

Figure 3. Case study network [3]

Table 1. Network specifications

Network components	Value
$r_1 = r_2 = r_3$	0.01 Ohm
$C_1 = C_2 = C_3$	25 mF
$L_1 = L_2 = L_3$	0.1 mH

Table 2. Network operating parameters

Network Initial Operating Parameters	Value
V_{10}	1196 V
I_{10}	80 A
V_{20}	1196 V
I_{20}	80 A
m_{p1}, m_{p2}	5e-5
K_{i1}, K_{i2}	120,120
K_{p1}, K_{p2}	30,30

Total state space equations is derived and shown in (19-21). Microgrid eigenvalues is evaluated and is shown in Figure 4.

$$x^T = [\Delta P_1,\ \Delta P_2,\ \Delta\varphi_1,\ \Delta\varphi_2, \Delta V_1,\ \Delta V_2,\ \Delta V_3,\ \Delta I_1,\ \Delta I_2] \tag{19}$$

Operating point eigenvalues of system are shown in Figure 4. Systems poles all are in left part of s-plane. A number of poles are far away from imaginary axis and a negligible effect on system and power sharing stability.

$$\begin{aligned}
&A=[a_{ij}]\ ,\ a_{11}=-\omega_c-k_{P_1}m_{P_1}\omega_c V_{10}\ ,\ a_{13}=k_{i_1}\omega_c V_{10}\\
&a_{15}=\omega_c I_{10}-k_{P_1}\omega_c V_{10}\ ,\ a_{22}=-\omega_c-k_{P_2}m_{P_2}\omega_c V_{20}\\
&a_{24}=k_{i_2}\omega_c V_{20}\ ,\ a_{26}=\omega_c I_{20}-k_{P_2}\omega_c V_{20}\\
&a_{31}=-m_{P_1}\ ,\ a_{35}=-m_{P_1}\ ,\ a_{42}=-m_{P_2}\ ,\ a_{46}=-1\\
&a_{51}=-k_{P_1}m_{P_1}/C_1\ ,\ a_{53}=k_{i_1}/C_1\ ,\ a_{55}=-k_{P_1}/C_1\\
&a_{58}=-1/C_1\ ,\ a_{62}=-k_{P_2}m_{P_2}/C_2\ ,\ a_{64}=k_{i_2}/C_2\\
&a_{51}=-k_{P_2}/C_2\ ,\ a_{69}=-1/C_2\ ,\ a_{79}=1/C_3\\
&L_T=l_1l_2+l_1l_3+l_2l_3\ ,\ a_{85}=(l_2+l_3)/L_T\\
&a_{86}=-l_3/L_T\ ,\ a_{87}=-(l_1+l_2+l_3)/L_T\\
&a_{88}=-(r_1l_1+r_1l_3+r_3l_2)/L_T\ ,\ a_{89}=-(r_3l_2+r_2l_3)/L_T\\
&a_{95}=-l_3/L_T\ ,\ a_{96}=(l_1+l_3)/L_T\ ,\ a_{89}=-(l_1+l_2+l_3)/L_T\\
&a_{89}=-(r_1l_3+r_3l_1)/L_T\ ,\ a_{99}=-(r_2l_1+r_2l_3+r_3l_1)/L_T
\end{aligned}\tag{20}$$

$$B^T=[0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ -\frac{1}{C_3}]\tag{21}$$

As seen from (20), changes in controller parameters, droops and system loading will affect A matrix that leads to a variation in location of system poles. Keep going, Controller parameters influence on system small signal stability is analyzed. For this purpose, only three most-right-positioned poles are studied to observe any possible instability in case of parameter variation.

Proportional gain of inverter 1 is increased from value. Location of poles changes according to Figure 5. As the proportional gain increases, Poles move to right hand of s-plane, tending to instability. So, it is important and vital that PI controller gains is shall tuned appropriately.

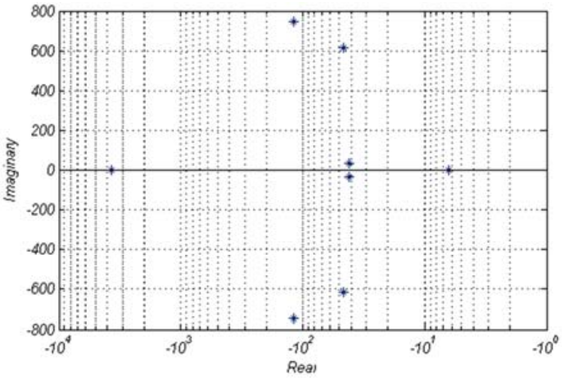

Figure 4. Poles of DC microgrid

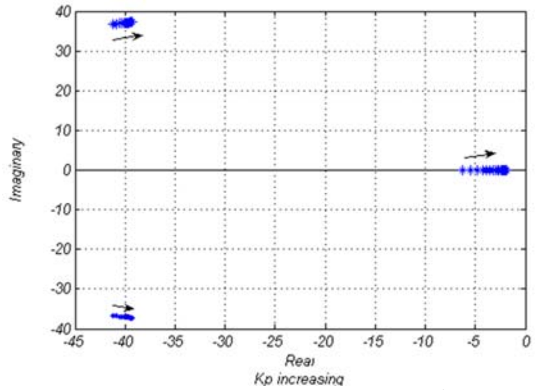

Figure 5. Poles trajectory under variation of K_p

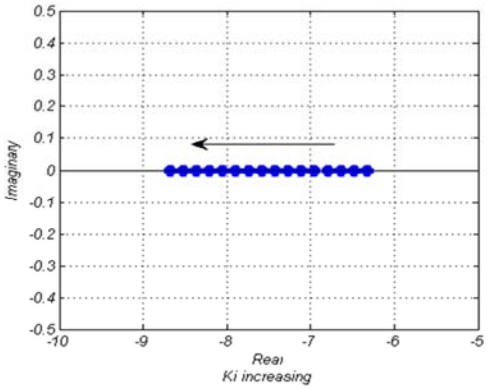

Figure 6. Pole trajectory under K_i variations

In Figure 6 as the Integrator gain of controller is also increased in same manner. Increasing K_i has a negligible effect on second and third poles. So, first pole trajectory is plotted during increase of K_i. Only first pole trajectory is quiet sensitive to integrator coefficient. Increasing of K_i, pushes the pole away from right hand and cause more stability and damping. Output power of each inverter unit is regulated by droop parameter. As we can see in Figures 5 and 6 that controller parameter values have great influence not only on its voltage controller, but also on power sharing. Voltage controller adjusts voltage in order to inject specified power by droop. So the PI parameters controllers are sensitive to keep the voltage terminal of each unit to constant voltage and these parameters are also important to keep stability of system.

IV. CONCLUSIONS

Based on the discussion in section III, Microgrid stability and suitable power sharing should be preserved during all operation conditions. Microgrid stability is analyzed by state space equations. A state space model of DC microgrid is extracted in this paper to investigate its stability. It is demonstrated that system poles location depends on droops, controller parameters and system loading level. Different values set on controller parameters to observe its effect on system poles. Results show that K_i has trends system toward stability while K_p pushes the system to unstable region of operation. It is seen that in a microgrid appropriate tuning of controller parameters is essential to avoid any potential instability.

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