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Stability Analysis of Parallel-Inverters in Microgrid

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***Abstract*—Renewable Energy is one of the fastest growing technologies. Renewable energy sources such as PV, wind and fuel cells are usually connected through voltage-source inverters to form a Microgrid. In order to share the same loads these inverters are connected in parallel. With the advances in network technology the control signals of the parallel inverters are exchanged through shared network. The time delay and the data loss may destabilize the system. In order to stabilize the parallel inverters a stability analysis should be carried out without considering the time delay. In this paper the stability of three-phase parallel inverters is analyzed to indentify the most effective control parameters on the system stability. The stability analysis in this study can be used as a guide for designing the controller in the case of time delay between the inverters controllers.**

Keywords; parallel inverter; stability; microgrid; space vector pulse width modulation

I. INTRODUCTION

The ever growing increased energy demands and the negative environmental effects of fossil fuel made the renewable energy resources one of the most viable alternatives for the large centralized fossil-fueled power plants. Recently distributed energy sources, such as fuel cells, wind turbines and photovoltaic cells are increasingly being used. Most of the renewable energy sources are usually equipped with DC/AC inverters which forms a parallel inverters system that can be connected to the grid. This configuration is known as Microgrid [1]. A Microgrid can be defined as a cluster of microsources, storage systems and loads which may be isolated (stand-alone) or connected to the grid as a single entity as shown in Fig 1. The Microgrid technology is proved to be one of the promising solutions that can cope with the increased energy demands and the negative environmental effects of fossil-fueled power plants. Distributed power sources in Microgrid must operate in parallel in order to share the load. Among renewable energy sources in Microgrid, wind and photovoltaic (PV) are smaller and more scalable. They are especially suitable to be integrated in Microgrid. Integrating many energy sources makes the control of Microgrids very challenging and an active research area.

There are many reviews on the control strategies in Inverter-based Microgrids. The role of the controller in parallel inverters in the Microgrid is to have good current sharing while maintain the system stability. Also the controller must achieve synchronization, and to guarantee that the frequency and the voltage are within the allowed limits. The control strategies can be classified into centralized, master-slave and decentralized control strategies [2]. In the centralized control strategy, all the information is sent to a centralized controller and then the commands are sent back to the system. In this control strategy all the inverters work as current sources and the voltage is controlled in the central controller. The main advantage is that the current sharing is forced at all times even during transient, and different power rating inverters can be connected without changing the control structure [2]. Also the system maintenance can be carried out easily. The main disadvantage of this strategy is the single point of failure and the need for sending the reference voltage to all the inverters in the network, which requires high bandwidth communication link. Additionally the system is sensitive to nonlinear loads [2].

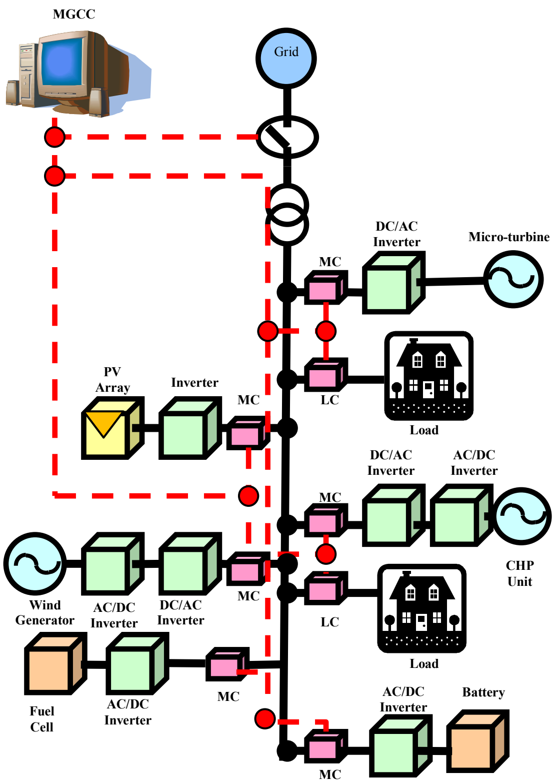

Figure 1. Inverter-Based Microgrid

The decentralized control is used to solve the problems associated with the controllers interactions. The decentralized controller relies only on local information and there is no need to send the information to a central controller. This technique usually used when the distance between parallel inverters is long, and it can be applied in islanded mode or grid-connection mode. One of the most widely used decentralized control is the Droop control [3]. The main idea is to regulate the voltage and the frequency by regulating the reactive and the active power respectively which can be sensed locally. The Droop control method has many desirable features such as expandability, modularity, redundancy, and flexibility. There are as well some drawbacks such as, slow transient response and possibility of circulating current. As the interconnections are neglected the overall system stability cannot be guaranteed.

The master slave control strategy is classified as a quasi-decentralized control which can be a compromise between the centralized and the decentralized control strategy. In the master-slave control strategy, one of the converters is known to be the master while the others are the slaves, the master controller contains the voltage controller while the slaves contain the current controllers and have to track the master's reference current [4]. Master/Slave control method gives a good load sharing and synchronization.

In the distributed control strategy the rotational reference frame (*dq₀*) is used instead of the stationary reference frame (*abc*). It can be used only in balanced systems. The voltage controller controls the output voltage by setting the average current demands [2]. In current/power sharing control method the average unit current can be determined by measuring the total load current and then divide this current by the number of units in the system. There are excellent features of the current/power sharing, the load sharing is forced during transient and the circulating currents are reduced. Additionally, lower-bandwidth communication link is needed.

With the advances in network technology, the Ethernet, industrial Ethernet and even Internet can be used for control signals exchange. These networks induces time delay which has strong effect on the system stability. Control strategies can then also be classified based on communication exchange between the controllers. Hence the control strategies are divided into communication based or communication-less. Many researchers reported master-slave and distributed control strategies that rely on shared-network for control signals exchange [5, 6 and 7]. When the control loop is closed through communication network, time delay and data loss are unavoidable which can lead to system instability. In order to achieve system stability, a stability analysis should be carried out. The distributed control strategy is adopted in this paper because it requires lower bandwidth network. In the next sections the mathematical model of parallel inverters with space-vector pulse modulation is briefly described. Then the distributed control strategy is explained. A simulation using Matlab/Sympower toolbox is carried out to identify the most effective control parameters on the system stability.

II. Mathematical Model of Parallel Inverters

The typical circuit of two parallel three-phase voltage source inverters with different DC sources is shown in Fig. 2

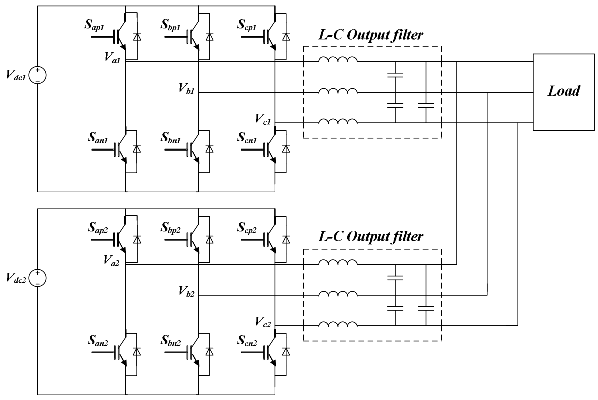

Figure 2. A Two Parallel inverters

The average model of the phase leg is derived based on the switching averaging. After transformation of the variables in the stationary coordinates $\mathrm{X_{abc}}$ into the rotating coordinates $\mathrm{X_{dqz}}$, the average model can be simplified [8, 9 and 10] based on $\mathrm{i_z = i_{z1} = -i_{z2} \approx 0}$:

$$\frac{d}{dt}\begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} = \frac{1}{L_1}\begin{bmatrix} d_{d1} \\ d_{q1} \end{bmatrix} V_{dc1} - \frac{1}{L_1}\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \cdot \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} \ldots (1)$$

$$\frac{d}{dt}\begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} = \frac{1}{L_2}\begin{bmatrix} d_{d2} \\ d_{q2} \end{bmatrix} V_{dc2} - \frac{1}{L_2}\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \cdot \begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} \ldots (2)$$

$$\frac{d}{dt}\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{1}{2C}\begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + \frac{1}{2C}\begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} - \frac{1}{RC}\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \cdot \begin{bmatrix} v_d \\ v_q \end{bmatrix} \ldots (3)$$

Assuming that the input DC power sources are ideal:

$$\frac{d}{dt}\begin{bmatrix} \tilde{i}_{d1} \\ \tilde{i}_{q1} \end{bmatrix} = \frac{1}{L_1}\begin{bmatrix} \tilde{d}_{d1} \\ \tilde{d}_{q1} \end{bmatrix} V_{dc1} - \frac{1}{L_1}\begin{bmatrix} \tilde{v}_d \\ \tilde{v}_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_{d1} \\ \tilde{i}_{q1} \end{bmatrix} \ldots (4)$$

$$\frac{d}{dt}\begin{bmatrix} \tilde{i}_{d2} \\ \tilde{i}_{q2} \end{bmatrix} = \frac{1}{L_1}\begin{bmatrix} \tilde{d}_{d2} \\ \tilde{d}_{q2} \end{bmatrix} V_{dc2} - \frac{1}{L_1}\begin{bmatrix} \tilde{v}_d \\ \tilde{v}_q \end{bmatrix} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_{d2} \\ \tilde{i}_{q2} \end{bmatrix} \ldots (5)$$

$$\frac{d}{dt}\begin{bmatrix} \tilde{v}_d \\ \tilde{v}_q \end{bmatrix} = \frac{1}{2C}\left(\begin{bmatrix} \tilde{i}_{d1} \\ \tilde{i}_{q1} \end{bmatrix} + \begin{bmatrix} \tilde{i}_{d2} \\ \tilde{i}_{q2} \end{bmatrix}\right) - \begin{bmatrix} \frac{1}{RC} & -\omega \\ \omega & \frac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} \tilde{v}_d \\ \tilde{v}_q \end{bmatrix} \ldots (6)$$

Writing (4), (5) and (6) in general matrix form:

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A}\tilde{\mathbf{x}} + \mathbf{B}\tilde{\mathbf{u}} \ldots (7)$$

$$\tilde{\mathbf{y}} = \mathbf{C}\tilde{\mathbf{x}} \ldots (8)$$

Where, the state vector is $\tilde{\mathbf{x}} = [\tilde{v}_d \tilde{v}_q \tilde{\imath}_{d1} \tilde{\imath}_{q1} \tilde{\imath}_{d2}\, \tilde{\imath}_{q2}]^T$ and the control variables are $\tilde{\mathbf{u}} = [\tilde{d}_{d1} \tilde{d}_{q1} \tilde{d}_{d2} \tilde{d}_{q2}]^T$ and $\mathbf{C} = \mathbf{I}$. The matrices $\mathbf{A}$, $\mathbf{B}$ are given as:

$$\mathbf{A} = \begin{bmatrix} \frac{-1}{RC} & \omega & \frac{1}{2C} & 0 & \frac{1}{2C} & 0 \\ -\omega & \frac{-1}{RC} & 0 & \frac{1}{2C} & 0 & \frac{1}{2C} \\ \frac{-1}{L_1} & 0 & 0 & \omega & 0 & 0 \\ 0 & \frac{-1}{L_1} & -\omega & 0 & 0 & 0 \\ \frac{-1}{L_2} & 0 & 0 & 0 & 0 & \omega \\ 0 & \frac{-1}{L_2} & 0 & 0 & -\omega & 0 \end{bmatrix} \ldots.(9)$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{V_{dc1}}{L_1} & 0 & 0 & 0 \\ 0 & \frac{V_{dc1}}{L_1} & 0 & 0 \\ 0 & 0 & \frac{V_{dc2}}{L_2} & 0 \\ 0 & 0 & 0 & \frac{V_{dc2}}{L_2} \end{bmatrix} \ldots.(10)$$

III. CONTROL STRATEGY

The distributed control strategy is used where the first and the second inverters have two control loops. The inner control loops independently regulate the inverter output current in the rotating reference frame, i_d and iq.The outer loops in the voltage control mode are used to produce the d-q axis current references for the inner loops by regulating the voltage at given reference values as shown in Fig 3. In power control mode, the outer loops are used to regulate the active and the reactive power at given operating point and provide the current references, $i_{d\text{-}ref}$ and $i_{q\text{-}ref}$, (Fig 4) in the rotating reference frame for the inner loops [9] and [10].

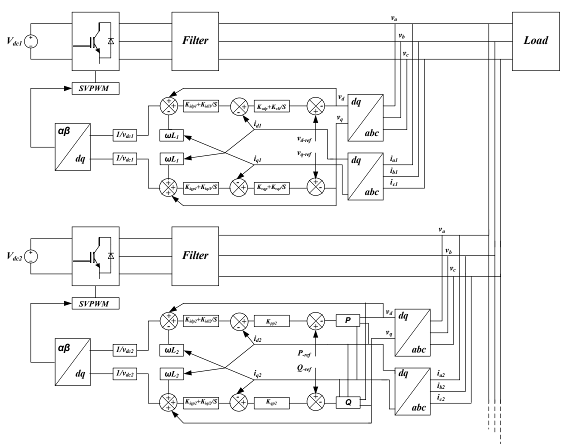

Figure 3. Closed-loop control of two Parallel Inverters

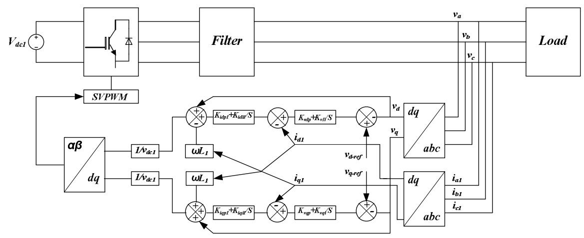

Figure 4. The first inverter with voltage and current control loops.

The Space Victor Pulse Width Modulation (SVPWM) [9] [10] is used to derive the six pulses. A proportional-Integral (PI) control scheme is used in both the voltage and the control loops, the duty cycles signals are given as:

$$\tilde{d}_{d1}.V_{dc1} = \left(K_{idp1} + \frac{K_{idi1}}{s}\right)\left(\tilde{\imath}_{d1-ref} - \tilde{\imath}_{d1}\right) - \omega L_1 \tilde{\imath}_{q1} + \tilde{v}_d \ldots(11)$$

$$\tilde{d}_{q1}.V_{dc1} = \left(K_{iqp1} + \frac{K_{iqi1}}{s}\right)\left(\tilde{\imath}_{q1-ref} - \tilde{\imath}_{q1}\right) + \omega L_1 \tilde{\imath}_{d1} + \tilde{v}_q \ldots(12)$$

The voltage control loop regulates the voltage and generates the d-q axis current references for the current loop.Therefore the output of outer voltage controller is input of inner control loop, a proportional-integral (PI) controller is also used in the current control loop. Then:

$$\tilde{\imath}_{d1-ref} = \left(K_{vdp} + \frac{K_{vdi}}{s}\right)\left(\tilde{v}_{d-ref} - \tilde{v}_d\right) \ldots(13)$$

$$\tilde{\imath}_{q1-ref} = \left(K_{vqp} + \frac{K_{vqi}}{s}\right)\left(\tilde{v}_{q-ref} - \tilde{v}_q\right) \ldots(14)$$

The second inverter operates in the power control mode. Where the instantaneous values of inverter output current components $i_{d\text{-}ref}$ and $i_{q\text{-}ref}$ are used to control the output active and reactive power respectively as shown in Fig 5.

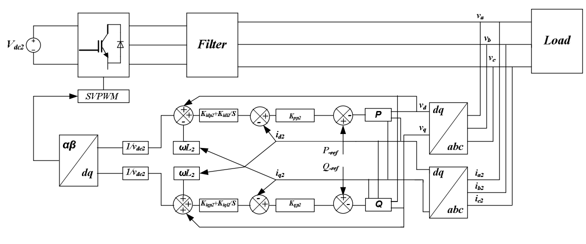

Figure 5. The control of the second inverter

The duty-cycle signals for the second inverter are given as:

$$\tilde{d}_{d2}.V_{dc2} = (K_{idp2} + \frac{K_{idi2}}{s})(\tilde{\imath}_{d2-ref} - \tilde{\imath}_{d2)} - \omega L_2 \tilde{\imath}_{q2} + \tilde{v}_d \ldots(15)$$

$$\tilde{d}_{q2}.V_{dc2} = (K_{iqp2} + \frac{K_{iqi2}}{s})(\tilde{\imath}_{q2-ref} - \tilde{\imath}_{q2)} + \omega L_2 \tilde{\imath}_{d2} + \tilde{v}_q \ldots (16)$$

In the power control mode the active and the reactive power are controlled at given set points by the outer loops to produce the d-q axis current references for inner loops [9], [10].Where:

$$P = \frac{3}{2}\left(V_d i_{d2} + V_d i_{q2}\right) \ldots (17)$$

$$Q = \frac{3}{2}\left(V_q i_{d2} - V_d i_{q2}\right) \ldots (18)$$

The outputs of these outer controllers are inputs of inner control loops. A proportional (P) controller is used. Then:

$$\tilde{\imath}_{d2-ref} = \left(K_{Pp2}\right)\left(P_{ref} - P_2\right) \ldots (19)$$

$$\tilde{\imath}_{q2-ref} = \left(K_{Qp2}\right)\left(Q_{ref} - Q_2\right) \ldots (20)$$

In order to write the closed loop equation in matrix form new control variables are introduced into (11)-(16). Then the new duty cycle signals can be expressed as:

$$\tilde{d}_{d1} = \frac{1}{V_{dc1}}[(1 - K_{idp1}K_{vdp})\tilde{v}_d - K_{idp1}\tilde{\imath}_{d1} - \omega L_1 \tilde{\imath}_{q1} + K_{idp1}K_{vdi}\tilde{\emptyset}_{d1} + K_{idi1}\tilde{\gamma}_{d1} + K_{idp1}K_{vdp}\tilde{v}_{d-ref}] \ldots (21)$$

$$\tilde{d}_{q1} = \frac{1}{V_{dc1}}[(1 - K_{iqp1}K_{vqp})\tilde{v}_q + \omega L_1 i_{d1} - K_{iqp1} i_{q1} + K_{iqp1}K_{vqi}\tilde{\emptyset}_{q1} + K_{iqi1}\tilde{\gamma}_{q1} + K_{iqp1}K_{vqp}\tilde{v}_{q-ref}] \ldots (22)$$

$$\tilde{d}_{d2} = \frac{1}{V_{dc2}}[\left(1 - \frac{3}{2}K_{idp2}K_{pp2}I_{d2}\right)\tilde{v}_d - \frac{3}{2}K_{idp2}K_{pp2}I_{q2}\tilde{v}_q - \left(\frac{3}{2}K_{idp2}K_{pp2}V_d + K_{idp2}\right)\tilde{\imath}_{d2} - \left(\frac{3}{2}K_{idp2}K_{pp2}V_q + \omega L_2\right)\tilde{\imath}_{q2} + K_{idi2}\tilde{\gamma}_{d2} + K_{idp2}K_{pp2}\tilde{P}_{ref}] \ldots (23)$$

$$\tilde{d}_{q2} = \frac{1}{V_{dc2}}[\frac{3}{2}K_{iqp2}K_{Qp2}I_{q2}\tilde{v}_d + \left(1 - \frac{3}{2}K_{iqp2}K_{Qp2}I_{d2}\right)\tilde{v}_q + \left(\omega L_2 - \frac{3}{2}K_{iqp2}K_{Qp2}V_q\right)\tilde{\imath}_{d2} + \left(\frac{3}{2}K_{iqp2}K_{Qp2}V_d - K_{iqp2}\right)\tilde{\imath}_{q2} + K_{iqi2}\tilde{\gamma}_{q2} + K_{iqp2}K_{Qp2}\tilde{\emptyset}_{ref}]..(24)$$

The system state equation is then:

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A}\tilde{\mathbf{x}} + \mathbf{B}\tilde{\mathbf{u}} \ldots (25)$$

The control output can be expressed as:

$$\tilde{\mathbf{u}} = \mathbf{H_1}(\tilde{\mathbf{z}}) + \mathbf{J}(\tilde{v}_d\tilde{v}_q\tilde{P}\tilde{Q})_{ref} \ldots (26)$$

Where$\tilde{\mathbf{u}} = [\tilde{d}_{d1}\tilde{d}_{q1}\tilde{d}_{d2}\tilde{d}_{q2}]^T$;
$\tilde{\mathbf{z}}$=$[\tilde{v}_d\tilde{v}_q\tilde{\imath}_{d1}\tilde{\imath}_{q1}\tilde{\imath}_{d2}\tilde{\imath}_{q2}\tilde{\emptyset}_{d1}\tilde{\emptyset}_{q1}\tilde{\gamma}_{d1}\tilde{\gamma}_{q1}\tilde{\gamma}_{d2}\tilde{\gamma}_{q2}]$

Substituting the control laws in the state equation and writing the equations in the s-domain:

$$\frac{\mathbf{z}(s)}{\mathbf{R}(s)} = (s\mathbf{I} - \mathbf{A}_1 - \mathbf{B}_1\mathbf{H}_1)^{-1}.\mathbf{B}_2 \ldots (27)$$

Where:$R(s) = [(\tilde{v}_d\tilde{v}_q\tilde{P}\tilde{Q})_{ref}](S)$

$\mathbf{A}_1$ and $\mathbf{B}_1$ are state and input matrixes of closed loop system.

IV. Stability Analysis

To determine the control parameters that affect the stability of the parallel inverters a simulation using MATLAB/SIMULINK has been carried out. Additionally an eigenvalue analysis based on the linearized model is linked to the simulation results. The parallel inverters parameters are as follows: the capacitance and the inductance of the filters are 22µF and 4mH respectively. The load resistance *R* equals 4.25 Ohm. Initially the active and reactive power of the second inverter are 10 KW and 2 KVAR respectively and reduced to half of their values after 0.35 seconds. The frequency reference is set to be 50 Hz.

Fig 6 shows the output three phase voltages of the parallel inverters maintained at 170V peak value. The active and the reactive power of the second inverter are shown in Fig 7. Output currents of the first inverter and the second inverter are shown in Fig 8 and 9 respectively. This shows that the first inverter with voltage control mode and the second inverter with power control mode have very good power sharing between the inverters.

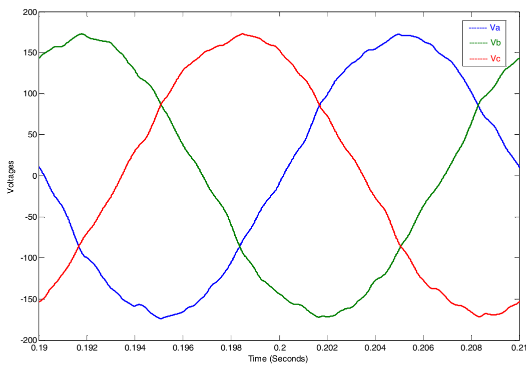

Figure 6 The three-phase output voltages

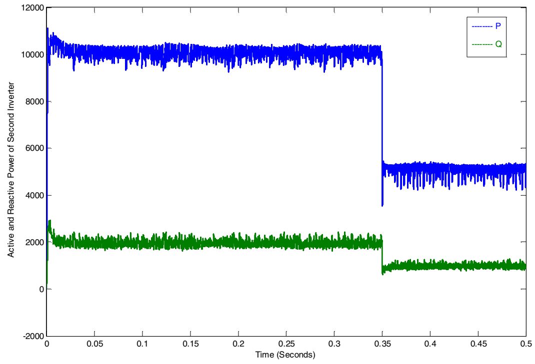

Figure 7 The active and reactive power of the second inverter

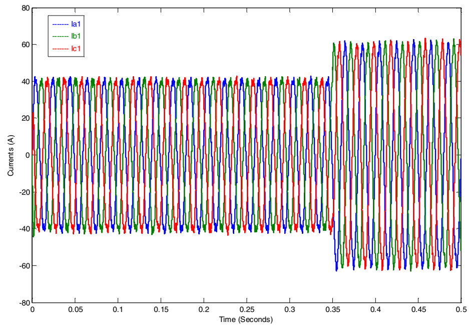

Figure 8 The output currents of the first inverter

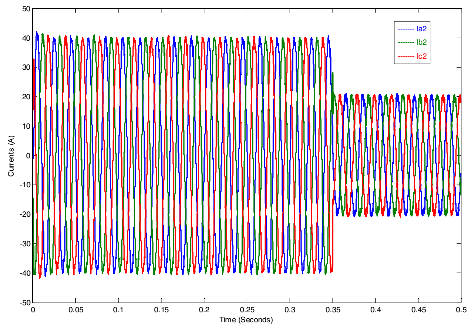

Figure 9 The output currents of the second inverter

In order to find the most important system and controller parameters that effect the stability of the system, a stability analysis must be carried out. The parameters are the capacitance and the inductance of the filter, the proportional and the integral gains of the voltage and current loops. Clearly, when the proportional gain in the PI controller of Ki_{dp1} equals 1 the system is more stable than when Ki_{dp1} equals 0.01. The system oscillation increases when $Ki_{dp1}$is increased further which is clear in Fig 10. The effect of the PI controller gain Ki_{dp2} is then tested. The Active and reactive power of the second inverter are shown in Figs 11 and 12. The impact of the inductance on the stability of the system is shown in Figs 13-16. From the simulation results, the system has large oscillation when the inductance is 0.63 mH. Increasing the inductance reduces the stability of the system dramatically.

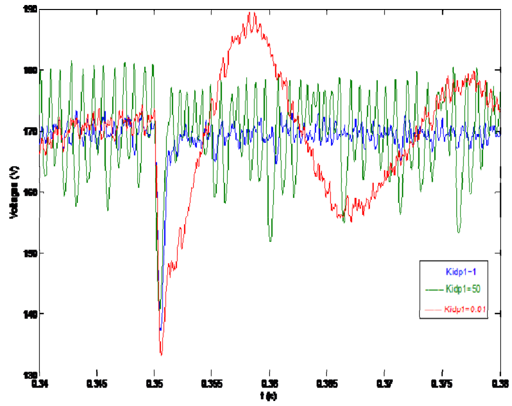

Figure 10. The voltage response (V_d) with different values of Ki_{dp1}

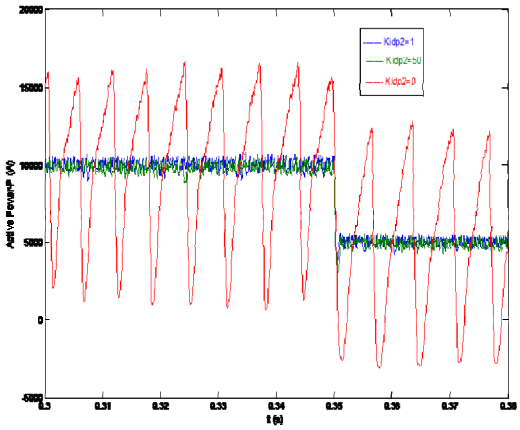

Figure 11. The active power with different values of Ki_{dp2}

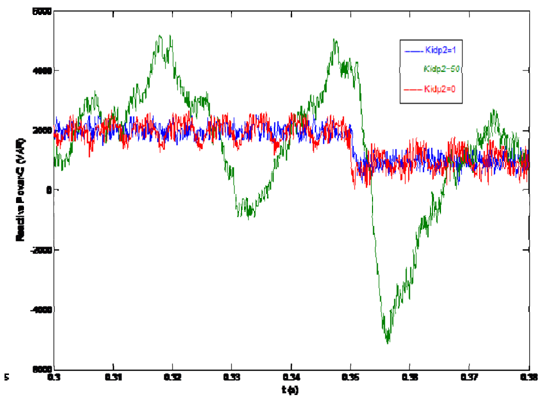

Figure 12. The reactive power with different values of Ki_{dp2}

Simulations show that the load sharing is forced even with different DC sources. The sharing between the inverters is good even during the transient. In addition to the simulation results, eigenvalue analysis has been carried out and it shows good agreement between the simulation results with the nonlinear models with the linearized models used in the eigenvalues analysis. The distributed control strategy is suitable for networked control system applications. The work in this paper is extended to deal with stability analysis with time delay and data loss [11].

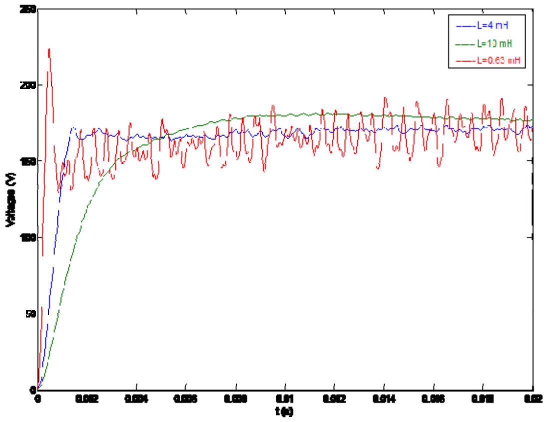

Figure 13. The voltage (V_d) with different values of *L*

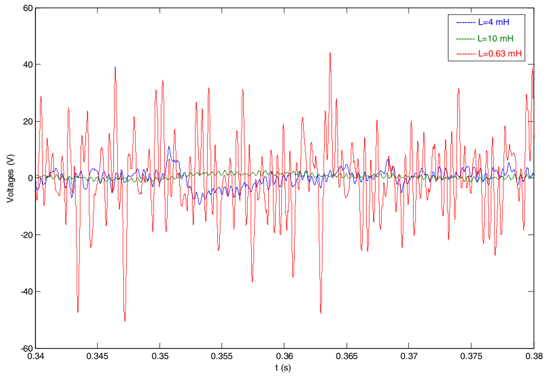

Figure 14. The voltage (V_q) with different values of L

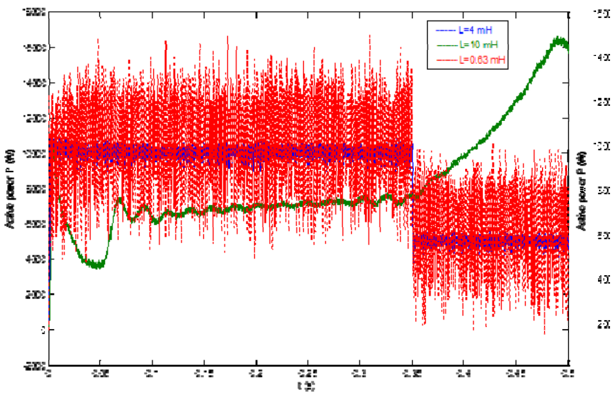

Figure 15. The active power with different values of *L*

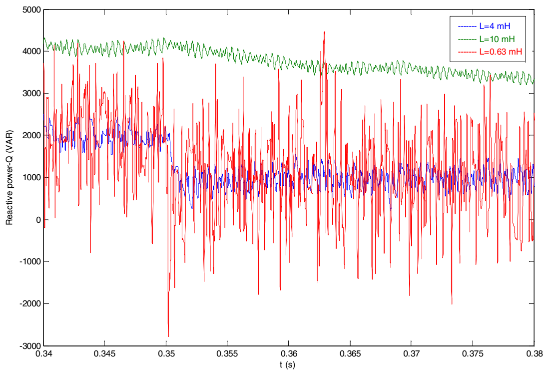

Figure 16. The reactive power with different values of *L*

V. Conclusion

In this paper the stability analysis of parallel inverter system implementing distributed control strategy is carried out. The small-signal model of voltage source inverter connected in parallel has been derived and used in the eigenvalue analysis. Simulation study and eigenvalue analysis is used to define the most important system and control parameters for the stability of the system. The inductance, the proportional gains in the PI current controller Ki_{dp1} and Ki_{dp2} have the greatest impact on the system stability. This is extremely important to help designers to improve the performance of the system by choosing the control and filters parameters which achieve the best response of the system.

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