Majumder, Ritwik and Ghosh, Arindam and Ledwich, Gerard and Zare, Firuz (2009) ***Power sharing and stability enhancement of an autonomous microgrid with inertial and non-inertial DGs with DSTATCOM***. In: Proceedings of the 3rd International Conference on Power Systems, 27-29 December 2009, Indian Institute of Technology, Kharagpur, India.

2009 Third International Conference on Power Systems, Kharagpur, INDIA December 27-29

Power Sharing and Stability Enhancement of an Autonomous Microgrid with Inertial and Non-inertial DGs with DSTATCOM

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Abstract—**This paper proposes a method of enhancing system stability with a distribution static compensator (DSTATCOM) in an autonomous microgrid with multiple distributed generators (DG). It is assumed that there are both inertial and non-inertial DGs connected to the microgrid. The inertial DG can be a synchronous machine of smaller rating while inertia less DGs (solar) are assumed as DC sources. The inertia less DGs are connected through Voltage Source Converter (VSC) to the microgrid. The VSCs are controlled by either state feedback or current feedback mode to achieve desired voltage-current or power outputs respectively. The power sharing among the DGs is achieved by drooping voltage angle. Once the reference for the output voltage magnitude and angle is calculated from the droop, state feedback controllers are used to track the reference. The angle reference for the synchronous machine is compared with the output voltage angle of the machine and the error is fed to a PI controller. The controller output is used to set the power reference of the synchronous machine. The rate of change in the angle in a synchronous machine is restricted by the machine inertia and to mimic this nature, the rate of change in the VSCs angles are restricted by a derivative feedback in the droop control. The connected distribution static compensator (DSTATCOM) provides ride through capability during power imbalance in the microgrid, especially when the stored energy of the inertial DG is not sufficient to maintain stability. The inclusion of the DSATCOM in such cases ensures the system stability. The efficacies of the controllers are established through extensive simulation studies using PSCAD.**

Keywords- Microgrid, Power sharing, Angle Droop, Stability, DSTATCOM

I. INTRODUCTION

THE INTERCONNECTIONS of different distributed generators (DGs) to an autonomous microgrid raise concern of system stability. The connected DGs can be synchronous machines or VSC interfaced solar cells. The combination of inertial and inertia-less DGs make the power sharing difficult in a microgrid. In case of VSC connected DGs, the real and reactive power sharing can be achieved by controlling two independent quantities – the system frequency and the fundamental voltage magnitude [1-2]. The power output from a VSC connected DG can be changed instantaneously by changing the output voltage angle. For a synchronous machine, the change in power output is not instantaneous. The inertia of the generator can provide the ride through during transients, but when most of the DG connected to the microgrid are VSC interfaced, and lack of system inertia leads the system to instability. This becomes critical if the power generation by some of the DGs suddenly reduces, e.g., when suddenly cloud covers photovoltaic cells. This paper addresses this issue along with proper load sharing during nominal operation.

Application of DSTATCOM in distribution systems has also gained considerable attention [3, 4]. In this paper droop control is used and output voltage magnitude and angle is controlled to deliver desired real and reactive power to the system by the DGs through parallel connected converters [5].

In order to avoid conflicting power demand amongst the inertial and non-inertial DGs that may result in large oscillations, the power output of the VSC based DG sources are controlled through a derivative component in the droop control. It is shown in this paper that a much larger inertial DG (synchronous machine) is capable of supplying the power shortfall for few cycles from its stored energy in the rotating mass, thereby allowing the much needed time to shed load. When the total capacity of the inertial DGs is comparable with the non-inertial DGs, an energy storage device has to be used. In this paper, a DSTATCOM is connected to the microgrid to provide voltage support. It is well known that a DSTATCOM can provide reactive power support in normal operation. However, it can release the energy stored in it dc capacitor during transients to provide enough ride through to facilitate load shedding [6].

The contribution lies in enabling proper power sharing with angle droop controller in presence of both inertial and non inertial DGs in a microgrid. The effect of sudden power loss is investigated with and without the DSTATCOM connection.

II. MICROGRID STRUCTURE

The structure of the microgrid system studied in this paper is shown in Fig. 1. It contains 3 DGs, two are inertia less and

VSC-interfaced, while one is a synchronous machine. The load and a DSTATCOM are also connected as shown. The feeder impedances are denoted by Z_{ij}, where ij indicates the buses between which these are placed. The DG output voltages are denoted by $E_i\angle\delta_i$, $i = 1, \ldots, 3$. Each non inertial DG and the DSTATCOM are connected to the microgrid through external inductors as shown in Fig. 1. The system data used for the studies are given in Table-I.

TABLE-I: MICROGRID SYSTEM PARAMETERS

System Quantities	Values
Systems frequency	50 Hz
Feeder impedance $Z_{12} = Z_{23} = Z_{34} = Z_{45} = Z_{45} = Z_{56} = Z_{67} = Z_{78} = Z_{89}$	$1.03 + j\,4.71\ \Omega$
DGs and VSCs	
DC voltages (V_{dc1} to V_{dc4})	3.5 kV
Transformer rating	3 kV/11 kV, 0.5 MVA, 2.5%
VSC losses (R_f)	1.5 Ω
Filter capacitance (C_f)	50 μF
Hysteresis constant (h)	10^{-5}
DG ratings	
Case_1	
DG-1	200 kW
DG-2	800 kW
DG-3	266 kW
Case_2	
DG-1	200 kW
DG-2	400 kW
DG-3	266 kW
Output inductances Case_1	
L_{G1}	75 mH
L_{G3}	56.7 mH
Output inductances Case_2	
L_{G1}	75 mH
L_{G3}	56.7 mH

III. CONVERTER STRUCTURE AND CONTROL

The converter structure that is connected to DG-1 is shown in Fig. 2 (a). Here DG-1 is assumed to be an ideal dc voltage source supplying a voltage of V_{dc1} to the VSC. The converter contains three H-bridges. The outputs of the H-bridges are connected to three single-phase transformers that are connected in wye for required isolation and voltage boosting [7]. The resistance R_f represents the switching and transformer losses, while the inductance L_f represents the leakage reactance of the transformers. The filter capacitor C_f is connected to the output of the transformers to bypass switching harmonics, while L_{G1} represents the output inductance of the DG source. The converter structures of DG-3 and the DSTATCOM are the same. However, the DSTATCOM is supplied by a dc capacitor with a voltage of V_C. The VSC are controlled under closed-loop feedback. In this, $u\cdot V_{dc1}$ represents the converter output voltage, where u is the switching function that can take on values ± 1. The main aim of the converter control is to generate u. The state space description of the system can be given as

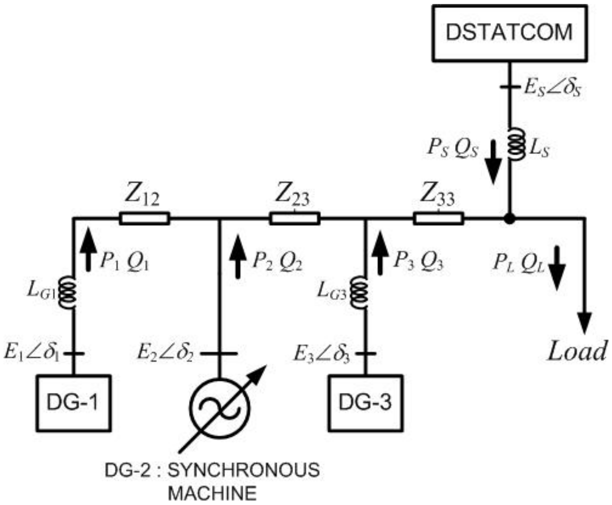

Fig. 1 .Structure of the microgrid system under consideration.

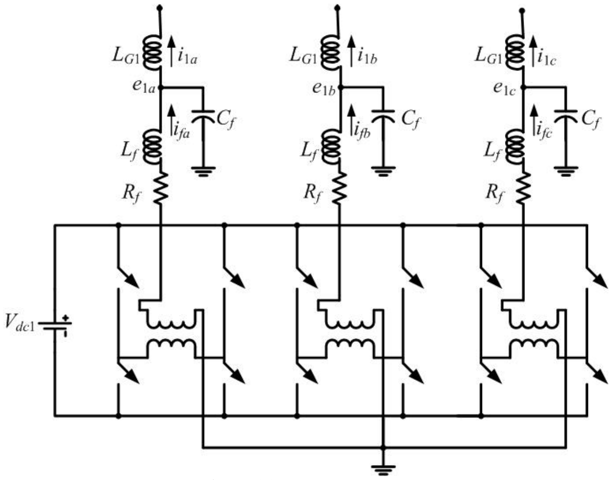

Fig. 2 (a) .Converter structure

$$\dot{x} = Ax + B_1 u_c + B_2 v_{PCC} \tag{1}$$

where u_c is the continuous time control input, based on which the switching function u is determined. The discrete-time equivalent of (1) is

$$x(k+1) = Fx(k) + G_1 u_c(k) + G_2 v_{PCC}(k) \tag{2}$$

Neglecting the PCC voltage v_{PCC} assuming it to be a disturbance input, the input-output relationship of the system in (2) can be written in the following two forms

$$\frac{v_{cf}(z)}{u_c(z)} = \frac{M_1(z^{-1})}{N_1(z^{-1})} \tag{3}$$

$$\frac{i_1(z)}{u_c(z)} = \frac{M_2\left(z^{-1}\right)}{N_2\left(z^{-1}\right)} \tag{4}$$

The feedback control laws of the converters are generated as discussed below.

A. Control of VSCs Connected to DGs

In the normal operating condition, the VSCs are controlled in state feedback. A state vector can be defined as

$$x^T = [v_{cf}\ i_{cf}\ i_1].$$

The state feedback control law is

$$u_c(k) = K\left[x^*(k) - x(k)\right] \tag{5}$$

where K is the feedback gain matrix and x^* is the reference state vector. In this paper, this gain matrix is designed using discrete-time linear quadratic regulator (DLQR) method.

When the power output of the DG suddenly reduces or the load demands more than the rated output power from the DG, it is switched to a sinusoidal current limiting mode. In this mode, the output current tracks a reference i_1^* using a pole placement method. The open-loop poles of (4) are shifted to get the closed-loop poles [8]. This results in the computation of the control input $u_c(k)$. How the references are set for either of the controller will be discussed in the next section.

B. Switching Control

Once the control $u_c(k)$ is computed using either the state feedback or output feedback control law, the switching function u is generated from hysteresis control as,

$$\begin{aligned} &\text{If } u_c > h \text{ then } u = +1 \\ &\text{elseif } u_c < -h \text{ then } u = -1 \end{aligned} \tag{6}$$

where h is a small number.

C. Control of DSTATCOM

Here the DSTATCOM is required to hold the magnitude of the output voltage E_s constant at E_s^* (see Fig. 1). Hence the DSTATCOM operates in voltage control mode output feedback pole placement method using (3) to compute $u_c(k)$ [8]. Once the magnitude reference E_s^* is chosen, the angle reference (δ_{sref}) for the output voltage is determined using the block diagram shown in Fig. 2 (b). First the measured capacitor voltage V_C is passed through a moving average filter with a window of one cycle (20 ms) to obtain V_{Cav}. This is then compared with the reference capacitor voltage V_{Cref}. The error is fed to a PI controller to generate the reference angle δ_{Sref}. The instantaneous reference voltages of the three phases are then derived from the pre-specified magnitude E_s^* and δ_{Sref}.

Once $u_c(k)$ is computed, the DSATCOM switching is generated in the same fashion as given in (6).

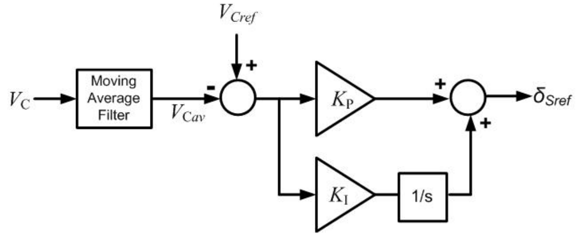

Fig. 2 (b). Angle controller for DSTATCOM.

IV. STRUCTURE AND CONTROL OF SYNCHRONOUS MACHINE

DG-2 is assumed to be an alternator that is connected to the PCC bus through the inductance L_{G2}. The generator field is supplied by a static exciter and automatic voltage regulator (AVR). A hydraulic turbine and governor is also assumed to be present in the system. The transfer function of the exciter-AVR is given by

$$\frac{e_{fd}}{err} = \frac{K_e}{sT_e + 1} \tag{7}$$

where e_{fd} is the field voltage and $err = V_{tref} - |V_2|$.

The reference for the rms value of generator terminal voltage is set from droop equation. Then the generator excitation reference V_{tref} is set as

$$V_{tref} = |V_2| + \frac{e_{fd}}{K_e} \tag{8}$$

The turbine governor model is shown in Fig. 3. This includes a proportional plus integral plus derivative (PID) controller. The input to the PID controller is

$$u_{pid} = \omega_{ref} - \omega_r + R_P\left\{\left(P_{2ref} - P_2\right)\overline{d}_{ref} - g_{opn} d_{ref}\right\} \tag{9}$$

where ω_r is the machine speed, ω_{ref} is the machine speed reference, g_{opn} is the gate opening, P_2 is the output power, P_{2ref} is output power reference and d_{ref} is a logical value, which is 1 when the system is steady state and is zero during the initial start up phase.

V. REFERENCE GENERATION FOR DG SOURCES

As mentioned in the previous section, the VSCs connected to the DGs are either controlled in state feedback or current feedback. The reference generation for these two different control modes is discussed in this section first. The power reference generation for the synchronous machine is also shown in this section.

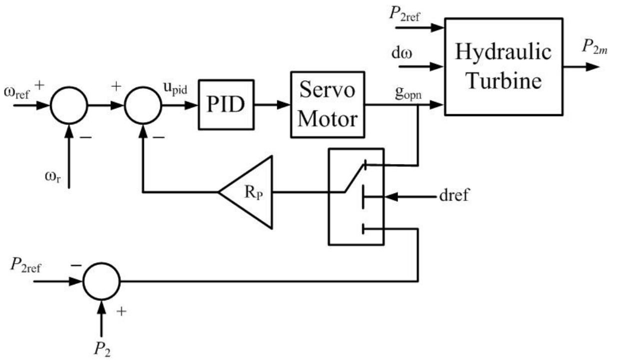

Fig. 3. Block diagram of the governor-turbine

A. Droop Control

The output voltages of the converters are controlled to share the load proportional to the rating of the DGs. Let us consider the i^{th} DG (i.e., DG-i). The droop equations are

$$\delta_i = \delta_{irated} - m_i \times \left(P_i - P_{irated}\right) \tag{10}$$

$$E_i = E_{irated} - n_i \times \left(Q_i - Q_{irated}\right) \tag{11}$$

where E_{irated} and δ_{irated} are the rated voltage magnitude and angle respectively of DG-i, when it is supplying the load to its rated power levels of P_{irated} and Q_{irated}. The coefficients m_i and n_i respectively indicate the voltage angle drop vis-à-vis the real power output and the magnitude drop vis-à-vis the reactive power output. The system stability with the angle droop can be further improved by using a derivative feedback of the angle for the VSC connected DGs. The rate of change in the output voltage angle of the synchronous machine is restricted by the machine inertia. To mimic this behavior with VSC interfaced DGs, a derivative feedback is added in the droop control (10) as

$$\delta_i = \delta_{irated} - m_i \times \left(P_i - P_{irated}\right) + K_{Di}\frac{dP_i}{dt} \tag{12}$$

This will ensure that a sudden change in the load demand will be picked by all the DGs at the same rate when a mixed set of DGs are present in the system. Note that the droop equation (12) are used for all non-inertial DGs, while (10) is used only for the synchronous alternator. The same voltage droop (11) is used for all the DGs.

B. State Feedback for VSC connected DGs

Once the reference phasor voltage $E_i\angle\delta_i$ is obtained from the droop equation, the reference phasor current I_{cf} can be obtained. Also from the measurement of the bus voltage and P_i and Q_i, the reference phasor current I_i can be calculated. The instantaneous quantities can be obtained from these phasor quantities.

C. Current Feedback for VSC connected DGs

As discussed in the previous section when the power output of the DG suddenly reduces or the load demands more than the rated output power from the DG, it is switched to a sinusoidal current limiting mode. In this mode, the droop is bypassed and the current is limited by the maximum rating of real and reactive power. Let the maximum available power rating of the DG-i be denoted by P_{imax} and Q_{imax}. Also note from Fig. 1 that the phasor bus voltage is denoted by $E_i\angle\delta_i$. Let the reference phasor injected current passing through the inductor L_{Gi} be denoted by $I_{Giref}\angle\beta_{ref}$. Then the maximum complex power that can be supplied by the DG is

$$\begin{aligned} P_{i\max} + jQ_{i\max} &= E_i\angle\delta_i\left(I_{Giref}\angle\beta_{ref}\right)^{*} \\ &= E_i I_{Giref}\angle\left(\delta_i - \beta_{ref}\right) \end{aligned} \tag{13}$$

where $*$ denotes the conjugate operation. From the above equation, the magnitude and the angle of the reference current can be calculated as

$$\begin{aligned} I_{Giref} &= \sqrt{P_{i\max}{}^2 + Q_{i\max}{}^2}\Big/E_i \\ \beta_{ref} &= \delta_i - \tan^{-1}\left(Q_{i\max}/P_{i\max}\right) \end{aligned} \tag{14}$$

The instantaneous quantities are then generated from these phasor quantities.

D. Power Reference Generation for Synchronous Machine

The desired voltage angle and magnitude reference for the synchronous machine is generated from the angle droop controller given by (10). The measured output voltage angle is compared with the angle reference and the error is passed through a PI controller to change the power reference of synchronous machine as shown in Fig.4.

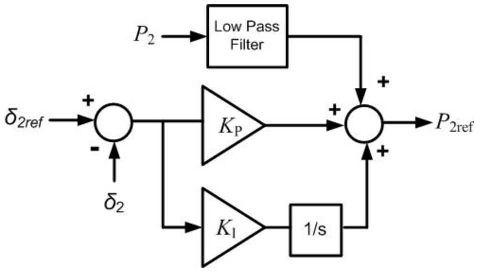

Fig. 4 . Power reference generation for the synchronous machine

VI. SIMULATION STUDIES

Simulation studies are carried out in PSCAD/EMTDC (version 4.2). DG-1 and DG-3 are considered as inertia-less dc sources supplied through the VSCs. The VSC data is shown in Table-I.

A. Case-1: When Synchronous Alternator has Larger Capacity than VSC Connected DGs

In this section the power sharing and system response is investigated in presents of a large inertial DG-2, which is assumed to have enough stored energy to provide ride through during power shortfall. This has the rated capacity that is 4 times that of DG-1 and 3 time that of DG-3. Here the DG-2 is represented by synchronous machine as described in section IV. The droop coefficients are chosen such that both active and reactive powers of the load are divided in a ratio of 1:4:1.33 among DG-1 to DG-3. The DSTATCOM shown in Fig. 1 is not connected in the system in this case.

Fig. 5 (a) shows the real power sharing in which the load demand changes at 1 s from 1.3 MW to 1.1 MW. It can be seen that the power supplied by each of the three DGs reduces proportionally in sympathy with the load change.

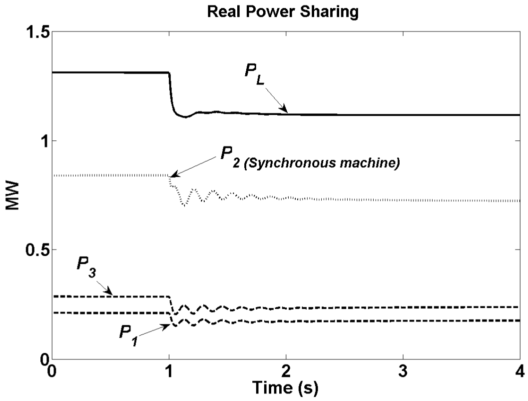

Fig. 5 (a). Power sharing of the DGs.

The output power of a VSC interfaced DG can be limited by switching the control mode from state feedback to current feedback as mentioned in Section V. Fig. 5 (b) shows the system response where power outputs of the synchronous machine and DG-3 are limited to 265 kW and 450 kW respectively at 1 s. It can be seen that the extra power requirement is supplied by DG-1. A load change at 4.5 s further changes the power requirement in the microgrid and the DG-1 power output automatically reduces to adjust that, while power output of the other two DGs remains constant as desired. With the power limit of the synchronous machine and DG-3 as in previous case, the power output of DG-1 is now limited to 500 kW at 4 s. This creates a marginal power imbalance in the microgrid. But the inertial DG (synchronous machine) can provide a ride through by supplying the power as shown in Fig.6 (a). The system becomes unstable at 6.2 s as the stored energy in the synchronous alternator dissipates. However, this allows a time of about 2.2 s, which will be enough for the protection system to shed a non-critical load. Fig. 6 (b) shows the system response where load is shed at 5 s to reduce the power demand. It can be seen that a stable operation of the system is achieved. The simulation results shown in Fig. 6 (a) and Fig. 6 (b) indicate that, a large inertial DG can provide a ride through in case of a marginal power imbalance in a microgrid. Protection unit should shed the load within this ride through time to achieve the power balance for stable operation of the system.

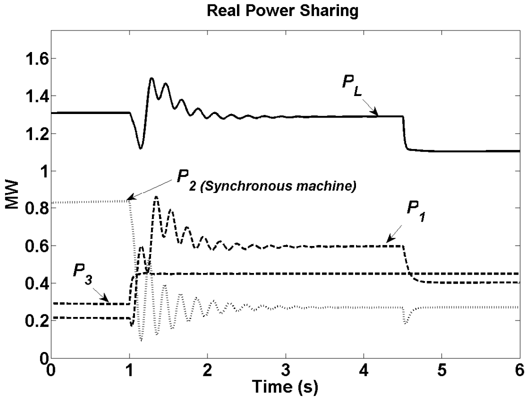

Fig. 5 (b). Power limit and power sharing of the DGs.

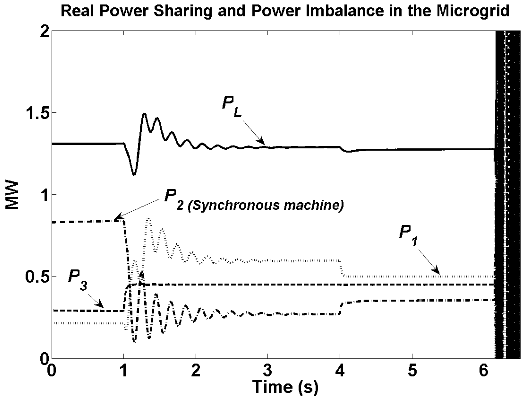

Fig. 6(a). Power limit and system instability

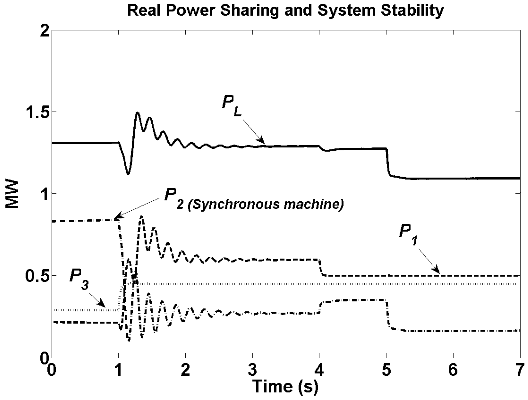

Fig. 6 (b). Power limit and system stability with load shedding

B. Case-2: When Inertial and Non-Inertial DGs are of Comparable Size

In the previous section, it is shown that a large inertial DG can provide a ride through in case of marginal power imbalance. When the size of the inertial DGs is comparable to the non inertial DGs, the ride through is not possible as the stored energy in the rotating machine is not enough to supply the power imbalance.

To investigate this, we have chosen the size of the synchronous alternator as half the rating of the one used in Case-1, while the size of the non inertial DGs remain the same. To accommodate this reduction in the size, the power is now shared by the DGs in the ratio 1:2:1.33. With the system is operating in steady state, the output power is limited at 4 s in a similar fashion as shown in Fig. 6 (a). The result is shown in Fig. 7. It can be seen that, the inertial DG is not capable of providing the ride through in this case and system becomes unstable within 2-3 cycle after power imbalance created at 4 s.

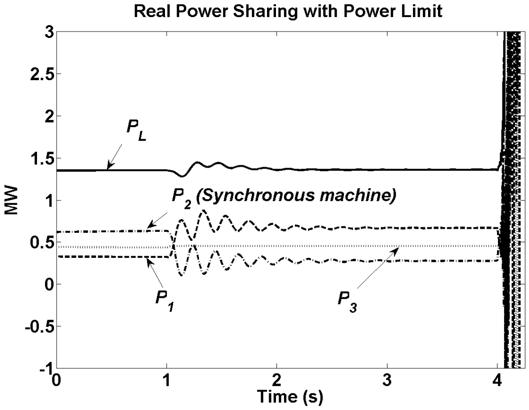

Fig. 7. Power limit and system instability

To investigate the fault ride through capability of the DSTATCOM, we repeat the above sequence of operation except that the load is not reduced after 4 s. The result is shown in Fig. 8 where a power shortfall of 20 kW is created. It can be seen that the DSTATCOM is able to provide the real power requirement and voltage support for some time. The DSTATCOM, in this case, can hold the PCC voltage for about 1 s. The system collapses thereafter since the dc voltage of the DSTATCOM collapses due to the persistent real power requirement by the load.

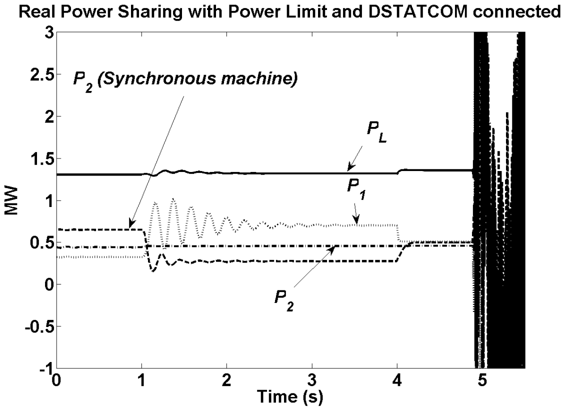

Fig.8. Ride Through capability of DSTATCOM

VII. CONCLUSIONS

In this paper, the co-ordination of inertial and inertia less DGs for load sharing is proposed and validated. It is shown that a large inertial DG can provide a ride through during the power shortfall in the microgrid. Otherwise a DSTATCOM needs to be connected to provide the much needed ride through during power imbalance in the microgrid. The size of the DSTSTCOM dc capacitor determines the time for which the DSTATCOM is able to hold the microgrid voltage during power shortfall. The choice of this capacitor is a trade-off between the ride through time and system response. A large number of case studies are provided to validate the efficacy of the droop control, as well as the operation of the DSTATCOM

ACKNOWLEDGEMENT

The authors thank the Australian Research Council (ARC) for the financial support for this project through the ARC Discovery Grant DP 0774092.

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