A Novel Controller for Inverters to Improve the Frequency Response of Micro Grid under Transient Conditions

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Abstract: The present scenario is towards shifting centralised power generation (central grid) to distributed generation (micro grid) with smaller sources of capacity. The isolated micro grid is connected to main grid with inverters at the front end for efficient exchange of power sharing; power exchange among distributed generation (DG) sources in an isolated micro grid is possible with droop characteristics as per their capacity. The stability and operation aspects of converter-dominated microgrids (MGs), however, are faced by many challenges. Important among these, are the absence of physical inertia, comparable size of power converters, mutual interactions among generators islanding detection delays and large sudden disturbances associated with transition to islanded mode, grid restoration, and load power changes. Sources in the MGs use droop control to share power according to their capacity without any form of communication. This paper proposes a novel controller for inverters in DG for improving transient frequency response of the micro grid under consideration of large disturbances with considerable frequency deviations to validate the effectiveness of the proposed P-F droop controller simulation is carried out on MATLAB Simulink platform.

Keywords: DG (Distributed Generator), MATLAB SIMULINK, Transient Frequency Responses, Droop Characteristics, P-F Control.

I. INTRODUCTION

Power sharing among different DGs in an isolated micro-grid is possible by employing droop control or by using some centralized communication. Traditionally active power-frequency (P-ω) and reactive power-voltage (Q–V) droop is implemented to control frequency and voltage in DGs having a power-electronic interface Inverters do not have a rotating mass and, hence, have low inertia. Higher penetration of inverter- based static sources in micro-grid may result in poor voltage and frequency response during large disturbances. If the issues are not addressed, this transient response problem may develop into a transient stability problem. Micro-grid transient stability depends on the DG technology and its control, its penetration level, type and location of fault, and nature of loads. The effect of high penetration of various DG technologies on transient stability of the system is studied. DGs based on synchronous machine reduce maximum frequency deviation at the expense of increasing oscillation duration (due to inertia), while inverter based DGs decrease rotor-angle deviations and improve voltage profile at the user end of the system on account of faster control and increased system damping, at the expense of increasing frequency deviations.

Transient response of the system can also be improved by using energy storage devices, such as ultra- capacitors and battery alongside DGs. However in a large power system with a greater number of DGs, disturbance location consideration can make the storage-based solution ineffective and costly. Disturbances in such a scenario can result in large frequency deviations exceeding frequency and df/dt threshold, resulting in the tripping of generation or unnecessary load shedding. The concept of adding inertia virtually to reduce frequency deviations in micro-grids by modifying inverter control has been reported in the literature as virtual synchronous generator virtual synchronous machine and synchronous converters. Increasing inertia virtually in the inverter results in a reduction in maximum rotor speed deviation of the nearby source. The concept of adding inertia virtually by modifying the control strategy of existing inverters rather than having a dedicated inertial source has not been reported so far. Reference analyses the interaction problem of inverter and diesel generator-based sources. Large - droop gain of diesel-based generator is shown to affect electromechanical modes and, hence, overall stability. Due to the time lag associated with synchronous generator control, micro-grid stability deteriorates if the diesel generator participates more by increasing the gain.

In case of planned islanding, the set points of DG of micro-grid are adjusted (prior to islanding) to have a smooth transition. This results in minimum transients when the micro-grid is moving from grid-connected mode to islanding mode. In case of unplanned islanding, the deviation in frequency and power swing depends on the

supply-demand gap in the islanded network. It is possible to reduce the transient by using fast-acting converter interfaced DG units. A large variation in load/source within a micro-grid may lead to a transient stability problem when it is islanded, and the same disturbance may pose a small-signal stability problem when it is grid connected. This paper proposes a control technique for inverter-based DGs to improve the frequency response of micro-grid in islanding in addition to power management. The micro-grid under study is modelled using the power system toolbox of Simulink/MATLAB with synchronous generator and inverters. The effect of the proposed strategy on system inertia, frequency deviation, and its rate of change are analyzed for a system with DGs based on synchronous machine and inverter through simulation. The effect of adding inertia on frequency oscillations and transient response is also investigated in the present study. The importance of inertia and its effect on improvement of transient response is discussed in Section II. The proposed droop control is presented in Section III. The simulation of the proposed scheme in an inverter and synchronous generator-based micro-grid system is presented in Section IV.

II. INERTIA AND TRANSIENT RESPONSE OF

MICROGRID

Rotational inertia is a measure of an object's resistance to changes in the rotational speed. The relation between power, angular speed, and inertia of a power system is given by

$$J\frac{d\omega}{dt} + D_e \omega_r = \frac{P_{mech} - P_e}{\omega_0} \qquad (1)$$

Where J is the moment of inertia and D_e is the coefficient of friction loss of the synchronous generator; ω_0 and ω_r are the synchronous and angular speed of the generator respectively; P_{mech} is the mechanical power produced at the shaft; and P_e is the electrical load seen by the generator. Neglecting D_e (1) can rewritten as

$$\frac{d\omega}{dt} = \frac{P_{mech} - P_e}{\omega_0} \qquad (2)$$

The rate of change of speed and, hence, system frequency deviation is inversely proportional to inertia. Stiff power grids maintain frequency and voltage during disturbances owing to large inertia and fast field control of synchronous generators, respectively. Due to high inertia of rotors, synchronous generators store a large amount of kinetic energy. Whenever there is a load increase, the imbalance in mechanical and electrical power for a synchronous generator, leads to speed deceleration. Momentarily, the kinetic energy stored in the rotor will be utilized to compensate for this imbalance. Meanwhile, the governor increases the input mechanical power so that in steady state P_{mech} is equal to P_e and the system stabilizes to a new frequency. Similarly, the field control of generators

acts quickly to maintain system voltage during reactive power demand, such as induction motor starting or faults. Thus, power system frequency and voltage are regulated within a tight band.

III. DROOP CONTROL THEORY

In micro-grid, the system reliability and stability is achieved only by the voltage regulation when more micro sources are interconnected. This voltage regulation damps the reactive power oscillations and voltage. In a complex power system, when multiple DGs are attached to the micro-grid, the power sharing among them is made properly with the help of a control strategy called droop control. Droop control also enables the system to disconnect smoothly and reconnect routinely to the complex power system. The role of droop control in power sharing is that it control the real power on the basis of frequency droop control and it controls the reactive power on the basis of voltage control. The voltage and frequency can be manipulated by regulating the real and reactive power of the system. This forms a conventional droop control equation. In a transmission line, the real and reactive power are designed as:

$$P = \frac{v_1 v_2}{x} \sin\delta \qquad (3)$$

$$Q = \frac{v_1^2}{x} - \frac{v_1 v_2}{x} \cos\delta \qquad (4)$$

In the above mentioned equation (3) and (4), Resistance (R) is neglected for an overhead transmission lines as it is much lower than inductance (L). Also the power angle δ is lesser, Therefore, $\sin\delta = \delta$ and $\cos\delta = 1$.

$$\delta = \frac{xP}{v_1 v_2} \qquad (5)$$

$$v_1 - v_2 \cong \frac{xQ}{v_1} \qquad (6)$$

Hence from the above equation (5) and (6), it is clear that the power angle δ can be controlled by regulating real power P. Also the voltage V1 can be controlled through reactive power Q. dynamically, the frequency control leads to regulate the power angle and this in turn controls the real power flow . Finally, the frequency and voltage amplitude of the microgrid are manipulated by adjusting the real and reactive power autonomously. As a result, the frequency and voltage droop regulation can be determined as:

$$f - f_0 = k_p (P - P_0) \qquad (7)$$
$$V - V_0 = k_q (Q - Q_0) \qquad (8)$$

Where f, V = The frequency and voltage at a new operating point; P, Q = Active and reactive power at a new operating point; f_0, V_0 = Base frequency and voltage;

P_0, Q_0= Temporary set points for the real and reactive power; K_p, K_q = Droop constant.

A. Droop Control Block Diagram
The droop control theory is explained with the block diagram as shown in Fig.1. This droop control block is composed of two function blocks:

- Frequency droop control
- Output limit control

The central controller delivers the inputs such as the system frequency (f) and the output of power generation (P), or feeder flow (FL) and set points. Inputs are local measurements of frequency (f) and power output (P), or feeder flow (FL), and the set points are provided by the central controller. The output of the current controller is current reference signal of the d-axis. In power grid attached mode, the micro grid frequency is same as the rated value, so that the power output (P) and the feeder flow (FL) are sustained to the fixed value. When the micro grid is detached from the power grid, the power mismatch are balanced by the droop control automatically. With this the system attain its steady state and finally the system frequency is restored to its rated value.
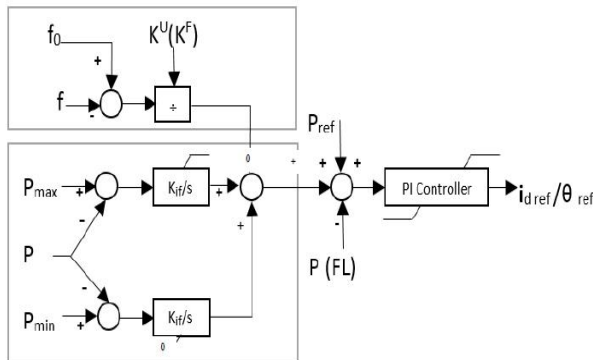
Fig.1. The Droop Control Block Diagram.

IV. MODIFIED DROOP CONTROL FOR IMPROVED

TRANSIENT RESPONSE
In the proposed scheme, the droop gain is modified as a function of df/dt. This loop will be effective when |df/dt| exceeds a predetermined value C. The modified droop control law for inverter control is given

$$m_i = m_{n,i} - k_1 \left(\left| \frac{df}{dt} \right| \right)^{\wedge k_2} \qquad (9)$$

Where, for $\left| \frac{df}{dt} \right| \geq$ C $= m_{n,i}$, for C $\left| \frac{df}{dt} \right| <$

Here, $m_{n,i}$ is the nominal droop gain, which gets modified only if the rate of change of frequency exceeds a

threshold. Constants k_1, k_2 can be designed for each inverter based on their maximum power ratings and maximum-allowable frequency deviation. The value of k_1 can be determined using the following equation:

$$k_1 = \frac{m_{n,i} - m_{i,min}}{\left(\left| \frac{df}{dt} \right| max \right)^{\wedge k_2}} \qquad (10)$$

$$m_{i,min} = \frac{\Delta \omega_i}{\Delta P_{i,max}} \qquad (11)$$

Where $m_{i,min}$ is the minimum droop gain, $\Delta \omega_i$ and is the frequency deviation corresponding to the maximum power changes that the inverter can support while operating at nominal power.
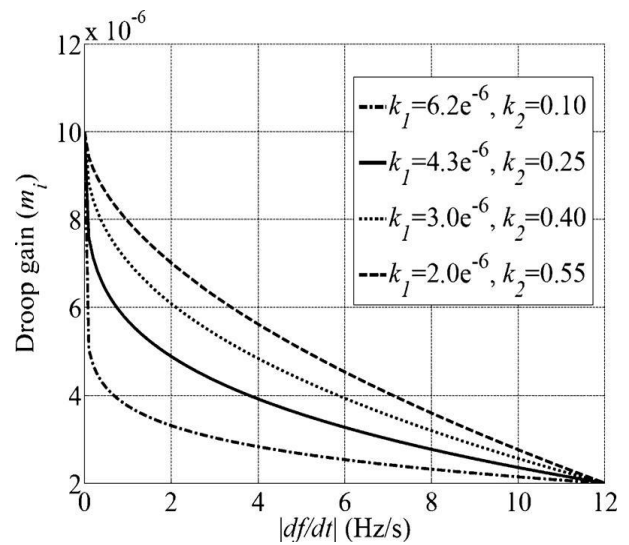

Fig.2. Droop gain variation with df/dt for different values of k_2.

Fig.1 shows the variation of droop gain (m_i) with df/dt for different values of k_2. From equations (9) to (11) and fig.2, the following inferences can be made regarding the design of the controller:

- The choice of k_1 depends on the maximum rate of change of frequency $\left| \frac{df}{dt} \right| max$ and inverter output-power limit which indirectly limits the minimum value of droop gain $m_{i,min}$.
- Amount of inertia added virtually to the system increases with an increase in k_1. A lower value of k_1 results in more peak overshoot in frequency while a higher value of k_1 results in oscillations in frequency. Hence, it is important to arrive at the optimal value of k_1.
- Minimum droop gain $m_{i,min}$ can be chosen to prevent the inverter from exceeding its maximum power limit.
- The micro grid can be operated within specified frequency limits by setting $\Delta \omega_i = \Delta \omega_{i,max}$.

The control block to incorporate the modified droop control in an inverter is shown in Fig. 3. The constant C is the predefined limit of $\left|\frac{df}{dt}\right|$. Under normal operation, the rate of change of frequency is below C and, hence, the comparator output remains at 0. Thus, the droop gain(m) is unchanged and the inverter works in traditional droop control mode.

Subsequent to a large disturbance, if $\left|\frac{df}{dt}\right|$ seen by the inverter exceeds C, the output of the comparator block changes to 1.

As a result, "m" gets modified in proportion to $\left|\frac{df}{dt}\right|$ as given by Eqn 8. This results in a decrease in droop gain (m) and, hence, lower deviations in inverter reference frequency) from nominal frequency (ω_n). To maintain lower frequency deviations, the corresponding inverter has to supply higher power (P_i). Thus inertia gets added virtually to the system by modifying the droop gain of the inverter. Since large disturbances take time to settle, k_1 is decreased at predefined time steps to slowly reduce the added inertia to zero, so that the frequency slowly reaches its steady-state value.
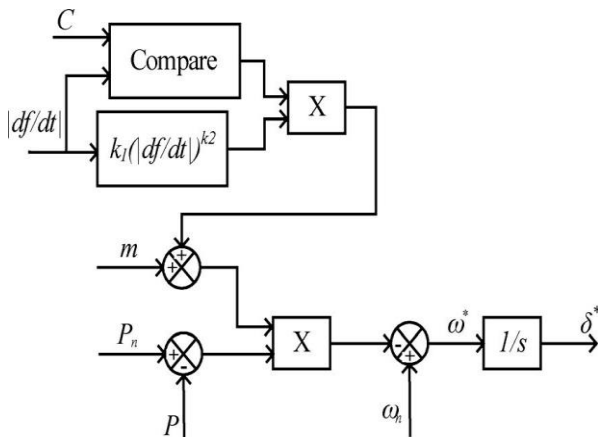
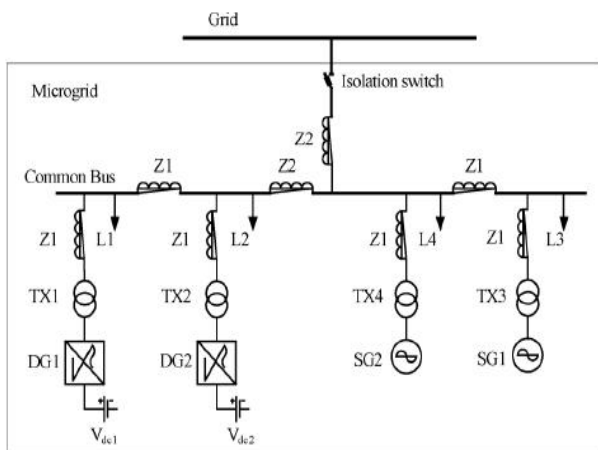

Fig.3. Block diagram of modified P –ω droop control.

Fig 4. System considered for simulation.

TABLE I: Parameters of Micro-grid

Nominal rarings	DG1	DG2	SG1	SG2
Active power	550KW	550KW	500KVA	500KVA
Reactive power	100KVAr	100KVAr	50 KVA	50 KVA

TABLE II: Load Details

Load	case A	case B	case C
L1	300kw +j100kvar	800kw +j100kvar	500kw + j100kvar
L2	400kw +j100kvar	800kw +j200kvar	500kw + j100kvar
L3	400kw +j50kvar	800kw +j200kvar	600kw + j100kvar
L4	400kw +j100kvar	800kw +j100kvar	600kw + j100kvar

TABLE III: Droop Constants and Impedance

Parameters	Symbol	Value
Inverter DC voltage	Vdc1, Vdc2	8kV
P-ω droop gain – DG1,DG2	m12	-15.0e-6 (rad/s)/W
P-Fdroop gain – DG1,DG2	n12	-1.55 e-4 V/Var
P-ω droop gain – SG1,SG2	m34	-25.8e-6 (rad/s)/w
P-Fdroop gain – SG1,SG2	n34	-2.3 e-4 V/Var
Impedance	Z1 Z2	0.32+j 0.38(Ω) 0.96+j 1.13(Ω)
Transformers	TX1,TX2 TX3,TX4	3.3KV-11KV 0.4KV-11KV

V. SYSTEM SIMULATION

The system consists of loads (L1 to L4) and DGs based with an inverter as the front end (DG1, DG2) and conventional synchronous generators (SG1, SG2).The details of rating of machines, loads, droop constants of inverters, and synchronous machines are given in Tables I-III. The block diagram of control strategy implemented for inverters is shown in Fig.6.P and Q calculated from sensed voltage and current, are used to obtain the reference voltage and phase angle using the droop control technique. Voltage magnitude and phase angle are regulated using an inner fast voltage-control loop which employs the proportional- integral (PI) controller. Capacitor current, with small gain, is fed back as shown in Fig.4 to provide damping. In this paper, the proposed technique is tested in two different scenarios when the micro-grid is islanded (unintentional) from the main grid.

Case A: Micro-grid Islanding
In this case, the micro-grid is islanded at 1.5 s while exporting power to the grid. The frequency and voltage of

the micro-grid follow grid values before islanding. After islanding, the sources in the island must reduce their power quickly to cater to the remaining load. Inverters do not have slow electromechanical modes associated with synchronous generators. As a result, DG1 and DG2 reduce their power output quickly compared to the synchronous generators. As shown in Fig.5, when the microgrid is islanded, the traditional droop control leads the frequency to increase up to 50.8 Hz before it slowly reaches a new steady state at 50.5 Hz. In the micro-grid, all of the sources must get disconnected from the micro-grid when 50.5 for 0.16 s. This will lead to a complete blackout in the system which is actually not necessary. Virtual inertia of the system is reduced slowly to zero by decreasing in four steps at predefined instants (3.5, 5, 7, and 8.5 s), so that the frequency slowly reaches a new steady-state value as shown in Figs 7 to 14.

Fig.6. (a) Frequency (b) df/dt profile with inverter using traditional, P-f droop control.

Fig.5. Frequency profile and df/dt profile with inverter using Traditional p-f control

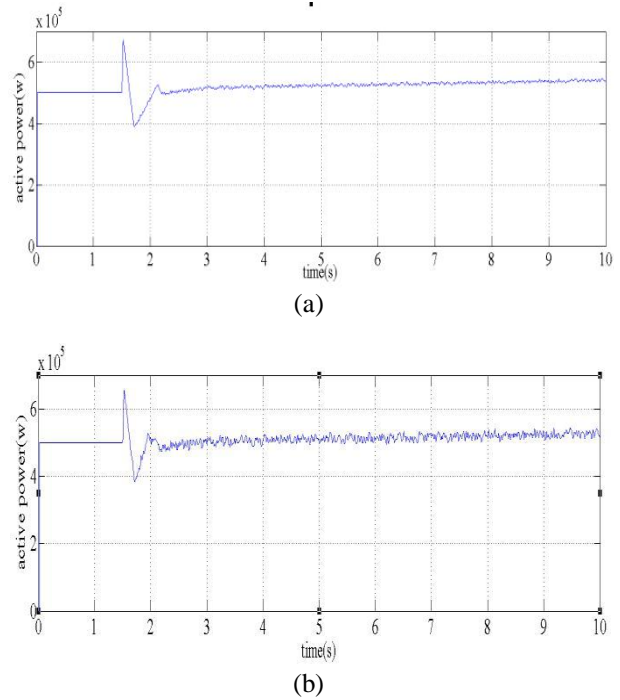**Case B: Micro-grid Islanded while importing Power**

Fig.7. (a)&(b) are load sharing by synchronous generator SG1 using traditional and modified droop control.
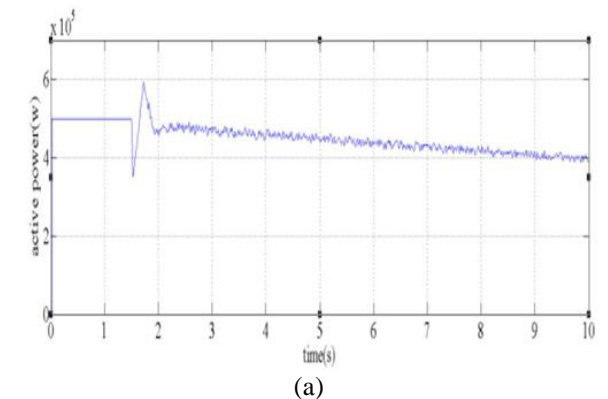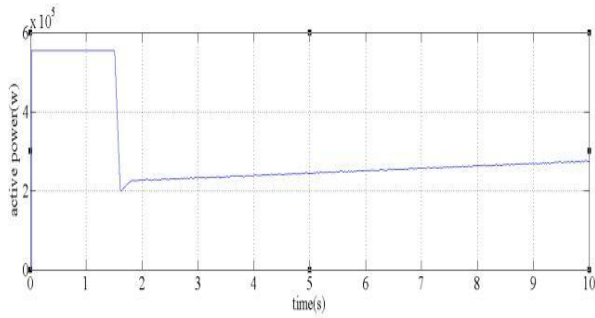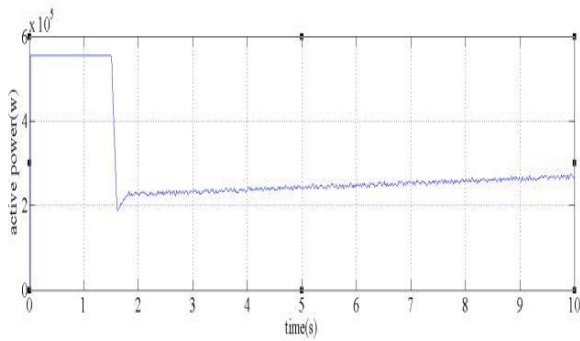

(a)

Fig.8. (a) is load sharing by synchronous generator SG2 using modified droop control.
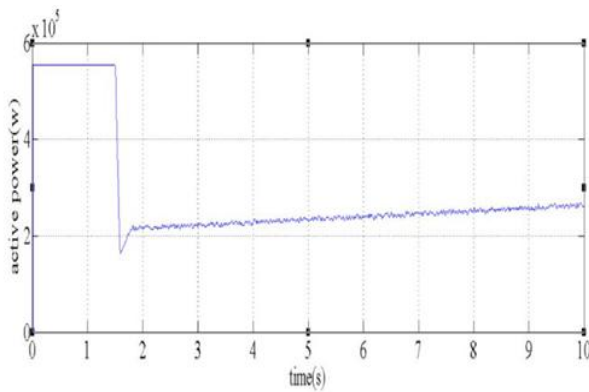
(a)

(b)

Fig.9. (a)&(b) are load sharing by synchronous generator DG1 using traditional and modified droop control.

(a)

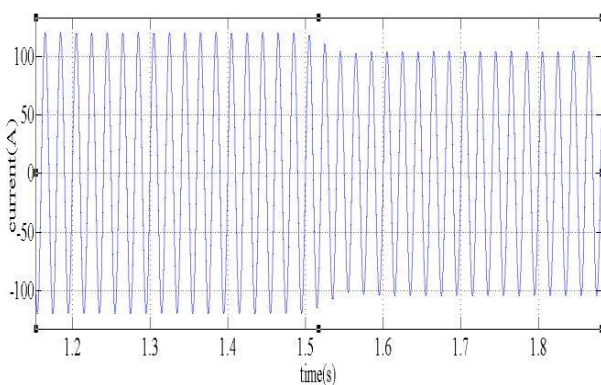Fig.10. (a) is load sharing by synchronous generator DG2 using modified droop control.
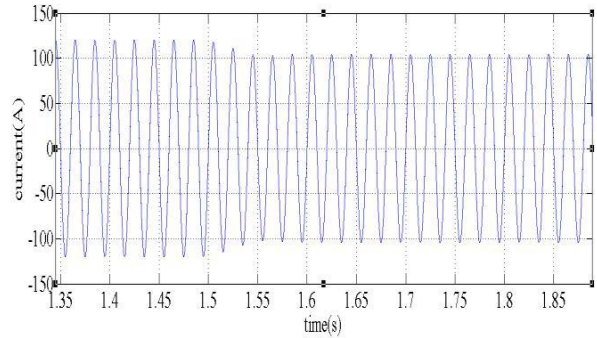

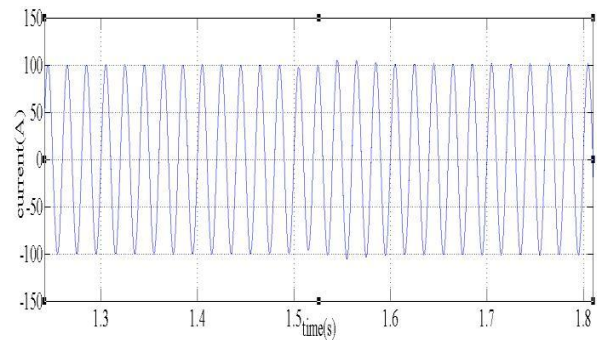Fig.11. Current profile of DG1

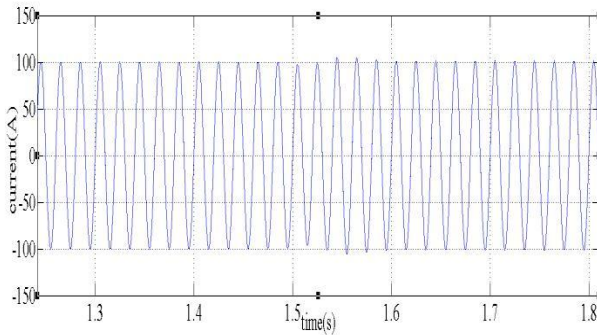Fig.12. Current profile of DG2

Fig.13. Current profile of SG1

Fig.14. Current profile of SG2

In this case, the micro-grid is islanded at 1.5 s while importing power from the grid. The frequency and voltage of the micro-grid follow grid values before islanding. After islanding, the sources in the island must increase power (depending on availability) quickly to cater to the remaining load. When micro-grid gets islanded, the traditional droop control leads the frequency to drop to 49.4 Hz at -1 Hz/s before it slowly reaches the new steady state of 49.5 Hz at 8 s. By using modified droop control, the drop in frequency is limited up to 49.6 Hz and to -0.8 Hz/s. Virtual inertia of the system is reduced slowly to zero by decreasing at predefined instants, so that the frequency slowly reaches the new steady-state value.

VI. CONCLUSION

A new control technique to improve the transient response in micro-grid in post islanding conditions is proposed.

A micro-grid consisting of a synchronous generator-based DG and inverter-based DG with loads is considered and is simulated in a Simulink/MATLAB environment. The proposed control technique is applied to inverter-based DGs. The droop gain of the inverter is modified based on the df/dt observed by the inverter during transition. The results show that by employing modified droop control in inverters allows them to take the bulk of the power change transiently, at reduced frequency deviations.

By adding virtual inertia as a function of df/dt, it is possible to reduce unwanted triggering of sources out of synchronism and to reduce load shedding in an islanded micro-grid. This approach can reduce the short-term storage requirements of a micro-grid where frequency is a major constraint, thus reducing the cost. The control can be designed to ensure micro-grid operation within prescribed frequency limits, also making sure that the inverter is not overloaded.

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BIOGRAPHIES

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