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Transient Stability Analysis in Micro grids Using P-f & Q-V dot droop controller

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***Abstract*— Generation is shifting from a centralized power generating facility having large synchronous generators to distributed generation involving sources of smaller capacity. Most of these sources require inverters on the front end while being connected to the grid. Lower available kinetic energy, coupled with less short-circuit current ratio compared to large synchronous generators, compromises the transient stability of the microgrid when isolated from the main grid. Sources in the microgrid use droop control to share power according to their capacity without any form of communication. This paper proposes a novel Q-V dot droop controller for inverters to improve the frequency response of microgrid under disturbances involving large frequency deviations. It also discusses design of various parameters defined for the proposed control. The microgrid, which has two inverters and two synchronous generators, is simulated using Simulink/MATLAB software to test the proposed control strategy.**

***Index Terms*— Distributed generation, droop control, Q-V dot droop control, frequency stability, transient response.**

I. INTRODUCTION

POWER generation and transmission so far has been a centralized one with power plant capacity in hundreds of megawatts having large rotating turbines and synchronous generators. Large inertia and, hence, high kinetic energy coupled with high short-circuit current ratio (SCR) associated with such synchronous generators result in grid having stiff voltage and frequency. However, generation is changing from a centralized, large power generating facility to distributed generators (DGs) involving sources of smaller capacity, such as photovoltaic (PV), microturbine, fuel cells, etc.Most of these sources require inverters on the front end when connected to the grid.

Power sharing among different DGs in an isolated microgrid is possible by employing droop control or by using some centralized communication [1], [2]. 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 [3]. Inverters do not have a rotating mass and, hence, have low inertia. Higher penetration of inverter- based static sources in microgrid 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. Microgrid 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[4]. 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 microgrids by modifying inverter control has been reported in the literature as virtual synchronous generator [6], virtual synchronous machine [7], and synchro converters [8]. Increasing inertia virtually in the inverter results in a reduction in maximum rotor speed deviation of the nearby source [9]. 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 [10] 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, microgrid stability deteriorates if the diesel generator participates more by increasing the gain.

In case of planned islanding, the set points of DG of microgrid are adjusted (prior to islanding) to have a smooth transition. This results in minimum transients when the microgrid 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 microgrid 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 microgrid in islanding in addition to power management. The

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microgrid under study is modeled 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 microgrid 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

$$J\frac{d\omega}{dt} + D_g\,\omega_r = \frac{P_{mech} - P_g}{\omega_o} \qquad (1)$$

Where J is the moment of inertia and D_g is the coefficient of friction loss of the synchronous generator; ω_o 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_g is the electrical load seen by the generator. Neglecting (1) can be rewritten as

$$\frac{d\omega}{dt} = \frac{P_{mech} - P_g}{J\,\omega_o} \qquad (2)$$

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_g 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.

Inverters are static and do not have rotating masses, but it is possible to have infinite inertia when the inverter output phase angle is controlled to a constant value during power change. However, droop control and current limitation on inverter switches lead inverters to have less inertia. Such sources may not be able to regulate voltage and frequency during disturbances. Thus, microgrids with inverter-based sources may suffer from voltage and frequency instability.

III. DROOP CONTROL IN MICROGRIDS

For medium- and high-voltage microgrids P-ω and Q-V droop control is widely used to control the real and reactive power flow. Traditional P-ω and Q-V droop control used to obtain the inverter reference frequency is given as

$$\omega_i = \omega_n - m_i(P_{ni} - P_i) \qquad (3)$$

where ω_i and ω_n are the i^{th} inverter reference frequency and microgrid nominal frequency, respectively; P_{ni} and P_i are the nominal and calculated active power of the i^{th} inverter, respectively; and m_i is the frequency droop gain. Traditional Q- V droop control used to obtain the reference voltage is given as

$$V_i = V_n - n_i\,(Q_{ni} - Q_i) \qquad (4)$$

Where V_i and V_n are the reference voltage and nominal voltage of the i^{th} inverter. Q_{ni} and Q_i are the nominal and calculated reactive power, respectively, of the i^{th} inverter and n_i is the voltage droop gain of the th inverter.

Sources that have identical nominal active power contribute in inverse proportion to their droop gain as given by

$$m_1P_1 = m_2P_2 = m_3P_3 = \cdots = m_nP_n \quad (5)$$

A source with higher droop gain will share less power compared to a source with lower droop gain. Likewise, a source with large power capacity can be made to supply higher power during disturbances by reducing its droop gain. Fig.1 shows the *P –ω* droop characteristic for various gains.

It is clear from Fig. 1 and (5) that an inverter with a lower value of droop gain "*m*" will supply more power. Similarly, an inverter with a higher value of "*m"* will have a droop frequency higher than the one with a lower value for the same power change.

Fig.2 shows the droop characteristic of inverters operating in constant voltage, constant power, and finite droop gain mode. The characteristic with infinite slope m_i refers to the inverter operating in constant power (i.e., constant currentmode). In this mode, the inverter operates with zero inertia. Characteristics with finite slope (m_1 and m_2) refer to the inverter operating with finite inertia with m_1 having a higher inertia than m_2 . The characteristic with zero slope m_0 refers to the inverter working in constant frequency mode, thus having infinite inertia.

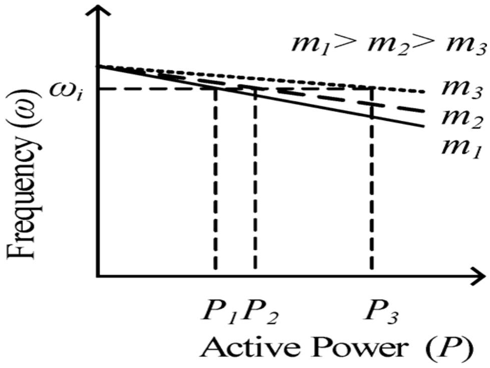


Fig.1 Power sharing with a variation in droop gain.

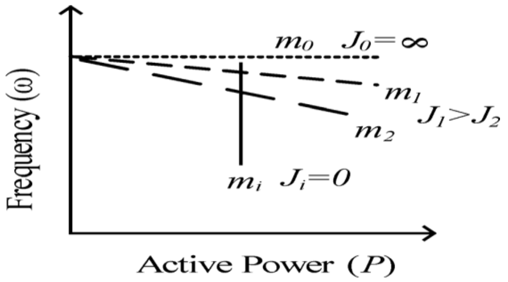


Fig. 2. Inertia variation with droop gain

From the aforementioned discussion, it is possible to control the peak overshoot in frequency for variation in load by dynamically changing the value of "m" during the transient. Therefore, the lower value of "m" enables the inverter to supply higher power with reduced frequency during transients, hence avoiding unwanted df/dt triggering. The inverter shall return to traditional droop control once the microgrid attains new steady state as indicated by low df/dt .

IV. MODIFIED DROOP CONTROL FOR IMPROVED TRANSIENT RESPONSE

The deviation in frequency in an isolated microgrid for disturbance in load depends on the supply-demand gap. As discussed in the earlier section, the disturbance, which is perceived as small in a grid-connected system, shall be large in an isolated system and may lead to tripping of the generator or load shedding. If adequate inertia is provided during the transient, it is possible to avoid unwanted triggering of CBs (df/dt ,under frequency
and over frequency) whenever there is a disturbance in the islanded microgrids.

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

$$\omega_i = \omega_n - m_i(P_{ni} - P_i)\quad(6)$$

Where

$$m_i = m_{n,i} - k_1\left(\left|\frac{df}{dt}\right|\right)^\wedge k_2, \text{ for } \left|\frac{df}{dt}\right| \geq C$$

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

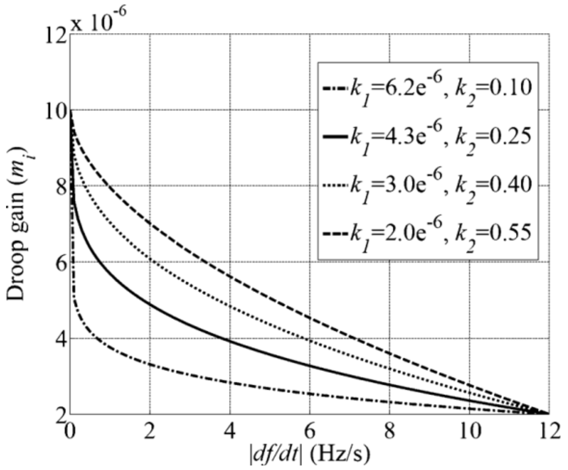


Fig.3. Droop gain variation with df/dt for different values of k_2

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:

$$k_1 = \frac{m_{n,i} - m_{i,min}}{\left(\left|\frac{df}{dt}\right|max\right)^\wedge k_2}\qquad(7)$$

$$m_{i,min} = \frac{\Delta\omega_i}{\Delta P_{i,max}}\qquad(8)$$

Where $m_{i,min}$ is the minimum droop gain, $\Delta\omega_i$ and is the frequency deviation corresponding to the maximum power change that the inverter can support while operating at nominal power. Fig.2 shows the variation of droop gain(m_i) with df/dt for different values of k_2. From equations (6) to (8) and fig.3,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 microgrid can be operated within specified frequency limits by setting $\Delta\omega_i = \Delta\omega_{i,max}$.
- A lower value of k_2 results in a lower value of droop constant (m_i) and, hence, more variation in output power from an inverter. This enables the inverter to cater to higher variations in load with reduced frequency deviation during transients and, hence, avoiding unwanted df/dttriggering.
- The inverter shall return to traditional droop control once themicrogrid attains a new steady state as indicated by low df/dt.

The control block to incorporate the modified droop control in an inverter is shown in Fig. 4. 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

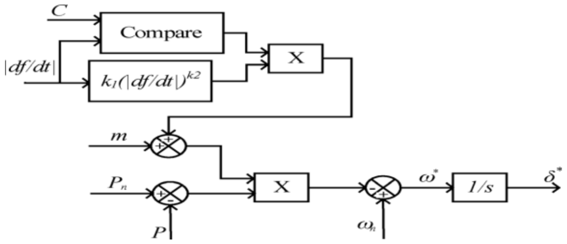


Fig.4 Block diagram of modified P –ω droop control.

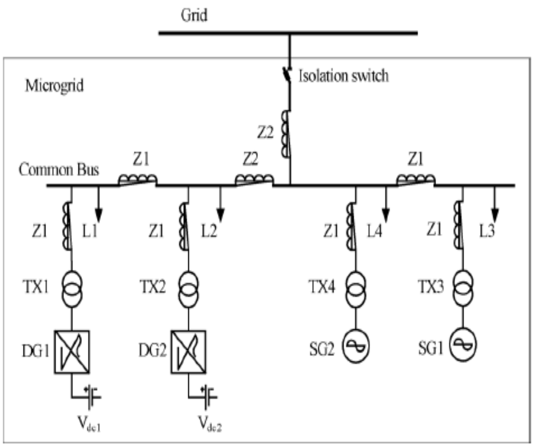
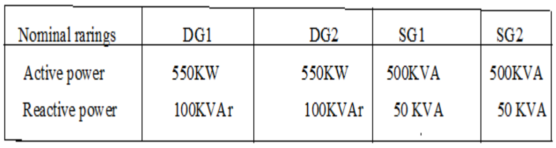


Fig. 5. System considered for simulation.



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

TABLE I :PARAMETERS OF MICROGRID

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 II :LOAD DETAILS

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 (6). This results in a decrease in droop gain (m) and, hence, lower deviations in inverter reference frequency (ω_i) 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.

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
Q-V droop gain – DG1,DG2	n12	-1.55 e-4 V/Var
P-ω droop gain – SG1,SG2	m34	-25.8e-6 (rad/s)/w
Q-V droop 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.Q-V Dot Droop Control

A novel droop control scheme for Distributed Energy Resource (DER) interlinked by means of Converters in an island operation of microgrid. In the views of their compilation, the main purpose was to eradicate the effect of line impedance of each DIC (DERs interface converters) and to rise the reactive power sharing. In order to improve reactive power sharing in DIC’s, Q-V dot droop control technique used, in which Vdot denotes the rate of change of voltage magnitude V. To make the Voltage magnitude in steady, a Vdot restoration technique was introduced. To get the desired reactive power sharing, DIC’s voltage has to vary. This technique helps to overcome the effect of line impedance of every DIC.

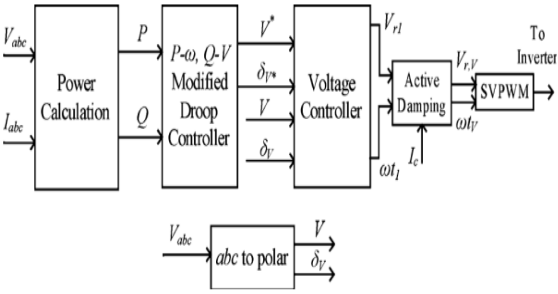


Fig.6.
Control block diagram for the inverter, including modified droop.

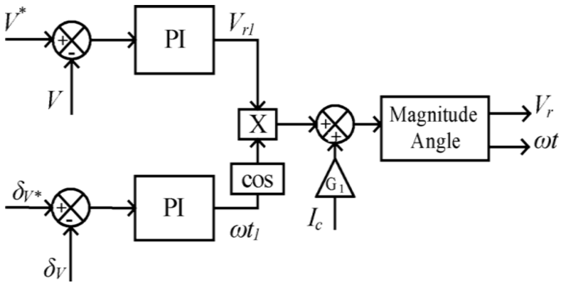


Fig.7. Voltage magnitude and phase controller with active damping.

V. SYSTEM SIMULATION FOR TRANSIENT RESPONSE

In order to validate the proposed control strategy, a microgrid shown in Fig. 5 is considered for 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.7 to provide damping. Finally, switching sequences for the inverter are generated from voltage magnitude and phase references using the space vector pulsewidth modulation (SVPWM) technique.

In this paper, the proposed technique is tested in two different scenarios when the microgrid is islanded (unintentional) from the main grid.

Case A: Microgrid Islanded While Exporting Power

In this case, the microgrid is islanded at 1.5 s while exporting power to the grid. The frequency and voltage of the microgrid 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.

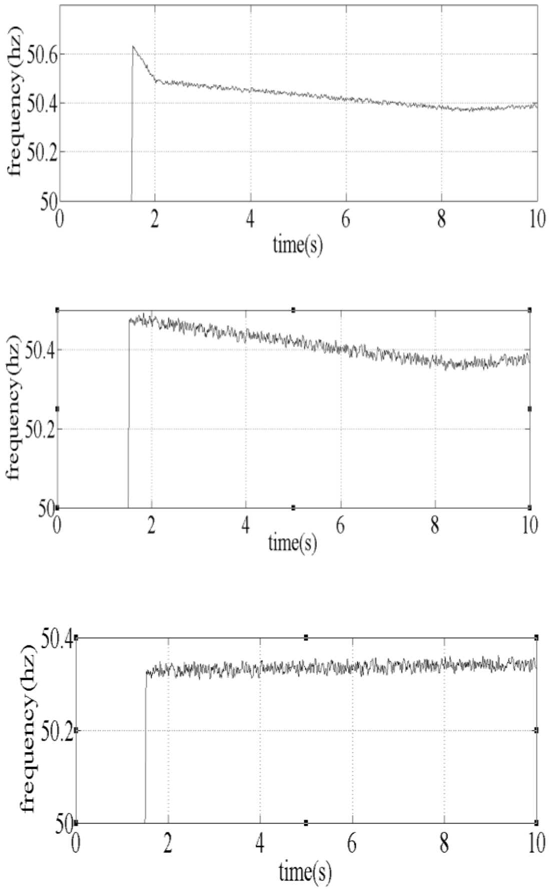
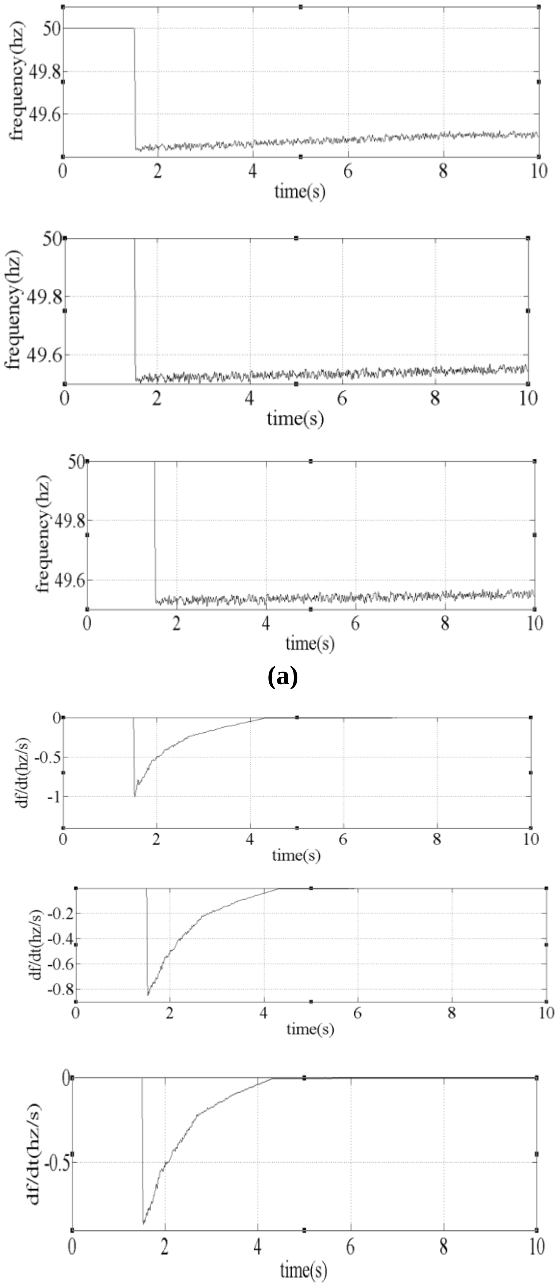


Fig 8.Frequency profile with inverter using traditional, modified and Q-V dot droop control.

As shown in Fig.8, 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 microgrid, all of the sources must get disconnected from the microgrid 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.

Case B: Microgrid Islanded While importing Power



(a)

(b)

Fig 9. (a)Frequency (b) df/dt profile with inverter using traditional, modified and Q-V dot droop control.

In this case, the microgrid is islanded at 1.5 s while importing power from the grid. The frequency and voltage of the microgrid 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 microgrid 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.

CONCLUSION

A new control technique (Q-V dot droop) to improve the transient response in microgrid in post islanding conditions is proposed. A microgrid 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 and Q-V dot 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 microgrid. This approach can reduce the short-term storage requirements of a microgrid where frequency is a major constraint, thus reducing the cost. The control can be designed to ensure microgrid operation within prescribed frequency limits, also making sure that the inverter is not overloaded.

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