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Improvement of Transient Stability of Microgrids for Smooth Mode Conversion Using Synchroconverters

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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 for connection to the grid. The stability and operation aspects of converter-dominated microgrids (MGs), however, are faced by many challenges. Important among these, are: 1) the absence of physical inertia; 2) comparable size of power converters; 3) mutual interactions among generators; 4) islanding detection delays; and 5) 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. In this paper a novel controller for inverters which makes the inverter to mimic the behaviour of the synchronous generator, called the synchroconverter is proposed. This introduces a virtual inertia in the system and improves the frequency response of MGs undertransients involving large frequency deviations. During mode conversioni.e., from grid connected mode to islanded mode or vice-versa, there is a mismatch in power generation and load demand mismatch. This causes instability in the system and leads to unwanted tripping of the MGs which further causes instability. The proposed controller maintains the stability of the system by increasing or decreasing the real power output of the inverter. A simple voltage source converter connected to a distribution grid and supplying a local load is simulated using PSCAD software to test the proposed control strategy.**

***Index Terms*—Distributed generation, droop control, frequency stability, transient response, synchroconverters.**

I. INTRODUCTION

POWER generation and transmission so far has been acentralized one with power plant capacity in hundreds ofmegawatts 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 requireinverters on the front end when connected to the grid. Power sharing among different DGs in an isolated MGs 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]. However, these droop control laws are applicable for high-voltage (HV) MGs where tie-line inductance is greater than its resistance [4]. P-V and Q-ω droop control laws improve power sharing [4] and are shown to improve efficiency [5] for low-voltage (LV) resistive MGs. In the last two decades (approximately), the traditional droop control laws have been modified to improve power sharing [6]–[8] and/or stability of MGs [9]–[11]. Small-signal stability of MGs deteriorates at higher droop gains while it is immune to other parameters, such as controller gains and tie-line impedance [12]–[14]. Virtual resistance [9], supplementary droop [15], and adaptive feedforward compensation [16] may be used to stabilize the system under high droop gains.

Inverters do not have a rotating mass and, hence, have low inertia. Higher penetration of inverter-based static sources in MGs may result in poor voltage and frequency responseduring large disturbances [17]. If the issues are not addressed,
this transient response problem may develop into a transient stability problem. MGs transient stability depends on the DG technology and its control, its penetration level, type and location of fault, and nature of loads [18], [19]. The effect of high penetration of various DG technologies on transient stability of the system is studied in [19]–[23]. 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 frequencydeviations [20]–[22]. Transient response of the systemcan also be improved by using energy storage devices, such asultra-capacitors and battery alongside DGs. However in a largepower system with a greater number of DGs, disturbance locationconsideration can make the storage-based solution ineffectiveand costly [23]. Disturbances in such a scenario can resultin large frequency deviations exceeding frequency andthreshold, resulting in the tripping of generation or unnecessaryload shedding.

The concept of adding inertia virtually to reduce frequency deviations in MGs by modifying inverter control has been reported in the literature as virtual synchronous generator [24], virtual synchronous machine [25], and synchronverters [26]. Increasing inertia virtually in the inverter results in a reduction in maximum rotor speed deviation of the nearby source [27].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

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so far. Reference [28] 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, overallstability. Due to the time lag associated with synchronous generator control, MG stability deteriorates if the diesel generator participates more by increasing the gain. In case of planned islanding, the set points of DG of MG are adjusted (prior to islanding) to have a smooth transition. Thisresults in minimum transients when the MG is movingfrom 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 MG 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 MG in islanding in addition to power management. The MG under study is modeled using PSCAD software. The importance of inertia and its effect on improvement oftransient 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 MG 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

$$J\frac{d\omega}{dt} + D_e\omega_r = \frac{P_{mec\,h} - P_e}{\omega_o} \tag{1}$$

Where J is the moment of inertia and De is the coefficient offriction loss of the synchronous generator; ω_o and ω_r are thesynchronous and angular speed of the generator, respectively; Pmech is the mechanical power produced at the shaft; and Pe is the electrical load seen by the generator. Neglecting De, (1) can be rewritten as

$$\frac{d\omega}{dt} = \frac{P_{mec\,h} - P_e}{J\omega_o} \tag{2}$$

The rate of change of speed and, hence, system frequencydeviation is inversely proportional to inertia. Stiff power gridsmaintain frequency and voltage during disturbances owing tolarge inertia and fast field control of synchronous generators,respectively. Due to high inertia of rotors, synchronous generatorsstore a large amount of kinetic energy. Whenever there is aload increase, the imbalance in mechanical and electrical powerfor a synchronous generator, leads to speed deceleration. Momentarily,the kinetic energy stored in the rotor will be utilizedto compensate for this imbalance. Meanwhile, the governor increasesthe input mechanical power so that in steady stateis equal to Pe and the system stabilizes to a new frequency. Similarly,the field control of generators acts quickly to maintainsystem voltage during reactive power demand, such as inductionmotor starting or faults. Thus, power system frequency andvoltage are regulated within a tight band.Inverters are static and do not have rotating masses, but it ispossible to have infinite inertia when the inverter output phaseangle is controlled to a constant value during power change[29]. However, droop control and current limitation on inverterswitches lead inverters to have less inertia. Such sources maynot be able to regulate voltage and frequency during disturbances.Thus, MGs with inverter-based sources maysuffer from voltage and frequency instability.

III. DROOP CONTROL IN MICROGRID

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

$$\omega_i^* = \omega_n - m_i(P_{n,i} - P_i) \tag{3}$$

where ω_i^* and ω_n are the ith inverter reference frequency and MG nominal frequency, respectively; Pn,i and Pi are thenominal and calculated active power of the th inverter, respectively; m_i and is the frequency droop gain.

Traditional - droop control used to obtain the reference voltage is given as

$$V_i^* = V_n - n_i\left(Q_{n,i} - Q_i\right)(4)$$

where $V_i^*$and V_n are the reference voltage and nominal voltage of the ith inverter. Qn,i and Qi are the nominal and calculated reactive power, respectively, of the ith inverter and is the voltage droop gain of the ith inverter. Sources that have identical nominal active power contribute in inverse proportion to their droop gain as given by

$$m_1P_1=m_2P_2=m_3P_3=\ldots m_nP_n \tag{5}$$

A source with higher droop gain will share less power comparedto a source with lower droop gain. Likewise, a source withlarge power capacity can bemade to supply higher power duringdisturbances by reducing its droop gain. Fig. 2 shows the P-ω droop characteristic for various gains.It is clear from Fig. 2 and (5), that an inverter with a lowervalue of droop gain “m” will supply more power. Similarly, aninverter with a higher value of will have a droop frequencyhigher than the one with a lower value for the same powerchange.Fig. 3 shows the droop characteristic of inverters operating inconstant voltage, constant power, and finite droop gain mode.The characteristic with infinite slope m_i refers to the inverteroperating in constant power (i.e., constant current mode). Inthis mode, the inverter operates with zero inertia. Characteristicswith finite slope (m_1 and m_2) refer to the inverter operatingwith finite inertia with m_1 having a higher inertia than m_2. Thecharacteristic with zero slope refers to the inverter workingin constant frequency mode, thus having infinite inertia. From the above discussion it is clear that if we implement a droop controller for inverter, the inverter behaves like a synchronous generator and is able to control the amount of real and reactive power injected to or consumed from the grid can be controlled. By controlling the real power, the load demand and power generation is balanced. This enhances the transient stability and frequency response during steady state and mode conversion. This

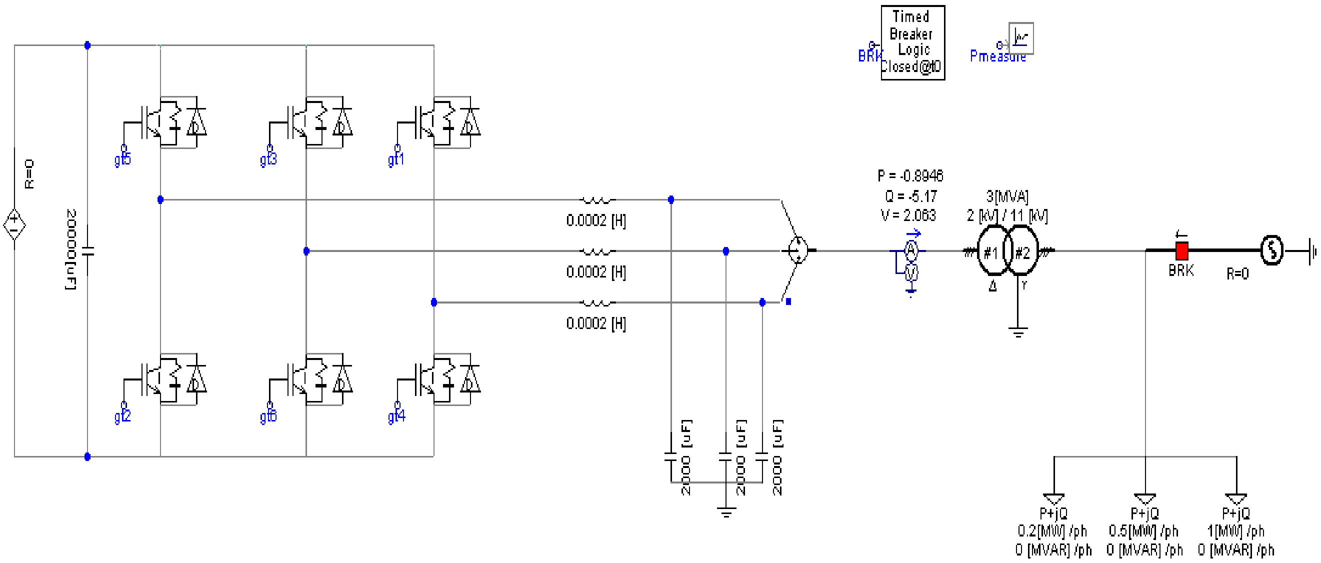

Fig. 1 PSCAD Simulation of microgrid

capability of real power control is particularly very important for a inverter interfaced MGs, because MGs are present in distribution network, where load demand continuously varies and inverter has to increase or decrease its real power generation accordingly very quickly. Also the power balance during mode conversion is balanced by use of real power control. Similarly by controlling the reactive power , the voltage profile of the system improves and voltage stability is maintained. The reactive power demand in the distribution network is also met easily. Thus by employing the droop control we can make the inverter to behave like a synchronous generator i.e. the function of Automatic Generation Control and Exciter is simulated by the droop control. This enhances the frequency and voltage stability of system.

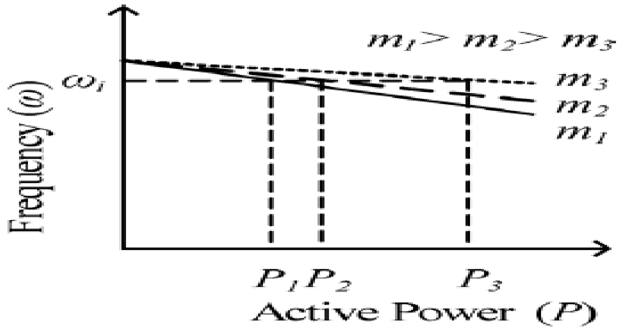

Fig. 2 Power sharing with variation in droop gain

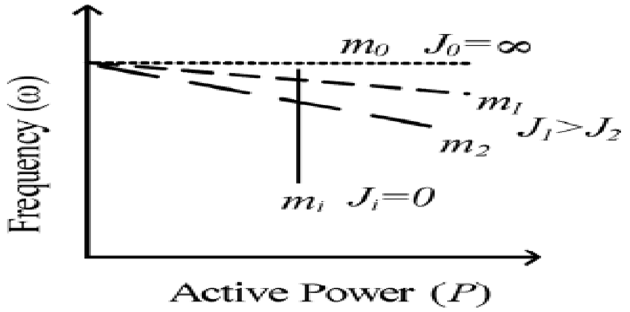

Fig. 3 Inertia variation with droop gain

IV. SIMULATION AND RESULT

In order to validate the proposed control strategy, a MG shown in Fig. 1 is considered for simulation. The simulation is carried out using PSCAD software. Fig. 1 shows a 8 kV voltage source converter (VSC) connected to 11 kV distribution system through a step up transformer. The converter also feeds a 1.7 MW per phase load which is present at the point of common coupling (PCC).The block diagram of control strategy implemented for inverters is shown in Fig. 4. 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 as shown in Fig. 5 to provide damping. Finally, switching sequences for the inverter are generated from voltage magnitude and phase references using the sinusoidal pulse width modulation (SPWM) technique. The block diagram showing the overall control structure of the inverter is shown in Fig. 6. In this paper, the proposed technique is tested in two different scenarios when the MG is islanded (unintentional)from and restored to the main grid.

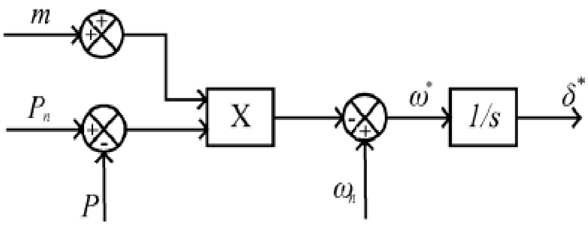

Fig. 4 Block diagram of P-ω droop control

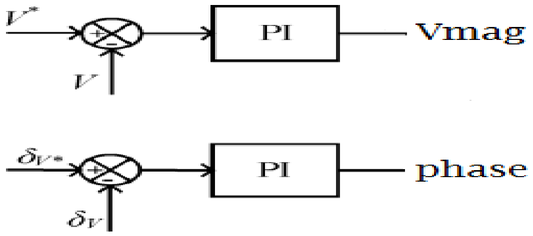

Fig. 5Voltage magnitude and phase controller

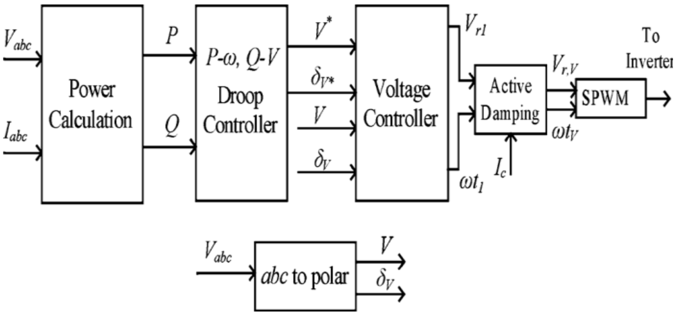

Fig. 6 Control block diagram of inverter

A. *Case A: Microgrid Islanded while importing power*

In this case the MG is islanded at 6s while importing 0.8946 MW power from the grid. The frequency and voltage of the MG follow grid values before islanding. After islanding, the sources in the island must increase power depending on availability, quickly cater to remaining loads. The power balance equation at PCC during steady state while MG imports power from the grid is given by Power consumed by inverter + Power consumed by load = Power from the grid. As long as this balance is maintained there is no stability problem. Fig. 7 shows the power at PCC when MG imports power from the grid.Since the inverter consumes power, initially the real power is negative. At 6s the MG is islanded from the grid. Now the grid does not supplies power to the load, this leads to unbalance in the above power balance equation. After islanding operation the inverter now has to supply the power demand of the load, hence at 6s when the islanded mode occurs, the action of the real power controller kicks in and the inverter now starts to deliver power to the load. Hence the power is now positive. During islanded mode the inverter supplies 1.95 MW to the load at PCC. At 8s the MG is re-connected back to the grid, again the action of the controller kicks in and causes the inverter to consume power from the grid. Steady state operation follows and inverter and load starts to consume 0.8946 MW from the grid. Thus the power balance at PCC is restored after grid restoration. From this discussion it is clear that the action of real power controller causes the inverter to behave like synchronous generator and maintain the power balance during and after mode conversion. This enhances the transient stability of the system.

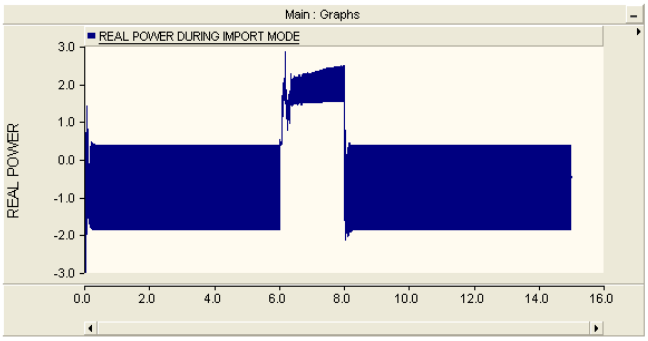

Fig. 7 Real power output of inverter during import mode

Fig. 8 and Fig. 9 show voltage and current at PCC when MG imports power from the grid. We see that voltage increases during islanded mode and again decreases to original value when MG is restored back to grid. Similarly the current output decrease during islanded mode and again increase to original value when MG is restored back to grid.

Fig. 8 Voltage at PCC during import mode

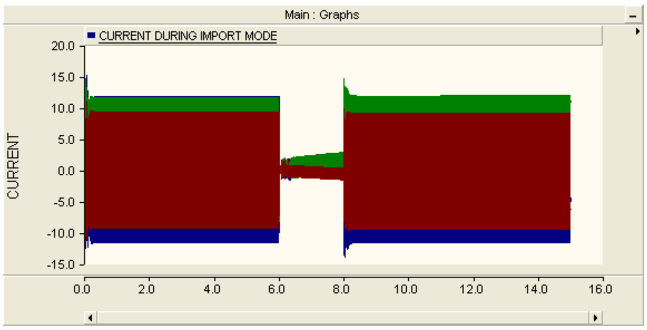

Fig. 9Current at PCC during import mode

B. *Case B: Microgrid islanded while exporting power*

In this case the MG is islanded at 6s while exporting 52 MW power to the grid. The frequency and voltage of the MG follow grid values before islanding. After islanding, the sources in the island must decrease power, quickly cater to remaining loads. The power balance equation at PCC during steady state while MG exports power to the grid is given by Power exported by inverter = Power consumed by load + Power injected to the grid. As long as this balance is maintained there is no stability problem. Fig. 10 shows the power at PCC when MG exports power from the grid. Here the inverter exports power. At 6s the MG is islanded from the grid. Now there is no power injected to the grid.Here the power produced by the inverter exceeds the load demand. This causes imbalance in the power balance equation at PCC. Hence to maintain the power balance the inverter has to decrease its power output and produce power demanded by local load at PCC only. Hence at 6s when the islanded mode occurs, the action of the real power controller kicks in and the inverter now decreases the power output required to meet the demand of the local load only. During islanded mode the inverter reduces its output to 43.82 MW. During islanded mode the inverter supplies 43.82 MW to the load at PCC. At 8s the MG is re-connected back to the grid, again the action of the controller kicks in and causes the inverter to inject power to load as well as the grid and maintains the load-power generation balance. Steady state operation follows and inverter increases its output power to 52 MW. Thus the power balance at PCC is restored after grid restoration. From this discussion it is clear that the action of real power controller causes the inverter to behave like synchronous generator and maintain the power balance during and after mode conversion. This enhances the transient stability of the system.

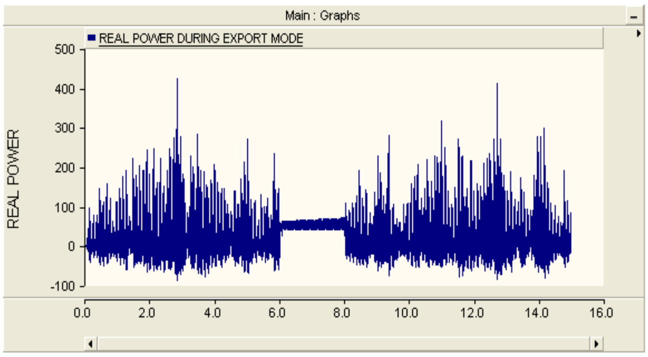

Fig. 10 Real power output of the inverter during export mode

Fig. 11 and Fig. 12 shows voltage and current at PCC when MG imports power from the grid. We see that voltage decreases during islanded mode and again increases to original value when MG is restored back to grid. Similarly the current output decrease during islanded mode and again increase to original value when MG is restored back to grid.

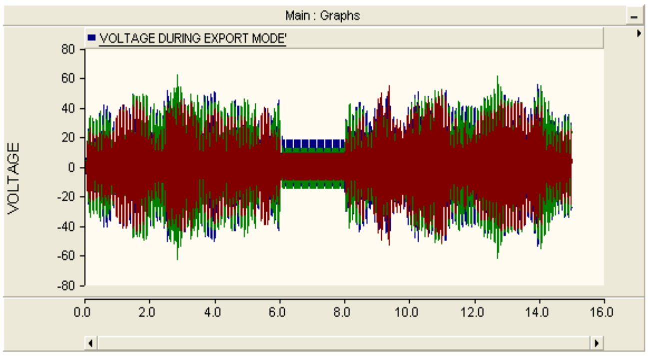

Fig. 11 Voltage at PCC during export mode

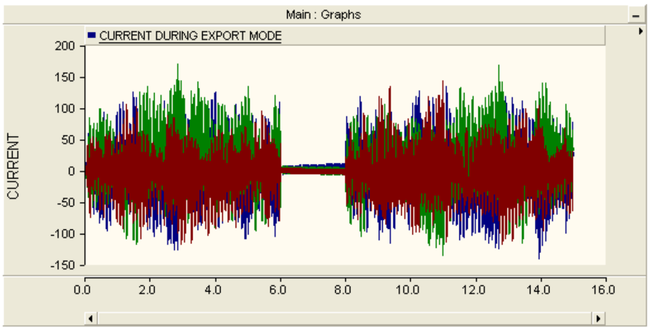

Fig. 12Current at PCC during export mode

V. CONCLUSION

A new control technique to improve the transient response of grid connected inverters for MG application is proposed in this paper. A VSC based MG with loads, connected to distribution grid is considered and is simulated using PSCAD software. The droop control technique is applied to inverter-based MGs. Simulation are carried to study the behaviour of inverter during steady state and during mode conversion. Results show that employing droop control to inverters allows them to take the bulk of the power change transiently, at reduced frequency deviations. The inverter behaves like a synchronous generator by increasing or decreasing its real power output during mode conversion. The action of droop controller adds a virtual inertia in the system and increases the transient stability. The effect of rotor acceleration and deceleration for frequency stabilisation in a synchronous generator is mimicked by the inverter. Thus it is possible to reduce unwantedtriggering of sources out of synchronism and to reduce loadshedding in an islanded MG. This approach can reducethe short-term storage requirements of a MG where frequencyis a major constraint, thus reducing the cost. The controlcan be designed to ensureMG operation within prescribedfrequency limits, also making sure that the inverter is not overloaded. Thus it can be concluded that droop control changes the static behaviour of inverter into a dynamic one and improves the transient stability of the system.

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