Power and Current Limiting Strategy Based on Droop Controller With Floating Characteristic for Grid-Connected Distributed Generations

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ABSTRACT The Grid-Connected Droop-Controlled Distributed Generations (GCDCDGs) are widely used in power systems. However, their power flow is very sensitive to the Upstream Grid (UG) frequency and voltage magnitude fluctuations. This paper focuses on the power and current limiting of inverter-interfaced GCDCDGs under UG frequency and/or voltage magnitude drops. GCDCDG output power and current increase under the UG frequency drop, and if this increase exceeds the maximum of them, current limiters are saturated and according to $P \sim \omega$ droop characteristic the GCDCDG frequency does not track the UG frequency, and this frequency difference leads to power oscillation between DG and UG and the system becomes unstable. In this paper, a new strategy based on the droop-control method is proposed to limit the output power and current of GCDCDGs without using a current limiter that realizes a stable operation under the mentioned conditions. In the proposed method instead of increasing the droop coefficients to limit $P$ and $Q$ at their constraints, the droop curves move down after powers and currents exceed maximum values, using two supplementary control signals. The performance of the proposed method is demonstrated with simulation results using MATLAB/Simulink environment under several case studies.

INDEX TERMS Distributed generation, droop controller, grid-connected, power and current limiting.

NOMENCLATURE

$v$ Output Voltage of VSC.
$i$ Output Current of VSC.
$v_0$ PC Voltage.
$i_0$ PC Output Current.
$m$ Modulating Index.
$V_{DC}$ VSC DC-Link Voltage.
$R_f$ Sum of Filter Resistance and Switches On-State Resistance.
$L_f$ Inter-Link Line Inductance.
$R_f$ Inter-Link Line Resistance.
$\omega_{DG}$ VSC AC-Side Frequency.
$\omega_0$ Rated Frequency.
$\omega_{ref}$ VSC AC-Side Frequency Reference.

$P_0$ Rated Active Power.
$Q_0$ Rated Reactive Power.
$P_{max}$ Maximum Active Power.
$Q_{max}$ Maximum Reactive Power.
$i_{dmax}$ Maximum Active Current.
$i_{dmin}$ Minimum Reactive Current.
$m_p$ Active Current Droop Coefficient.
$m_q$ Reactive Current Droop Coefficient.
$K_{P-d}$ PI Controller Proportional Gain of Active Current.
$K_{I-d}$ PI Controller Integral Gain of Active Current.
$K_{P-iq}$ PI Controller Proportional Gain of Reactive Current.
$K_{I-iq}$ PI Controller Integral Gain of Reactive Current.

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I. INTRODUCTION
GRID-connected Distributed Generation (DGs) are extensively used to provide the demand of the consumers. These micro-power plants are usually interfaced with power inverters. These inverter-interfaced DGs to contribute in providing required power of power system which have connected to it are equipped with droop control mechanism. Droop control is usually used to enhance the stability of power systems dominated by grid-connected inverters without any communication between the different units [1]–[4]. Droop control has different forms based on the involved impedances [5]:

1) when the impedance is inductive, the droop control takes the form of \( P \sim \omega \) and \( Q \sim V \),
2) when the impedance is resistive, the droop control takes the form of \( P \sim V \) and \( Q \sim -\omega \) and,
3) when the impedance is capacitive, the droop control takes the form of \( P \sim -\omega \) and \( Q \sim -V \).

There are two arguments about GCDCDGs. The first is the stability of the droop control strategy which has been widely investigated in [6]–[8]. The second is to maintain the current below a given maximum limit [9]–[14]. Usually, grid-connected inverters are current-controlled, and limiting the output current of them is not difficult, while the ability to voltage regulation is a crucial aspect of power-electronics-enabled autonomous power systems [5]. It is important for a GCDCDG to be equipped with the current-limiting property where should be maintained at all times during both normal and abnormal grid conditions [10], [11], [14], [15]. Current-limiting controllers can be used to achieve the desired current limitation by triggering suitably designed protection circuits [16] or with using several Low-Voltage Ride-Through (LVRT) structures [17], [18], but these methods have difficult stability proof. External limiters and saturation units are often added into the current or voltage control loops to limit output current, but those can lead to undesired oscillations and instability [9].

A current-limiting droop controller has been proposed in [5] for single-phase grid-connected inverters that can operate under either normal or faulty grid conditions. Opposed to the conventional current-limiting methods, the current limitation in this reference is achieved without external limiters, and the controller guarantees system stability. In [22] a PV-based grid-forming inverter with a modified droop control has been considered to operate under abnormal grid voltage conditions. The proposed approach in [22] realizes current-limiting control with LVRT capabilities. A unified current-limiting control scheme for grid-connected inverters under both normal and faulty grids with a simplified voltage support mechanism has been developed in [23]. This paper focuses on the current limiting of GCDCDGs in GCMGs while UG frequency and/or voltage magnitude drop. In this paper, a new strategy based on the droop-control method is proposed to limit the output currents of GCDCDGs without using current limiters which realizes a stable operation under the above-mentioned conditions.

The main features of the proposed strategy are summarized as follows:

- power and current limiting are simultaneously occurred under UG frequency and voltage magnitude drops
- conventional current limiter which leads to instability has been deleted.
- the system has a stable operation while powers and currents are limited.
- static and dynamic load switching can not disturb performance of this limiting strategy.

The rest of the paper is divided as follows. Section II explains GCDCDG unit and its controller. Section III presents a mathematic model of the proposed droop-control based current limiting strategy. In section IV, time-domain simulation studies have been represented and finally, the conclusions are drawn in Section V.

II. GCDCDG STRUCTURE AND ITS CONTROLLERS
A typical inverter-based GCDCDG and its controllers are shown in Fig. 1. The internal controller regulates the LCL filter capacitor voltage magnitude and frequency (\( \omega_{DG} \)) at their given references where are produced by the droop controller. The internal controller is based on the PI controller that has been proposed in [21]–[23]. This controller regulates control variables in \( dq \) reference frame and uses the output currents of the DG as feed-forward signals to better regulation. Fig. 2 shows the block diagram of the used internal controller. The proposed droop-control based power and current limiting strategy are discussed in the next section in detail.

III. PROPOSED DROOP-CONTROL BASED CURRENT LIMITING STRATEGY
A. CONVENTIONAL DROOP-CONTROLS USED FOR GCDCDGs
Reference of the DG frequency is determined as:

\[
\omega_{ref} = \omega_0 - m_p(P - P_0)
\]  
(1)

where \( P \) is produced by low-pass filtering of \( p = \frac{3}{2} v_{od} i_{od} \) according to

\[
P = \frac{\omega_c}{s + \omega_0} p
\]  
(2)

Based on (1) when the DG injects rated active power at the UG normal conditions the reference of the DG frequency is \( \omega_0 \). But under the un-normal conditions when the UG frequency decreases, because of any reasons (for example suddenly increasing demanded active power or decreasing power plant productions at UG), output active power of GCDCDG begins to increasing and based on droop characteristic (1) DG frequency is decreased to DG drawn active power be proportional to capacity of it.

Reference of the DG voltage magnitude is determined as follow:

\[
v_{ref} = v_0 - n_q(Q - Q_0)
\]  
(3)
where $Q$ is produced by low-pass filtering of $q = -\frac{3}{2}v_{od}i_{oq}$ according to:

$$Q = \frac{\omega_c}{s + \omega_c} q$$

(4)

Based on (3) when the DG injects rated reactive power at the UG normal conditions the reference of the DG voltage magnitude is $v_0$. But under the abnormal conditions when the UG voltage magnitude decreases, because of any reasons (for example short circuit faults at UG), output reactive power of GCDCDG begins to increase, and based on droop characteristic (3) DG voltage magnitude is decreased to DG drawn reactive power be proportional to the capacity of it.

Under the above UG conditions, if UG frequency and/or voltage magnitude drop be large values, output powers of the GCDCDG maybe exceed the maximum of them. One solution to limit the output powers to maximum values is using current limiters to limit $i_{od}$ and $i_{oq}$ to maximum values. This method in order to limit output reactive power performs correctly, but in output active power limiting a problem occurs. If UG frequency decreases, $i_{od}$ increases, and if this increasing exceeds the maximum of $i_{od}$, the current limiter is saturated and according to $P \sim \omega$ droop characteristic (Fig. 3) the GCDCDG frequency does not track the UG frequency and this frequency difference, leads to power oscillation between DG and UG and the system becomes unstable. Also, increasing $m_p$ to limit the output active power due to stability limit is not possible [9].
To overcome the above-mentioned problems the proposed unified droop-control based current limiting strategy will be described as follows.

B. PROPOSED STRATEGY

In the proposed strategy, same as the conventional method the drop of DG frequency and voltage magnitude is based on $P$ and $Q$ increasing, respectively. Thus (1) and (3) are used as previously used. According to (1) and (3), in steady-state, minimum values of $\omega_{\text{ref}}$ and $v_{\text{ref}}$ occur at the maximum value of $P$ and $Q$, respectively.

$$\omega_{\text{min}} = \omega_0 - m_p(P_{\text{max}} - P_0) \quad (5)$$

$$v_{\text{min}} = v_0 - n_q(Q_{\text{max}} - Q_0) \quad (6)$$

Thus, using (5) and (6), a maximum drop from rated values of frequency and voltage magnitude that protection strategy is not active until they are

$$\Delta \omega_{\text{max}} = \omega_0 - \omega_{\text{min}} = m_p(P_{\text{max}} - P_0) \quad (7)$$

$$\Delta v_{\text{max}} = v_0 - v_{\text{min}} = n_q(Q_{\text{max}} - Q_0) \quad (8)$$

According to $P \sim \omega$ and $Q \sim v$ droop characteristics in Fig. 4, if frequency and voltage magnitude drops be greater than $\Delta \omega_{\text{max}}$, $\Delta v_{\text{max}}$, $P$ and $Q$ will be exceed the maximum values in steady-state, respectively. In the proposed method instead of increasing the droop coefficients to limit $P$ and $Q$ at their constraints, the droop curves move down after exceeding $\Delta \omega_{\text{max}}$ and $\Delta v_{\text{max}}$, using two supplementary control signals as follows:

$$\omega_{\text{ref}} = \omega_0 - m_p(P - P_0 - \Delta P) \quad (9)$$

$$v_{\text{ref}} = v_0 - n_q(Q - Q_0 - \Delta Q) \quad (10)$$

where $\Delta P$ and $\Delta Q$ are calculated so that $P$ and $Q$ limit to $P_{\text{max}}$ and $Q_{\text{max}}$ even after increasing of $\Delta \omega$ and $\Delta v$ from their maximums, respectively.

$$\Delta \omega = m_p(P_{\text{max}} - P_0 - \Delta P) \quad (11)$$

$$\Delta v = n_q(Q_{\text{max}} - Q_0 - \Delta Q) \quad (12)$$

Note that (11) and (12) can be rewritten as

$$\Delta P = \begin{cases} - \frac{1}{m_p} \Delta \omega + (P_{\text{max}} - P_0) & \Delta \omega > \Delta \omega_{\text{max}} \\ 0 & \Delta \omega \leq \Delta \omega_{\text{max}} \end{cases} \quad (13)$$

$$\Delta Q = \begin{cases} - \frac{1}{n_q} \Delta v + (Q_{\text{max}} - Q_0) & \Delta v > \Delta v_{\text{max}} \\ 0 & \Delta v \leq \Delta v_{\text{max}} \end{cases} \quad (14)$$

where (13) and (14) limit $P$ and $Q$ to maximum values. Also, to ensure that in a transient state, instantaneous active and reactive power (i.e. $P$ and $Q$) and currents $i_{od}$ and $i_{oq}$ do not exceed their boundary values, two other supplementary control signals are added to (11) and (12), as

$$\omega_{\text{ref}} = \omega_0 - m_p(P - P_0 - \Delta P) + \delta \omega \quad (15)$$

$$v_{\text{ref}} = v_0 - n_q(Q - Q_0 - \Delta Q) + \delta v \quad (16)$$

where $\delta \omega$ and $\delta v$ are respectively produced based on minimizing the difference between instantaneous and steady-state.
TABLE 1. Parameters for DG.

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| Rated power                | \( S_n (kVA) \) | 1.1 |
| Rated voltage              | \( V_n (V) \) | 62.5 |
| DC bus voltage             | \( V_{DC} (V) \) | 200 |
| Rated frequency            | \( f_0 \) | 50 |
| Switching frequency        | \( f_{SW} (kHz) \) | 20 |
| Filter inductance          | \( L_f (mH) \) | 1.5 |
| Filter capacitance         | \( C_f (\mu F) \) | 20 |
| Filter resistance          | \( R_f (m\Omega) \) | 1.5 |
| Rated active power         | \( P_0 (W) \) | 240 |
| Rated reactive current     | \( Q_0 (W) \) | 60 |
| Maximum active current     | \( i_{odmax} (A) \) | 12 |
| Minimum reactive current   | \( i_{qmax} (A) \) | -7.2 |
| Active power droop coefficient | \( m_d \) | 0.001 |
| Reactive power droop coefficient | \( m_q \) | 0.002 |
| PI controller proportional gain of active current | \( K_{P-od} \) | 0.4 |
| PI controller integral gain of active current | \( K_{I-od} \) | 0.5 |
| PI controller proportional gain of reactive current | \( K_{P-oq} \) | -4 |
| PI controller integral gain of reactive current | \( K_{I-oq} \) | -5 |
| LPF cut-off frequency      | \( \omega \) (rad/s) | 15 |
| Interlink line resistance  | \( R_L (\Omega) \) | 0.001 |
| Interlink line inductance  | \( L_L (m\Omega) \) | 0.001 |

Since steady-state values of currents are produced by low pass filtering instantaneous value of them and have not predefined values, to ensure that \( i_{od} \) and \( i_{oq} \) do not exceed their boundary values, \( i_{od} \) and \( i_{oq} \) signals are saturated at them. In the proposed scheme the steady-state power control is based on droop control, thus the current saturation mechanism does not deal with system instability. Fig. 5 shows a block diagram of the proposed droop-control based power and current limiting strategy.

IV. TIME-DOMAIN SIMULATION RESULTS

In this section, the performance of the proposed strategy is investigated under four various case studies. The proposed droop-control based power and current limiting strategy is applied to a GCDCDG. The detailed switched model of the system is simulated using MATLAB/Simulink environment. A Diagram of this system has been shown in Fig. 1 in which the UG block is replaced with a series inter-link line and ideal voltage source. Parameters of this DG are given in Table 1. In these cases, until \( t = 2 \) sec, DG operates in its rated conditions i.e. \( V_{od} \approx 51 \) V, \( f_o = 50 \) Hz, \( P_o = 235 \) W,

\[
\delta \omega (s) = \left( K_{P-id} + \frac{K_{I-id}}{s} \right) (I_{od} - i_{od}(s))
\]

\[
\delta v(s) = \left( K_{P-iq} + \frac{K_{I-iq}}{s} \right) (I_{oq} - i_{oq}(s))
\]

where

\[
I_{od} = \frac{\omega_c}{s + \omega_c} i_{od}
\]

\[
I_{oq} = \frac{\omega_c}{s + \omega_c} i_{oq}
\]

Since steady-state values of currents are produced by low pass filtering instantaneous value of them and have not predefined values, to ensure that \( i_{od} \) and \( i_{oq} \) do not exceed their boundary values, \( i_{od} \) and \( i_{oq} \) signals are saturated at them. In the proposed scheme the steady-state power control is based on droop control, thus the current saturation mechanism does not deal with system instability. Fig. 5 shows a block diagram of the proposed droop-control based power and current limiting strategy.

A. CASE STUDY 1: UG FREQUENCY DROP

At \( t = 2 \) sec the UG frequency drops to 49 Hz (\( \omega_g = 307.867 \) rad/s). Since the UG voltage phase lag from the voltage phase of DG, active power injection from DG to UG begins to increase and this is because of \( i_{od} \) increasing. As shown in Fig. 6, 1 Hz Frequency drop is large and \( i_{od} \) exceeds the maximum of it if the current limiting strategy is not used. Also, the injected active power reaches about 2 kW which is lonely greater than the rated power of the DG. To limit the active current \( i_{od} \) to its maximum value, the proposed strategy is applied and the simulation results are shown in Fig.7. As can be see, \( i_{od} \) limited to \( i_{odmax} = 12 \) A.

\[
Q_o \approx 59.6 \text{ VAR}, \quad i_{od} = 3.068 \text{ A} \quad \text{and} \quad i_{oq} \approx -0.779 \text{ A}.
\]

Also, the line to line voltage of \( UG(V_{gL-L}) \) is 61.24 V.
FIGURE 8. Simulation results in UG voltage magnitude drop under proposed current limiting strategy.

In steady-state, injected active and reactive power under this frequency drop are about 900 W and 60 VAr respectively where result $S \approx 902$ VA.

B. CASE STUDY 2: UG VOLTAGE MAGNITUDE DROP

In this study at $t = 2$ sec the UG voltage magnitude drops to 27.56 V(L−L) from 62.5 V(L−L) i.e. 44 percent decrease at PCC. As shown in Fig. 8, $i_{dq}$ decreases and is limited to the minimum value of it i.e. -7.2 A. Because of this reactive current decrease, reactive power injection increases and in steady-state raised to 301 VAr. The steady-state value of $i_{od}$ and $P_{DG}$ remain without changes but since the proposed strategy decreases LCL filter capacitor bus voltage magnitude to control and limit $i_{dq}$, the output active power decreases during transient state and in steady-state restores to the previous value. Fig. 9 represents $i_{dq}$ when the proposed current limiting strategy is not used. In this study, 56 percent decrease for UG voltage magnitude is applied at PCC. As can be seen from Fig. 9, $i_{dq}$ exceeds boundary and decreases to about -12 A if conventional droop without current limiter is used.

C. CASE STUDY 3: DROP IN UG FREQUENCY AND VOLTAGE MAGNITUDE AND BALANCED LOAD SWITCHING

To show the ability of the proposed current limiting strategy, UG frequency and voltage magnitude are simultaneously decreased to 49 Hz and 27 V(L−L) (i.e. $V_{d,geria} = 22$), respectively. Fig. 10 shows simulation results in this case study. After $t = 2$ sec, when frequency and voltage magnitude are decreased, $i_{dq}$ and $i_{dq}$ move to boundary values and in steady-state reach to them and active and reactive powers are 471 W and 293 VAr, respectively. Between $t = 4$ sec and $t = 5$ sec, a three-phase balanced load is connected at PCC and starts to drawing current. For this load $P_L = 174$ W and $Q_L = 45$ VAr. As can be seen in Fig. 10, output currents of the DG are controlled and do not exceed boundary values, and are limited under the proposed strategy. The required power of the load is provided from the grid under this abnormal condition.

D. CASE STUDY 4: DROP IN UG FREQUENCY AND VOLTAGE MAGNITUDE AND INDUCTION MOTOR LOAD SWITCHING

This case study is the same as case study 3, but, instead of a three-phase balanced load, an induction motor with
have been switched on. Results of studies indicate that the proposed strategy will be perfectly able to limit the output currents of the grid-connected DGs under frequency and/or voltage magnitude reductions.

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