Fault Characteristics of PV and Energy Storage Integrated Grid-connected Converter under Different Control Strategy

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Abstract. PV and energy storage integrated grid-connected converter (GCC) is used popularly in distribution generation (DG) system. As there is a significant increase in the size and capacity of grid-connected power plants, the stability and reliability of the grid become more important. Different from the traditional synchronous generator, the fault characteristics of GCC are affected by its control strategy, thus this paper researches the fault characteristics of GCC under different control strategies. Firstly, active and reactive power decoupling control strategy and fault characteristics of GCC under PQ control are analyzed. The fault current characteristics of GCC under low voltage ride through (LVRT) control are studied as well. And equivalent current source model of the GCC under PQ and LVRT control during grid fault period are derived. Finally, the working principle and fault characteristics of GCC under droop control are studied. The influence that the voltage sag level at point of common coupling (PCC) has on the fault characteristics of GCC is researched, and equivalent model of GCC with droop control is obtained. The simulation results verify the correctness of the theoretical analysis.

Introduction

Nowadays, the renewable energy generation has developed rapidly due to the environmental protection and energy sustainable development [1]. PV generation, as an important family of DGs, has been enlarged in the share of power generation market due to its environment friendly features. The output power of PV system fluctuates when weather changes, which could lead to unbalanced power of power grid and fluctuation of grid voltage and frequency. Energy storage device can smooth the output power of photovoltaic and realize GCC's friendly connection to grid. PV and energy storage can share a common DC/AC circuit, making it feasible to integrate their circuits into one device, i.e. PV and energy storage integrated GCC. Different from traditional synchronous generator, fault characteristics of GCC are influenced by its control strategy. Therefore, it is necessary to analyze the fault characteristics of GCC under different control strategies.

Several researches have been presented on the performances of GCC under grid fault. The output current of GCC contains harmonic components resulting from the negative sequence voltage component during unbalanced grid fault, and [2] puts forward a control strategy to eliminate the influences that the negative sequence voltage component has on the output current of GCC. [3] has researched transient characteristics of GCC and its influences on distribution network, but the paper only studied balanced fault situation and the proposed equivalent model of GCC is only applicable to balanced fault analysis. [4] has studied the fault current characteristics of inverter interfaced distribution generation (IIDG) running in isolated islands mode. But the control strategy of grid-connected IIDG is different from the IIDG operating in island mode, which results in a great difference in fault current characteristics between the two situations. [5] has studied the fault current characteristics of GCC, but the LVRT process that many country demand has not been considered.

The fault characteristics of GCC under PQ, LVRT and droop control are studied and the equivalent models of GCC are derived in this paper. The simulation results and discussions are given to verify the correctness of the theoretical analysis

Fault Characteristics of GCC under PQ Control

Steady-state power decoupling control strategy. As shown in Fig. 1, the GCC consists of PV array, DC-link capacitor, grid-connected inverter and LC filter.

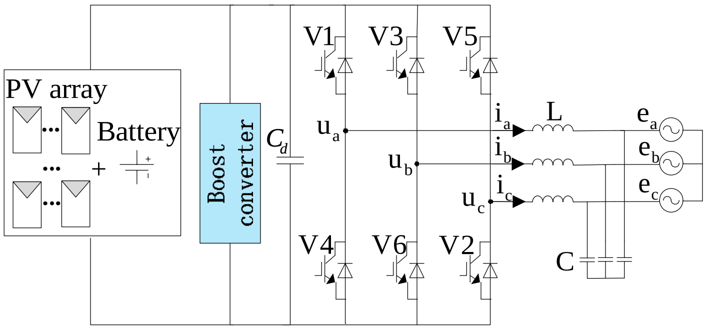


Fig. 1 Schematic diagram of the PV system

The mathematical model of GCC under synchronous rotating reference frame (D-Q axis) is:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \mathrm{R+Lp} & -w\mathrm{L} \\ w\mathrm{L} & \mathrm{R+Lp} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} \tag{1}$$

where, the subscript ***d*** and ***q*** respectively represent the d-axis and q-axis components, $p=d/dt$ and ω is the angular velocity of grid.

According to the instantaneous power theory [6], when ***d*** axis is oriented to the direction of the resultant grid voltage space vector ***E***, the formulas of the active and reactive power that the inverter provides are:

$$\begin{cases} P_{out} = u_d i_d \\ Q_{out} = u_d i_q \end{cases} \tag{2}$$

Fault Characteristic Analysis. PQ control is a typical current control mode and the control goal is to maintain the constant output power of GCC. The basic control structure is shown in Fig. 2.

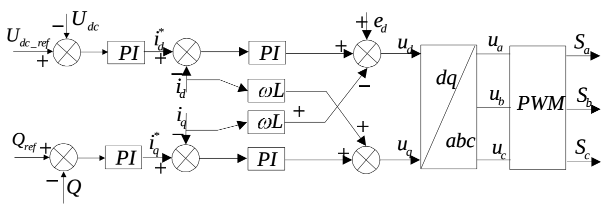


Fig. 2 PQ control structure

Based on the assumption that the fault time is short and external weather condition does not change during fault period, it is reasonable to consider that the active reference power value tracked by MPPT remains the same before and after fault happens. Due to the existence of battery energy storage, the DC side voltage can remain constant during the fault period as well. When the fault occurs, U_{PCC} will fall. If the inverter is subject to normal power-tracking control and that the acquired grid voltage is always of positive sequence [7], according to Eq. 3, the active current of the inverter will increase in order to keep the output power constant. The output current of the inverter during fault period can be obtained from Eq. 3:

$$\begin{cases} i_{d\_f} = i_{d\_f}^{*} = \dfrac{P_{PV}}{U_{PCC\_f1}} \\ i_{q\_f} = i_{q\_f}^{*} = 0 \end{cases} \tag{3}$$

where, i_{d_f} and i_{q_f} are respectively active and reactive fault current, U_{PCC_f1} is the positive sequence voltage of PCC.

As the fault location gets close to PCC, U_{PCC} will decrease and the active current of inverter will increase. Hence, there is a U_{PCC_fm1} at which the inverter's output current just reaches $I_{\max}$ and usually $I_{\max}$ is considered to be 1.2 I_{N}.

Based on the above analysis, GCC can be equivalent to a current source model during grid fault period:

$$\dot{I}_{PV\_f} = \begin{cases} \dfrac{P_{PV}}{U_{PCC\_fm1}} \angle q & \mathrm{U}_{\mathrm{PCC}\_f} > \mathrm{U}_{\mathrm{PCC}\_f0} \\ \dfrac{P_{PV}}{\mathrm{U}_{\mathrm{PCC}\_fm1}} \angle q & \mathrm{U}_{\mathrm{PCC}\_f} \le \mathrm{U}_{\mathrm{PCC}\_f0} \end{cases} \tag{4}$$

where, θ is the angle of PCC positive sequence voltage vector.

At present, many countries has issued codes that require the large capacity grid-connected GCC to have LVRT capacity. During fault period, the GCC ought to provide reactive current to the grid in priority. When the positive sequence voltage falls below 0.9p.u, send active and reactive current directives directly to the inner current loop according to Eq. 5 and Eq. 6:

$$i_q^{*} = \begin{cases} 0 \quad , & a > 0.9 \\ 2*(1\text{-}a) \quad , & 0.4 \le a \le 0.9 \\ 1.2 \quad , & a < 0.4 \end{cases} \tag{5}$$

$$i_d^{*} = \min\{i_{d0}^{*}, \sqrt{I_{\max}^{2} - (i_q^{*})^{2}}\} \tag{6}$$

where, all quantities are per unit values and α is positive sequence voltage value of PCC.

Under LVRT control, GCC can be regarded as a positive sequence current source $\dot{I}_1 = I\angle\varphi_{i1}$. The mathematical model $\dot{I}_1 = F(\acute{U}_{\mathrm{PCC}\_f1})$ which represents the relationship between $\dot{I}_1$ and $\acute{U}_{\mathrm{PCC1}} = \mathrm{U}_{\mathrm{PCC}\_f1}\angle\varphi_u$ can be obtained as follows:

$$\begin{cases} I_1 = i_d^*,\ j_{iu}=0\ ; & a > 0.9 \\ I_1 = \sqrt{(i_{d0}^*)^2 + 4(1-a)^2},\ j_{iu}=\arctan[2(1-a)/i_{d0}^*]; & 0.4 \le a \le 0.9,\ 2(1-a) \le \sqrt{1.2^2-(i_{d0}^*)^2} \\ I_1 = 1.2,\ j_{iu}=\arctan[2(1-a)/\sqrt{1.2^2-4(1-a)^2}; & 0.4 \le a \le 0.9,\ 2(1-a) > \sqrt{1.2^2-(i_{d0}^*)^2} \\ I_1 = 1.2,\ j_{iu}=90^{\circ}; & a < 0.4 \end{cases} \tag{7}$$

Fault Characteristics of GCC under Droop Control

The Principle of Droop Control. PV and energy storage integrated power generation system can apply droop control. We consider the circuit in Fig. 3 to study the power flow between a source and an AC bus through a transmission line or a transformer.

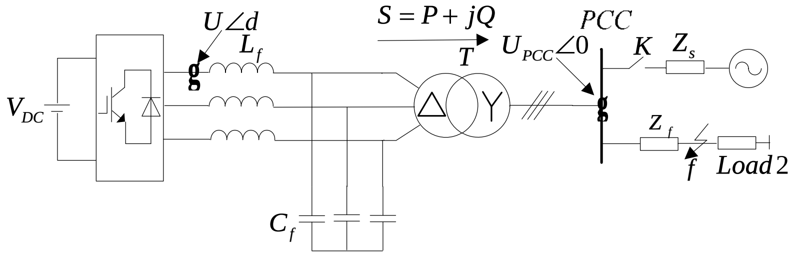


Fig. 3 Simplified model of grid-connected GCC

When the line impedance satisfies X/R >1, the power transmission between two sources can be obtained as follows [8]:

$$P = \frac{U_{PCC}U}{X} d \tag{8}$$

$$Q = \frac{U(U - U_{PCC})}{X} \tag{9}$$

It can be seen that active and reactive power provided by GCC are respectively decided by δ and U, which means the active power and reactive power can be controlled separately. The control relationship is shown in Eq. 10 and Eq. 11:

$$f - f_0 = -k_p(P - P_0) \tag{10}$$

$$U - U_0 = -k_q(Q - Q_0) \tag{11}$$

Fig. 4 shows the droop control curves. When load power change is detected, GCC regulates its voltage amplitude and frequency to change the output power and the control goal is to maintain the amplitude and frequency of inverter side voltage within a certain range. Fig. 5 presents the droop control block diagram.

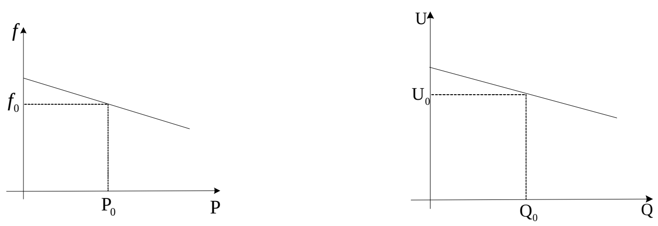


Fig. 4 Voltage and frequency droops based on inductive network mode

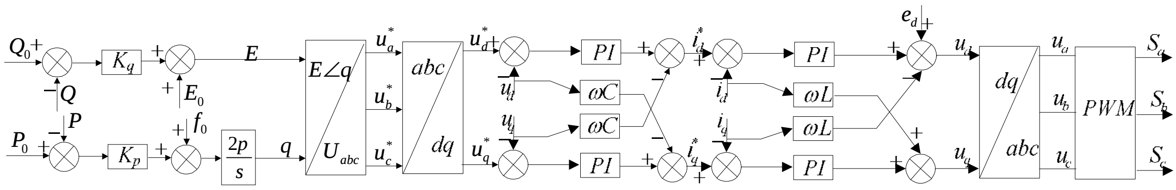


Fig. 5 Block diagram of droop control

Fault Characteristic Analysis. According to the above analysis, GCC based on droop control presents voltage source features. When the loads fluctuate, GCC can maintain the amplitude and frequency of PCC voltage within a certain range. As for the GCC, short-circuit fault is equivalent to load increase for fault impedance is smaller than load impedance.

When point *f* is far away from PCC, PCC voltage sag level is slight, so the equivalent increase of load is small and the output active and reactive power adjustment amount of GCC is small as well according to droop curve. If the output current does not exceed I_{max}, the GCC can still be considered as a voltage source. As the fault point *f* gets close to PCC, PCC voltage falls seriously and power adjustment amount will increase, which will lead to GCC's over-current. Assuming that the GCC with droop control has current limiter in current loop, once the output current exceed I_{max}, the limiter will pull current back to $I_{max,}$ thus the inverter can be seen as a current source when the voltage falls seriously. Based on the above analysis, we can suppose that the positive sequence voltage of PCC is $U_{PCC\_fd1}\angle\theta$ when the output current just reached I_{max}, then the equivalent model of GCC under droop control can be obtained as follows:

(a) (b)

Fig. 6 Equivalent model of GCC.

1) when $U_{PCC\_f1} \geq U_{PCC\_fd1}$, GCC can be equivalent to a voltage source as Fig. 6(a) shows. According to Eq. 9 and Eq. 10, the $U\angle\theta$ can be derived as:

$$\dot{U} = (U_0 - k_p\Delta Q)\angle\left(\frac{PX}{U_{PCC\_f1}U} + q\right) \tag{12}$$

2) when $U_{PCC\_f1} < U_{PCC\_fd1}$, GCC can be equivalent to a current source as Fig. 6(b) presents. According to equation Eq. 2 and Eq. 9, the current can be computed as:

$$\dot{I} = \frac{U}{XU_{PCC\_f1}}\sqrt{(dU_{PCC\_f1})^2 + (U - U_{PCC\_f1})^2}\angle\left(q + \arctan\frac{U - U_{PCC\_f1}}{U_{PCC\_f1}Ud}\right) \tag{13}$$

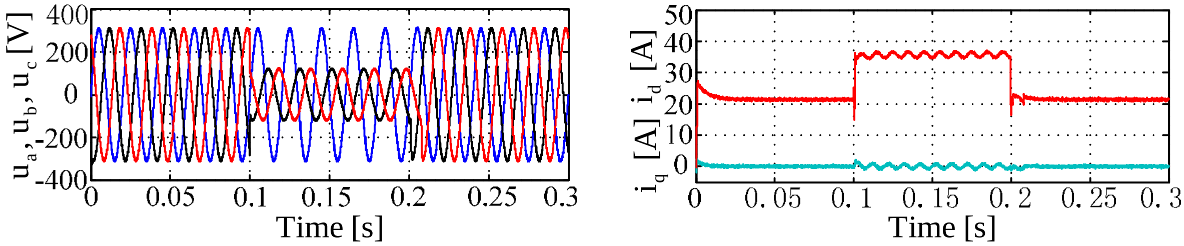
Simulation Result and Discussion

In order to verify the above analyses, the simulation model is built in Matlab/Simulink according to Fig. 3 and all the physical parameters of the system are defined in Table 1 and the voltage and current values in the table refer to amplitude values.

Table 1 Physical parameters of system

Symbol	Value	Symbol	Value
Z_s	0.07+j0.35 [Ω]	E	380 [V]
Z_{Load}	10 [Ω]	S_N	10000 [V•A]
U_{DC}	800 [V]	I_{max}	25.68 [A]

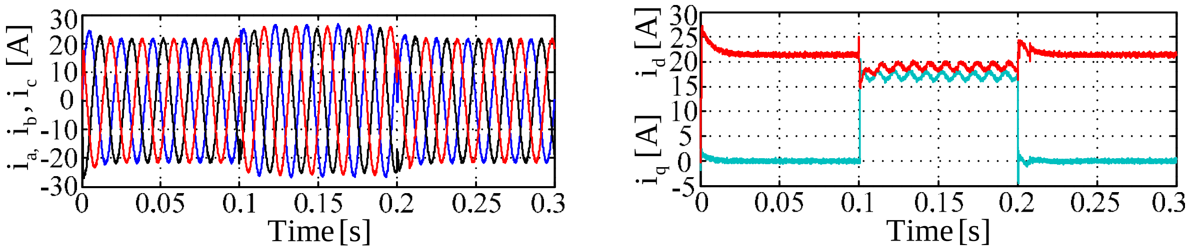
Fault Characteristics under PQ control and LVRT control. In this case, before the grid fault occurs, the GCC operates in unit power factor mode and provides rated active power. The fault duration is 0.1s which occurred between 0.1s and 0.2s and the PCC voltage drop to 0.4p.u at 0.1s. The total simulation is done within 0.3 second and voltage acquired from PLL is always positive sequence component.



(a) (b)

Fig. 7 Phase B, C ground fault. (a) PCC three phase voltage. (b) d/q axis current of GCC.

Fig. 7 describes the response of the GCC with PQ control under unbalanced grid fault at point *f*. When the PCC voltage falls to 0.4p.u, the positive sequence voltage component falls from 1.0p.u to about 0.6p.u. According to Eq. 3, the active current reference value can be acquired, and Fig. 11(b) suggests that the output active current keeps up with the reference value swiftly. There are double frequency component in d/q axis current waveforms during unbalanced fault, and this phenomenon results from the negative sequence component of PCC voltage. It can be found that GCC with PQ control only output active current and reactive current is about 0.



(a) (b)

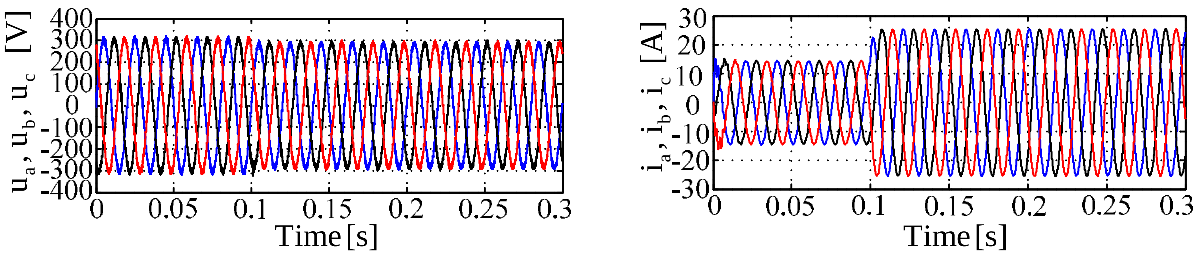
Fig. 8 Phase B, C ground fault. (a) Three phase current of GCC. (b) d/q axis current component of GCC

Fig. 8 is the response of the GCC with LVRT control under unbalanced fault. When PCC voltage drops to 0.4p.u, positive sequence voltage falls from 1.0p.u to about 0.6p.u. According to the LVRT control strategy, the reactive current directive is 0.8p.u and the active current is reduced to 0.89p.u during LVRT period. Fig. 8 (b) shows that GCC still output balanced current waveform, which contains only positive sequence component. The current amplitude increases from 1.0p.u to 1.2p.u and its phase change 42.4 degrees at 0.1s.

Table 2　Base Values

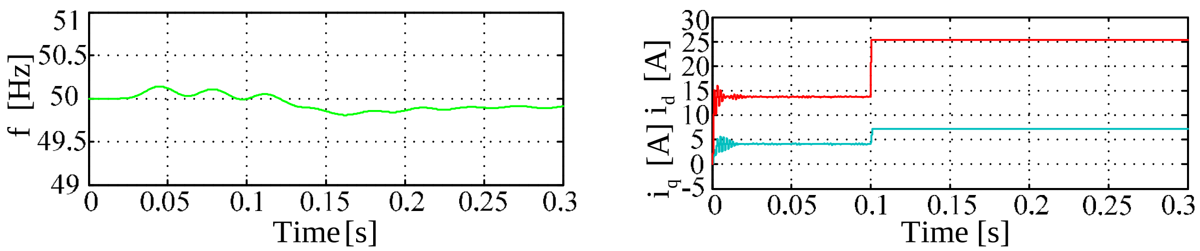
P_0	Q_0	U_0	f_0	k_p	k_q
7000 [W]	2000 [Var]	380 [V]	50 [Hz]	0.03	0.005

Fault characteristics under Droop control. In this case, the parameters of GCC are presented in Table 1 and Table 2. P_0 and Q_0 are the initial set-point for the reference active and reactive powers that are approximately equal to the expected power from the GCC based on the local load power factor. Before the fault happens, the active and reactive power that GCC provides is respectively 7000W and 2000Var. The fault occurred between 0.1s and 0.3s. The total simulation is done within 0.3 seconds.



(a)　(b)

Fig. 9　PCC voltage falling to 0.93p.u. (a) Amplitude and frequency. (b) Output three phase current of GCC.



(a)　(b)

Fig. 10　PCC voltage falling to 0.5p.u. (a) PCC voltage frequency. (b) d/q axis current of GCC

Fig. 9 is the response when PCC voltage drops to 0.93p.u. As shown in Fig. 9(b), the output current of GCC with droop control just reaches I_{max} at 0.93 under the parameters of Table 1 and Table 2. The voltage sag level is very slight for fault impedance is relatively large. The equivalent increased load is small and the output active and reactive power adjustment amount of GCC is small as well. Consequently, the output current does not exceed I_{max}. Fig. 10 presents the frequency and d/q current component response of GCC when PCC voltage falls to 0.5p.u. It can be seen from Fig. 10(b) that the current limiter acts after grid fault happens and the output d- and q- axis current component remain a constant value during fault period, which suggests that GCC acts as a current source under serious voltage sag level. With current limiter, the GCC can still keep connected to grid and provide reactive support to some extent under serious voltage sag, which is beneficial to power grid. Fig. 10(a) suggests that the frequency of inverter side voltage fluctuates noticeable as the voltage falls seriously, however the frequency still meet the codes.

Conclusions

This paper analyzed the fault characteristics of GCC under PQ control, droop control and LVRT control strategy. The simulations results showed the fault characteristics of GCC are subject to the control strategy. Through a reasonable PLL which can track positive component of PCC voltage, the output current of GCC under PQ and LVRT control does not contain negative sequence component under unbalanced grid fault, which differs from the traditional synchronous generator. Under PQ control model and LVRT control strategy, the GCC can be regarded as current source. When the PCC Voltage drops too low, the output current of GCC under PQ control will exceed I_{max} and the relay protection equipment will act. For GCC with droop control, it appears as a voltage source under normal situation. A slight voltage droop, e.g. ΔU_{PCC} =0.07p.u, will make GCC's output current exceed I_{max}. Usually when the fault happens, ΔU_{PCC} is much more than 0.07p.u. So it is reasonable to consider that GCC with current limiter under droop control appears as a current source during grid fault period.

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