Fault Characteristics of Full Power Inverted Source Considering Low-voltage Ride Through Control Strategy

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Abstract. New energy source is thriving in China. However, the fault characteristics of grids have been altered significantly with the penetration of new energy source increasing. In conventional researches, the fault features of wind farms were discussed briefly or simply overlooked. This paper began with the theoretical analysis of control system of full power inverted (FPI) sources and indicated that the response time of current control loop is 8.5 ms, while the steady state current of FPI source is controlled by reference values and set value of current limiter; the expressions of steady state current of FPI source were presented then. In addition, main factors affecting fault current, including different active power generation before fault, different fault locations and different fault types, were analyzed comprehensively and compared through simulation to gain a clear insight into the whole process of faults. The research is helpful to obtain a better understanding of new energy source.

1. Introduction
The contradiction between energy shortage and pollution is outstanding against the sharply increasing energy requirement. Renewable energy generation, represented by wind/solar power generation, is rapidly increasing. In China, the accumulated capacity of wind power integrated to grid has reached 129 million kW national wide, accounting for 8.6% of the total power generation[1]; The accumulated capacity of solar power has reached 43.18 million kW, rendering China the largest country in solar power generation capacity around the world[2].

The power generation principle and current changing patterns of wind/solar power generation system, equipped with fast switching power electronic devices, differ from synchronous generators during fault. The penetration of FPI (full power inverted) source, including PMSG(Permanent Magnetic Synchronous Generator) and solar cell, keeps going up and grid codes for renewable energy generation are issued to ensure their LVRT( Low Voltage Ride-Through) ability in China[3-4]. Therefore, the fault characteristics of renewable energy generation system are basically changed, resulting in the difficulty in instant and correct tripping of relay protection. This paper dealt with the fault characteristics of FPI source under LVRT control strategy.

Literature[5,6] only study the fault characteristics of PMSG under grid integration control strategy. However, LVRT strategy for FPI source according to present grid codes is distinguished from the grid
integration strategy[7]. For the former, DC voltage loop is blocked, current reference values for current inner loop directly ordered, to accelerate the response of FPI[8]. For the latter, current output by FPI can't be regulated effectively under asymmetric faults because of negative sequence current represented in the form of the 2nd harmonic current under positive sequence coordinate system. Thus researches on fault features of FPI source under grid integration strategy could hardly meet the requirements of present grid code[3,4,9], necessitating the further study on fault features under LVRT strategy.

In respect of LVRT strategy, existing research concentrated on the effect of current inner loop on FPI source. Literature[10] neglected the transient process brought by current inner loop with ideal PI parameters. In literature[11-13], FPI source was equivalent to a voltage controlled steady current source, fundamentally ignoring current loop transients. In fact, with current loop parameters chosen empirically, its effect on FPI current cannot be neglected.

Considering the problems in the previous research, response of FPI control system under LVRT strategy was analysed to study the fault features of FPI source in this paper. Furthermore, the current changing patterns in different scenarios, such as different active power output/ fault locations/ fault types, were revealed with simulation. The research provides theoretical support for the future study on adaption and theories of relay protection implemented in grid with a large portion of FPI source.

2. Modelling of FPI source

Figure 1 is the topology of power generation system with FPI source. The DC side, which is either solar cells or PMSGs, is entirely separated from grid, transmitting power to grid through FPI. Thus it's equivalent to DC source for its minor impact from grid faults.

The mathematical model of FPI source, including the impedance between grid and FPI source, in dq synchronously rotating frame is presented:

\[ \begin{align*}
L \frac{di_d}{dt} + i_d R &= e_{sd} - u_{td} + \omega L i_q \\
L \frac{di_q}{dt} + i_q R &= e_{sq} - u_{tq} - \omega L i_d
\end{align*} \tag{1} \]

Where, \( i_d, i_q \) are dq component of input current of FPI source; \( e_{sd}, e_{sq} \) are dq component of grid voltage; \( u_{td}, u_{tq} \) are dq voltage component at the terminal of FPI source; \( L,R \) are the impedance between grid and FPI source.

With all vectors oriented to grid voltage, active and reactive power are controlled respectively through dq current control of FPI. Based on equation (1), a dual-PI current loop control is designed and its governing equation is presented:

\[ \begin{align*}
u_{td} &= -(K_r + \frac{1}{K_s})(i_d^* - i_d) + \omega L i_q + e_{sd} \\
u_{tq} &= -(K_r + \frac{1}{K_s})(i_q^* - i_q) - \omega L i_d + e_{sq}
\end{align*} \tag{2} \]
Where, $K_p$, $K_i$ are parameters of portion section and integration section respectively; $i_d^*, i_q^*$ are dq component of current reference value; $\omega$ is synchronous speed; $s$ is Laplace operator.

According to equation (1) and equation (2), control loop of FPI source is drawn in figure 2. During normal operation, FPI source implements grid integration strategy, outputting active current. Its active current reference value is calculated from DC voltage governing control loop, while the reactive one is set to zero, ensuring FPI source to run in unit power factor.

![Figure 2. Current control loop diagram of FPI](image)

When grid voltage plunges below threshold, control strategy of FPI is switched to LVRT mode, with DC voltage loop blocked. Figure 3 is the control system of FPI source under LVRT strategy. Reference generation module initially calculates dq current reference value $I_{ref}^{(dq+)}$ according to LVRT requirements; Current limiter module determines whether recalculates reference value according to limitation judgement, and then outputs to current inner loop.

![Figure 3. FPI source control system diagram](image)

3. FPI source current analysis
FPI source output current is mainly related to its control system. Thus FPI source control system is studied to analyse fault features of FPI source.

In the whole control system, transients of PWM are neglected for the electronics switch rather fast; The output of integrator in current control loop is determined by input of present and the next time step, as a result, current loop causes dynamic process, affecting the transients of FPI; Reference generation and current limiter module using input from present time step, completing calculation instantly, outputting to current loop as reference value, affect steady fault current merely. Therefore, the response of FPI current loop is explored to investigate the transient fault current of FPI source, followed by the study of reference generation and limiter module to analyse steady fault current.

3.1. Effect of current loop on fault characteristics
With negative sequence current eliminated control strategy, current reference value for negative sequence current is set to zero, regardless of normal operation and fault. During faults, only the reference values of positive PI current are changed. Therefore, the transients of fault current is embodied in the response of positive current loop in time domain.
PWM transfer function added, the reduction of figure 2 is shown in figure 4. $K_p + K_i/s$ is PI controller transfer function; $K_{PWM}((T_{PWM}/s)+1)$ is converter transfer function, with $K_{PWM}$ the gain of converter and $T_{PWM}$ the inertia time constant; $1/(Ls+R)$ is impedance transfer function.

![Diagram of q-axis positive current loop structure](image)

**Figure 4.** q-axis positive current loop structure

Current control loop transfer function is presented accordingly:

$$\frac{i_d}{i_{dq}} = G_q(s) = \frac{K_{PWM}K_p(s + \frac{K_i}{K_p})}{sL(s + R/L)(sT_{PWM} + 1)}$$ *(3)*

Once fault occurs, current reference values change instantly. Considering typical step response of current reference value:

$$i_q = \frac{1}{s} \frac{G_q(s)}{1 + G_q(s)}$$ *(4)*

Equation (4) is substituted with the following parameters (in unit): $K_p = 0.25$, $K_i = 4.04$, $K_{PWM} = 3.17$, $T_{PWM} = 0.2992$, $L = 0.43368$, $R = 0$. After inverse Laplace transformation is implemented, the step response of current is shown in figure 5.

In figure 5, the adjusting time of step response is 8.5 ms, indicating that output current traces reference value within 10 ms after the abrupt change of reference value. Nevertheless, reference value is not always a step signal, the corresponding current loop response time will be longer.

![Graph showing unit step response of current loop and its error](image)

**Figure 5.** Curve of unit step response of current loop and its error

### 3.2. Effect of reference generation and current limiter module on fault characteristics

During steady state, fault current is in line with reference value precisely. According to grid code for wind/ solar energy generation in China[3,4], once grid voltage plunges to $0.2~0.9$ $U_N$, reactive current output from FPI source to grid must be no less than $1.5(0.9-U_s)I_N$, thus the dq positive current reference values is given:

$$\begin{align*}
    i_d &= i_{d0} \\
    i_q &= K_d(0.9-U_s)I_N
\end{align*}$$ *(5)*

Where, $i_{d0}$ is d-axis current reference value before fault; $K_d$ is reactive current gain factor; $U_s$ is voltage at FPI terminal; $I_N$ is rated current.

Considering the limited capacity of inverter, a limiter is implemented based on equation (5):
\[
\begin{align*}
\dot{i}_{d,\text{lim}} &= \begin{cases} 
\dot{i}_d, & (\sqrt{\dot{i}_d^2 + \dot{i}_q^2} \leq I_{\text{max}}) \\
\sqrt{I_{\text{max}}^2 - \dot{i}_{d,\text{lim}}^2}, & (\sqrt{\dot{i}_d^2 + \dot{i}_q^2} > I_{\text{max}})
\end{cases} \\
\dot{i}_{q,\text{lim}} &= \begin{cases} 
\dot{i}_q, & (\dot{i}_q \leq I_{\text{max}}) \\
I_{\text{max}}, & (\dot{i}_q > I_{\text{max}})
\end{cases}
\end{align*}
\]

(6)

Where, \(I_{\text{max}}\) is the maximum current that the converter is able to bear.

When grid voltage plunges to enable FPI source to alter to LVRT strategy, \(i_d^*\) is determined by active power generation before fault, \(i_q^*\) depends on the voltage after fault. Once the output of reference generation module exceeds \(I_{\text{max}}\), limiter module will adjust \(i_q^*\) primarily to enable FPI source to provide enough reactive power, and recalculate \(i_d^*\) considering the margin of converter.

4. Main factors affecting fault current

From the above analysis, it’s acknowledged that, during steady-state, fault current of FPI source is related to the active power generation before fault and grid voltage, restrained by a limiter. However, during transient process, the explicit expression for FPI source fault current is not given.

To further investigate the main factors affecting FPI current during the whole process of fault, three typical fault scenarios, including different active power generation before fault/ different fault locations/ different fault types, were simulated, to study their effect on FPI source.

4.1. Simulation model

As shown in figure 6, a renewable energy generation system with FPI source integrating to infinite system is built in RTDS (Real-Time Digital Simulator). The of FPI station is 99 MW in rated capacity, connecting to the infinite bus with a 25 km outgoing line.

4.2. Different active power generation before fault

Symmetric fault was set at the head of outgoing line, while the FPI sources within station generated different amount of active power before fault and the voltage drop in each case was almost the same. Figure 7 is the waveform of A phase current of outgoing line.

![Figure 6](image1.png)

**Figure 6.** Sketch of renewable energy generation system with FPI source

![Figure 7](image2.png)

**Figure 7.** Fault current curve under different active power generation before fault
In Figure 7, fault current increases with the rising of active power generation. This is because active current reference value increases and the reactive current reference value remains unchanged for the voltage drop is almost the same. Thus the total fault current increases.

4.3. Different fault locations
Symmetric fault was set at the head/middle/end of outgoing line, while the FPI sources within station generated the same amount of active power before fault. The waveform of A phase current of outgoing line is shown in Figure 8.

![Figure 8. Fault current curve under different fault location](image)

It can be seen from Figure 8 that fault current decreases with the distance between fault location and FPI source increases. This is because grid voltage drop is less severe when fault is set far away from inverter. According to equation (5), reactive current reference provided by FPI source decreases in proportion. Meanwhile, active current reference keeps constant with the active power generation of FPI source unchanged. Therefore, it can be concluded that fault current of FPI source is lower when fault location is far away from inverter.

4.4. Different fault types
Different fault types, including AC fault/ ACg fault/ Cg fault were set at the head of outgoing line, while the active power generation of FPI sources within station were the same before fault. Figure 9 shows the fault current sequence components of FPI source side(up) and system side(down).

![Figure 9. Fault current curve under different fault type](image)
For positive sequence current, affected by current loop, a rather short transient process appeared; Steady positive sequence current during faults is larger than that in normal operation, below the set value of limiter; Positive sequence current at FPI source side is well below that at system side because of the current-restrained nature of FPI source.

For negative sequence current, its reference value is always set to zero to eliminate negative sequence current. Negative sequence network is open-circuit at FPI source side thereupon. Thus transient process of negative sequence current can hardly be seen and FPI source never provides negative sequence current.

For zero sequence current, the zero sequence impedance at FPI side is station transformer impedance because of the connection mode of station transformer, thus zero sequence current at FPI side is much larger than that at system side.

5. Conclusion
This paper analysed the fault characteristics of FPI source. The conclusions are as follows.

(1) Under LVRT strategy, the fault characteristics of FPI source is affected by the response of current control loop, whose response time is 8.5 ms; In fault steady state, current of FPI source is determined by current reference values and the set value of current limiter.

(2) During the whole process of fault, with the rising of active power generation and the decreasing of the distance between fault and FPI source, the fault current of FPI is larger; Under asymmetric faults, positive and negative sequence current are affected by control strategy, while zero sequence current only depends on the connection mode of station transformer.

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