Research on Fault Characteristics and Line Protections Within a Large-scale Photovoltaic Power Plant

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Abstract. Centralized photovoltaic (PV) systems have different fault characteristics from distributed PV systems due to the different system structures and controls. This makes the fault analysis and protection methods used in distribution networks with distributed PV not suitable for a centralized PV power plant. Therefore, a consolidated expression for the fault current within a PV power plant under different controls was calculated considering the fault response of the PV array. Then, supported by the fault current analysis and the on-site testing data, the overcurrent relay (OCR) performance was evaluated in the collection system of an 850 MW PV power plant. It reveals that the OCRs at downstream side on overhead lines may malfunction. In this case, a new relay scheme was proposed using directional distance elements.

In the PSCAD/EMTDC, a detailed PV system model was built and verified using the on-site testing data. Simulation results indicate that the proposed relay scheme could effectively solve the problems under variant fault scenarios and PV plant output levels.

1. Introduction

Grid codes require PV power plants with the fault-ride-through (FRT) ability [1]. For the FRT accomplishment, variant PV inverter controls have been investigated. The different FRT controls result in diverse fault characteristics for the PV inverter. Due to the safety of the electronic devices, the fault current of the inverter is limited, which brings challenges to current based protection designs.

The current controllers under a double synchronous rotating frame (DSRF) are widely used in centralized PV inverters. In this control frame, several FRT controls have been investigated: 1) the control that eliminates the active output power oscillation results in injection of the negative-sequence current and the reactive output power oscillation [2]; 2) the control that suppresses the negative-sequence current causes both the active and the reactive output power oscillations [3]; 3) the control that eliminates both the active and the reactive power oscillations has the problem of current distortions [4]. The diverse controls lead to variant fault current characteristics. Researches on the fault current calculation of inverter-interface sources took the assumption that the active power supply from dc side keeps constant after a grid-side fault [5]. Those papers held the view that the slow dc-link voltage control loop provides a constant power reference and the fast response of the PV panel to the...
grid voltage variation is ignored. In [6] the PV panel characteristic was considered to help enhance the FRT ability but those effects on the fault current were not analysed.

In this paper, in order to comprehensively evaluate the performance of the existing protection design within the PV power plant, a consolidated expression of the fault current, suitable for different control strategies is calculated and analysed. The analysis is confirmed using both the fielding-testing and simulation results. Based on this, the existing line OCR within the plant is examined and some problems are revealed. A distance relay based scheme is proposed to improve the existing OCR and is highly robust to different fault scenarios and output levels of the PV power plant.

### 2. Characteristics of fault current

One of the collection systems within an 850 MW PV plant is discussed here. The collection system collects 64 PV units totally, 1 MW for one generation unit, as shown in Figure 1. Every 4 cables feed into one 35 kV bus and each cable collects 8 PV units. The collection system is connected with the main transformer through 35 kV overhead lines.

![Figure 1. A collection system within a large-scale PV power plant](image)

The fault characteristics within the collection system are dependent on the PV inverter control and hence the analysis of fault currents is based on the proper modelling of the control system. In order to realize a flexible fault-ride-through (FRT), inner-loop current control uses the regulators under the DSRF. The DSRF-based solution is widely used in commercial products for its decoupling relation between the active and reactive powers, which helps simplify the estimation of reference currents [7]. The dc-link voltage is regulated by the outer voltage control to realize the maximum power point tracking (MPPT).

In the DSRF, with a factor $K$ denoting the used control strategy, the current references under different controls can be rearranged and calculated as:

$$
\begin{bmatrix}
  i^*_d \\
  i^*_q \\
  i^+_d \\
  i^+_q
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
  e^+_d & e^+_q \\
  e^-_d & -e^-_q \\
  3 & -K e^-_d & K e^-_q \\
  -K e^+_d & -K e^+_q
\end{bmatrix} \begin{bmatrix}
  P^*_d \\
  D \\
  Q^*_d \\
  E
\end{bmatrix}
$$

(1)

where $K=0, \pm 1$. $D=(e^+_d)^2+(e^+_q)^2+K[(e^-_d)^2+(e^-_q)^2]$, $E=(e^+_d)^2+(e^+_q)^2+K[(e^-_d)^2+(e^-_q)^2]$.

By tracking the references in (1), the control aims of injecting symmetrical currents under unbalanced voltage conditions (if $K=0$), eliminating reactive power oscillations (if $K=-1$), and eliminating active power oscillations (if $K=1$), can be accomplished. The equation (1) is suitable for both balanced and unbalanced voltage conditions.

Based on (1), the amplitudes of positive- and negative-sequence injection currents can be calculated as
\[
\begin{align*}
\{ I_{dq}^{m}\} &= \frac{2}{3} |E_{dq}^{m}| \sqrt{\frac{P_0'}{D}} + \frac{Q_0'}{E} \\
\{ I_{dq}^{m}\} &= \frac{2}{3} |K| |E_{dq}^{m}| \sqrt{\frac{P_0'}{D}} + \frac{Q_0'}{E}
\end{align*}
\]

(2)

where \(|I_{dq}^{m}|=|d^{m}+j\beta^{m}|, |E_{dq}^{m}|=|e^{m}+je_{dq}^{m}|, (m=+,-).\)

The power references in (2) are substituted with the actual power provided by the PV unit during a fault and (2) can be rearranges as

\[
\begin{align*}
\{ I_{dq}^{m}\} &= \frac{2}{3 \gamma E_m} \sqrt{1 + (K \beta)^2} \left( 1 - K \beta \right) \\
\{ I_{dq}^{m}\} &= \frac{2 \beta}{3 \gamma E_m} |K| \sqrt{1 + (K \beta)^2} \\
\end{align*}
\]

(3)

where \(\gamma\) is the coefficient of positive-sequence voltage sag, \(E_m\) is the pre-fault voltage amplitude at the point of common coupling (PCC), \(\beta = |E_{dq}^{m}|/|E_{dq}^{m}|\) is a measure of the voltage unbalance, \(P_0'\) and \(Q_0'\) are the average values of the active and reactive powers supplied by the PV unit during a fault.

In a three-wire system, grid currents consist of the positive- and negative-sequence components. The three-phase instantaneous fault currents can be calculated as

\[
\begin{align*}
I_a &= \{ I_{dq}^{m}\} \sqrt{1 + (K \beta)^2} + 2 K \beta \cos \phi \sin(\omega t + \phi_a) \\
I_b &= \{ I_{dq}^{m}\} \sqrt{1 + (K \beta)^2} + 2 K \beta \cos(-4\pi / 3 + \phi) \sin(\omega t + \phi_b) \\
I_c &= \{ I_{dq}^{m}\} \sqrt{1 + (K \beta)^2} + 2 K \beta \cos(4\pi / 3 + \phi) \sin(\omega t + \phi_c)
\end{align*}
\]

(4)

where \(\phi = \theta^+ + \theta = \arctan(e_{dq}^{m}/e_{dq}^{m})\), is the phase shift of the negative-sequence voltage at the PCC. And the phases \(\phi_a, \phi_b, \phi_c\) are dependent on the used control scheme and the voltage profile.

This implicates that the PV fault current is determined by several factors: \(\gamma, \beta, P_0'\) and \(Q_0'\), and no current distortions appear under unbalanced faults. The converter interface has fast response ability and the PV panel itself can help restore the dc-link power balance, which makes the fault current enter into the steady state smoothly.

Because static var generators (SVGs) are equipped in real plants, PV units work at unity power factor during faults (\(Q_0'\) in (3) is zero). Considering that the control \((K=0)\) is used within the plant (In Section 4, the field-testing data confirm this), the post-fault currents in (4) are further simplified as

\[
\begin{align*}
I_a &= \frac{2 P_0'}{3 \gamma E_m} \sin(\omega t + \frac{\pi}{2} + \theta^+) \\
I_b &= \frac{2 P_0'}{3 \gamma E_m} \sin(\omega t - \frac{\pi}{6} + \theta^+) \\
I_c &= \frac{2 P_0'}{3 \gamma E_m} \sin(\omega t + \frac{7\pi}{6} + \theta^+)
\end{align*}
\]

(5)

With the control \((K=0)\), the post-fault currents keep symmetrical during even unbalanced faults. The active power \(P_0'\) is determined by the operating point on the I-V characteristic curve of the PV panel. Considering the non-linear I-V characteristic, the factor \(\gamma\) is dependent on the fault profile. It is hard to perform the precise calculation of fault currents. However, the above fault characteristics provide the possible applications of the protective relays based on the system frequency measurement.
3. Evaluation on the line protection within the collection system

3.1. Performance of the overcurrent relays
The coordination principles of the OCRs are detailed in Table 1. The performance of the existing OCRs is evaluated considering the fault analysis in the Section 2.

Table 1. Coordination principles of the OCRs in the collection system

| Location                  | Protection | Coordination Principle                        | Setting Value | Delay |
|---------------------------|------------|----------------------------------------------|---------------|-------|
| Overhead line             | OCR        | Zone I Sensitivity of 2 when a fault occurs at the end | 0.866I_{f1}/2 | 0.1s  |
| (Upstream)                | OCR        | Zone II Coordination with next zone I         | 1.2×6Ie        | 0.6s  |
|                           | OCR        | Zone III Maximum load current                 | 1.3nIe         | 0.9s  |
| Overhead line             | OCR        | Zone I Coordinating with upstream zone I      | 0.866I_{f1}/2I/1.1 | 0s    |
| (Downstream)              | OCR        | Zone II Coordination with next zone I         | 1.2×6Ie        | 0.3s  |
|                           | OCR        | Zone III Maximum load current                 | 1.3nIe         | 0.6s  |
| Cable                     | OCR        | Zone I Step-up transformer inrush currents    | 6Ie            | 0s    |
|                           | OCR        | Zone II Maximum load current                  | 1.3nIe         | 0.3s  |

$I_{f1}$ means the short-circuit current from the upstream in case of a three-phase fault at the line end. $I_e$ is the rated current supplied by PV units on one cable. $n$ means the number of branches connected into one bus in a collection station.

For a fault as $f_1$ in Figure 2, the relay measured current is large enough to trigger the OCR on the cable due to the grid-side large short-circuit capacity. Similarly, the OCR on the overhead line, which links the faulted cable, can initiate its zone II and III protection. The downstream OCR’s zone I covers a longer distance, and this might cause the downstream OCR on the overhead line in malfunction when a close-end fault occurs.

For a fault on one overhead line, as $f_2$ in Figure 2, similarly the upstream OCR can operate correctly due to the grid-side large capacity. On the opposite side, the fault current from the PV side is limited (generally 1.2 times the rated current). Thus the OCRs on the neighboring lines are prevented from malfunction, however those on the faulted line cannot operate. When the pilot protection is out of service, the downstream OCR cannot isolate the PV side from the fault either, which may bring risk to the maintenance personnel.

![Figure 2. Schematic diagram of the collection system](image)

3.2. Proposed protection scheme
When the fault occurs close to the upstream side, the faulted overhead line and the neighboring lines share the similar voltage profile. Then it is difficult to distinguish the faulted overhead line from the neighboring ones only using the fault current information from the PV side.

Based on the analysis in Section 2, a two-zone directional distance relay (shown as the dashed circles in Figure 2) is proposed to replace the downstream OCR on the overhead line. Influenced by the grid-side large current, the measured impedance at relay $p^s$ is much larger than the actual impedance between the relay and the fault. It can be used to discriminate the faulted line from the non-
fault ones.

In consideration of an extremely serious situation that the fault is almost at the upstream relay on the overhead line ($\alpha=0$), the measured impedance at the downstream relays will be the respective line impedances. If the distance relay is set with only one zone, in order to prevent the neighboring lines from mal-operation, zone I should not operate until the opposite OCR operate and isolate the neighboring overhead lines from the fault. This leads to the distance relays operating with a time delay (>0.9 s, as the relay settings shown in Table 1) wherever the fault occurs on the overhead line.

In order to isolate the PV side from the fault as soon as possible, zone II with a time delay is coordinated with zone I. Zone I covers part of the overhead line, in which the fault can be isolated without delay, whereas zone II covers the whole line and has a time delay longer than the upstream OCR's to deal with the extremely serious situation ($\alpha=0$). For faults on the cable, it is seen by the directional distance relay as outside the operation region. At this moment, the upstream OCR on the overhead line coordinates with that on the cable and this can ensure the correct relay operation.

Considering the appropriate margin, the detailed principle is set as ($K_{\text{rel}}$ is the reliability factor)

$$
\begin{align*}
Z_{\text{set}}^{\text{I}} &= K_{\text{rel,1}}Z_1 \quad (K_{\text{rel,1}}=80\%) \quad \Delta t_1 = 0s \\
Z_{\text{set}}^{\text{II}} &= K_{\text{rel,II}}Z_1 \quad (K_{\text{rel,II}}=1.2) \quad \Delta t_\text{II} > 0.9s
\end{align*}
$$

(6)

4. Field-testing and simulation results

4.1. Comparison between field-testing and simulation results

A real short-circuit test was carried out within the plant, and the fault was imposed on one overhead line near to the downstream relay ($\alpha$ is close to 1), as $f_3$ in Figure 2.

As shown in Figure 3(a), the fault applied at 8.86 s was phase B to ground (BG), then changed into phases B and C to ground (BCG) at 9.09 s, and was isolated at 9.17 s. Before the test, the PV units output about 0.6 pu and worked at unity power factor. The step-up transformers (35/0.3 kV) have Y/d connections and the main transformer (330/35 kV) has YN/d connections. The grounding transformer was not working in the test, so PV units experienced no significant current increase during BG, in Figure 3(c). The currents recorded on a neighboring overhead line were supplied only by PV units.

During BCG fault (9.09 s-9.17 s), the fault currents from the PV side keep symmetrical and the fault current amplitude does not reach the upper limit (1.2 pu). This is related to the reduction of output power from the PV arrays which operated away from their MPP during the fault.

In PSCAD/EMTDC, a detailed model of the collection system was built using the same control ($K=0$) and the simulation results are shown in Figure 3(b) and (d). Compared with the field-testing results, the simulation produces highly similar fault current characteristics. The fault transient in Figure 3(b) is a little longer time. Considering the unknown parameters inside of a commercial inverter, the relatively small transient differences in the simulations are acceptable.

(a) Voltages recorded in the test  
(b) Voltages in the simulation
4.2 Verification of the proposed protection scheme

In order to verify the proposed distance relay at PV side, all the factors that includes the grid capacity, the PV output level and fault types, are considered in simulations. Here gives one typical cases:

The ratio of the PV power plant's rating capacity to the grid's is 1:10 and the plant works at 0.6pu, an ABG fault occurs on the overhead line 0.1l away from the downstream relay location (l is the line length). The protection zones of the ground distance relay and the phase distance relay are depicted in Figure 4(a) and (b) respectively. The similar results from the neighbouring line are shown in Figure 4(c) and (d). The measured impedances of the ground distance elements (AG and BG) and the phase distance element (AB) on the faulted overhead line fall in zone I constantly, as shown in Figure 4(a) and (b). The measured impedances of the distance elements on the neighbouring overhead line all fall outside the protection zones as shown in Figure 4(c) and (d). Therefore, AG, BG and AB distance elements on the faulted overhead line can operate correctly.

Table 2. Operation results of the original and the proposed relays

| Fault locations   | PV output levels | Fault types | Overcurrent relays | Distance relay |
|-------------------|------------------|-------------|--------------------|---------------|
|                   |                  |             | Cable              |               |
|                   |                  |             | Overhead line      |               |
|                   |                  |             | Downstream         | Upstream      |
| Cable             | Close to the relay location | 40% | LL, LLG, LLL     | Downstream, Upstream, Downstream |
| Overhead line     | \( \alpha = 0.5 \) | 20%         | LL, LLG, LLL     | Downstream, Upstream, Downstream |
|                   | \( \alpha = 0.9 \) | 60%         | LL, LLG, LLL     | Downstream, Upstream, Downstream |

Figure 3. Field-testing and simulation results

Figure 4. Results of the distance relays operation at downstream side on the overhead lines in case an ABG fault 10%l away from the downstream relay location. (a) (c) results of the ground distance relay operation on the faulted and neighboring lines (b) (d) results of the phase distance relay operation on the faulted and neighboring overhead lines
In Table 2, the performances of the existing and the proposed relays are presented when different fault positions, fault types and output levels of the PV power plant are considered. In the table, the symbol + (-) represents the protection can (not) operate and the Roman number represents the corresponding operation zone. For faults near the relay installation on the cable, the directional distance element detects the faults outside the protection zone whereas the OCR at downstream side on the faulted overhead line can operate. For faults on the overhead line, the distance relay responses correctly in case of different fault positions, PV output levels and fault types. In case the pilot relay is out of service, the distance relay can isolate the PV system from the fault correctly. The single line to ground faults within the plant are not included in Table 2, because fault currents from the PV side do not experience significant increase and the OCRs do not operate. However, the distance relay still has a good performance due to the correct impedance estimation.

5. Conclusion
The fault current characteristics within a large PV power plant are analysed considering the control used in practice. The PV panel characteristic can help reduce the fault current, which challenges the conventional method of fault analysis and the existing coordination of OCRs. By comparing the field-testing results with the simulation results, the existing OCR are proved to have the problems of mis-operation and mal-operation. A distance relay based protection design is proposed to substitute for the defective OCR scheme. Simulation results show that the proposed relay can effectively solve the existing OCR's problems. Apart from being highly robust to variant fault scenarios, the proposed protection has a good performance in case of different output levels of the PV power plant and so can meet the requirements for industrial applications.

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