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Negative-Sequence Current Injection of Transmission Solar Farms

Gefei Kou, *Senior Member, IEEE*, Jacob Jordan, Brett Cockerham, Russell Patterson, *Senior Member, IEEE*, Philip VanSant, *Senior Member, IEEE*

***Abstract*--Integrating solar generation brings about unique challenges in power system protection. Previous studies have found inverter-based resources featuring distinct fault responses compared to conventional generators. The reduction in fault current magnitude and lack of negative and zero sequence currents can fundamentally impact the way that the power system is protected. This paper studies the negative-sequence current injection from transmission-connected solar farms. Using field recorded data, this paper reveals the negative-sequence current injection behaviors of solar farms by analyzing how inverters respond to faults. In addition, the paper studies how the negative-sequence current can impact negative-sequence directional elements used in protective relays. The response of protective relays' is evaluated by replaying field events using actual relay settings applied on conventional systems.**

***Index Terms*--solar generation, power system protection.**

I. Introduction

It is understood by the industry that inverter-based resources (IBRs) exhibit differing fault characteristics compared to synchronous generators. Most profoundly, solar inverters produce low magnitude of fault current with insufficient levels of negative and zero sequence currents [1]. The shift in system fault characteristics has implications on fault detection and protective relaying. A whitepaper by Electric Power Research Institute indicates that protection schemes based on negative-sequence components, including overcurrent elements and pilot protection, can be affected and experience mis-operations [2]. BC Hydro's field experience with Type 3 wind turbines and STATCOM confirmed that negative-sequence relaying could be undependable and not trip for in zone faults due to false directional declaration [3]. Most recently, an extensive simulation study using original equipment manufacturers' electromagnetic transient models of their equipment was carried out by Sandia National Laboratories. The study evaluates the impact of negative-sequence current injection on transmission relaying and discovers that inverter fault responses are inadequate to ensure reliable operation of protection elements in certain realistic scenarios [4]. The industry is proactively addressing the challenge. A major effort is led by IEEE P2800 Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems, which aims to standardize inverter fault responses to simplify protection scheme selection and relay settings. Meanwhile, it is desirable to understand how exactly solar inverters in the field react to faulted conditions so that the risk of protection maloperation can be evaluated. In addition, the findings will shed light on ideal inverter fault responses and guide standardization. This paper is intended to serve those two goals.

Distribution and transmission protection schemes typically operate in different time scales. On distribution systems, where overcurrent protection is prevalent, fault clearing can take up to tens of cycles, due to the need of coordinating multiple overcurrent relays along a radial feeder. In contrast, transmission protection usually operates in high speed for system stability, power quality, and equipment exposure considerations. A transmission line fault can be cleared within 5 cycles, which includes 1-2 cycles of relay time and 2-3 cycles of breaker interruption time. Therefore, solar farms' fault responses are perceived differently by distribution and transmission relays. This statement can be illustrated in Fig. 1. The event demonstrates the fault response of a 20-MW utility-scale solar farm connected to a distribution feeder. A single-phase-to-ground fault dropped Phase B voltage to 0.33 per unit (pu) and produced a negative-sequence voltage of 0.19 pu at the point of measurement. Looking at the negative-sequence current response, the current magnitude surged immediately after the fault and maintained for about two cycles before it was suppressed by inverter control actions. In the two cycles of transient, the inherent inverter response was to provide negative-sequence current, whereas during the steady-state timeframe, the inverters acted as an open negative-sequence circuit. The observed transients are consistent among several recorded events reported in [5] and the transmission system events later presented in this paper. It is therefore noted that, unlike overcurrent protective devices in distribution systems, transmission line relays (which react to faults within two cycles) see solar inverters as negative-sequence sources. The negative-sequence current injection can affect multiple protection elements of a transmission line relay, including negative-sequence directional elements. Thus, it is critical to understand inverter fault responses, so that proper protection settings are applied to avoid a mis-operation or a failure to operate. The rest of the paper explores this topic.

Dr. Kou, Mr. Jordan and Mr. VanSant are affiliated with Dominion Energy, Richmond, VA, USA. The team specializes in system protection, solar interconnection, and relay testing. Mr. Cockerham is an Application Engineer with Schweitzer Engineering Laboratories, Charlotte, NC, USA. Mr. Patterson is the owner of Patterson Power Engineers, LLC, Chattanooga, TN, USA and Chairman of the IEEE Power System Relaying and Control Committee.

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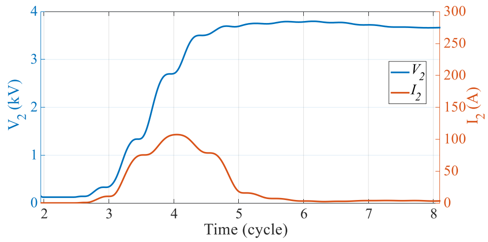

Fig. 1. Solar Farm Response to an Unbalanced Fault

The major contribution of this paper includes:

- Studied the transient fault response of transmission solar farms based on real fault events;
- Analyzed the interaction between the negative-sequence current of solar inverters and transmission line relays' directional elements;
- Verified the findings by playing back real, high-resolution fault data on relays using actual field settings.

Section II presents multiple field captured fault responses of transmission-connected solar farms with a focus on negative-sequence current injection. Section III evaluates the impact of the negative-sequence current injection on typical protection schemes by replaying real events on transmission relays. The study is concluded in Section IV.

II. Measured Negative-Sequence Current Injection From Transmission Solar Farms

Transmission-connected solar farms are typically interconnected to the grid through a three-breaker ring bus as shown in Fig. 2. This topology provides operational flexibility and high reliability. Solar farms are connected to the transmission bus via a system step-up transformer. Current and voltage measurements are taken on the high voltage side of the transformer for relay operation and system monitoring. The measurement data presented in the paper are collected by digital fault recorders with a reporting rate of 80 samples per cycle. Inside the solar farm, the system transformer steps down the transmission voltage (i.e. 500, 230, or 115 kV) to a medium voltage level. Multiple medium voltage feeders interconnect solar inverters via distribution transformers. Typically, each solar inverter is rated in 1-3 megawatts (MW) with the total capacity of the solar farm sized from 20 MW to a few hundred MW.

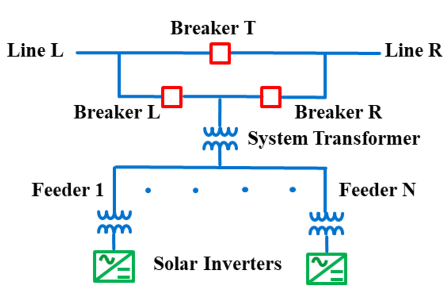

Fig. 2. Three-breaker Ring Bus Topology

A single-phase-to-ground fault took place on the 115-kV system. The fault led to a voltage drop to 0.82 pu on a nearby 75-MW solar farm. The solar farm's negative-sequence current response was captured in Fig. 3. The data shown are fundamental frequency values, which are resistant to harmonic content, and used for relay operation. The voltage imbalance created 6.0 kV negative-sequence voltage (V_2) at the solar farm's primary side. In response, 28 A of negative-sequence current (I_2) was observed on the 115-kV side in the first three cycles after the fault. The negative-sequence voltage went away after transmission line fault clearing.

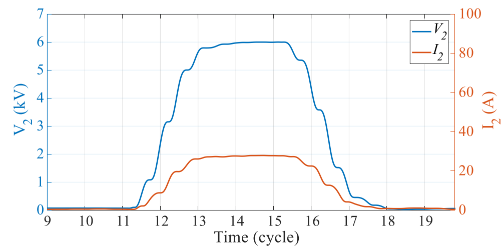

Fig. 3. Transmission Solar Farm Negative-Sequence Current Response

To identify the directionality of the negative-sequence current, apparent negative-sequence impedance, Z_2, is derived by dividing V_2 by I_2 per Equation (1). Assuming current is polarized towards the solar farm (i.e. load convention. This convention is used throughout the paper), Z_2 with zero degree angle means purely resistive, whereas Z_2 in the third quadrant means the observed component is a source. Fig. 4 provides an example and shows the calculated negative-sequence impedance of a conventional source. The event captured the change of the source apparent impedance during the fault. It is noted that the measured impedance magnitude quickly reduces from 0.5 to 0.025 pu after fault inception. Meanwhile, the impedance angle converges from -65 to 74 degrees, indicating that the negative-sequence impedance of the machine is highly inductive as expected.

$$Z_2 = \frac{V_2}{I_2} \tag{1}$$

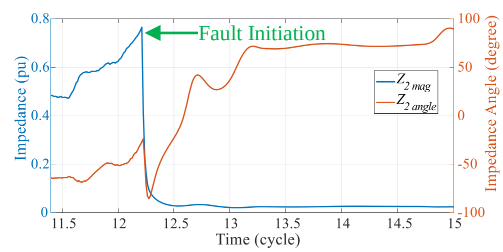

Fig. 4. Negative-Sequence Impedance of a Conventional Source

By comparing the apparent negative-sequence impedance of the solar farm in Fig. 5 (the same event as shown in Fig. 3) with the conventional source in Fig. 4, a few observations can be made: 1) Unlike the conventional source, the solar farm has a relatively high apparent impedance (1.22 pu). This may affect negative-sequence directional declaration, which will be discussed in the next section; 2) The impedance angle converges to -86 degrees, which means the solar farm acted as a source during the transient and injected negative-sequence reactive power. In contrast, synchronous generators behave as a negative-sequence impedance (load). Analysis on a total of five transmission events at four solar farms verifies the finding above. The fault types are summarized in Table I. The apparent negative-sequence impedance magnitude and angle of solar farms are summarized in Fig. 6. It is noted that the impedances

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may fluctuate at fault inception and the average values are presented.

The figure shows that the calculated negative-sequence impedance of solar farms can vary within a wide range (from 0.22 to 1.22 pu) and the per unit values are higher than that of synchronous generators. The impedance angle can also fluctuate between -86 to 30 degrees. Within this angular range, solar farms act either as a resistance or reactive source. The observed angular behavior is drastically different from conventional sources that typically have an inductive angle between 70 to 90 degrees. While more empirical data is necessary to draw a firm conclusion, it is speculated that the wide variation in negative-sequence impedance magnitude and angle may be associated with the following factors: 1) Inverter controls play a key role in transient fault responses. The four solar farms under study use inverters provided by different manufacturers, who likely apply their own proprietary inverter control algorithms; and 2) Solar inverters exhibit non-linear fault responses at different fault conditions. Cases 4 and 5 were captured at the same solar farm. However, the negative-sequence impedance is measured at 1.1 and 0.4 pu, respectively. The variation may have to do with the fault type, i.e. phase-to-phase versus single-phase-to-ground. It may also be correlated to the pre-fault condition. Case 4 was output at 36% of the full capacity, whereas Case 5 operated at 19%. There is no guarantee that the negative-sequence impedance of transmission solar farms will behave in a consistent manner across different operating conditions. Protective relaying should avoid such presumption to avoid delayed tripping or mal-operation.

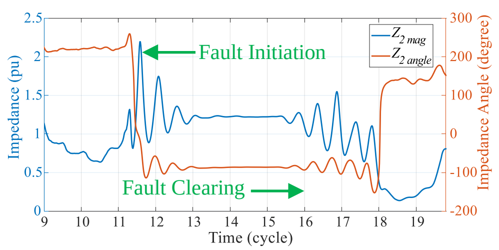

Fig. 5. Negative-Sequence Impedance of a Solar Farm

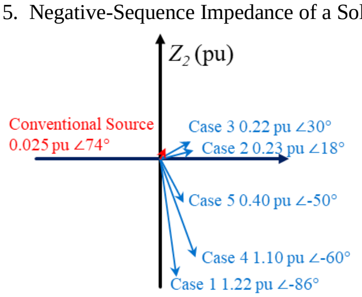

Fig. 6. Solar Farm Apparent Negative-Sequence Impedance

Table I Summary of the Studied Cases

Case No.	Fault Type	MW Capacity
1	Single-phase-to-ground	75
2	Single-phase-to-ground	75
3	Phase-to-phase	80
4	Phase-to-phase	100
5	Single-phase-to-ground	100

III. Impact on Protective Relaying

The calculated apparent negative-sequence impedance is used by relays for various purposes. A major application is in operation of negative-sequence directional elements, which are used to supervise phase-phase distance elements, ground distance elements, and ground overcurrent elements. Those elements serve as primary and secondary protection elements for unbalanced faults. A common approach to identify directionality for unbalanced faults is to compare the calculated negative-sequence impedance against settable forward and reverse thresholds. If the calculated negative-sequence impedance is less than the forward threshold (Z_{2F}), the fault is considered forward. If the calculated impedance is greater than the reverse threshold (Z_{2R}), the fault is viewed as reverse. Typical pre-set thresholds are centered on the origin, such as Z_{2F}= -0.3 and Z_{2R} = +0.3 ohms secondary for relays with 5 amp nominal current [6]. Another long-standing approach is a simple directional element that exhibits maximum operating torque when I_2 leads V_2 by 90 degrees. This element suffers from the same problem in the presence of a solar farm, whose negative-sequence current is not leading V_2 as it is in a conventional source.

The angle of the apparent negative-sequence impedance of solar farms can undermine the effectiveness of negative-sequence based directional elements. To evaluate the impact, the recorded events were played back on a line relay that mirrors actual field settings. The playback emulates Case 1 where the fault occurred in the forward direction of Line R relay (Fig. 7). Bus voltage measurement at the substation, along with the solar farm's fault current, I_s, are fed to the relay analog input channels as shown in Fig. 8. By feeding the solar farm's fault current to the Line R relay, it represents a scenario where 1) Line L does not source any fault current; or 2) Breakers T and L are open due to maintenance; or 3) Line L side is a weak source or connects to another solar farm. Among the three scenarios, the studied solar farm provides the dominant fault current for relay operation.

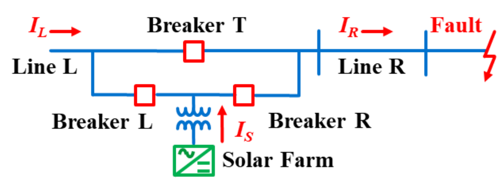

Fig. 7. Event Playback Setup

It is observed in Fig. 8 that the forward negative-sequence ground directional element, F32QG, never asserted for the forward fault. This element provides directional supervision for multiple tripping elements, including ground and phase distance elements. The negative-sequence ground directional element failed to declare a direction because of the solar farm's negative-sequence impedance characteristics revealed in Section II. As shown in Fig. 9, the apparent impedance of the solar farm source reaches 48 ohms on the secondary side. Its colinear projection on the line positive-sequence impedance Z_1, which can be formulated as in Equation (2), equals to 24 ohms (It is noted that Equation (2) is modified from the relay actual

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implementation to adjust for the current transformer (CT) polarity connections). This value is much greater than the forward fault impedance threshold (or the forward boundary as shown in Fig. 9), -0.3 ohms. Thus, the fault is not considered as in the forward direction and the line relay would not trip for this in-zone fault.

$$Z_2(colinear\ projection) = \frac{Re\left[-V_2 I_2^*\left(1\angle Z_{1angle}\right)^*\right]}{|I_2|^2} \quad (2)$$

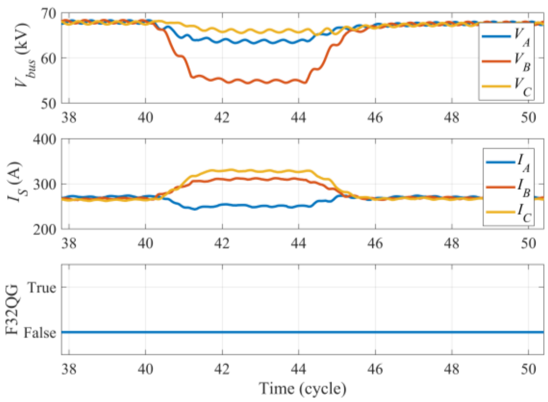

Fig. 8. Playback of a Solar Farm Fault Event

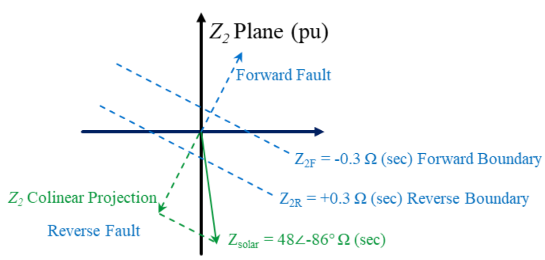

Fig. 9. F32QG Forward Direction Declaration

IV. Conclusions

The paper explores real solar farms' negative-sequence current injection responses to transmission system faults. It is found from these field measurements that solar farms can act as negative-sequence sources throughout the transients. Such fault response can interfere with conventional relay fault direction declarations, especially in scenarios where solar farms are the dominant source for fault currents. Phase and ground distance elements that are supervised by negative-sequence directional elements will be affected and become less secure and reliable. A thorough protection scheme review is warranted on transmission lines relays with exposure to IBRs to account for their impact.

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