Fault Characteristics of Distributed Solar Generation

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***Abstract*--Inverter-based distributed energy resources (DERs) are characterized with low fault current and negligible amount of negative and zero sequence currents. Understanding DER's fault characteristics is critical for fault analysis and protective relay setting. Despite the abundant work on DER modeling, few research studies have been done to analyze DER's fault behaviors during actual fault events. This paper explores recorded fault events collected by Dominion Energy. Fault magnitude, angle, and sequence components are analyzed to show that actual DER fault response may differ from previous understandings.**

***Index Terms*--Distributed Energy Resource (DER), solar generation, power system protection, fault analysis.**

I. Introduction

Traditional distribution feeders are radial systems, where the utility serves as the sole source of fault current. Overcurrent schemes are prevalently used for fault detection. In overcurrent schemes, an overcurrent device operates when the measured current exceeds a predetermined value, either momentarily or with a time delay. Primary and backup protective devices are time coordinated so that the former can safely clear a fault before the latter initiates an interruption. As Distributed Energy Resources (DERs) emerge on distribution circuits, they present another source of fault current. The fault current from DERs can partially offset the utility's fault current contribution, resulting in delayed relay operations. With DER's impact on fault current, an accurate representation of DER fault characteristics is therefore paramount to fault analysis and protective relay setting.

It has been well known that inverter-based generators have noticeably different fault characteristics from that of conventional generators. In a recent IEEE report [1], inverter-based generators are characterized as contributing a low magnitude of fault current. The magnitude is limited to 100-120% of rated output current. Additionally, the fault current does not contain sufficient levels of negative or zero sequence quantities for proper detection. In [2], it is stated that solar inverters, in general, can provide fault current contribution of about 1.2 per unit (pu). As solar inverters are designed to inject the maximum power available from solar panels, it is argued in [3] that solar inverters act as a constant power source during faulted conditions. A current limit as high as 2 pu can be reached due to depressed voltage. A detailed description on renewable inverter control systems can be found in [4].

This paper studies the fault event recordings collected at Point of Interconnection (POI) reclosers by Dominion Energy. Seven fault events from three solar DER sites are analyzed. Both transient and steady-state fault responses are captured. The analysis will be focused on steady states, during which relay operations take place. In Section II, the DER system configuration is described. Fault events are presented in Section III. Conclusions are drawn in Section IV.

II. DER System Configuration

The solar sites under study are utility scale inverter-based DERs that are interconnected at 34.5 kV distribution circuits (19.92 kV phase to neutral). As shown in Table I, the electrical distance from the solar sites to corresponding substations is approximately 3 miles. Each solar site consists of multiple three phase solar inverters and step-up transformers. The solar generation capacity ranges from 22.0 to 22.5 MVA. Each inverter is rated between 2.0 to 2.5 MVA. All step-up transformers are Wye-ground/Delta connected with the Wye side facing the utility. This type of transformer connection provides a zero sequence source. Neutral grounding resistors (NGRs) are installed between the Wye neutral and the ground to limit ground fault current being injected from solar sites.

Table I Distributed solar generation site information

Site Name	Voltage kV	Electrical distance in mile	MVA Capacity
C	34.5	2.5	22.5
P	34.5	3.6	22.0
S	34.5	3.0	22.5

All three sites are equipped with direct transfer trip. If an up-line protective device between the POI and substation feeder breaker asserts trip, a transfer trip command will be sent to the POI recloser and trip the recloser. Direct transfer trip avoids unintentional electrical islanding, mitigates transient overvoltage, and ensures personnel safety. Unity power factor control is applied on the studied solar inverters. Despite the newly approved IEEE Standard 1547-2018 [5], which requires DERs to have fault ride-through capacities, unity or fixed power factor controls are common in existing distributed solar inverters.

III. Fault Event Study

A simplified system schematic is shown in Fig. 1. The

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studied faults are on the feeders and external to the solar sites. Fault data is collected by POI reclosers, which measure fault current contribution from DER inverters. The POI reclosers have a reporting rate of 7680 Hz for 32 cycles. Fault type, voltage, and pre-fault current are detailed in Table II. The rated output current is 377 A for Sites C and S, and 368 A for Site B. None of the sites were operating at full power capacity when the fault events occurred.

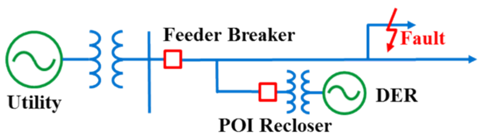

Fig. 1 Simplified System Schematic

Table II Fault type and voltage

Case Number	Fault Type	Fault Voltage (pu)	Pre-fault Current (A)	Site Name
1	ACG	0.47	52	C
2	BG	0.05	322	P
3	AB	0.53	172	P
4	BG	0.35	268	S
5	ABCG	0.19	104	S
6	BG	0.32	40	S
7	BC	0.55	69	S

A. Transient Fault Response

The fault response of distributed solar inverters is discernibly divided into two stages. Within 1.5 cycles after the inception of a fault, excessive phase and negative sequence currents are present. After the short transient period, negative sequence current is quickly subdued and phase current becomes stable. The current change during a fault is not clearly visible in instantaneous phase current plots. Fig. 2 shows instantaneous current of Case 4, which is demonstrated as an example throughout this paper. The transient response is more observable in the root mean square (RMS) current plots of Fig. 3 and Fig. 4.

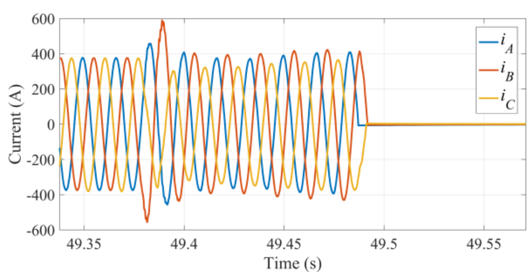

Fig. 2 Instantaneous phase current of Case 4

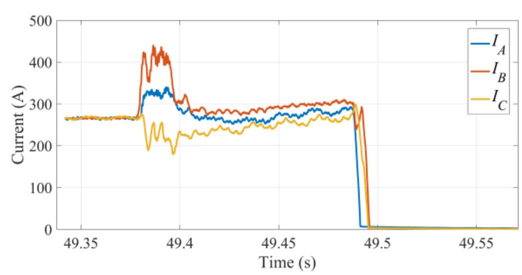

Fig. 3 RMS phase current of Case 4

Despite being exposed to a single phase ground fault and having phase B voltage dropped to 0.35 pu (Fig. 5), the inverters manage to balance three phase output after the transient period. As negative sequence current reduces to the level of 10 A, the three phase imbalance is largely attributed to the zero sequence current (Fig. 4), which circulates in the Delta winding of the Wye-ground/Delta transformers. The POI recloser isolates the solar generation site at time 49.49 s and causes load rejection overvoltage on the solar inverter side in Fig. 5. The fault continues on the utility side.

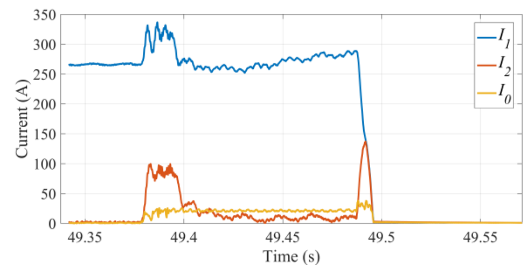

Fig. 4 RMS sequence current of Case 4

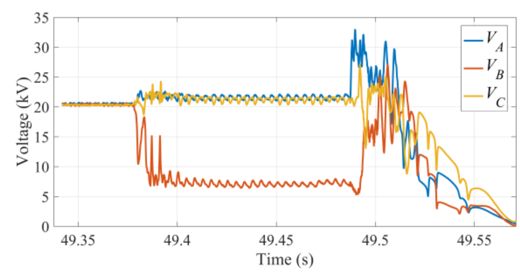

Fig. 5 RMS phase voltage on the solar inverter side of Case 4

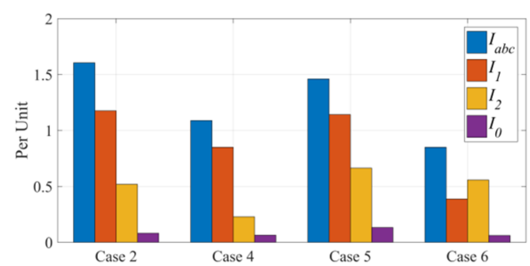

Fig. 6 Transient fault response indices

The transient response is successfully captured in four of the seven events (Cases 2, 4, 5, and 6). The transient time ranges from 23 ms to 27 ms. Transient current values are converted to per unit based on rated output current and plotted in Fig. 6. Phase current (I_{abc} represents phase current of the faulted phase) is higher than inverter rating and reaches 1.25 pu on average. The only exception is 0.85 pu of Case 6, in which the solar site has a low capacity factor of 11% prior to the fault. Negative sequence current surges to an average of 0.49 pu and eventually subdues after the transient response. Zero sequence current is insignificant and only reaches an average of 0.08 pu. It is noticed that transient response intensity is closely related to the severity of the voltage depression. Comparing Case 5 against Case 4 (both are from Site S), the former, which experiences a three phase fault at a lower voltage, sees higher amount of fault current. It also can be inferred that higher output condition can result in higher transient fault current by comparing Case 4 with Case 6.

B. Steady-State Fault Response

Both phase and sequence currents are reduced after the transient period. As shown in Fig. 3 and Fig. 4, the steady-state fault currents remain near the level of the pre-fault and are less than rated output current. This is also true for the other six cases. In Fig. 7, fault currents are normalized by rated output current. It is evident that the steady-state fault current is less than the rated output current. Phase current is on average 50% of rated output current, while positive sequence current is 47% of rated output current. The fault current is also affected by pre-fault output conditions. The most heavily loaded case, Case 2, shows the highest amount of fault current. This is in contrast with synchronous generators, whose fault current magnitude is not largely impacted by pre-fault loading conditions. Looking at sequence components, positive sequence current prevails over negative and zero sequence currents. Both negative and zero sequence currents are subdued to 3% of rated output current. Zero sequence current exists partially due to the Wye-ground/Delta transformer connection.

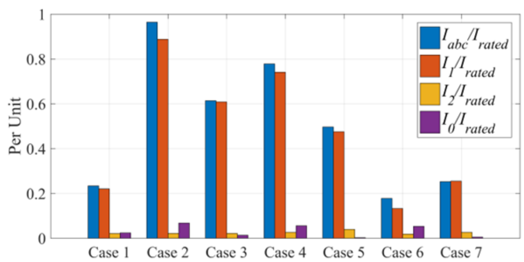

Fig. 7 Steady-state phase fault current

A high power factor is observed during steady-state fault. It is seen in Fig. 8 that positive sequence voltage and current, i.e. V_1 and I_1, maintain a narrow angle difference, ranging from 4 to 9 degrees. Being close to unity power factor is likely the result of inverter controls and leads to low reactive power contribution. This property is drastically different from synchronous generators or solar inverters in fault ride-through mode, whose fault currents appear to be reactive. The only exception is Case 5 (not shown in the graph), in which a three phase fault occurs and the angle difference is 50 degrees. During the low voltage (0.19 pu) of Case 5, inverter grid support may have been activated to feed in higher reactive current to prop up terminal voltage.

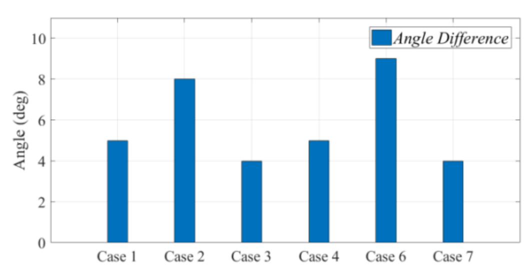

Fig. 8 Angle difference between positive sequence voltage and current

A proportional relationship is also observed between inverter active power output and positive sequence voltage magnitude. In Fig. 9, the ratio of active power in per unit versus positive sequence voltage magnitude in per unit (P/V_1) is presented. Four cases, in which pre-fault active power was successfully captured, show that inverter active power output scales down proportionally based on voltage magnitude during a fault. The curtailment explains why less than rated output current is observed during faulted periods.

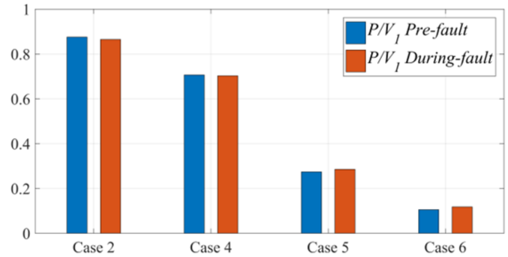

Fig. 9 Active power and voltage relationship

The fault characteristics revealed in this paper have implications on short circuit modeling and protective device setting. By modeling the inverters at Site P with features including low fault current, close to unity power factor, and power curtailment, it is found that there can be a 10% reduction in fault current seen by distribution feeder relays, compared to inverters in the fault ride-through mode. The discernible reduction in fault current can impair feeder relays' sensitivity to downline faults and therefore deserves relay setting reviews.

IV. Conclusions

This paper explores the fault characteristics of inverter-based solar DERs through multiple recorded fault events. Both transient and steady-state fault responses are analyzed. High phase and negative sequence fault currents are noticed during transient periods. The fault current magnitude is affected by fault severity and pre-fault output conditions. During steady state, it is discovered that fault currents are consistently less than rated output current. Both negative and zero sequence currents are negligible. Power factor is regulated during faults, resulting in tight phasor alignment between positive sequence voltage and current. The active power output is proportionally curtailed to positive sequence voltage magnitude. The findings in this paper affect fault analysis and relay setting that involve distributed solar generation.

V. References

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