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A Comparative Study of the Reliability of Reverse Power and Directional Overcurrent Elements for Distribution Level Fault Identification

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SUMMARY

The power distribution system is rapidly undergoing changes with increasing penetration of Distributed Energy Resources (DERs) at the consumer end. This changes the earlier notion of unidirectional flow of power i.e. from the utility end to the consumer end. For this reason, conventional protection schemes need to undergo modifications in order to be able to trip DERs in the case of faults upstream of the Point of Common Coupling (PCC). Failure to trip before the open period of the upstream recloser might lead to out of step reclosing. Out of step reclosing can cause damage to utility served load due to high electromagnetic transients and is also a potential safety hazard for personnel. In order to achieve proper coordination, certain protective functions need to be put in place by the consumer installing the DERs, as required by the utility. Two of such functions are the Directional Overcurrent (DOC) element, 67, and the Reverse Power element (RP), 32R. The DOC element is primarily used to detect faults upstream of the PCC and is primarily used for feeder protection. The RP element is used to detect any abnormal reversal of power flow that may result due to sudden generation loss from the utility side or islanding scenarios. This paper presents a comparative analysis between the performance and feasibility of DOC and RP elements to identify faults at the PCC when DERs are present in the distribution circuit. This work uses hardware-in-the-loop (HIL) technology to combine a relay with a custom distribution circuit modelled in RSCAD to test various types of faults at different locations downline of the distribution substation. The results are showcased along with a comparative study at the end explaining the delineation of the functionalities of both elements.

KEYWORDS

Islanding, Unsymmetrical Fault, Hardware-in-the-Loop, Real Time Digital Simulator

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I. Introduction

One of the most important aspects of power system planning and operation is the design of proper and reliable protection schemes. Protection scheme design used to be straightforward, as distribution systems were based upon radial power flow from the utility to the consumer. However, the emergence of consumers Distributed Energy Resources (DERs) has created a new challenge for protection engineers. Properly ensuring reliability and preventing mis-operation of the protective equipment is no longer the commonplace task it once was. DERs are sources of energy located on the load side of the Point of Common Coupling (PCC). Parallel connection of DER to the utility warrants certain protection schemes to be installed at the PCC for the safety of various electrical equipment as well as utility/non-utility personnel. Improper protection design might lead to faults not being cleared, which can cause tremendous destructive energy in the form of heat and magnetic forces. This can heavily damage electrical equipment and endanger utility/non-utility personnel safety. Directional protection schemes are integral to achieving such a desired performance. Directional protection enables the utility to better identify the location of the fault than simply overcurrent protection. It is mostly used in the following conditions [1]:

1. Multi-source power distribution systems
2. Closed loop or parallel-cabled systems
3. Isolated neutral systems for the feedback of capacitive currents
4. To detect an abnormal direction of flow of active or reactive power

The directional element uses phase angle displacement between the current phasor of a particular phase and the reference variable to determine the directionality (forward or reverse). In other words, the directional element relies upon the direction of a reference variable to determine the direction of current. This reference variable is called the polarization quantity and can be either a voltage or current phasor. The Directional Overcurrent (DOC) element, 67, combines directionality with the standard overcurrent element.

The Reverse Power (RP) element, 32R, is also a directional protection element that relies upon both voltage and current values to determine reversal of power. The applications for RP are mostly confined to detecting abnormal reversal of power for a Non-exporting DER at the PCC during sudden loss of generation at the utility side or Loss of Mains (LOM) situation. However, the feasibility of using the RP element to detect faults has always been a question. This paper answers that question by providing a comparative analysis of the 67 and 32R elements for fault identification. A comprehensive comparison of the two protection techniques was completed by placing various faults at numerous locations in a relatively complex RSCAD model. This RSCAD model was then combined with a relay via Real Time Digital Simulator (RTDS) Hardware-in-the-Loop (HIL) technology.

Section II discusses about setting up the Test bench and building the custom model. Section III discusses about the testing and actual results obtained, and finally, section IV summarizes the conclusions drawn from the overall study and a brief scope of the future work possible as an extension to this paper.

II. Simulation Test Bench Setup

A custom distribution circuit model was created in RSCAD to simulate actual fault conditions, as shown in figure 1.

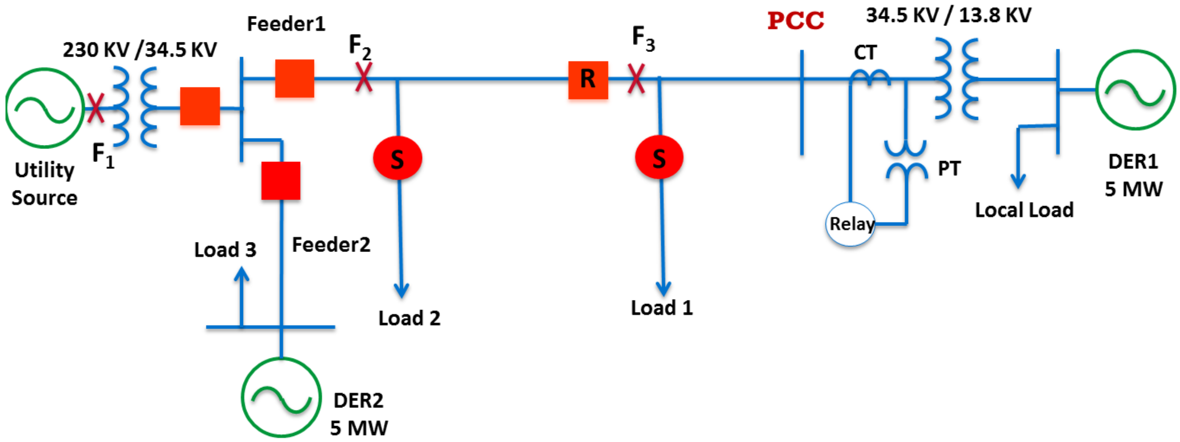

Fig 1: Custom distributed energy system model

The system consists of the Utility modelled as an infinite grid, capable of maintaining constant voltage and frequency. At the distribution substation, two feeders emerge to supply power to two separate circuits. The parameters of the feeders, line equipment, and transformers were designed with Dominion Energy system models as reference in order to replicate practical scenarios and performance. The relay under consideration is situated at the PCC of DER 1, which is connected at the end of Feeder 1 as shown in figure 1. In order to perform a more comprehensive analysis, two DERs were connected in the system and the performance of the relay in presence or absence of the DER2 (at the end of Feeder 2) was also studied. Both DERs are modelled as synchronous machines. Faults were placed at various locations, F1, F2, and F3, to carry out the comparative studies, as shown in figure 1.

By using RTDS HIL technology, a custom made RSCAD model, and a relay, realistic simulations were run for different fault scenarios with different parameters. The RTDS system was connected to a Doble amplifier that generated the required analog signals to emulate the secondary voltages and currents of the PTs and CTs which were sent to a microprocessor relay. The relay then sent the DOC and RP pickup output signals to the RTDS and the results were compared on a single graph within the RSCAD software. This allowed for easy comparison of the two elements, allowing the formulation of the conclusions shown in later sections.

III. Results and Discussion

Different types of faults were placed at the various locations along the feeder as shown in figure 1. The fault impedance (Z) is also varied in order to simulate bolted faults (Low Z), and high impedance (High Z) faults in order to show how the performance of both the elements would vary under various circumstances. Tables 1 & 2 present the results of this work. Column 1 shows the location and type of fault, while columns 2 and 3 show if the DOC and RP elements pick up, respectively. To illustrate the results, Figures 2-4 show three specific scenarios that give greater insight into the capability of both elements: High impedance 3-

phase to ground fault at F1 with both DERs in service, bolted 3-phase to ground fault at F1 with both DERs in service, and high impedance phase to ground fault at F2 with both DERs in service.

With DER2 Connected			
LOW Z FAULTS		Directional OC Pickup	Reverse Power Pickup
F_1	$3\varphi G$	Yes	No
F_1	$1\varphi G$	Yes	No
F_2	$3\varphi G$	Yes	No
F_2	$1\varphi G$	Yes	No
F_3	$3\varphi G$	Yes	No
F_3	$1\varphi G$	Yes	No
HIGH Z FAULTS		Directional OC Pickup	Reverse Power Pickup
F_1	$3\varphi G$	Yes	Yes
F_1	$1\varphi G$	Yes	No
F_2	$3\varphi G$	Yes	Yes
F_2	$1\varphi G$	Yes	No
F_3	$3\varphi G$	Yes	Yes
F_3	$1\varphi G$	Yes	No

Table 1: Response of DOC and RP elements to faults in various conditions with DER2 connected

Without DER2 Connected			
LOW Z FAULTS		Directional OC Pickup (67)	Reverse Power Pickup (32)
F_1	$3\varphi G$	Yes	No
F_1	$1\varphi G$	Yes	No
F_2	$3\varphi G$	Yes	No
F_2	$1\varphi G$	Yes	No
F_3	$3\varphi G$	Yes	No
F_3	$1\varphi G$	Yes	No
HIGH Z FAULTS		Directional OC Pickup (67)	Reverse Power Pickup (32)
F_1	$3\varphi G$	Yes	Yes
F_1	$1\varphi G$	Yes	No
F_2	$3\varphi G$	Yes	Yes
F_2	$1\varphi G$	Yes	No
F_3	$3\varphi G$	Yes	Yes
F_3	$1\varphi G$	Yes	No

Table 2: Response of DOC and RP elements to faults in various conditions without DER2 connected

The DOC element picks up for all scenarios as each scenario elicits a current response from the DG above the set pick up level. The RP element is only able to sense the high impedance 3-phase to ground faults. This is because the terminal voltage reduction is not substantial, allowing a significant amount of reverse power to be seen by the relay. The RP element does not pick up for the majority of the scenarios because of two reasons: the voltage drop is too low and the power output is negligible or the fault does not affect all three phases and the 3 phase output power does not substantially change.

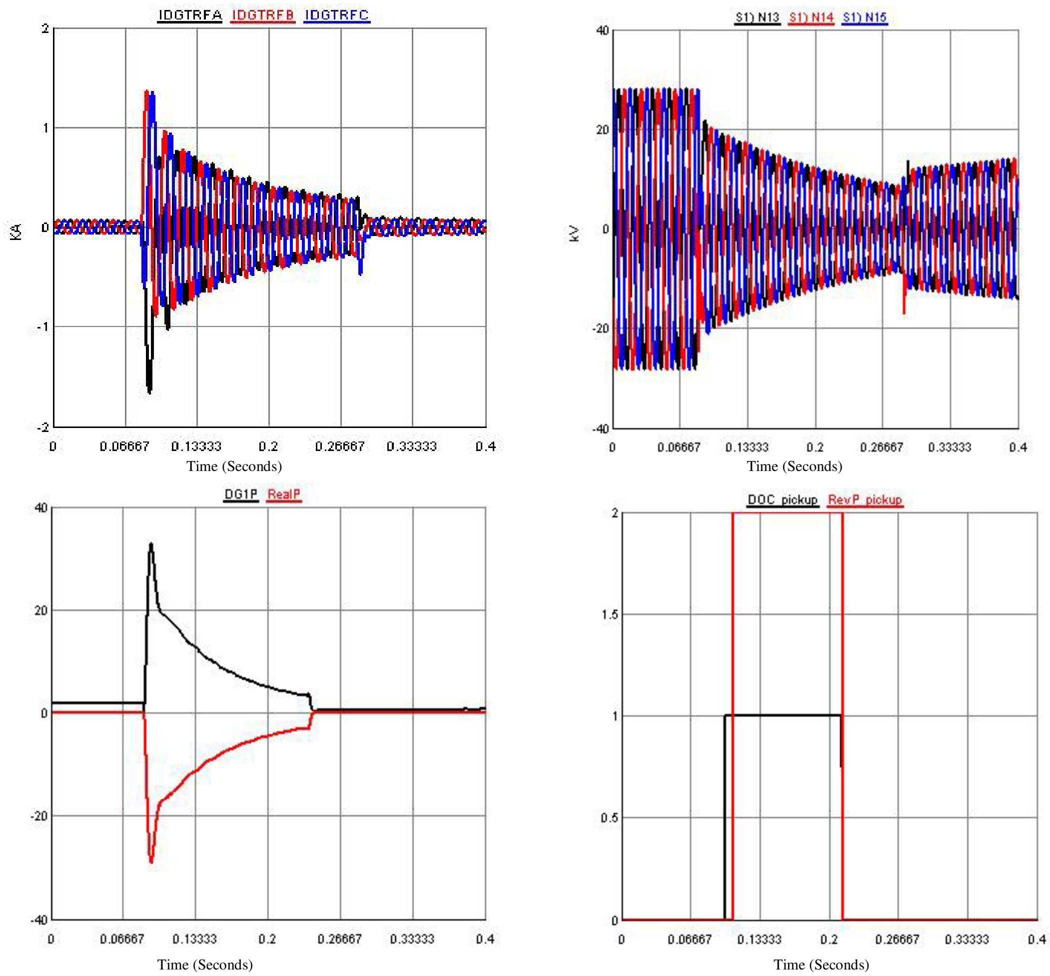

Fig 2: High impedance 3-phase to ground fault at F1 with both DERs in service

Figure 2 subfigures show the 3 phase current, 3 phase voltage, DER1 3 phase real power generation (DG1P in MW), 3 phase real power flow (RealP in MW) at the PCC and the relay's pick up outputs. The high impedance fault does not cause the voltage to collapse to 0V so reverse power can be seen by the relay. The current rises due to the fault so adequate power and current is seen by the relay, leading to both elements picking up.

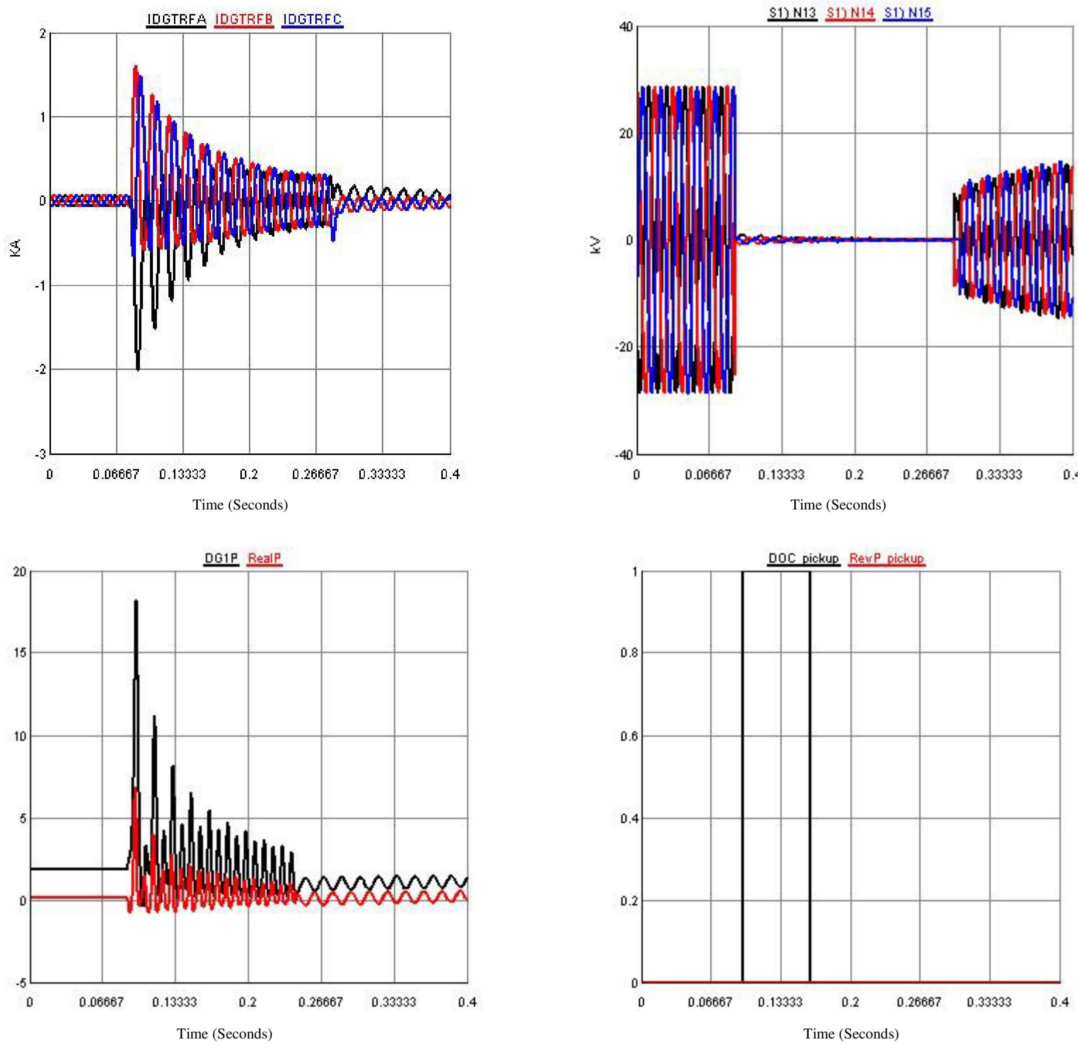

Fig 3: Bolted 3 phase to ground fault at F1 with both DERs in service

The same variables are shown in figure 3's subfigures. In this case, the bolted fault causes a sudden steep reduction in voltage, therefore reverse power flowing is negligible even though the current increases greatly. The DOC element picks up due to the large increase in current but the RP element is blinded due to lack of voltage.

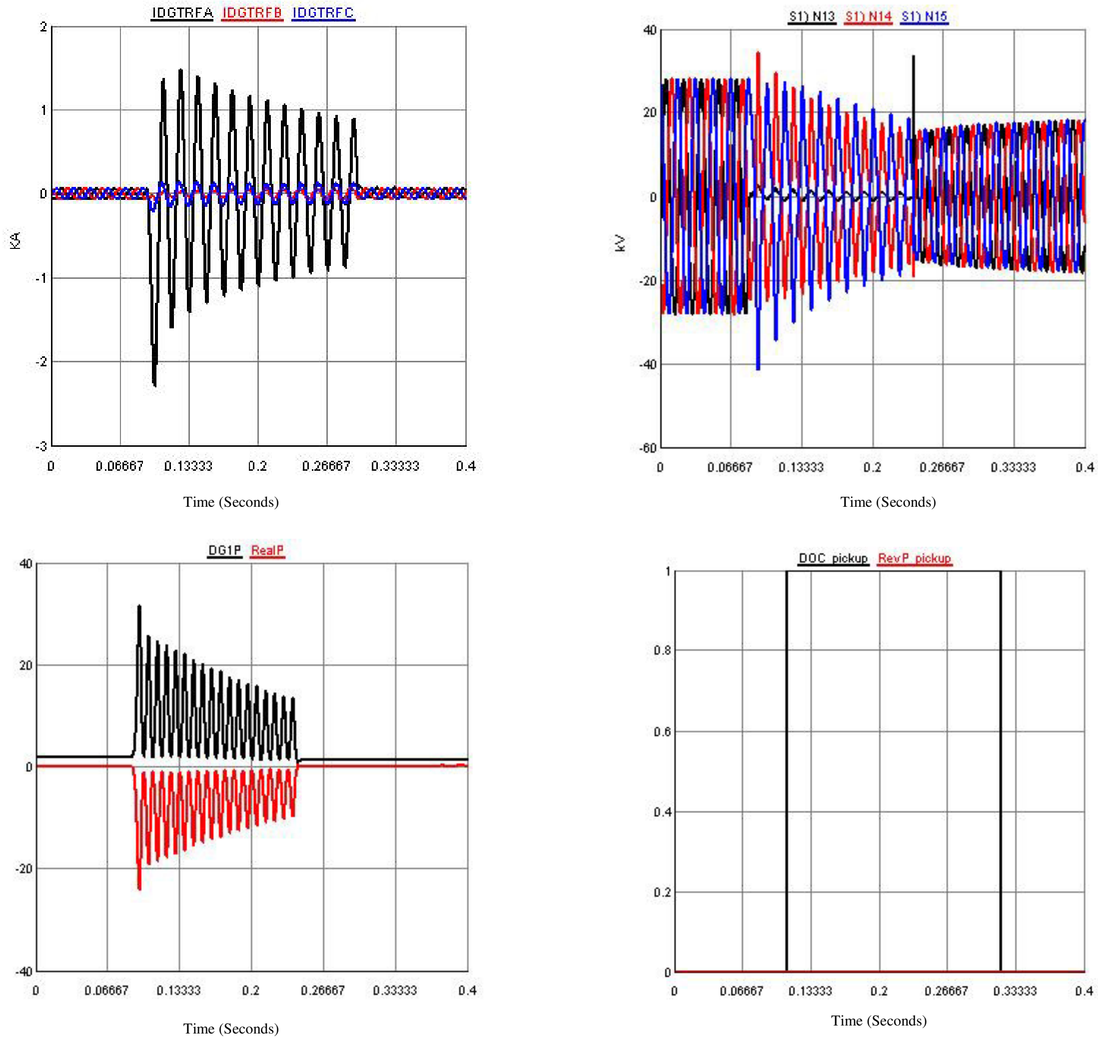

Fig 4: High impedance single phase to ground fault at F2 with both DERs in service

The same variables are shown in figure 4's subfigures. In this case, the high impedance fault does not cause the voltage to collapse to 0V so reverse power could have been seen by the relay. But, the single phase to ground fault only causes power in one phase to reverse directions. Even though the power flow of A phase is the in reverse direction, the overall 3 phase power is still considered to be in the forward direction as the sudden loss of one phase leads to more current being drawn in the other two phases to meet the demand of the loads. Therefore, the RP element does not pick up. However, the DOC element does pick up due to the increased current magnitude.

IV. Conclusion

A comparative analysis was carried out to evaluate the capability of DOC and RP elements to detect various faults. Feeder protection is increasing in importance as DERs are added to the system and back feeding fault current becomes a large concern. A custom model was built to test consider multiple fault types and locations. The fault impedance and the presence of other DERs were also taken into account, as they play a deciding role in delineating the appropriateness of both the relays. It was found that a proper pickup value of current would guarantee the correct action of a DOC relay. However, because the reverse power relay is dependent on two variables, voltage and current, it was not able to perform accurately in most scenarios. This work shows that low fault impedance will cause the voltage to collapse, which causes a negligible power magnitude. It was also shown that phase to ground faults cause one phase to reverse direction, but the three phase power is not considered in the reverse direction as the other two phases increase power to compensate. It is concluded that reverse power is not a reliable indicator of fault identification, and the DOC element should be considered instead for feeder protection. Research not shown in this work gives the authors reason to believe the RP element can be used for islanding detection in case of LOM situations, which can be studied and analysed as part of the future work .

V. Acknowledgement

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