6-15-2024

Incremental Quantities Based Permissive Overreaching Transfer Trip Scheme for Protecting Inverter-Based Renewable Resources

Osama Zangoti

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Abstract

The power generation landscape evolves, with the increase of inverter-based resources (IBRs) such as solar photovoltaics and wind turbines, providing sustainable and clean energy sources. The shift towards IBRs mitigates climate change, creating considerable challenges to traditional power system protection due to their low fault current. Conventional protection schemes are designed around the internal dynamic of synchronous generators where they can supply an elevated fault current. This thesis explores a protection scheme designed to enhance the security of IBRs. The incremental characteristics of voltage and current coupled with the Permissive Overreaching Transfer Trip scheme (POTT) provide a remarkable ability to detect a spectrum of fault conditions with a marginal fault current. A spectrum of simulation studies is conducted to test the proposed protection scheme's effectiveness under various fault conditions and transient change. The proposed solution affirms security during external faults and normal transient conditions. During extensive testing, the proposed protection solution proved its efficacy, utilizing the incremental quantity-based POTT scheme in protecting IBRs. The findings and the analyses ensure that there is a critical need for advanced protection with the IBRs penetration.

Document Type

Masters Thesis

Degree Name

M.S. in Electrical Engineering

First Advisor

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Keywords

Power, Renewable energy, Inverter-based resources (IBRs), Fault current, Permissive overreaching transfer trip scheme (POTT)

Subject Categories

Electrical and Computer Engineering | Engineering | Power and Energy

Incremental Quantities Based Permissive Overreaching Transfer Trip Scheme for Protecting Inverter-Based Renewable Resources

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A Thesis

Presented to

the Faculty of the Daniel Felix Ritchie School of Engineering and Computer Science

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

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June 2024

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Title: Incremental Quantities Based Permissive Overreaching Transfer Trip Scheme for Protecting Inverter-Based Renewable Resources
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Degree Date: June 2024

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List of Abbreviations

IBRs	Inverter-Based Resources
PV	Photovoltaic
SGs	Synchronous Generators
POTT	Permissive Overreaching Transfer Trip
SLG	Single Line to Ground
OCRs	Overcurrent Relays
SC	Short-Circuit
PE	Power Electronics
AI	Artificial Intelligence
VR-OCR	Voltage-Restrained Overcurrent Relays
PMUs	Phasor Measurement Units
EMF	Electro-Magnetic Flux
Rf	Fault Resistance

Chapter One: Introduction

1.1. Overview

In recent years, there has been a significant shift in the power generation process, from conventional synchronous AC rotating machine to IBRs, technologies such as solar photovoltaic PV providing sustainable energy integration. The traditional method of power generation, such as synchronous generators (SGs), is gradually being replaced by IBRs. Traditionally, SGs are the backbone of electrical power systems relying on mechanical inertia for operation, providing stability over frequency and voltage. Moreover, conventional machines use fossil fuels, providing reliable and stable power. However, there are drawbacks of using traditional methods of power generation since they rely on fossil fuels, and their environmental impact. Also, sustainable energies are crucial for reducing climate change effects, and carbon emissions. IBRs technologies are the energy sources that convert DC power from solar photovoltaic (PV) or battery storage systems into AC power by inserting power electronics interface between energy sources and the utility grid. Besides, the low costs of renewable energy resources, it offers a sustainable and environmentally friendly alternative to fossil fuels. Furthermore, renewable energy sources produce power without gases or organic matter. The shift towards renewable energy and IBRs represents a development in power generation. Figure.1.1 shows the projected contribution of renewable energy by 2050; the power generation from renewable sources will increase from 21% in 2021 to 44% in 2050. The increase of renewables will primarily consist of new wind and solar power.

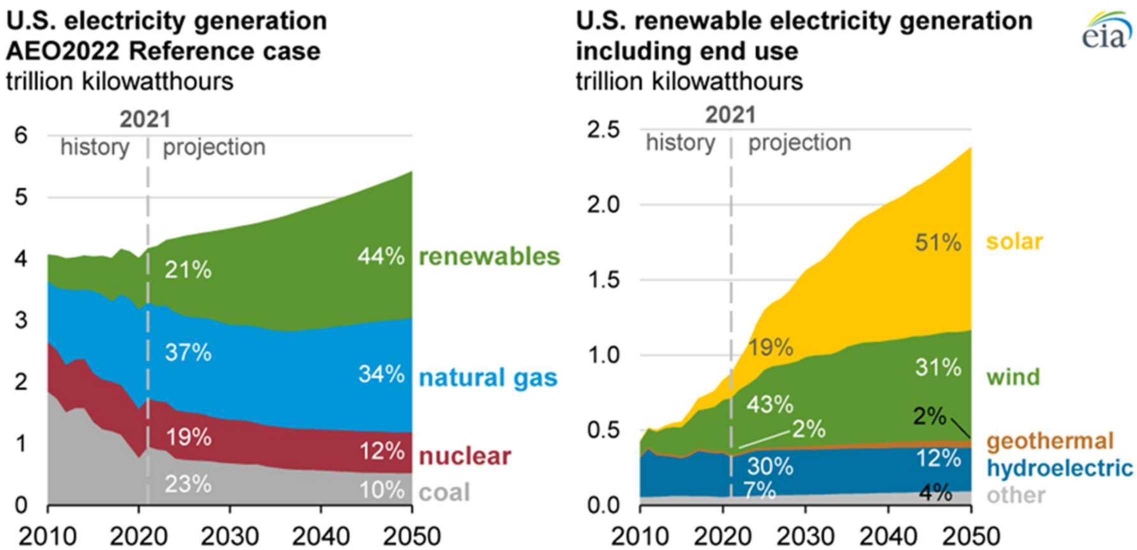


Figure 1.1: Projected mix of energy in the US[1].

The penetration of IBRs poses a challenge of maintaining the stability and resilience of the grid and a change in the dynamic of fault current which leads to difficulty in the detection process of the traditional protection method [1]. The traditional protection elements such as overcurrent and distance relays are relayed on conventional setups and may not respond to fault occurrence accurately in the context of increasing IBRs penetration. The IBRs have low fault currents contribution and lack of negative and zero sequence components, that impede the operation of the exciting protection elements during fault conditions [11]. The grid protection depends on high fault currents from SGs, and the presence of IBRs encumbers the process of fault detection by limiting fault current contribution to prevent damage of components.

1.2. Problem Statement

The high increase of IBRs integration into existing transmission grids interfaced with the grid conventional sources like SGs. Solar photovoltaics and wind turbines are vital movement towards sustainable and low-carbon future. Renewable energy technologies integrated into grid through inverters, presenting significant departure from the traditional energy systems that relied on conventional SGs. Moreover, the increase of awareness about how clean energy can reduce carbon emission results in a high penetration of renewable energy sources, such as solar and wind. However, the surge in penetration of renewable resources poses new challenges to the protection systems, which in turn results in unsecure and unreliable power systems. The main challenge is the short-circuit behavior of IBRs which is very different from a traditional rotating synchronous machine [12]. The synchronous generator's fault contribution has played a big role in the existing protection schemes by exhibiting a high magnitude of fault current, while the contribution of IBRs fault current is much lower.

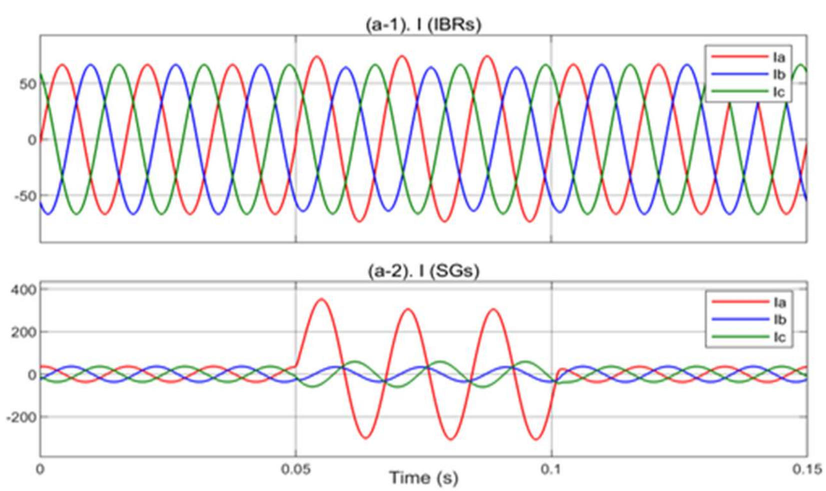


Figure 1.2: The fault current during SLG faults[2].

Figure 1.2 shows the obvious difference of typical single line to ground (SLG) fault currents for a synchronous machine and a PV system where the short circuit occurs at 0.05s and both systems react differently [2]. Figure 1.2 (a-2) shows that the fault current increased to about 6 to 10 times the rated current. In contrast, Figure1 (a-1) illustrates the IBRs the fault current during SLG, the current increased by 1.1 or 1.2 of the rated current, the limitation action occurred due to the control algorithms for protecting the inverter components from damage. Traditional protection schemes are based on high values of fault currents and would not operate properly with the IBRs penetration of renewable energy like PV in the utility grid. Thus, the low fault current contribution of IBRs is considered as a challenge for traditional protection schemes.

In [13], it is stated that IBRs have unique characteristics of fault currents from solar inverters in limiting the magnitude of fault current and the lack of sequence currents. This limitation can challenge traditional protection schemes. The authors in [3] state that solar inverters are designed to inject only positive-sequence current due to the control of inverters, as depicted in figure 1.3.

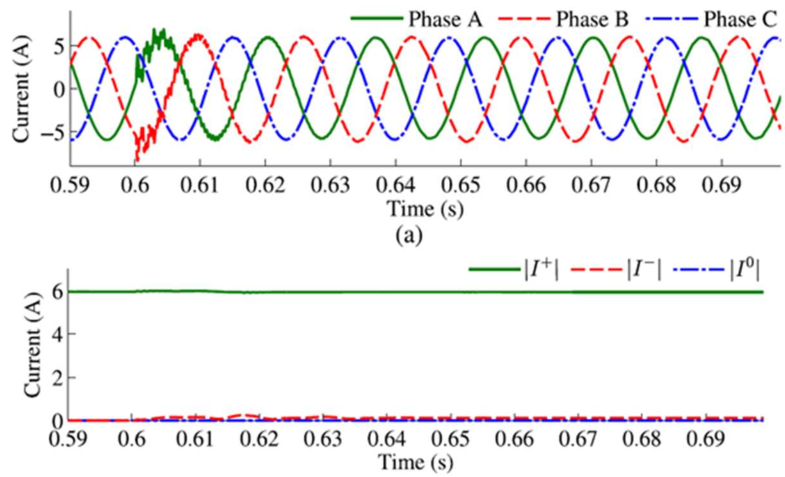


Figure 1.3: The lack of sequence currents during faults[3].

In fault conditions, the fault current contribution from IBRs does not contain sufficient levels of negative or zero sequence quantities and that causes mis-operation for overcurrent protection and directional elements. As explored in [11]'s work, the process of limiting the phase fault current is designed to protect inverter's electronic components by setting a cutoff value which varies by manufacturer design. Furthermore, there are two components of the IBR fault currents, an initial inception current lasting for a quarter to two cycles with 2.5 pu times the rated current and low magnitude fault current last for long duration. During fault condition, the voltage at the inverter's terminal drops to low values, then the inverter will increase the output current to manufacturer-specified maximum current value, trying to maintain its P - Q setpoints. At that current level, IBR will act as constant current source until the voltage level recovers to the ideal case and inverter can inject sufficient P - Q outputs.

The fault current phase angle IBRs affects protective relaying, especially distance and directional relays. IBRs can adjust the phase angle between the fault current and voltage by using the control settings [14]. The adjustment during fault events utilizes the amplitude of the voltage at the inverter terminals and control settings. Unlike SGs which generate a fault current with a phase angle close to 90 degrees leading the voltage.

Previous research by [4] has demonstrated the V -I characteristics pf PV model under normal condition and fault condition. As indicated in figure 1.4, the PV model operates to maintain constant power output along the sloping part of the curve under normal condition. In fault condition, the voltage drops dramatically, the inverter increases the current to its maximum limit and the inverter will not supply more current to avoid potential damage. The formula $I = \frac{P(pv)}{V}$ presents the constant power operation of the PV model the current output of the inverter is inversely proportional to the terminal voltage. However, reliable protection schemes for IBRs are needed for system stability.

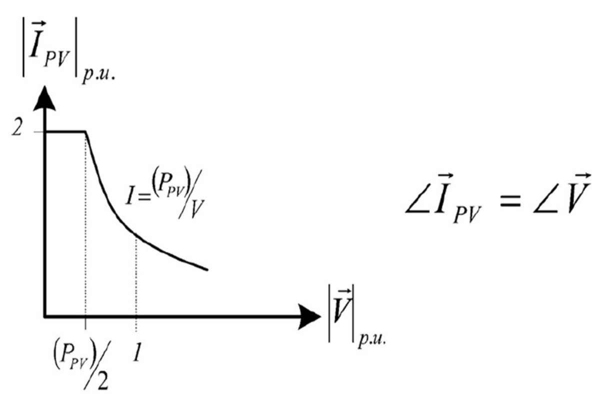


Figure 1.4: V -I characteristics PV model[4].

In [15], the authors state that the fault current characteristics of IBR are different from synchronous machines. Additionally, IBRs do not create a large magnitude of fault current because there is no stored electro-magnetic flux (EMF). In other words, IBRs do not sustain current flow and must limit fault currents because they rely on PE without such physical inertia or lack magnetic characteristics of synchronous generators. The fast limiting the fault currents is to minimize the risk to IBRs components.

The studies by [7] address how the IBRs control strategies can adjust the fault response. As illustrated in Figure 1.5, IBRs are designed to inject only positive sequence current during normal and fault (balanced/unbalanced) conditions. However, the traditional relays are designed for fault current signatures of a SG-dominated power system.

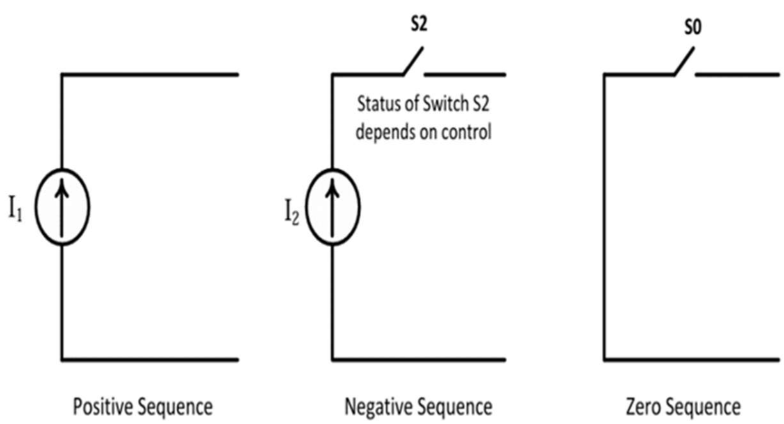


Figure 1.5: Positive, Negative and Zero Sequence diagram of IBR[5].

As [16] points out that the fault current profiles change with high penetration of PV systems, particularly those based on inverters. Furthermore, this change poses challenges for traditional protection schemes, especially overcurrent relays, which might face complexities in detecting faults reliably due to reduced fault currents. The fault current characteristics due to PV penetration can cause false tripping of overcurrent relays.

However, there is a need for revised protection strategies for adjustments in relay settings and coordination to ensure effective fault detection.

[6] discuss the response of inverter currents during system faults in a distribution system change with the photovoltaic (PV) systems presence. Also, they highlight three transient regions during fault and how inverters contribute to fault currents in a system. Figure 1.6 shows the three transient regions starting with an initial spike in output phase current immediately following a fault. Regulation period after the initial spike, the inverter controls attempt to stabilize the voltage back to normal levels, lasting a few milliseconds. Following by current limited period, the inverter phase current is limited, which is the maximum fault current that the inverter can deliver to a fault without damaging its PE.

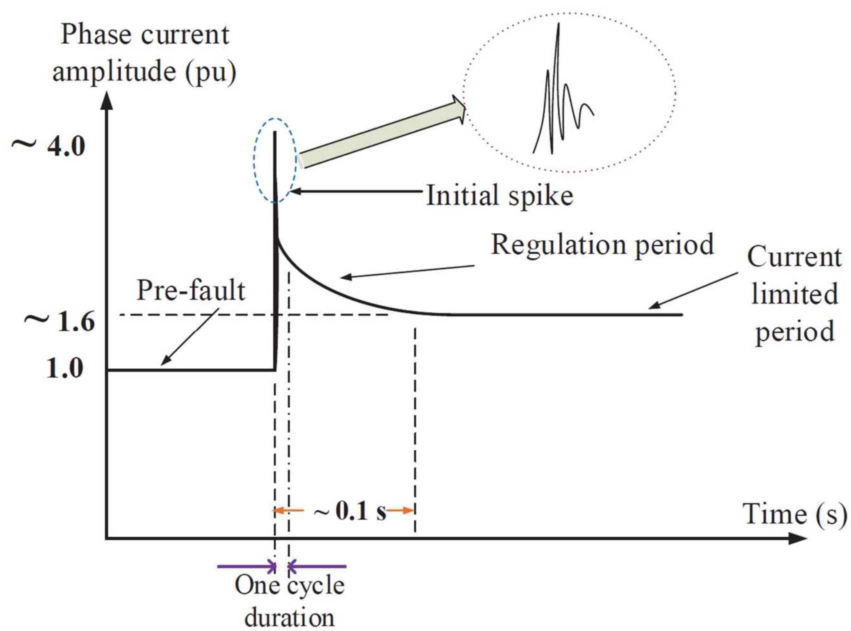


Figure 1.6: Inverter phase fault current response with IBR penetration[6].

The study by [7]highlights fault response of a single inverter and how it reacts to faults. During fault response, there is a sudden drop in voltage and inverter's control strategy attempts to maintain its power output by increasing the current. As the voltage decreases the inverter reaches maximum fault current without risking damage.

Figure 1.7 illustrates the fault response of inverter by attempting to adjust its output current to maintain a constant power output. Also, it shows how the inverter response to a significant drop in voltage by increasing the current to a specific threshold.

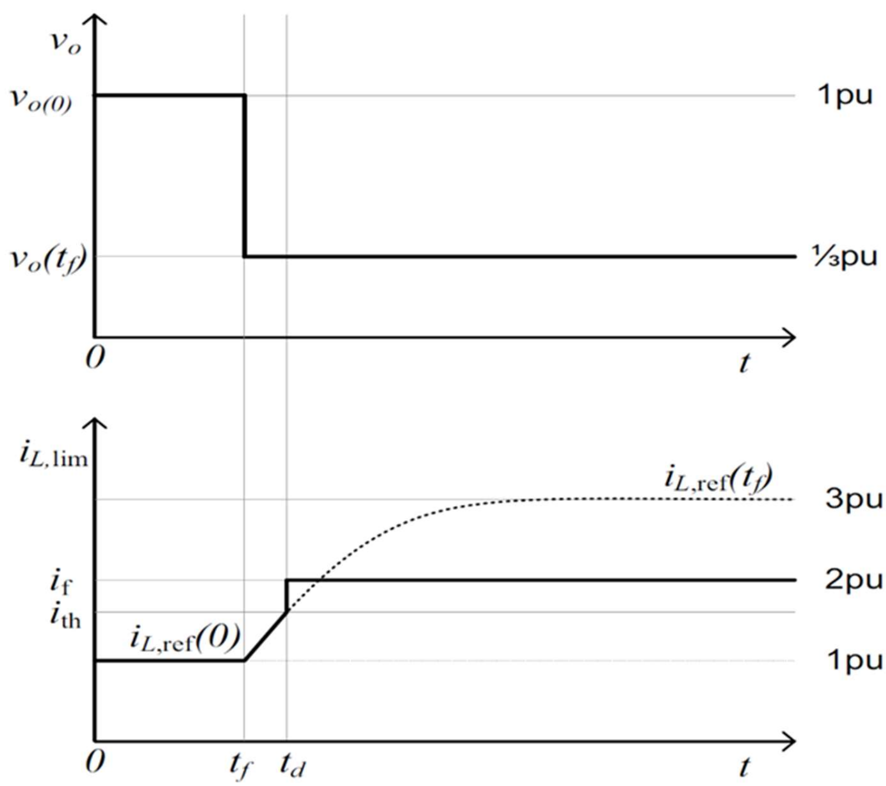


Figure 1.7: Inverter behavior under fault conditions[7].

At a pre-fault output voltage (vo,0) the inverter operates at a normal power output with current reference ($iLref$,0). At the moment t=tf (fault time), fault occurs, causing a sudden voltage drop to one-third of its original value (vo, f=1/3 pu). Subsequently, the inverter's control strategy limits the fault current to a threshold (ith==1.6 pu).

1.3. Summary

Fault events in power systems require rapid and efficient protection methods to maintain stability and protect system components from damage. A study was conducted to contrast the behaviors of both conventional SGs and IBRs, capturing their response during fault events. Conventional generators have dominated the electrical power system and the current shift towards renewable energy sources has led to a mix of generation technologies, creating a new dynamic. SGs can supply significant fault currents because of the rotating mass and electric field. During fault condition, the sudden increase in current known as sub-transient current could be several times higher for a few cycles, then decreasing regularly to a steady state fault current level. This behavior is essential for protection elements operation which are designed to detect the high fault current and clear it.

The fault current is a vital component in the detection process and plays a key role in grid protection. Traditional protection schemes were initially designed around high fault currents from synchronous generators, facing an obstacle with the presence of IBRs which are engineered to limit their fault current contribution to prevent damage. The fault current contribution by the IBRs has a nonlinear relationship with the inverter terminal voltage. During fault occurrence the voltage at the terminals drops, and the inverter reduces the fault current by a certain control system for protection purpose [14]. However, this limitation creates significant protection challenge for existing protection schemes by increasing the fault current magnitude to a limit around 1.2 times their rated current [17].

To get over this issue, this research introduces a functional approach for protecting IBRs by employing incremental quantities associated with POTT functions to maintain the stability and the reliability of the electric power system. The POTT scheme is a protection mode that uses communication channels and relays at both ends of a transmission line, enabling fast clearing of faults avoiding unnecessary delays [18]. The incorporation of incremental quantities for protection purposes provides accurate capture of the dynamic behavior of the IBRs during fault events[19]. This research discusses the integration of incremental quantities into the POTT protection solution and analyzes benefits and challenges of this protection scheme in the distribution system. The scheme shows the capability to detect internal faults and sensitivity by ensuring security measures during external faults and normal transient conditions. A modified simulation of a 2-MW PV farm connected to a 25-kV distribution system was established to examine and validate this potential protection solution under different fault and transient scenarios.

Chapter Two: Literature Review

2.1 Overcurrent Relay

Overcurrent Relays (OCRs) protection elements are vital in the process of ensuring the safety and reliability of electrical power systems. OCRs schemes use the value of the fault current to isolate the fault and prevent damage to the distribution network equipment's [20]. Furthermore, phase or sequence components can be used to set the operating quantity of the overcurrent relay. OCRs detect excessive current in the transmission network and initiate a tripping signal to isolate the fault within the protected zone. In addition, to detect the fault, the operating setting like pickup current needs to be low to isolate the fault but high to avoid unnecessary tripping. Short circuits, ground faults, or equipment failures can cause over currents in power system. Currently, electrical power systems are experiencing modern and sustainable power sources which relate to renewable energy sources.

IBRs exhibit different behavior, in terms of their operational characteristics and fault response, especially their output current during abnormal conditions. Moreover, this variability can complicate the mechanisms of OCRs in the distribution system. The dynamic nature of IBRs creates a significant challenge to OCRs in detecting and response mechanisms. The authors of [11] present the integration of IBRs poses a challenge to overcurrent relay in detecting ground and unbalanced phase faults. As described in chapter one, the IBRs fault current is reduced to a limit around 1.2 times their rated current for phase faults causing a mis-operation of the protection scheme. The work by [8] indicates that IBRs limit the fault current to protect the power electronic switches from high magnitude fault current. In addition, the limitation process decrees the ability of overcurrent relay's operation. For example, an electric power system contains two types of power sources a conventional rotating machine source and IBRs of 2 MW, 10 kV has rated current 115.4 A. Figure 2.1 shows when single line to ground SLG fault occurs at 2.38 s with fault resistance of 0.1 Ω. It is obvious that current contribution from IBRs is limited and does not exceed the pickup setting of overcurrent relay (230 A).

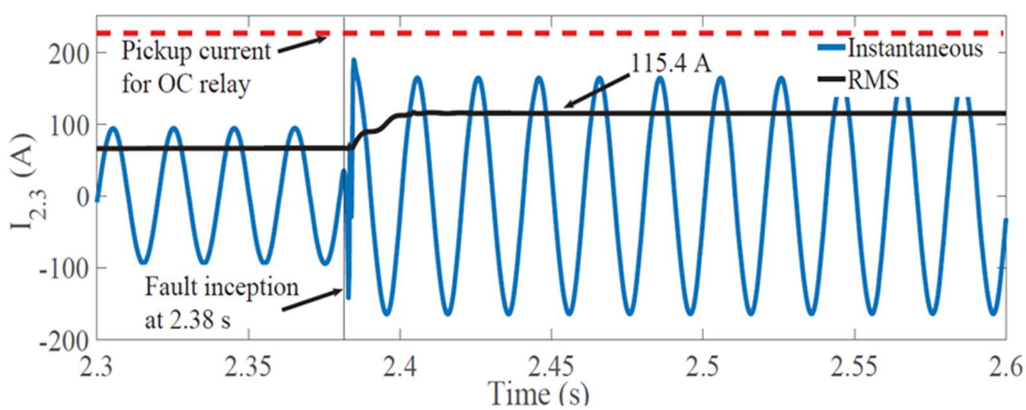


Figure 2.1: The limited fault current during SLG at overcurrent relay[8].

The review in [21] presents the ability of the IBRs control in adjusting the current rising rate and limit the short-circuit (SC). Furthermore, current challenges faced by transmission line protection are influenced by IBRs. In addition, traditional protection elements in transmission line protection OCRs may experience challenges in isolating faults. PV systems and other renewable energy applications often include a limitation strategy to limit the fault current [22]. This process is vital to prevent high fault currents that might damage power electronics (PE) components. The research presented in [23] investigates the traditional protection performance with the unique characteristics of IBRs in restricting short circuit current. Also, the main finding of the investigation is that the limitation is a lack of inertia and the internal dynamic of IBRs like limited thermal capacity of PE. Also, the limited fault current can cause a mis-operation of overcurrent elements. Furthermore, sequence-based elements, such as the negative sequence overcurrent element, zero sequence overcurrent element can be affected by the limited value of fault current sequence component.

In [24], the impact of IBRs on protection schemes based on negative sequence components specifically overcurrent protection and directional elements. OCRs might face challenges in operating with IBRs presence since the low fault current contribution form IBRs might not exceed the predefined threshold. In addition, directional elements utilize the phase angle differences and magnitudes of the negative sequence components and under IBRs these elements might lead to incorrect directional decisions. In essence, the integration of IBRs necessitates an improvement for reliable protection scheme that can maintain system stability under abnormal conditions.

The study by [25] which presents adaptive schemes for voltage-restrained overcurrent relays (VR-OCR), the adaptive scheme utilizes pre-fault current data and input voltage to overcome the challenges caused by a PV plant presence. The adaptive schemes capture the changes in the pre-fault current and input voltage and update the pickup current settings of the VR-OCR in every cycle. The PV plant cause variations in fault current and the adaptive setting provides effective approach in managing these changes. The research [26] examines the capability of the adaptive overcurrent protection scheme based on the operating mode, and fault current size. The adaptive protection successfully detects the operational mode of the microgrid whether it is connected to the main grid or operating in islanded mode. In islanded mode, the microgrid depends on local generation like solar PVs and that causes low fault current levels due to inverters design. Traditional OCRs are designed around higher currents expected under grid-connected conditions. The adaptive overcurrent protection scheme can adjust the settings of the overcurrent relays based on the operational mode of the microgrid.

2.2 Distance Relay

Distance protection schemes are commonly used for the protection of transmission lines, and they measure current and voltage level at their locations to calculate the positive sequence impedance to the reach point from the relay location as show in figure 2.1. The distance elements usually used for the protection of transmission lines robust to system stability [27] , [28] . The distance elements have a reach point which is the percentage of the line length, and the line length is in impedance units instead of distance units. The apparent impedance is calculated by (1) to detect if the fault occurs within predefined protective zone. V represents the voltage of the line and is the I *relay* is the current through the relay[29].

$$Z_{apparent} = V/I_{relay} \qquad (1)$$

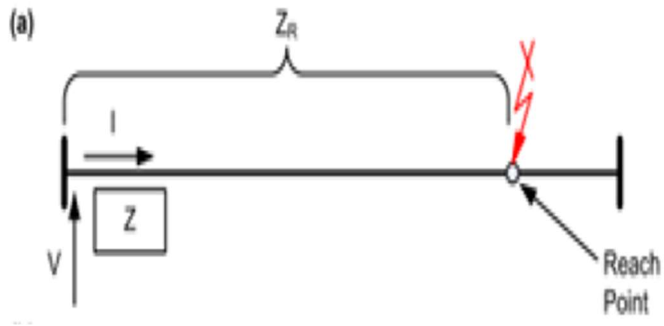


Figure 2.2: Distance protection scheme [10].

The presence of IBRs affects the impedance measurements in distance protection between the fault location and the relays. Furthermore, the impedance measurements seen by the relays can underreach or overreach [30]. In [31], the high integration of the renewable energy sources, the low fault current contribution of the IBRs result in under-reach and mis operation in distance relay. In addition, the performance of IBRs can change the characteristic of the fault. The calculation of the impedance is utilized to determine the fault location relative to the relay. IBRs characteristic during fault condition can influence distance relays function in measuring the impedance along a line to detect faults. The apparent impedance is directly influenced by the magnitude and phase angle of the fault current.

The authors of [14] indicate that the low magnitude of fault current because of the presence of IBRs can lead to failure in detecting the fault. Also, as outlined in [32] the presence of IBRs and their response under fault conditions cause distance relays to trip incorrectly and miss faults in their zone. The low magnitude of fault current might cause the relay to underreach or overreach. Underreach cases occur when the relay does not detect a fault within its protection zone due to short-circuit characteristics of IBRs. Overreach happens when the relay incorrectly identifies a fault outside its zone, causing unnecessary tripping.

The authors in [33] discuss the challenges of distance relays with IBRs during faults and how the characteristics of IBRs can change the power supplied unpredictably. However, the IBRs behavior during faults can vary the apparent impedance significantly and this variation can cause the relay to not detect the fault or miss a present fault. As the global energy landscape shifts towards sustainable sources, the continuous integration of IBRs into existing power grids creates a challenge to traditional distance relays.

In the [34] results, this study addresses zone protection challenges of distance relay. The distance relay experience difficulties for faults within its predefined protection zone due to underestimated impedance values. The unique fault current characteristics of IBRs can result in wrong impedance calculations. For instance, the relay may not see the right impedance, it might be significantly higher or lower than the actual impedance, leading to errors in impedance calculation of the fault location. However, traditional distance relays are designed for fault current characteristics of synchronous generators. These challenges require effective solutions for maintaining the reliability of the power grid.

The variability of fault current characteristics of renewable plants can influence conventional distance relays and they may not accurately detect faults. While [28] suggests adaptive distance protection scheme, that employs the phase angle of the faulted loop current and the pure-fault sequence impedances of the renewable plant. The fault characteristics caused by different control schemes of the connected renewable plants can be captured by adaptive distance protection scheme. In response involve fault current characteristics of renewable plants, the authors in [35] outlined an adaptive distance protection strategy for microgrids involves the use of Phasor Measurement Units (PMUs). PMUs provide precise data such as real-time measurement of electrical quantities of the network for enhancing the accuracy of fault detection. In islanded mode, the adaptive distance protection strategy adjusts the protection settings of relays to adapt to low fault current levels by using coordination and adaptation of protective devices. In addition, the adaptive scheme enhances the stability of the entire microgrid by fast isolating faults.

Chapter Three: Proposed Scheme

3.1 Incremental Quantities

Incremental quantities Δv and Δi are based on instantaneous voltage and current, they are calculated by taking the difference between the present value and the memorized value (1 or 2 cycles old) [36]. Incremental quantities represent the system stability when zero values are present. When the electric power system starts having disturbance in the power system like faults, non-zero-values appear for a limited cycle as shown in figure 3.1. For high-speed fault detection, incremental quantities provide an essential role and has the immunity from load changes which symbolizes a reliable method. In addition, Incremental quantities-based protection provides several advantages, including increase the sensitivity and selectivity, faster fault detection, and improve the stability under varying system conditions.

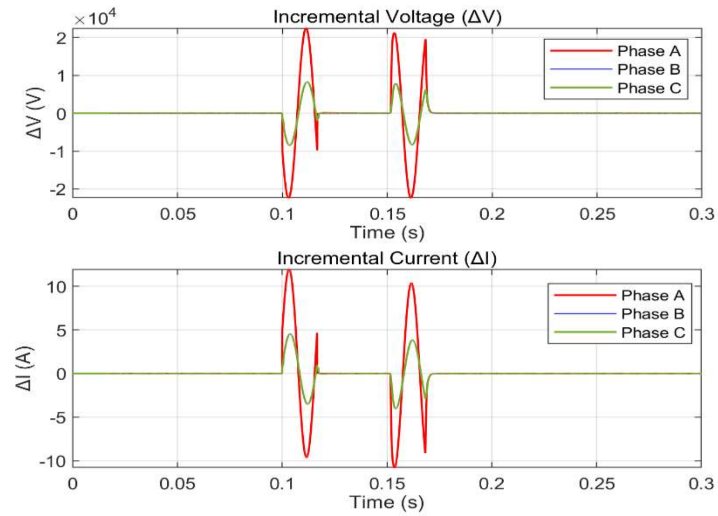


Figure 3.1: Incremental quantities waveform of voltage Δv and current Δi during SLG fault.

The calculation of incremental quantities captures the dynamic change in the system and allows distinguishing between faults and disturbances in the power system by typically spanning 1 or 2 power system cycles. Equations (1) and (2) used to calculate incremental voltage and current quantities Δv and Δi, depending on measured voltage $v(t)$ or current $i(t)$ samples and memorized values from one cycle prior (t-1 cycle).

$\Delta v = v(t) - v\ (t\text{- 1cycle})$ (2)

$\Delta i = i(t) - i\ (t\text{- 1cycle})$ (3)

As depicted in Figure 3.1, the Δv and Δi involve continuously monitoring assume zero values mean there is no change in the monitored parameters and the system is in a healthy state. Non-zero incremental quantities indicate that monitored electrical parameters are experiencing abnormal conditions within the system and they are crucial in the process of detection fault like the changes in voltage and current induced by faults or transients. Consequently, the use of incremental quantities with the presence of IBRs can be highly sensitive to changes in electrical parameters, particularly in scenarios with low fault currents, as observed in IBRs.

3.2 The Permissive Overreaching Transfer Trip (POTT)

The POTT is a protection scheme of pilot protective relay that implements communications channels to exchange information from both ends of the transmission line for fault detection [37]. In the POTT scheme, the relays at each end of the line are connected through high-speed communication links, which make both ends synchronized and fast in initiating tripping decisions. This robust communication between the ends empowers tripping decision process during fault conditions to ensure the security of the protected zone [38]. The distinctive feature of the POTT scheme is the ability to isolate the fault effectively. This scheme isolated the faulted section by allowing a relay to trip if it detects a fault and simultaneously receives a permissive signal from a remote relay as shown in figure 3.2. The use of communication links ensures fast fault isolation and prevents unnecessary tripping.

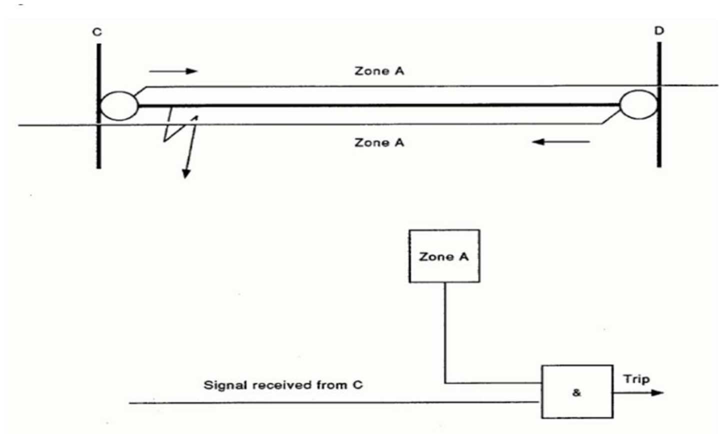


Figure 3.2: Permissive Overreaching Transfer Trip (POTT) scheme[9].

This scheme prevents unnecessary outages by acting as a confirmation mechanism when a fault occurs within the protected line. POTT scheme requires a permissive signal from the remote end before tripping. Moreover, this feature helps in maintaining system integrity and ensures that only the faulted section is isolated. The term 'Overreaching' in POTT describes the extension of the protection zone beyond the line segment to include any fault close to the line ends, to be cleared. This extension enhances the overall reliability of the protection scheme by ensuring the approach ability to clear not only faults directly on the pre-defined line but also those in proximity.

3.3 Fault Detection Mechanism of the Proposed Approach

Implementing POTT based incremental quantities involves the utilization of distance protection relays R1 and R2 at the end of the transmission line. This implementation harnesses the capability to drive the change of voltage and current at relays location, thereby facilitating fast fault clearing as shown in Fig.3. In addition, both R1 and R2 measure voltages (V) and currents (I) at their locations and calculate their incremental quantities ΔV, ΔI during fault events. Furthermore, the measured incremental quantities manifest the system's response to faults. The measured quantities like voltage and current are exploited along with the known line impedance (ZLine) to compute the change in voltage at the reach point (ΔVReach) [10]. In the process of fault detection, the pre-fault voltage (VPre) serves as a baseline, representing the voltage level under normal operating conditions. At normal operation the instantaneous incremental quantities settle to near zero values. However, upon the occurrence of a fault, both voltage and current waveforms turn to non-zero values, announcing initiation of fault.

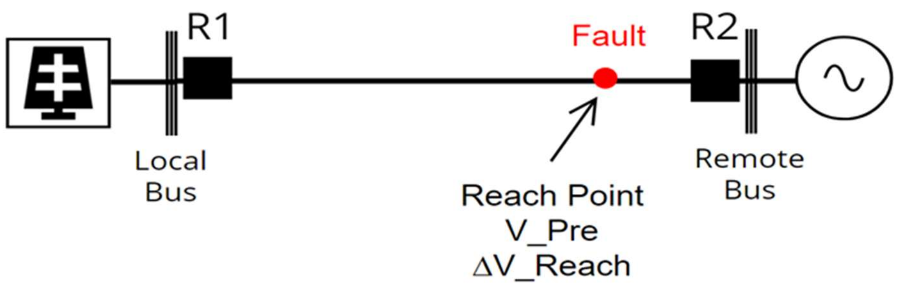


Figure 3.3: Network diagram of incremental quantities-based POTT scheme with distance protection relays[2].

The operating equations for the incremental-quantity distance element:

$$\text{Fault\_Detected} = (|\Delta \text{VReach}| > |\text{VPre}|) \quad (4)$$

$$\text{VPre} = (v - r \cdot |\text{ZLine1}| \cdot i) \quad (5)$$

$$\Delta \text{VReach} = (\Delta v - r \cdot |\text{ZLine1}| \cdot \Delta i \quad (6)$$

where:

VPre: the pre-fault voltage at the reach point.

ΔVReach: the calculated voltage changes the reach point.

ZLine1: the positive-sequence line Impedance value.

r: the reach sitting of the element.

i: the instantaneous current at the relay location.

ΔV and Δi: the changes in voltage and current.

Equation (4) serves as the primary criterion for fault detection. It compares the magnitude of the change in voltage at a specific reach point ($|\Delta V$Reach$|$) against the pre-fault voltage magnitude at the same point ($|V$Pre$|$)), ensuring accurate detecting. The fault is detected when the absolute value of ($|\Delta V$Reach$|$) exceeds the absolute value of ($|V$Pre$|$). This equation expresses the instantaneous disturbance in the power system, indicates abnormal voltage levels and normal operating conditions. Equation (5) determines the pre-fault voltage at the reach point. It utilizes the measured voltage (v) at the relay location, the reach setting of the element (r) the absolute value of the positive-sequence line impedance ZLine1 and the instantaneous current (i) at the relay location. The reach setting (r) adjusts the sensitivity and operational range of the relay. Equation (6) calculates the change in voltage at the reach point during fault condition. Also, it uses the change in measured voltage (Δv) and the change in current (Δi), with the reach setting (r) and the positive-sequence line impedance (|Z Line1|). This equation indicates how the voltage at a specific point on the line is influenced by the fault condition changes. Equations (5) and (6) have similar structure; (5) utilize the line impedance and current to calculate the actual voltage. While the change in voltage is determined at (6) at the reach point by employing the line impedance and the change in current, as presented in figure 3.4.

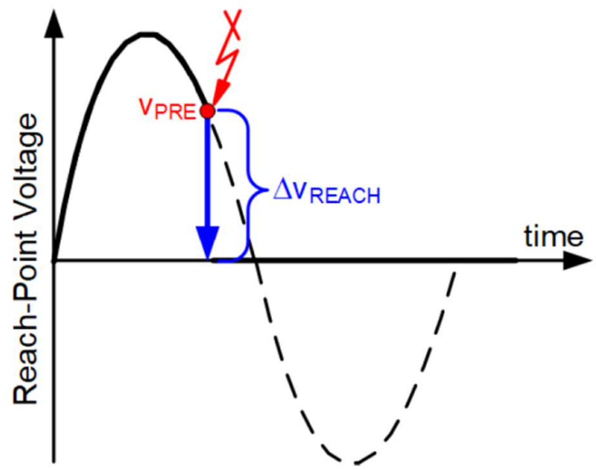


Figure 3.4: The change in voltage at the specific point during fault condition[10].

The POTT scheme harnesses the outputs of the distance protection relays R1 and R2 for its operation. During fault events the distance element at each end of the line performs its calculation. If the distance element detects the faults within its overreaching zone, it sends a permissive trip signal through communication channels to the remote end's relay. Collaborative action of both relays in detecting the fault within the protected zone, ensuring a fast trip decision.

Chapter Four: Case Studies and Results

4.1 Power Distribution System

To evaluate the effectiveness of our proposed approach, we established a power distribution system that incorporates IBRs, illustrated in Figure 4.1. The system has two main sources a 2 MW PV array feeding into a 25kV grid bus, and a SG rated at 2500 MVA and 120kV through a 47 MVA transformer. The power sources supply power to multiple loads through a 37-kilometer transmission line. The proposed protection strategy utilizes a POTT scheme assisted with incremental quantities, supported with measurements from two installed strategically relays at grid bus 1 and 2.

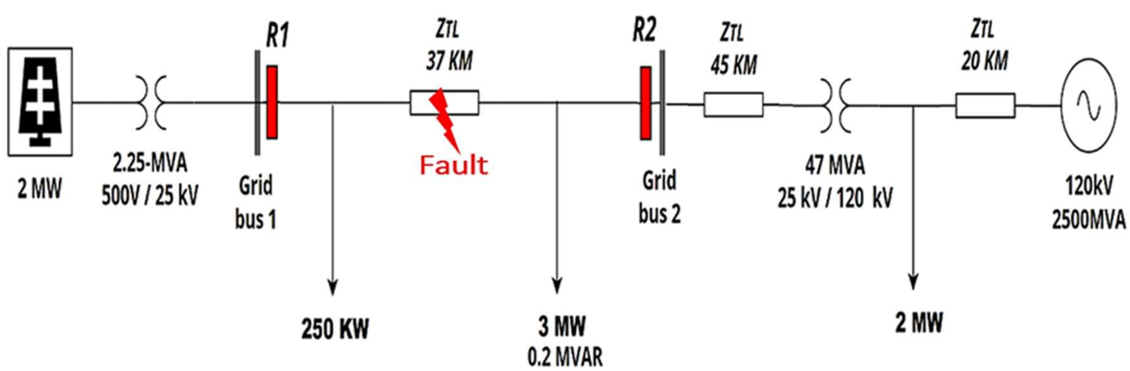


Figure 4.1: Modified 2 MW PV Farm Connected to a 25-kV Distribution System[2].

In this research, some scenarios have been conducted on the system to evaluate the protection dependability and security of the protection equations under several operating conditions.

4.2 Spectrum of Scenarios

4.2.1 Internal Fault

In this investigation, we explore the occurring of internal faults and the detection processes within a predefined segment of the transmission. The main goal is understanding the detection mechanisms for various fault types, including SLG and three-phase faults. Exploring the detection mechanisms for faults is vital for enhancing the reliability and safety of power systems. Both relays 1 and 2 utilize the operating equations (3), (4), and (5). They operate based on the change in ΔV_{Reach} and V_{Pre} with fault resistance (Rf) set to zero ohms for all types. With reference to figure 4.2, when SLG fault occurs in the transmission line, both relays capture the change in voltage, communicate rapidly, and operate precisely as shown in figure 4.2 (a-1), and (a-2). In addition, the fault current at grid bus 1 is smaller than fault current at grid bus 2 because of the inverter's control strategies in limiting the fault current. Consequently, a higher ΔV_{Reach} is obtained from equation (5). Similarly, for three-phase faults case, the detection is achieved by comparing ΔV_{Reach} and V_{Pre} as shown in figure 4.2 (b).

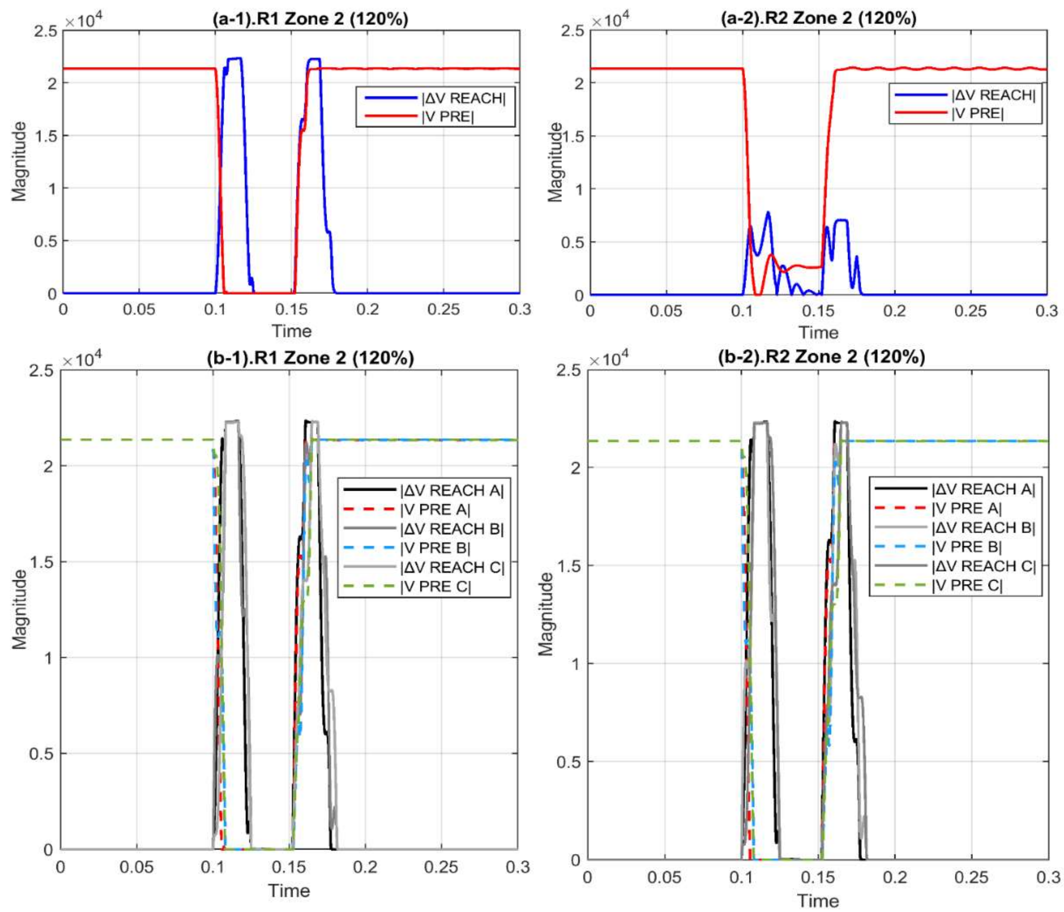


Figure 4.2: The fault detection of relays R1 and R2 (a). SLG fault
(b). Three phase faults.

4.2.2 Sensitivity Study of High Fault Resistances

The fault current magnitude can be affected by different Rf. IBRs have a limited current contribution and varying Rf can significantly affect their fault current during fault events. A high Rf decreases the amount of fault current, whereas a low Rf will result in a high fault current. It's important to delve into the possible range of fault resistance and thoroughly examine their influence on the detection system.

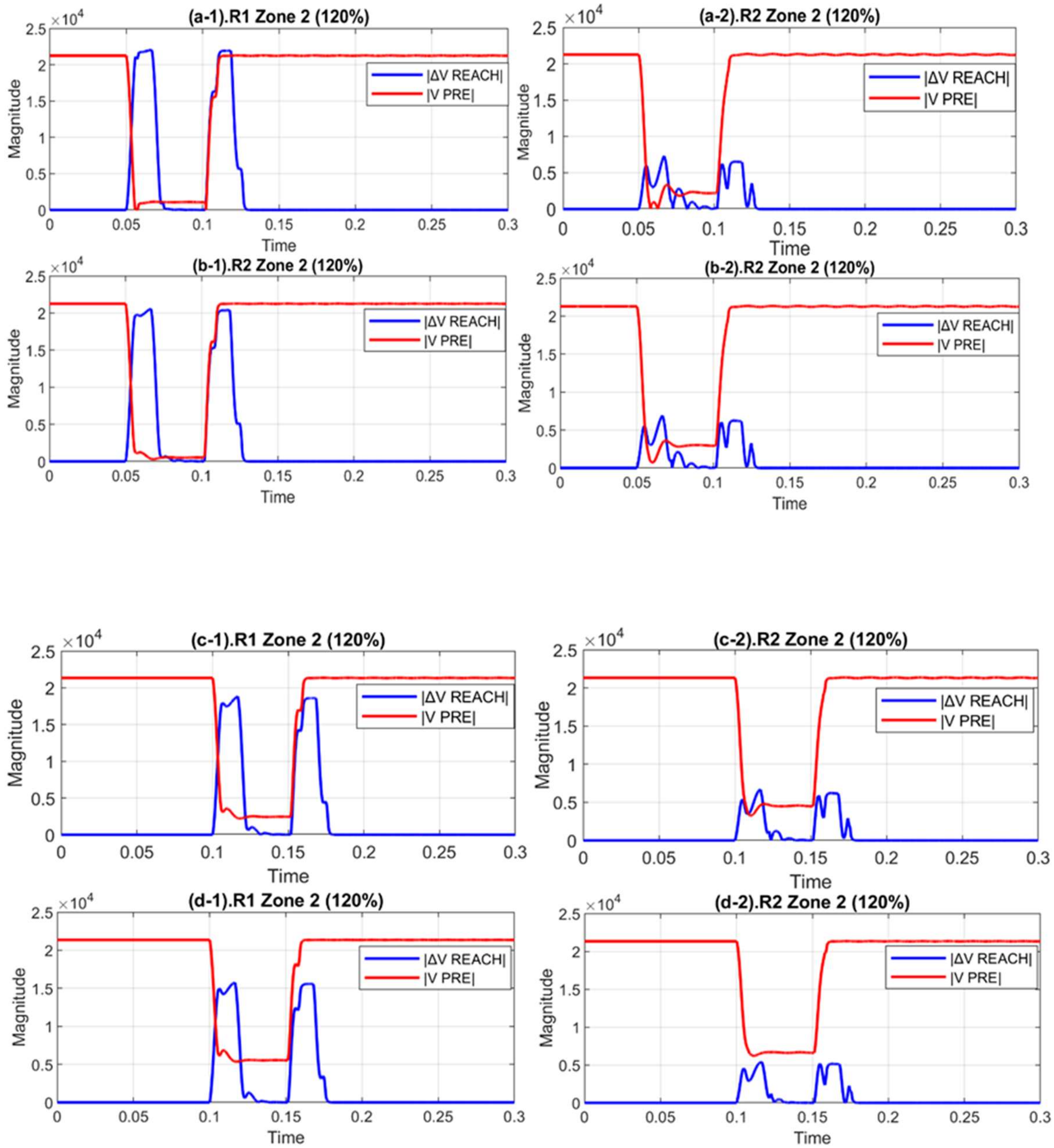
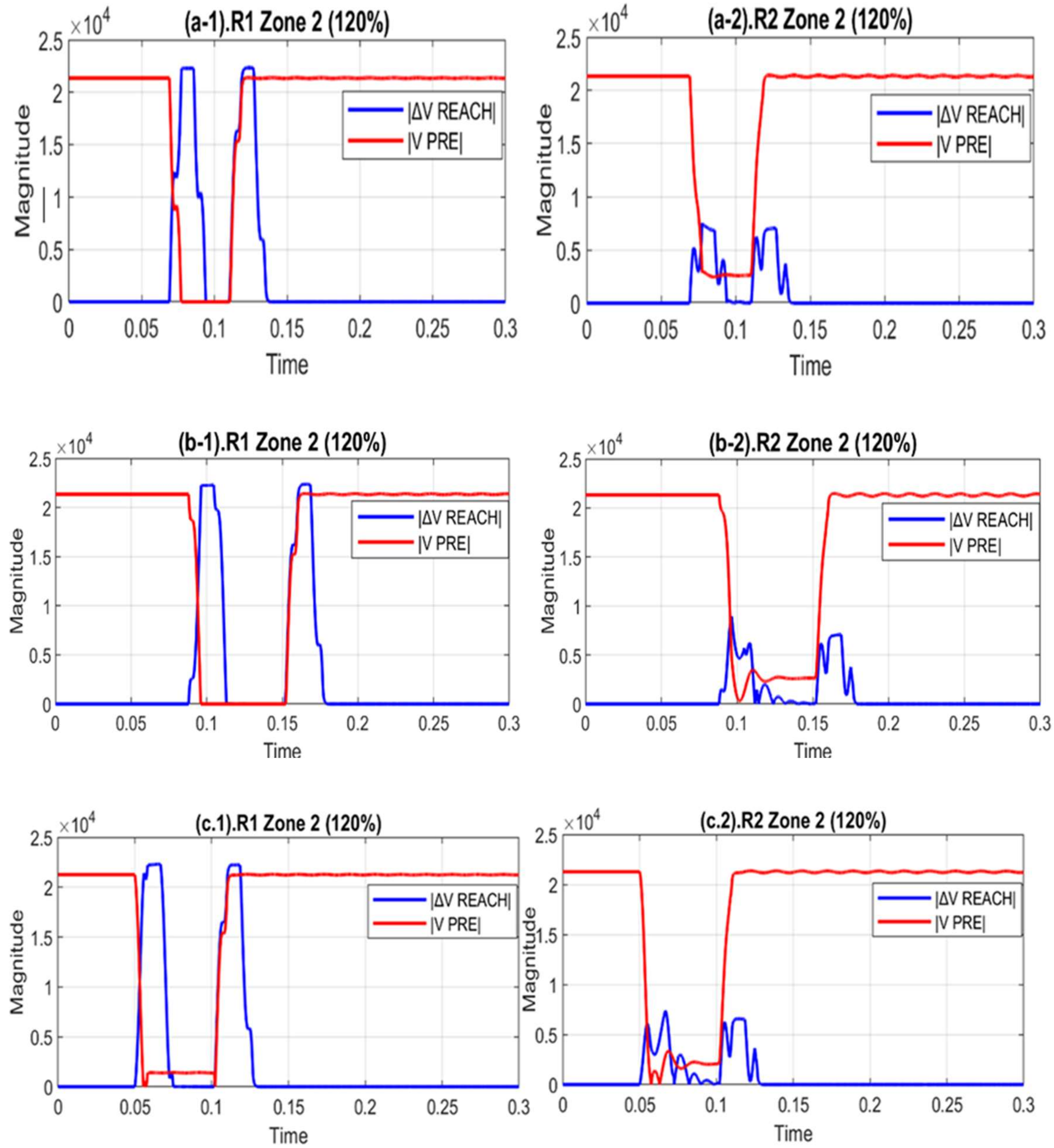


Figure 4.3: The sensitivity of the proposed scheme under different fault resistance
(a). Rf =1 ohm, (b). Rf =5 ohm, (c). Rf =10 ohm, (d). Rf =20 ohm.

As illustrated in figure 4.3 (a), (b), and (c) show a valid detection of R1 and R2 for fault resistance Rf that sets to different values. At (a) the Rf is set to 1 ohm and both relays detected the fault successfully. Similarly, for (b) when Rf=5 ohms, the fault is detected by comparing ΔVReach, and Vpre. Also, in (c) a valid detection by R1 and R2 is demonstrated for a fault resistance of 10 ohms. Nevertheless, with an increase to 20 ohms, the fault was detected successfully in (d-1) whereas in (d-2), the fault goes undetected. Both 20 ohms and 10 ohms indicate a high fault impedance in the power distribution system. The proposed scheme is designed to operate for various fault conditions, and it might experience certain scenarios involving high impedance faults which result in limitations cases. Notably, this discrepancy occurred because of the high fault resistance and the substantial fault current contribution from the generator [2]. As evident in (d-2), the relay's decision not to operate because of the influence of high fault resistance and the reduced fault current of IBRs. However, the proposed scheme shows the ability to protect the system from common fault resistance.

4.2.3 Sensitivity Study of Fault Occurrence Angle

The characteristics of the fault can be influenced by the fault occurrence angle on the waveform of the electrical signal. The fault current magnitudes vary based on the position of the fault point on the AC waveform. Specifically, the fault current will be higher when the fault occurs at or near the peak of the voltage waveform (90° or 270°). The elevated current is a result of the fault current occurrence when the driving voltage is at its maximum on the AC waveform. In contrast, the fault point near zero (0° or 180°) can lead to a lower fault current due to the minimum driving voltage. In figure 4.4 (a) and (b) shows the effectiveness of the detection equation in detecting the fault at different timing on the AC waveform. Faults at 45° and 200° in (c) and (d) are detected whether the AC waveform is in its rising phase towards the positive peak or the negative peak. The proposed scheme proved the ability to detect the fault regardless of the fault occurrence angle.



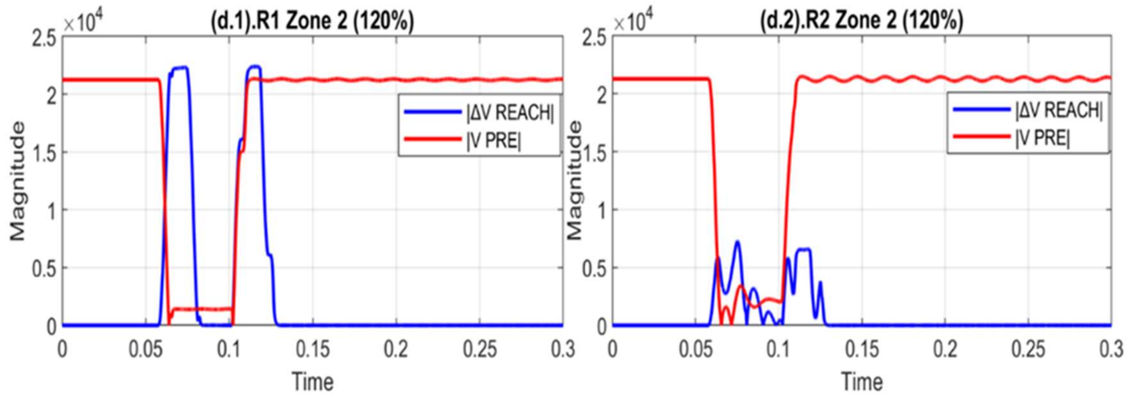


Figure 4.4: The sensitivity of the detection equation of R1 and R2 at different fault occurrence angle (a) at or near the peak (90° or 270°). (b) near zero (0°or 180°) (c) 45°. (d) 200°.

4.2.4 Protection Security Regarding External Fault

The external fault scenario evaluates the reliability of the protection scheme when external fault occurs beyond the predefined protected zone. As illustrated in figure 4.5 shows that the relays distinguish between internal fault that occurs at 0.05 s, clearing at 0.1 s, and followed by external fault at 0.2 s. Both relays operated successfully and initiated a trip signal only for internal faults. In the case of external faults, the proposed scheme adeptly distinguishes between internal and external faults and the results affirm the security and reliability of the proposed protection scheme [2].

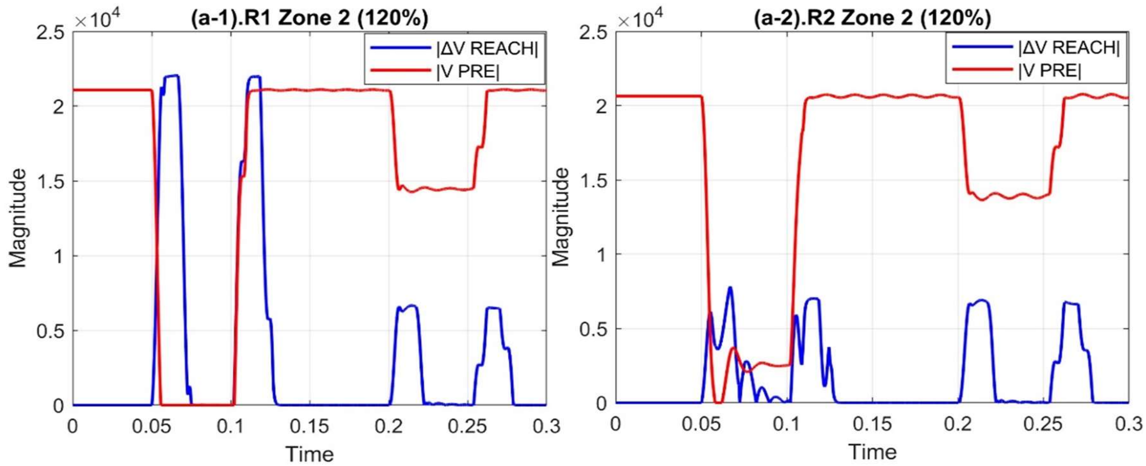


Figure 4.5: Using R1 and R2, examination of the detection system; not responding to faults outside the protected zone.

4.2.5 Protection Security Regarding Capacitor Banks Switches

The capacitors banks have a big role in maintaining the voltage levels of the power system by supplying reactive power. Moreover, a sudden demand for reactive power can cause a temporary voltage overshot because of the transient characteristics of the capacitors during their switching. Capacitor banks start to supply reactive power to the system when they are switched on. During the sudden increase in the demand for reactive power, such as during heavy load conditions capacitor banks provide significant amount of reactive power [2]. Capacitor banks can provide instantaneous reactive power which can lead to an overshot in voltage. These transient changes in voltage level can influence the sensitivity of grid equipment's and the overall stability of the power system. Figure 4.6 shows a sudden change in incremental quantities because of (3 MVAR) capacitor banks switched on at 0.15 s. However, the operational mechanism of the proposed protection scheme, the relays refrain from initiating a trip action, ensuring the security of protection approach.

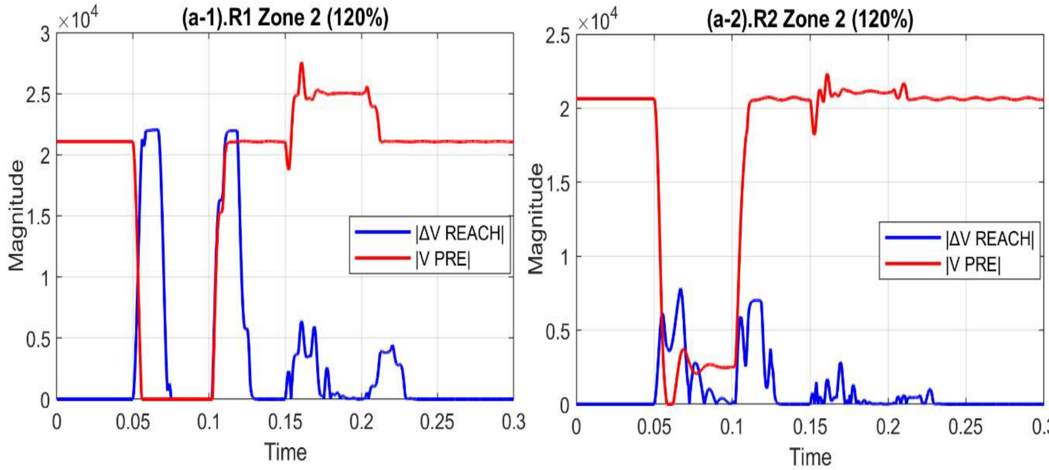


Figure 4.6: The detection system under the impact of the capacitor banks.

4.2.6 Protection Security Regarding Load Variations

Load changes are common in the distribution system, and it can significantly influence the voltage and current of the power systems. The voltage drop occurs when the load increases, there is a corresponding increase in the current flowing through the distribution lines, which results in a greater voltage drop across the line impedance. Figure 4.7 illustrates the comparison between ΔVReach and Vpre and it shows whether the captured change in voltage is a consequence of transient load variations or actual faults. With reference to Figure 4.7 the detection equations, depending on Δv and Δi measurements are sensitive in responding to faults condition and maintain the stability of the power system [2]. The obtained results affirm the security of the proposed protection scheme.

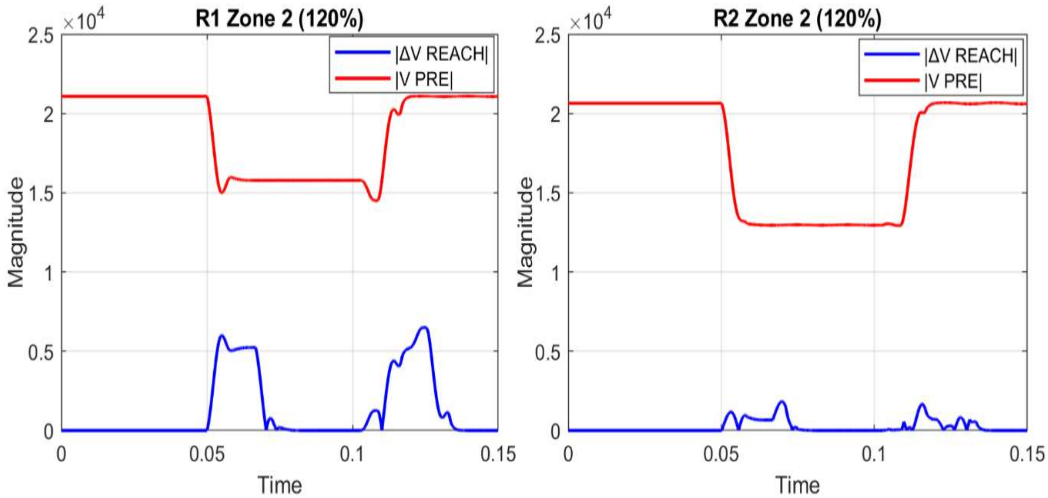


Figure 4.7: R1 and R2 capture variations in load, no fault was detected.

4.2.7 Protection Security Regarding Conventional Power Systems

The conventional power systems, especially those incorporating SGs, rely on protection schemes that utilize high fault currents in detecting faults. This scenario explores the effectiveness of a POTT scheme associated with incremental quantities tailored for conventional systems. Conventional power systems exhibit high fault currents and traditional protection schemes like overcurrent and distance relays operate accurately in detecting faults. The adapted POTT scheme with incremental quantities can recognize fault current characteristics of SGs to enhance the fault detection and isolation process. This scheme is particularly effective in scenarios where fault currents are significantly above the high because of the internal dynamic of SGs. Figure 4.8 illustrates the comparison between ΔVReach , Vpre and the detection process of the fault at conventional SGs presence, ensuring high reliability and security against faults. These relays can detect the fault conditions based on fault current characteristics of SGs. In addition, both relays confirm the presence of the fault within their monitored segment, a permissive signal is sent between the two, enabling immediate isolation of the faulted section. This scheme significantly detects the high fault current contribution from SGs and enhances the reliability of the system.

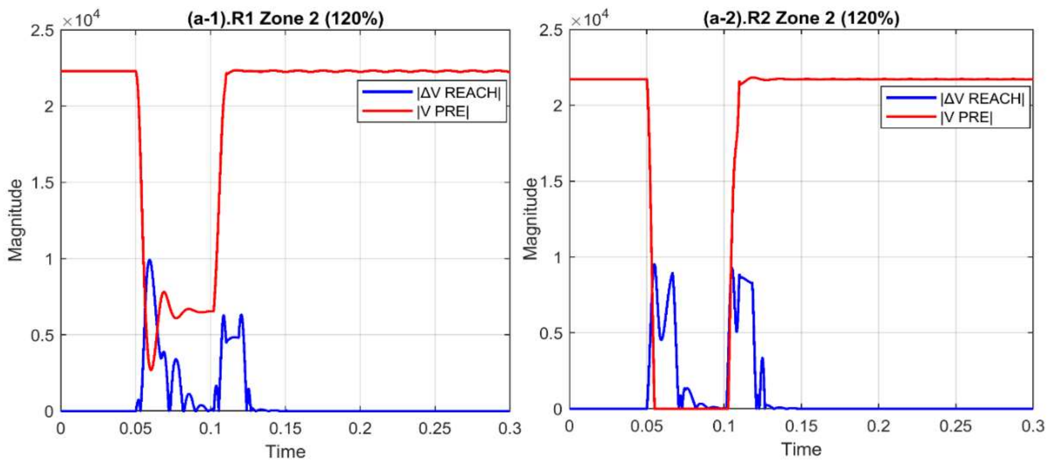


Figure 4.8: Both relays confirm the presence of fault, ensuring security[2].

Chapter Five: Conclusion

The high integration of renewable energy such as solar photovoltaics into power systems requires an understanding of the characteristics exhibited by IBRs. The presence of IBRs presents a significant challenge to the existing protection schemes in power systems such as overcurrent relays and distance relays. This thesis introduces an effective protection scheme to address the unique challenges associated with IBRs in limiting fault current. In this thesis, a study was conducted on fault current contributions between SGs and IBRs. SGs produce high fault currents due to their internal dynamic and traditional power system protection schemes designed for SGs. Conversely, IBRs limit the fault current to prevent damage to PE, causing a protection challenge to the existing protection elements. Incremental quantities offer accurate capture of transient changes of system conditions, taking the differences in measurements of voltage and current to enhance the sensitivity. The implementation of the POTT strategy, utilizing incremental quantity, exhibiting precise detection of internal faults within IBRs. The comprehensive evaluation of proposed protection schemes under diverse fault scenarios, fault impedances, and occurrence angles, the corporation of capacitor banks to load changes. Different fault scenarios illustrate potential combinations between system components and the fault detection mechanism. The 2-MW PV system, as a part of this test environment, includes a series of extensive simulations, to examine, and validate the performance and effectiveness of the proposed protection solution under a variety of fault scenarios. To extend this research, artificial intelligence (AI) algorithms can select the optimal protection strategies, balancing efficiency, and system safety. Moreover, AI could enhance fault detection with the integration of renewable energy sources into power systems. AI models can analyze the patterns and trends of data sets to improve the security of power systems. There is a critical need for continuous development in protection schemes as the landscape of power generation sources shifts towards sustainable sources.

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