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A survey on analysis of 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 modelling, few research studies have been done to analyse DER's fault behaviours during actual fault events. This paper explores recorded fault events collected by Dominion Energy. Fault magnitude, angle, and sequence components are analysed to show that actual DER fault response may differ from previous understandings. The general reclosure over current relay is replaced with counter set reclosure over current relay which completely triggers off when the restricting number crosses 3 times. So, the over current relay only closes to short transient faults but not long-time faults. The analysis with respect to different conditions is checked using a DER (PVA) connected to this counter set reclosure over current relay.
Key words: Photovoltaic Array Over Current Relay, Counter Set reclosure over current relay, MPPT, PWM Generator, Buck -Boost converter, Inverter

1.Overview Of Distributed Energy Resources (DER)

With the increased demands of the electrical power systems and events of electricity shortages, power quality issues, rolling blackouts and spikes in electricity price have led to research of alternate sources of energy. This led to the development of Distributed Energy Resources (DER) that is a small-scale power generation source located close to where electricity is used and primarily acts as an alternative to or an enhancement of the existing electric power grid. With consideration to the construction of large, central power plants and high-voltage transmission lines, DER is a faster and less expensive option. It offers higher reliability, increased power quality, high energy efficiency and energy independence. The utilization of renewable distributed energy generation methods and green power like wind, biomass photovoltaic, geothermal or hydroelectric power provides a noteworthy environmental benefit.

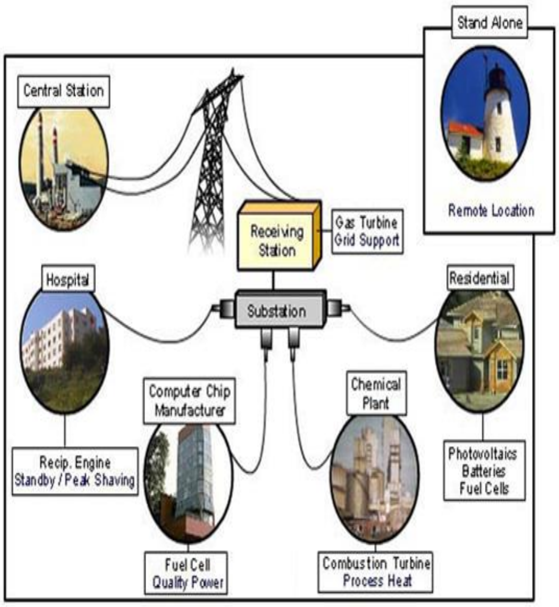

Fig. 1.1 Types of distributed energy resources and technologies

DER has been in the field for many years and is commonly known by names such as generators, back-up generators or on-site power systems. But within the electric industry the requisites that have been used are distributed generation (DG), distributed power (DP), and DER.

Distributed Generation: technology that produces power outside of the utility grid like fuel cells, micro turbines and PV cells

Distributed Power: technology that produces power or stores power such as batteries and flywheels

Distributed Energy Resources: combination of technology included in DG and DP as well as demand-side measures. In this configuration power can be fed back to the grid.

1.1 Components of DER Technologies

A DER technology mainly consists of energy generation and storage systems placed at or near the point of use which usually includes fuel cells, reciprocating engines, micro turbines, load reduction and energy management techniques. DER also engages power electronic interfaces, communications and control devices so as to obtain higher efficiency and for the operation of single generating units, multiple system packages and collective power blocks.

1.2 Characteristics and Application Of DER

The primary application of DER includes:

- **Premium power**: lesser frequency variations, voltage transients and other disruptions
- **Back-up power**: used as a back-up in the event of an outage
- **Peak shaving**: used when electric use and demand charges are high
- **Low-cost energy**: locally available and economical primary power source
- **Combined heat and power (cogeneration)**: increase the efficiency during power generation by using the waste heat for existing thermal process

Basically, the DER provides better reliability, adequate power quality, helps to mitigate overloaded transmission lines, manage price fluctuations, build up energy security and provides superior stability to electric grid.

1.2 Solar Energy Power Generation

The conversion of sun's radiation into electricity via the use of solar photovoltaic cells is termed as solar power generation. Photovoltaic effect is the basic principle of this power conversion. A minimum number of steps are included in the power generation as compared to conventional generation methods which paves way for wide range of applications. Converting sunlight into electricity can be mainly done in two ways. First method is where solar energy is used as a source of heat which is further used to produce the steam that drives the steam turbine. This method of power generation is termed as solar thermal power generation. Second method makes use of silicon PV cells to directly convert solar energy into electricity and is termed as solar power generation.

Major factor for choosing the solar power generation are:

- free availability
- lesser time is needed for installation of solar power plants
- clean energy production
- economical as only one-time initial investment is needed

1.2.1 PV CELLS

A PV cell also termed as solar cell is a semiconductor device which converts the sunlight energy falling on it into electricity without carrying out much energy conversion steps. This conversion takes place by photovoltaic effect and thereby they are called Photovoltaic (PV) cells. It generates voltage and current at its terminals when sunlight is incident on it.

Electrical Characteristics of A PV Array

The electrical attributes that a photovoltaic cell exhibits are showcased in the connection between voltage and the present-day yield. Their sum and power of sun-primarily based insolation (daylight-based irradiance) governs the measure of modern-day yield (I), also the working temperature of the sun-based cells affects the yield voltage (V) of the PV show off. Photovoltaic board (I-V) creates the connection among the modern-day yield and voltage and is given as:

1.3 Power System Protection

The main objective of power system protection is to isolate a faulty section of electrical power system from rest of the healthy system so that this portion can function suitably without any serve damage because of fault currents. The circuit breaker isolates the faulty system from rest of the live system as they automatically open during fault condition because of its trip signal which comes from the protection relay. The system cannot be fully prevented from fault currents but we can prevent the continuation of flow of fault current by quickly disconnecting the short circuit path from the system for which the protection relays should have following functional requirements.

- **Reliability:** Relays remain inoperative for a long time before a fault occurs; but it must respond instantly and accurately during fault occurrence.
- **Selectivity:** The relay must be operated only in those conditions for which relays are custom-made in electrical power system i.e. at some fault point it should not be operated or must be operated at some definite time.
- **Sensitivity:** The relaying equipment must be sufficiently sensitive to operate precisely when level of fault condition just crosses the predefined limit.
- **Speed:** The protective relays must operate at the required speed i.e. it should neither be too slow which may result in damage to the equipment nor it should be too fast which may result in undesired operation.

Important elements for power system protection mainly include:
Switchgear: oil circuit breaker, SF_6 circuit breaker, air blast circuit breaker and vacuum circuit breaker etc.
Protective Gear: power system protection relays such as current relays, voltage relays, impedance relays, power relays, frequency relays, etc.
Station Battery: Almost all the circuit breakers of electrical power system are DC operated. Since DC power can be stored in battery and in case of total failure of incoming power the circuit breakers can be operated for restoring the situation by the power of storage station battery. Therefore it is also referred as the heart of the electrical substation. During the period of availability of AC supply the station battery cells accumulate energy and discharge at the time when relays operate so that appropriate circuit breaker is tripped at the fault time.

2. Literature Review

This chapter presents the literature review of various types of faults in distributed solar generation, protection gaps of conventional solutions, as well as existing approaches of fault detection, classification and protection solutions. The benefits and limitations of these existing approaches are also explored and compared.

H. Hooshyar and M. E. Baran [4] Fault current profile on a PV-dominated distribution feeder is rather different than a conventional feeder. To estimate the fault current profile on such a feeder, the paper proposes a new method which extends the capability of conventional short-circuit analysis method. The paper also shows that this time-varying fault current profile makes it also more difficult to estimate the time it will take for an overcurrent relay/device to interrupt such a fault current.

Alsfasfeh et.al. [6] establishes accessible capacity maximization problems from the Institute of Electrical and Electronics Engineers (IEEE) standard node system and power system analysis theory for PV power sources with constraints of voltage fluctuations. A MATLAB R2017B simulator is used for the performance analysis and evaluation of the proposed work. Through the simulation of the IEEE 33-node system, the integration capacity range of the PV power is analyzed, and the maximum integration capacity of the PV power at each node is calculated, providing a rational decision-making scheme for the planning of integrating the distributed PV power into a small-scale power grid.

Mohamed-M-H et.al.[7] In distribution system, wind power plants are becoming popular renewable energy sources. It employs Doubly Fed Induction Generator (DFIG) to generate power based on wind conversion. Short and long transmission lines, presence of faults and presence of Static Synchronous Compensator (STATCOM) are highlighted issues in this paper. Basically, this research develops investigations on some electrical variables such as voltage and current to control them. Distribution Static Synchronous Compensator (DSTATCOM) is proposed in this paper. Wind farm acts as a source while DSTATCOM is connected to the distribution system with a DFIG based wind farm.

D. Kim and N. Cho et.al. [8] The objective of this paper is to provide a method for steady-state short-circuit analysis in power networks with distributed energy resources (DERs). For this purpose, we suggest an approach that takes into account the impact of current controlled DERs in the fault analysis. The current controlled DER has some characteristics that we should consider-1) DER's large filter inductance and 2) the limit effects of DER's output current and voltage. In addition, for the fault analysis, we should consider the characteristics of loads demanding constant power in the network. Therefore, to resolve these problems, we propose a power-flow based fault analysis technique.

Lucian loan Dulau [10] This paper describes the effect of distributed generation of electric power system. distributed generation in terms that refer to production of electricity near the consumption place. The effect of distributed generation are short circuit level are increased load losses change, voltage profile change along the network, voltage transient will appear congestions can appear in system branches power quality and reliability may be affected and the network may not function properly.

Namhun Cho [11] in this paper describes the Recently, the interconnection of distributed energy resources (DERs) has been observed to hinder the reliability of power supply. To solve this problem, the Korea Electric Power Corporation (KEPCO) has attempted to develop a practical fault analysis methodology for DERs that can be applied to distribution management system (DMS). This novel methodology to analyze the impacts of various DERs during shunt faults is presented in this paper. First, the basic concepts behind the proposed methodology are introduced. Then, the fault analysis methodology is introduced to determine the contributions of balanced and unbalanced DERs during shunt faults.

Madeleine and han slootweg et.al.[12] This paper explores a revenue maximization problem for distributed energy resources in a local day-ahead and balancing market. The local market creates opportunities for competition among distributed energy resources, however it may also lead to exercising market power. In the day-ahead market, the strategic revenue maximization of the distributed energy resources is modelled through a bi-level optimization. The upper-level in the bi-level optimization is from the strategic distributed energy resource's perspective and the lower-level problem is from the local market operator's perspective. The balancing market (where there is perfect competition) is modelled by the shrinking rolling horizon approach.

Dong-Eok Kimand Namhun Cho et.al. [13] In this paper describes a fault analysis method for a power distribution grid with PCSbased DERs. We first explain the characteristics of a PCS-based DER. According to the characteristics, the DER is considered as a current-controlled voltage source, which produces varying voltages within a certain limit so that currents equal to given references flowing from the DER to the grid (currents controlled). So, we introduce the symmetrical equivalent models in the form of varying voltage source for fault analysis and then, construct a convex optimization problem to solve the fault problem associated with the equivalent models and grid conditions. Thus, the proposed method enables to perform a proper fault analysis considering the characteristics of the DER, which are currents controlled, voltage limited, and unity power factor achievement.

3. Proposed Methodology

3.1 Three Phase Transmission Line

The power transmission line is one of the major components of an electric power system. Its major function is to transport electric energy, with minimal losses, from the power sources to the load centers, usually separated by long distances. Three-phase electric power is a common method of alternating current electric power generation, transmission, and distribution. It is a type of polyphase system and is the most common method used by electrical grids worldwide to transfer power. It is also used to power large motors and other heavy loads. A three-wire three-phase circuit is usually more economical than an equivalent two-wire single-phase circuit at the same line to ground voltage because it uses less conductor material to transmit a given amount of electrical power. (Cleber da Silva & Kurokawa, 2013)

3.1.1Transformer: Transformers play a key role in the interconnection of power systems at different voltage levels. Without the transformer, it would simply not be possible to use electric power in many of the ways it is used today. Consequently, transformers occupy important positions in the electric power system, being the vital links between power generating stations and points of electric power utilization. A transformer has been defined by ANSI/IEEE as a static electric device consisting of two or more windings, with or without a magnetic core, for introducing mutual coupling between electric circuits. Better transformer design and the use of superior grade electrical steel can drastically reduce no-load loss, one of the prime components of loss in a transformer. No-load loss can be further reduced in some cases if conventional electrical steel can be replaced with amorphous metal.

3.1.2 Feeder Electric Power Distribution System is very important infrastructure because it delivers electricity to users either domestic or commercial consumers. Its continuous and reliable performance is essential to nation building and citizens' way of life. Failure of Power Distribution Systems has direct and indirect negative effect on daily activities and the social-economy well-being of users. Feeders are circuits that carry electric power to substations. Its performance and 24-hour a day consistent delivery of energy is central in Reliability of electric power distribution systems. Better feeder design and feeder automation provides robust and more than one path of supply while automation will help in identifying and locating fault point on the feeder length. (Ogheneovo, 2015)

3.1.3 Load: In recent years, with the large amount of distributed generations (DGs) access, the traditional single-source radial distribution network has been transformed into a multi-source distribution system. When the system fails, a certain amount of load can be separated from the power grid to form a power supply region off-grid. In the power supply region off-grid, DGs can be used to power the load to improve reliability for users. With the large amount of distributed generation in use, the structure of the distribution system is increasingly complex. herefore, it is necessary to establish a method to improve load reliability. (Ren et al., 2018)

3.1.4 POI Reclosure: The POI relay accomplishes automatic islanding by opening a circuit breaker (or recloser) at the POI. The relay opens the POI when it detects short circuits, open circuits, or back feed conditions. The relay is configured by skilled engineers to distinguish internal from external system disturbances and to avoid nuisance tripping. Opening the POI provides a crucial indication to the microgrid protection and control systems. The POI opening commonly initiates fast load shedding or distributed energy resource (DER) runback (curtailment) to prevent the microgrid from blacking out. The POI opening indication is also used to change relay protection settings throughout the microgrid to adapt to reduced fault current levels, and it can also signal DER control systems to change their modes of operation.

3.1.5 DER: DER is playing an increasing role in providing the electric power quality and reliability required by today's economy. It has also become clear that DER can play a critical role in avoiding the dysfunctions in competitive electricity markets caused by concentrations of market power. DER systems are beginning to participate in demand reduction programs recently established by independent system operators to help meet peak summer loads. DER interconnection systems consist of all of the equipment (both hardware and software) that makes up the physical link between DER and the EPS, usually the local electric distribution grid. Because the interconnection system is the means by which the DER unit electrically connects to the EPS, it controls power flow in one or both directions and can provide autonomous and semi-autonomous functions supporting the operations of both the EPS and the DER facility.

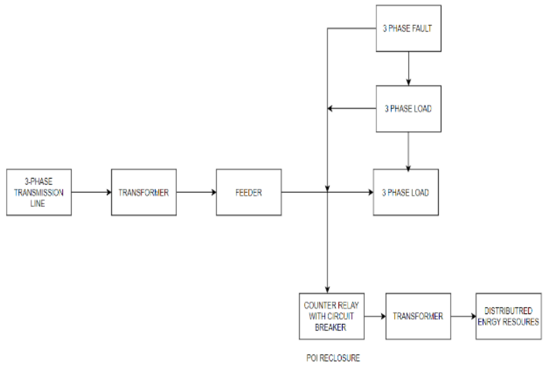

Fig. 4.1 Proposed system of Fault Characteristic of DER System

3.2 Working of Proposed system

This presents the modeling of a three-phase transmission line connected photovoltaic system incorporated with a predictive technique of short circuit current management controller from PVA and load. This technique is based on the rate of rise of current together with the magnitude in a PV solar system-based DER. The study system model consists of a typical feeder used in it. The transmission line supplies electric energy, with minimal losses, from the power sources to the load centers. It is a type of polyphase system and is the most common method used by electrical grids worldwide to transfer power. First, a coupling transformer known as step up transformer is connected between the feeder and the transmission line. Transformers occupy important positions in the electric power system, being the vital links between power generating stations and points of electric power utilization. After this, the power is provided to the feeder from transformer. Feeder is a kind of transmission line which transports power from source station to the distribution point. They are similar to distributors except the fact that there is no intermediate tapping done and hence the current flow remains same at the sending as well as the receiving end. Through POI reclosure and transformer, the power from the feeder is supplied to DER. POI reclosure detects short circuits, open circuits, or back feed conditions. The POI provides a crucial indication to the microgrid protection and control systems. Before DER, a coupling transformer known as step down transformer is connected between the POI reclosure and the DER. The DER stores power in PVA for future use. The output current and voltage of a PV array may be used directly to supply light loads like DC motors and lighting systems.

3.3 PV Array

The main problem of photovoltaic panels is, of course, their dependence on climatic conditions,

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which greatly change the power output. In this thesis, a PV array is created through the MATLAB simulation, which is simple and effective in different climatic conditions. Sunlight can be directly converted into electricity by a PV system while wind energy can be utilized to generate electrical energy which can further be purified by using some efficient electronic load controllers. A photovoltaic cell is the fundamental unit of a PV system. The PV cells can be arranged into series /parallel to make PV panels and PV arrays. The energy generated by a single module is rarely sufficient for commercial use, so the modules are grouped together to form a photovoltaic array which is capable to supply required load demand. The output current and voltage of a PV array may be used directly to supply light loads like DC motors and lighting systems. More power demanding applications need power electronics converters to meet demand with power of PV array.

3.4 Circuit Breaker

An electrical circuit breaker is a switching device which can be operated manually and automatically for controlling and protecting an electrical power system. As the modern power system deals with huge currents, special attention should be given during designing of a circuit breaker to ensure it is able to safely interrupt the arc produced during the closing of a circuit breaker.

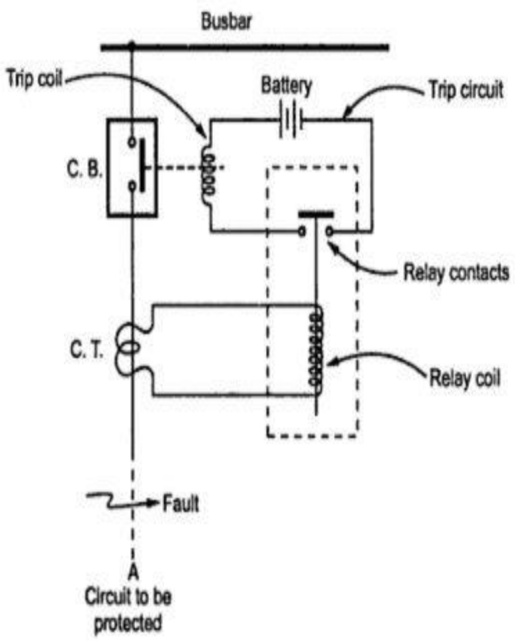

Fig. 4.2 Circuit Diagram of circuit breaker

3.4.1 Working Principle of Circuit Breaker

The circuits breaker mainly consists of fixed contacts and moving contacts. In normal "ON" condition of the circuit breaker, these two contacts are physically connected to each other due to applied mechanical pressure on the moving contacts. There is an arrangement stored potential energy in the operating mechanism of circuit breaker which is released if the switching signal is given to the breaker.

The potential energy can be stored in the circuit breaker by different ways like by deforming metal spring, by compressed air, or by hydraulic pressure. But whatever the source of potential energy, it must be released during operation. The release of potential energy makes the sliding of the moving contact in a speedy manner. The circuit breaker has to carry large rated or fault power. Due to this large power, there is always dangerously high arcing between moving contacts and fixed contact during operation of the circuit breaker. Again as we discussed earlier the arc in circuit breaker can be quenching safely if the dielectric strength between the current carrying contacts of circuit breaker increases rapidly during every current zero crossing of the alternating current.

3.4.3 Circuit breaker with counter set reclosure over current relay

A circuit breaker, whose tripping and reclosing functions are programmed and controlled automatically by an intelligent control unit called as "AUTO RECLOSER". Auto Recloser can interrupt fault currents, and also programmed to reclose, to restore the supply. The supply gets restored if the fault is of transient in nature. If the fault is of permanent type, the Auto Recloser tries to reclose the supply in two or three attempts (as set in the program) and finally goes to 'lock out' status, after which manual intervention is essential.

The control unit is facilitated with manual control switches for circuit breaker trip and close operations. The circuit breaker status is indicated through indicating lamps. The operation of the circuit breaker is monitored by control unit after extending the trip/ re-closing. The lockout contact will operate if breaker is mal-operated. The control unit has inbuilt trip counter which counts number of trips after installation. The count can be reset. The fault zone indicator is very useful only when several sectionalisers are used along the feeder. The zone numbers are based on time interval of closing the sectionaliser from the time of closing of auto recloser. The zone number will be displayed on the display. Zone number gives very useful information to locate the faulty section of feeder quickly. Inbuilt power pack will generate sufficient DC power supply required to operate circuit breaker.

The lockout contact will operate on following conditions.

- On permanent fault
- Breaker mal-operation
- Very low voltage
- Trip when unit is manual modes

4.1 Conclusion

In the given comparison the reclosure over current relay has less fault current converging at the fault location as compared to over current relay and no relay models. However, the no relay model is a completely failed model as the fault remains in the line and the modules are damaged. The overcurrent relay continuously triggers ON and OFF during the fault and damages the modules connected to the test system. The reclosure over current relay helps the breaker to shut OFF completely after some restrickings and the test system is protected from the fault and the modules remain intact.

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