Analysis on Relay Coordination in IEEE 9 bus PV integrated Hybrid Power System using ETAP software: A case study

Subhajit Mukherjee 1, Ratan Mandal 2, *, Arijit Ganguly 3, Asoke Kumar Paul 4
1Department of Electrical Engineering, Brainware University, Barasat, Kolkata - 700125, India
2School of Energy Studies, Jadavpur University, Kolkata 700032, India
3Department of Electrical Engineering, Techno India University, Salt Lake, Kolkata - 700091, India
4Email: subhijit2018@gmail.com, er.arijitganguly@gmail.com, asokepaul@yahoo.co.in
* Corresponding author: ratan.mandal99@yahoo.co.in

Abstract. The modern power system of the country like India, there is an important need to design an uninterrupted electrical power system network having adequate security, stability and reliability. In this present paper an IEEE 9-Bus hybrid system is considered for a short circuit analysis and protection relying coordination for designing of overcurrent relaying scheme to operate the relay efficiently and disconnect the fault section from healthy section instantly. It also compares the differences between existing systems with PV connected hybrid system. Now days, when Electrical Power System adopts the Renewable energy source with existing power source of the network, the main challenge is to design a protection scheme to protect the hybrid system where different intermittent sources make a great impact. To design such a power system the behavior of the existing protection scheme need to be analyzed. In this paper authors simulate an IEEE 9-Bus system using ETAP simulation and analysis is made through Load Flow Study and Short Circuit Analysis. The study reveals that the behavior of the protection system changes with variation of the renewable energy sources integrated with in the bus system. Also set point of the protection relays varies with percentage sharing of the load by PV sources compared to the existing scheme. Observation of the behavior of existing protection system with PV connected hybrid system generates a road map to design an accurate protection scheme for hybrid system.

Keywords - ETAP, Photo voltaic generation; Direct Normal Irradiance (DNI), Short Circuit Analysis.

1. INTRODUCTION

In abnormal condition, it includes an electrical failure of power system equipment operating at one of the primary voltage within the system that causes a fault in a power system network. Under balanced load condition, when disturbed by a fault due to either flashover, insulation failure, physical damage or human error creates excessive high currents flow through the system that causes the system to operate in the abnormal state which is not desired. Classification of the short circuit faults in the system as: (i) symmetrical fault, (ii) asymmetrical fault. Symmetrical faults can be as follows, (i) the three phase are short-circuited to each other i.e., L-L, L-L, (ii) the three phase are grounded i.e., L-L-G. The three phases are equally affected and can be called balanced fault. But these faults occur irregularly. Whereas, Asymmetrical faults can be, (i) single phase to ground i.e., L-G, (ii) double phase to ground i.e., L-L-G, (iii) phase to phase faults i.e., L-L, in which the single phase to ground fault occurs frequently [1, 2]. In the present work, a short circuit analysis is carried out to ensure the stability of the power system network and to confirm the safety of the general public also it will help to determine the ratings of protective equipment. Here, the minimum device rating is determined considering the maximum steady-state short circuit current and the relay coordination is analyzed based on the minimum steady-state short circuit value of the power system network. In this case the circuit breaker can safely isolate the faulty circuit but proper protection scheme with proper selection and settings of protective devices i.e., fuse, circuit breaker and relays are needed [3]. In this paper, a single line diagram of IEEE 9-bus PV connected system based on actual data is considered and simulated in ETAP software for analysis purpose. The short circuit characteristic has been analyzed at different bus at different fault conditions using IEC standard in ETAP platform.

1.1. ABOUT ETAP

Electrical Transient Analyzer Program (ETAP) is the foremost integrated database for electrical systems having multiple representations of a power system for design, analysis, simulation, monitoring, control, and optimization and automation purpose. This software offers the most comprehensive and integrated suite of power system network that spans from modeling to operation. ETAP is the best Electrical Transient analysis software for performing rigorous analysis on electrical network. The objective of this paper to provide the basic understanding of the load flow studies and use of Electrical Transient Analyzer Program (ETAP) application software as a successful and accurate tool to conduct load flow study and short circuit analysis of complex electrical power systems within minimum time period [4, 5]. Short circuit current can be calculated using ETAP through the ‘Short Circuit Analysis’ module [6, 7, 8]. This module allows the C37 Series of the ANSI/IEEE standardcalculation of fault duties and other modes of options and preferences within ETAP.

1.2. RELAY SETTING

The protective relay is used for detecting the fault current that send the trip signal to the circuit breaker. In every zone of the power system network a primary relay installed to protect the system. If the primary relay does not operate then the fault is cleared by backup relay. If the relay has quick response to identify the fault at suitable time and send the signal to the auxiliary devices then only it can implement relay coordination [10]. Therefore, a suitable relay setting is required for any particular network. The protective relay has two types of settings: (i) plug setting for deciding the time of relay operation, (ii) plug setting for deciding the current required to pick up for the relay [11]. After the main relay operation, an adequate time has to be given to operate the backup relay i.e., relay coordination. In this paper, authors show the over current relay coordination of IEEE 9-bus system using ETAP’s star view. The star view feature in ETAP presents relays with their associated characteristic curves, and circuit breaker with their actions and opening times.

A. Overcurrent Relay Setting: The actual current flowing in the relay expressed as a multiple of current setting i.e., pickup current is known as the plug setting multiplier (PSM) [12].To find the PSM, it is given by in equation 1 as follows:


\[
PSM = \frac{I_{f}}{CTR\times f_{p}} \cdots \cdots (1)
\]

where, \( I_{f} \) = Fault Current, \( CTR \) = Rated current of CT (secondary), \( I_{p} \) = Current setting of Relay or Pickup Current.

The primary current of CT is selected by the maximum load current which is passed through primary side of CT. The pickup value of the relay is set in such a manner that it can operate both in normal load condition and certain overload supply. The current setting of relay could be set on 110% of the full-load current or more (up to 200%). Therefore maximum allowable load must be less than the pickup value. To find out Pickup Current Setting, following equation 2 is considered.

\[
I_{p} = \frac{K_{r} \times I_{f}}{R_{se} \times CTR} \cdots \cdots (2)
\]

where, \( I_{f} \) = Full-load current, \( K_{r} \) = Reliability coefficient, it is taken as 1.3, \( K_{d} \) = The drop-off coefficient, it is taken as 0.95. To find out operating time of normal inverse time over current relay is given as equation 3.

\[
T_{op} = \frac{0.1 \times (TMS)^{1/3}}{PSM} \cdots \cdots (3)
\]

where, \( T_{op} \) = Relay operation time, \( TMS \) = Time Multiplier Setting.

B. Coordination Time Interval: The coordination time interval is the time of coordination between the primary and backup protective devices. Coordination time interval should lie between 0.2 second to 0.4 second [13]. Coordination time interval can be expressed as,

\[
y_{backup} - y_{main} \geq Coordination \ Time \ Interval
\]

C. Setting Instantaneous Unit: Instantaneous units are more effective when the source impedance is low in comparison to the impedance of the power system elements being protected. They are two basic advantage: (i) They reduce the operating time of the relay for critical system fault, (ii) Relay consist with different characteristics to avoid the loss of selectivity in a protection system.

The settings of instantaneous units vary with the location and the condition of different types of system element being protected. There are three groups of elements given by:

a) Lines between substations: The settings of instantaneous units are carried out at the next substation at least 125% of the maximum fault level.

b) Distribution lines: 6 to 10 times of the rated current can be set for the setting of the instantaneous units at the outgoing feeders.

c) Transformer units: On the primary side of the transformer the instantaneous element of the overcurrent relay is installed. The value of that instantaneous element should be set at a value between 125 to 150% of existing short-circuit current at secondary side.

1.3 CONCEPT OF PHOTO VOLTAC GENERATION

Photo voltaic power generation system is used of PV cells directly into solar energy i.e., light energy to electrical energy. The number of solar cells connected in electrically series and parallel combination to make a solar module and solar array respectively.

The equivalent circuit diagram of the solar cell is shown in Fig. 1. The load current can be determined using equation 4 as given below [14]:

\[
I_{L} = I_{ph} - I_{L}\left[\exp\left(\frac{q(V+R_{se})}{NKT}\right) - 1\right] - \frac{(V+R_{se})}{R_{sh}} \cdots \cdots (4)
\]

where, \( I_{L} \) = the output load current by the PV cell, \( I_{ph} \) = the photo-generated current which is proportional to the area of the photo voltaic cell and the intensity of the incident light. When the ambient temperature rises then the value of the photo voltaic current is slight rises, \( R_{se} \) = series resistance, \( R_{sh} \) = shunt resistance which is greater than the series resistance \( R_{se} \), \( K \) = Boltzmann constant, \( N \) = ideal factor of the diode and \( T \) = temperature of the cell. Present work deals with performance analysis of PV connected IEEE 9-bus system without a storage system. The grid-connected system is more economical because it can operate without a battery storage system [15].

1.4 OVERVIEW OF THE IEEE 9-BUS NETWORK

1.4.1 Without PV connected IEEE 9-Bus Network: The single line diagram of IEEE 9-bus network is shown in Fig. 2. In this paper, author use three alternators, transformer and loads. Alternator (G1) is connected to slack Bus 1, another two alternators G2 and G3 are connected to Load A, Load B and Load C are connected in Bus 14, Bus 15 and Bus 16 respectively. Total generation is 567 MVA and total load is 321 MW [16].

![Fig.1: Equivalent circuit of solar cell](image)

![Fig.2: IEEE 9-bus Network without PV connected](image)
1.4.2 With PV connected IEEE 9-Bus Network: The PV arrays are connected in Bus 5, Bus 6 and Bus 8 as shown in Fig.
3. Each PV based power generating system has 10098 kWp output powers with 8894.34 V DC.

![Fig. 3: IEEE 9-bus Network with PV connected](image)

2. METHODOLOGY WITH DISCUSSION
To make an analysis on relay coordination of PV connected IEEE 9-bus system authors follow the following steps of as given below:

**STEP 1:** Load flow Analysis on IEEE 9-bus system to obtain the maximum current value of different load bus.

**STEP 2:** Short Circuit Analysis on IEEE 9-bus system to obtain maximum fault current value of different load bus.

**STEP 3:** From Load Flowand Short Circuit Analysis the value of current help us to establish Relay Coordination of PV connected IEEE 9-bus system.

### 2.1 LOAD FLOW ANALYSIS DATA
#### 2.1.1 Three Alternator and without PV array connected IEEE 9-Bus system

| Monitoring Bus | Rated kV | Load Flow | Current in Amp. | % Power factor |
|----------------|---------|-----------|-----------------|----------------|
| Bus 1          | 16.5    | 163.0     | 10.25           | 5110.8         | 99.8 |
| Bus 2          | 18      | 163.0     | 10.25           | 5110.8         | 99.8 |
| Bus 3          | 13.8    | 85        | -8.506          | 3486.7         | -99.5 |
| Bus 14         | 230     | 122.989   | -49.186         | 331.3          | -92.9 |
| Bus 15         | 230     | 28.970    | 34.942          | 261.9          | 94.4 |

#### 2.1.2 Three Alternator and with PV array connected IEEE 9-Bus system

| Monitoring Bus | Rated kV | Load Flow | Current in Amp. | % Power factor |
|----------------|---------|-----------|-----------------|----------------|
| Bus 1          | 16.5    | 58.314    | 46.628          | 2391.2         | 82 |
| Bus 2          | 18      | 163.0     | 10.25           | 5110.8         | 99.8 |
| Bus 3          | 13.8    | 85        | -8.506          | 3486.7         | -99.5 |
| Bus 14         | 230     | -122.989  | -49.186         | 331.3          | -92.9 |
| Bus 15         | 230     | -89.170   | -25.723         | 234            | 94.9 |
| Bus 16         | 230     | -99.875   | -34.942         | 261.9          | 94.4 |

### 2.2 SHORT CIRCUIT ANALYSIS DATA
#### 2.2.1 Fault occur at load Bus 14, Bus 15, Bus 16 with three alternator and without PV IEEE 9-Bus system

**Fault at bus: BUS 14**

|                         | 3-Phase | L-G | L-L | L-L-G |
|-------------------------|---------|-----|-----|-------|
| Initial Symmetrical Current (kA, rms) | 2.475   | 2.521 | 2.444 | 2.581 |
| Peak Current (kA)       | 6.220   | 6.335 | 6.141 | 6.486 |
| Breaking Current (kA, rms, sym) | 2.521 | 2.444 | 2.581 |
| Steady State Current (kA, rms) | 2.475   | 2.521 | 2.444 | 2.581 |

**Fault at bus: BUS 15**

|                         | 3-Phase | L-G | L-L | L-L-G |
|-------------------------|---------|-----|-----|-------|
| Initial Symmetrical Current (kA, rms) | 2.348   | 2.401 | 2.316 | 2.450 |
| Peak Current (kA)       | 5.715   | 5.846 | 5.638 | 5.965 |
| Breaking Current (kA, rms, sym) | 2.401 | 2.316 | 2.450 |
| Steady State Current (kA, rms) | 2.348   | 2.401 | 2.316 | 2.450 |

**Fault at bus: BUS 16**

|                         | 3-Phase | L-G | L-L | L-L-G |
|-------------------------|---------|-----|-----|-------|
| Initial Symmetrical Current (kA, rms) | 2.549   | 2.024 | 2.656 | 2.679 |
| Peak Current (kA)       | 6.306   | 5.166 | 6.779 | 6.838 |
| Breaking Current (kA, rms, sym) | 2.024 | 2.656 | 2.679 |
| Steady State Current (kA, rms) | 2.549   | 2.024 | 2.656 | 2.679 |
2.2.2 Fault occur at load Bus 14, Bus 15, Bus 16 with three alternator and with PV system (Different DNI) [14, 17]

Fault at bus: BUS 14

| Current (A) | L-G | L-L | L-L-G |
|-------------|-----|-----|-------|
| Breaker A   | 2.250| 2.250| 2.250 |
| Breaker B   | 2.250| 2.250| 2.250 |
| Breaker C   | 2.250| 2.250| 2.250 |

2.3 RELAY COORDINATION SIMULATION

Following methods are followed to have short circuit fault analysis simulation for relay coordination [18].

CASE 1: Fault occurs at Bus 14

A. Without PV connected IEEE 9-bus system:

The circuit breaker trip in this following sequence \(i.e\), CB50→CB5→CB9, Circuit breaker of CB5 and CB9 are used for backup protection. Figure 4 shows simulation of fault that occurs at Bus 14 without PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

B. With PV connected IEEE 9-bus system:

The circuit breaker trip in this sequence \(i.e\), CB50→CB37→CB44, Circuit breaker of CB37 and CB44 are used for backup protection. Figure 5 shows simulation of fault that occurs at Bus 14 with PV connected IEEE 9-bus system where ‘×’ indicate relay operating.
CASE 2: Fault occurs at Bus 15

A. Without PV connected IEEE 9-bus system:
The circuit breaker trip in this sequence i.e., CB6→CB51→CB13, Circuit breaker of CB51 and CB13 are used for backup protection. Figure 6 shows simulation of fault that occurs at Bus 15 without PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

![Fig. 6: Simulation of fault occurs at Bus 15 without PV connected IEEE 9-bus system (× indicate relay operation)](image)

B. With PV connected IEEE 9-bus system:
The circuit breakers trip in this sequence i.e., CB6→CB51→CB44, Circuit breaker of CB51 and CB44 are used for backup protection. Figure 7 shows simulation of fault that occurs at Bus 15 with PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

![Fig. 7: Simulation of fault occurs at Bus 15 with PV connected IEEE 9-bus system (× indicate relay operation)](image)

CASE 3: Fault occurs at Bus 16

A. Without PV connected IEEE 9-bus system:
The circuit breaker will trip in this sequence i.e., CB53→CB13→CB15. Circuit breaker of CB13 and CB15 are used for backup protection. Figure 8 shows simulation of fault that occurs at Bus 16 without PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

![Fig. 8: Simulation of fault occurs at Bus 16 without PV connected IEEE 9-bus system (× indicate relay operation)](image)
B. With PV connected IEEE 9-bus system:
The circuit breaker will trip in this sequence i.e., CB5→CB13→CB15. Circuit breaker of CB13 and CB15 are used for backup protection. Figure 9 shows simulation of fault that occurs at Bus 16 with PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

3. CONCLUSION
Present work deals with the problems related to large scale solar energy integration into the conventional grid. A short circuit analysis is carried out to determine the ratings of protective equipment. A single line diagram of IEEE 9-bus PV connected system based on actual data is considered and simulation is done using ETAP software for analysis purpose. The short circuit characteristic has been analyzed at different bus at different fault conditions using IEC standard in ETAP platform. The relay operating sequence with PV and without PV connected IEEE 9-bus system are identified and few steps are specified corresponding to the fault occur at different bus in the network. Figure 2 to 9 are the outputs of the simulation results with different case studies give a complete idea about how relay operation sequence get changed with PV and without PV during fault condition. It is also observe that in case of PV connected bus, the rating of the fault current is very low to sense that fault current therefore the C.T. ratio should be low compared with others C.T. ratio. This study generates a promising technique for fault analysis of PV connected hybrid system with existing protection system. Study also shows a road map to design accurate protection scheme for hybrid system.

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Fig. 9: Simulation of fault occurs at Bus 16 with PV connected IEEE 9-bus system (× indicate relay operation)