



Short Circuit Modelling and Analysis of PV Inverters in Large Solar Farms

Manohar Singh* and Dinesh Patil

Power System Division, Central Power Research Institute, Bengaluru – 560012, Karnataka, India; manoharsingh@cpri.in

Abstract

The short circuit behavior of solar farms are different from conventional generating stations. These generating resources are static in nature and have a rich power electronic interface with a grid, limiting these solar farms' short circuit capabilities. The solar inverter voltage versus short circuit current characteristics is modeled to supply the fault current within inverter designed ratings. In this research paper, a large number of solar power investors are grouped to pool their power into the grid. Short circuit studies are carried out for a 500 MW solar farm with string inverters rating of 3125 kW per IEC 60909. The protective relaying coordination is performed as per IEEE C37.90 and IEC 60255-1 relaying standard.

Keywords: Relay Coordination, Renewable Solar Park, Transient Short Circuit Analysis, IEC 60909

1. Introduction

The electric utility business is seeing a fast change bulk power system network. This utilities are organized and maintained, owing mostly to the increased penetration of renewable power reserves such as wind and solar. These resources are also known as Inverter Based Resources (IBR) or non-synchronous resources¹.

In spite of various benefits, the solar PV inverters has its own drawbacks as it is static load. Therefore the short circuit contribution from solar PV inverters is negligible. The renewable power generator such as solar and wind, which depend on irradiance and wind speed have flexible generation. This will affect voltage stabilities or voltage over-limits on the grid. Wind and solar power stations are built in regions where there is a lot of wind and sunshine. It is located farther from the load center due to the environmental conditions. To put it another way, IBRs are installed in places where the system's strength is low^{2,3}. The connection of IBRs to system having low strength will affect the point of interconnection. The decrease in short circuit ratio and grid strength can impact the design of inverter-based control systems. Lower the short-circuit strength at the point of interconnection of inverter based resources can result in control loop instability

in various control function of inverter such as voltage control, frequency response but also on-grid dynamics and controls. An insight study for the inverter controls interactions for high dominant power systems is needed.

Inverter-based resources based on power electronics do not supply fault current since power electronic inverters closely control and restrict current². Their short circuit involvement is frequently limited to zero and three times rated current output. The short circuit strength will continue to decrease in the presence of inverter based resources for Bulk Power System (BPS) and transmission system. The reduction in flow of fault current has an influence on transmission protective relaying.

The detection and reliable functioning of protection systems is based on fault current amplitude for operation². During the fault periods, synchronous generators delivering high short circuit current to the BPS. In case of inverter based resources such as wind and solar photovoltaic generators there will be huge drop in fault currents and short circuit levels. Most of transmission systems protection schemes are designed to operate for high short circuit currents and their operation becomes unreliable for inverter powered transmission systems.

The majority of existing research is concerned with the effects of implications of large-scale centralized solar

*Author for correspondence

PV with grid-connected systems⁴⁻⁶. The centralized grid-connected solar PV generation has emerged as a significant topic of study and the primary focus of advancement. Literature on the influencing the different grid-connected renewables power generation is relatively mature at the instant, while the literature on the effect of solar PV grid-connected power generation is in its early stages²⁻⁴.

The goal of this work is to present the short circuit modeling, short circuit analysis and its performance on the protective relay coordination. The article is framed as four sections, short circuit modeling for solar farms, simulation result and analysis and conclusion.

2. Short Circuit Analysis of Solar Farm

2.1 Problem Formulation

Inverters generate less fault current than traditional synchronous generators. The amplitude of the fault currents formed is small. The fault current of the inverters does not include enough negative or zero sequence values to identify and determine the directionality needed by directional relaying. The poor fault current levels at primary side may lower relay sensibility for fault or polarity identification at specific bulk power system sites. Insufficient negative and zero sequence presence can result inaccurate directional declaration of polarized directional components⁶. Transmission owners can update specific current relay settings when possible, or protective relays may need to be updated or changed in some cases to make use of emerging, more versatile technology⁷. Unlike synchronous generators, the output of short circuit current from inverter-based generation is typically restricted to 100-120 percent of the rated load current.

When an inverters are in the current-limiting phase, it is thought to pump a continuous current into the system that is restricted by the current-limiting curve. The graph beneath depicts the current-limiting curves that are accessible for the current magnitude.

When the terminal voltage of the inverter is less than $V_{op,min}$ the magnitude of the output short-circuit current magnitude is between $I_{sc,min}$ and $I_{sc,max}$ for voltages between $V_{sc,max}$ and $V_{op,min}$, between $I_V = 0$ and $I_{sc,max}$ for voltages between 0 and $V_{sc,max}$ and it is considered to operate in current-limiting mode. If terminal voltage of

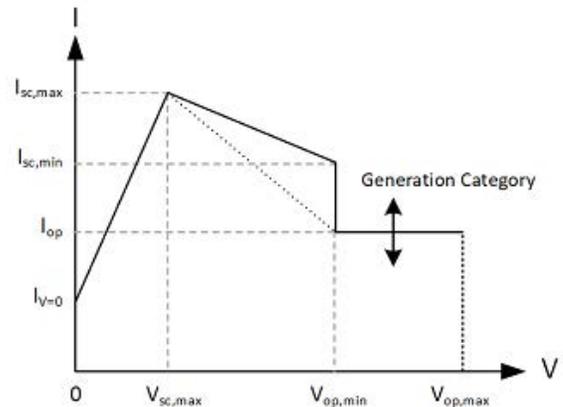


Figure 1. Current limiting curve: Ramp function.

inverter happens to fall below $V_{op,min}$ or above $V_{op,max}$ at any iteration, the WTG/Inverter stays in short-circuit mode even if voltage converges to a value greater than $V_{op,min}$. This means that, the current will be limited to $I_{sc,min}$ for voltages above $V_{op,min}$.

The modern digital relays can generate any characteristic. These features operation time is inversely proportionate to fault current and it respond variably depending on fault current amplitude. Quickly functioning of primary relays is essential for relay coordination to isolate a small area of the power system⁷. To avoid miscoordination, backup relays must be operated at a subsequent time because backup relays cut off a more significant amount of the electrical system. Furthermore, backup relays should not take too long to operate since this might pose a significant risk to the power system's equipment. As a result, the prior goal of optimal relay coordination, which may be accomplished by determining the best settings is to reduce the working duration of primary relays while avoiding miscoordination between primary and backup relays⁸. Operating time of relay is solely depend on the magnitude of the fault current. If the magnitude of the fault current varied it will also affect the operating time of relay or tripping signal. Therefore for performing optimal relay coordination and short circuit analysis of the BPS is necessary.

2.2 Calculation Methodology

Short circuit currents are classified in IEC 60909, and technical specifications are based on their amplitudes (highest and lowest), and fault ranges from the generator (far and near). Device ratings are determined by total

short circuit currents, whereas maximum short circuit currents determine protective device parameters. The IEC 61363-1 Standard calculates and displays the short-circuit current as time-dependent by using the device sub-transient reactance and time constants. This delivers a precise evaluation of the short-circuit current for sizing protecting equipment and corresponding relays for isolates network⁶⁻⁸.

The fault currents produced by the inverters are low in magnitude. The inverter based resources fault current does not contain sufficient levels of negative or zero sequence quantities for proper detection and determination of directionality required by directional relaying. Lower fault current levels (primary side) can result in lower relay sensitivity for fault or polarity detection at some locations. Lack of adequate negative and zero sequence quantities may result in incorrect directional declaration of directional relays^{7,8}. Using proper settings and providing additional supervision are critical for secure and dependable protective relaying. There are alternative for transmission owners to modify some existing relay settings where possible. In some instances, protective relays may have to be upgraded or replaced in order to take advantage of newer, more flexible technologies⁸.

The fault current developed by a three-phase short circuit fault generally contains two aspects: the DC component and symmetrical AC component of fault current. The 3-phase short circuit fault current grows asymmetrically for the first few cycles since the DC output of the fault current can last very few cycles from the fault origin. Also, the mixing of the DC part and the symmetrical AC part results in a significantly instantaneous value of the asymmetrical fault current when it hits the first peak at the fault inception. The DC part of the fault current decays with time, it can never potentially achieve zero. In practice, it only exists in the system for 4-5 cycles at an instance of the fault and then disappears.

As an outcome, computing the symmetrical fault current at the problematic site is the first step for identifying DC component of the fault current, the asymmetrical fault current, and the peak short circuit current of that network. The MVA approach or IEC 60909-0 solution No. 29 as indicated in Eqn. (1) below may be used to compute the symmetric short circuit current at any specified power system location.

$$i_k'' = \frac{(c * U_n)}{(\sqrt{3} * Z_k)} \quad (1)$$

where, i_k'' is the initial symmetrical short circuit current, U_n is the nominal system voltage is measured in kV, Z_k

is system short circuit impedance at fault point and C is Voltage Factor. K is system R/X ratio at fault point.

Peak short circuit calculation can also illustrated as in equation (2).

$$i_p = \sqrt{2} * k * i_k'' \quad (2)$$

where, k is system R/X ratio at fault point.

Fault current of DC part is computed using IEC 60909-0 equation No. 64, as shown in equation (3).

$$i_{DC} = \sqrt{2} * I_K'' * e^{\left(\frac{-2\pi * f * t * R}{X}\right)} \quad (3)$$

where, i_{DC} is fault current's DC component (kA), f is Frequency of the network (Hz), t is Computed time at i_{DC} (sec) and R/X is Reciprocal of the system's DC component at the faulty point.

To find out Z_{BASE} of the network as shown in equation (4),

$$Z_{BASE} = \frac{V^2}{S} = \frac{220^2 \text{ kV}}{125 \text{ MVA}} = 387.2 \Omega \quad (4)$$

Z_S is the impedance offered by grid as shown in equation (5),

$$Z_S = \frac{V^2}{S} = \frac{220^2 \text{ kV}}{18700 \text{ MVA}} = 2.588 \Omega \quad (5)$$

Impedance offered by Transmission Line is shown in equation (6).

$$I_{F-LINE} = 37.002 \Omega \quad (6)$$

$$Z_L = \frac{V}{\sqrt{3} * I_{F-LINE}} - Z_S = \frac{V}{\sqrt{3} * 37.002} - 2.588 = 0.844 \Omega$$

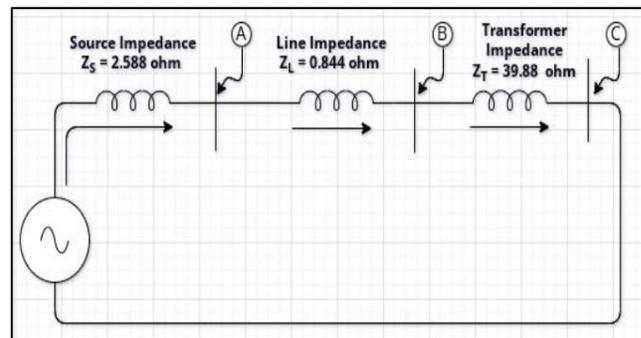


Figure 2. Impedance diagram.

Impedance offered by Transformer is shown in equation (7)

$$Z_T = \% \text{Impedance Trafo of } X Z_{BASE} \tag{7}$$

$$= 0.103 \times 387.2 = 39.88 \Omega$$

The three phase fault at different locations are performed and calculated as per Eq. (8), Eq. (9) and Eq. (10).

$$I_{F_A} = \frac{V}{Z_S} \tag{8}$$

$$= \frac{220 \text{ kV}}{\sqrt{3} \times 2.588 \Omega} = 49.07 \text{ kA}$$

$$I_{F_B} = \frac{V}{\sqrt{3} X (Z_S + Z_L)} \tag{9}$$

$$= \frac{220 \text{ kV}}{\sqrt{3} X (2.588 + 0.844)} = 37.002 \text{ kA}$$

$$I_{F_C} = \frac{V}{\sqrt{3} X (Z_S + Z_L + Z_T)} \tag{10}$$

$$= \frac{220 \text{ kV}}{\sqrt{3} X (2.588 + 0.844 + 39.88)} = 2.93 \text{ kA}$$

2.3 Modelling

The 500 MW solar farm designed for case study in ETAP 20.04 simulation software. The solar farm Grids at 220 kV upstream side and Solar Power Developers 33 kV feeders on downstream as shown in Figure 3. The fault are simulated at, 33 kV bus and grid 220 kV bus and it is found that major short circuit current contribution is from Grid side due to strong grid. For any fault on 33 kV side, the fault current circulation through the 125 MVA transformers is only controlled by 220 KV transmission lines and 125 MVA Power Transformers (% impedance: 10.3) as shown in Figure 3. The value of fault current for bolted faults may reach to short circuit limit of transformers. Additional higher operational grid voltage more than 1.0 p. u during fault will enhance the grid short circuit strength and it will be act as boosting factor.

2.4 Transient Short Circuit Analysis

The transient short-circuits computation plot the fault current waveforms as a function of time, assuming several

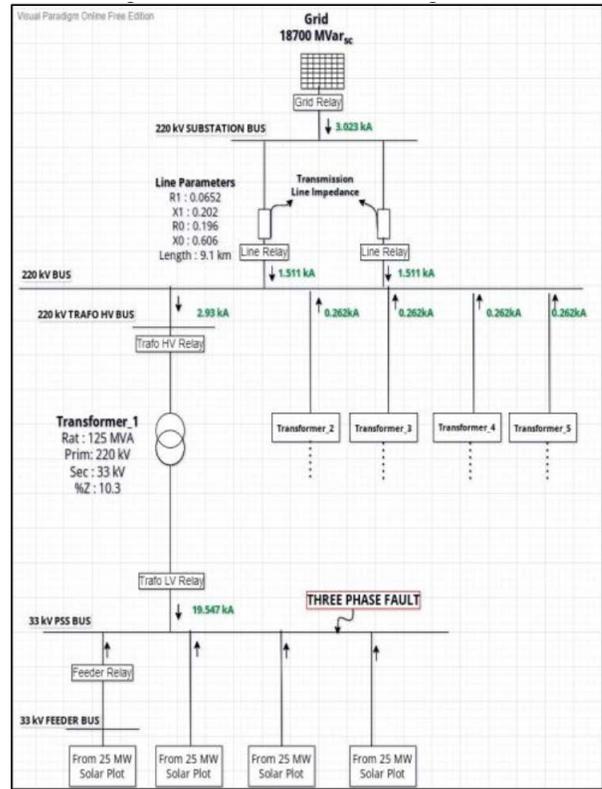


Figure 3. System diagram: When fault on 33 kV bus.

aspects that influence short-circuit current performances at various times. The factors that affect the short circuit current variations are sub-transient reactance, transient reactance, sub-transient time constant, transient time constant, DC time constant, and machine sub-transient reactance^{9,10}. This explicit modeling delivers a detailed evaluation of the short-circuit current for sizing protective devices and coordinating relays for solitary methods¹¹. The computation can be performed on radial and looped configurations with numerous sources.

As observative results, short-circuit current is a function of time up to 0.1 seconds at 0.001 second time increment. It also offers to short-circuit current as a function of 1 cycle at 0.1 cycle increment. Along with the immediate current values, transient short circuit analysis also delivers the calculated AC symmetrical component (RMS), Total fault current and DC component. All the above factors were compiled for different case studies, as illustrated in Figures 4 and 5.

2.5 Short Circuit Case Study

Short circuit studies for 500 MW solar farm are carried out as per IEC 60909 ETAP 20.04 software. The C factor

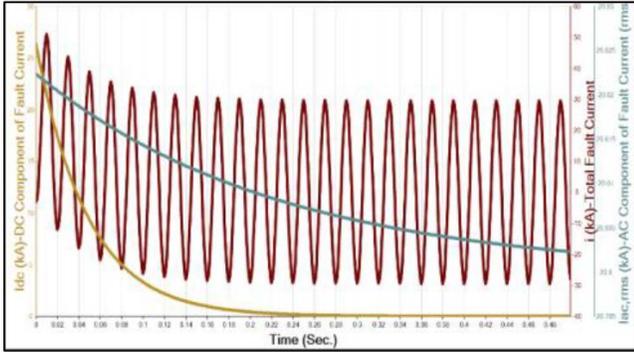


Figure 4. (A) Total Fault Current (B) AC component of fault current (rms) (C) DC component of Fault current on grid 33 kV bus.

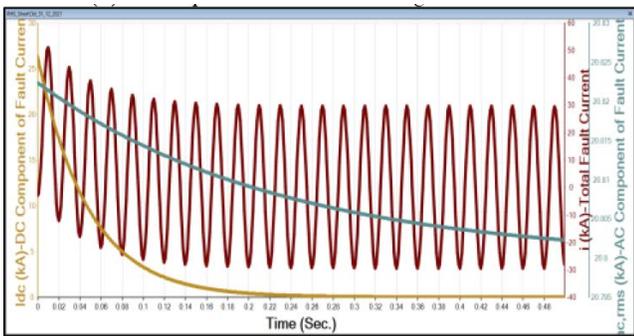


Figure 5. (A) Total Fault Current (B) AC component of fault current (rms) (C) DC component of Fault current on grid 220 kV bus.

Table 1. Pooling Substation Input Data

Pooling Station (MW)	Grid (kV)	Three Phase (MVA)	Three Phase Current (KA)	Single Phase (MVA)	Single Phase Current (KA)
500	220	18700	49.075	14960	39.26

of 1 pu has been considered for short circuit studies. The three phase short circuit strength at 765/400/220 kV substation are as tabulated under in Table 1. The system contribution under three phase short circuit fault at 33 kV bus has been shown in Figure 3.

2.6 Overcurrent Relay Coordination

There are two essential settings utilized in relay to create a tripping signal: PSM (Plug setting Multiplier) and Time Multiplier Setting (TMS). For any of the curves and PSM, the time of operation of relay is computed and this time is the point at which the relay sends tripping signal^[11,12]. The longer the tripping time, the smaller the current

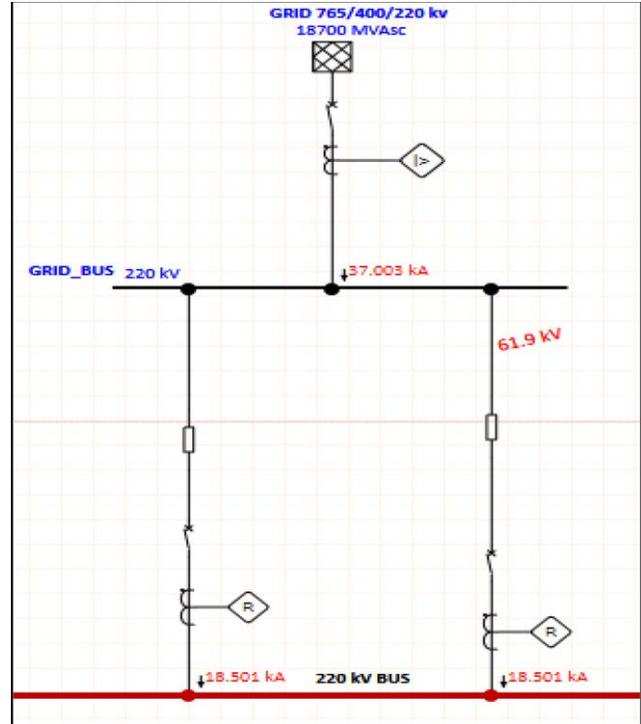


Figure 6. ETAP: Solar plant contribution when three phase fault on 220kV grid bus.

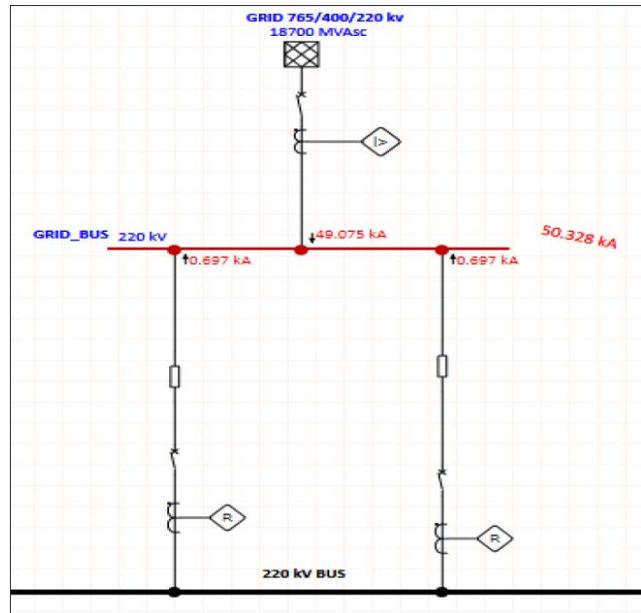


Figure 7. ETAP: Solar Plant Contribution when Three phase fault on 220kV Bus.

multiplier, allowing for overloading of equipment such as motor starting, transformer energization, or other operations. A greater current multiplier will result in a shorter trip time, which is beneficial in a malfunction

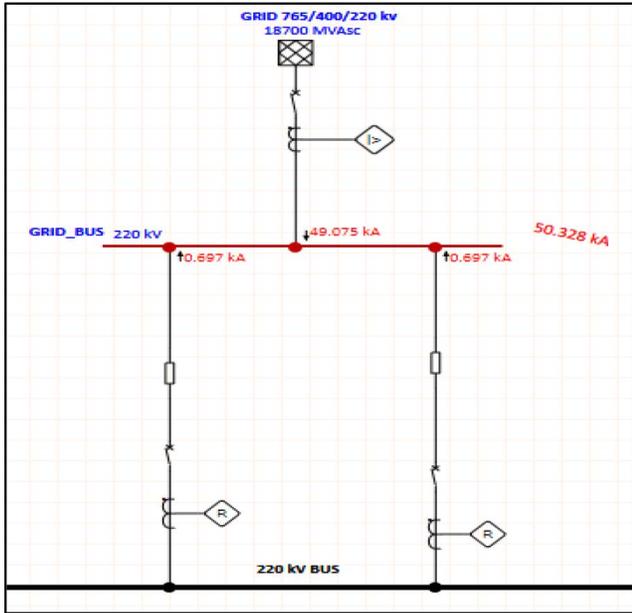


Figure 8. ETAP: Solar plant contribution when three phase fault on 33kV bus.

Table 2. Curve constants

Curve type	k	α
Long time inverse	120	1
Standard inverse	0.14	0.02
Extremely inverse	80	2
Very inverse	13.5	1

or extreme overloading of equipment¹³. The following formula and curve constants were used to calculate the time of operation of relay as illustrated in Table 2.

The standard overcurrent characteristics relay equation is stated in Eq. (11) and Eq. (12). Where k and α are scalar quantity which is tabulated in Table 2. The overcurrent relay acts when the amplitude of the current surpasses the preset value^{12–14}. However, the features are typically plotted among time and PSM. The perceptiveness and performance of individual characteristics can be scrutinized for low and high fault currents by using miscellaneous fault currents.

$$PSM = \frac{\text{Fault Current}}{CT \text{ ratio} * IP(\text{Pickup Current})} \quad (11)$$

$$TOP(\text{Time of Operation}) = \frac{k * TMS}{PSM^{(\alpha)} - 1} \quad (12)$$

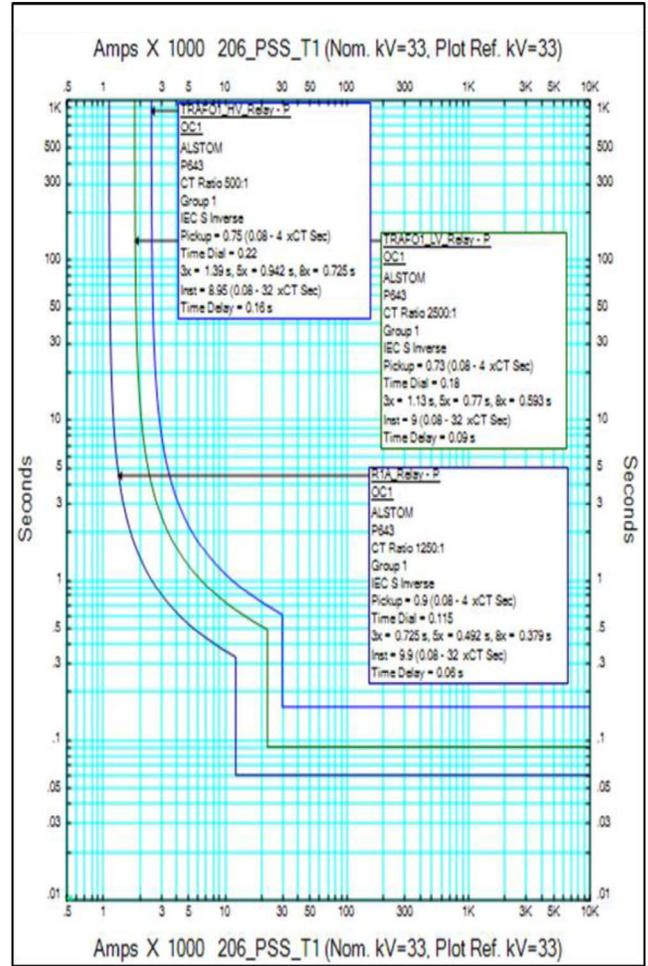


Figure 9. Case - (a): Phase relay coordination for fault on 33 kV PSS bus.

ETAP Simulations of three-phase short circuits at different locations are used to evaluate the appropriate operation of overcurrent protection as shown in Figures 6 to 8, and time-current curves of protection devices are displayed. Figures 9 and 10 show time-current curves for the case of a three-phase short circuit at 33 kV PSS (Pooling Substation) bus and 33 kV feeder bus. Considering the three phase short circuit fault, the time of operation of relay also calculated and tabulated in Tables 3 and 4.

Table 3. Three Phase Fault on Feeder 33 kV Bus

Name	TMS	IP	PSM	Top
R1A FEEDER CB1	0.115	0.900	15.428	0.286
LV side Transformer	0.18	0.730	8.997	0.561
HV side Transformer	0.22	0.750	6.568	0.803

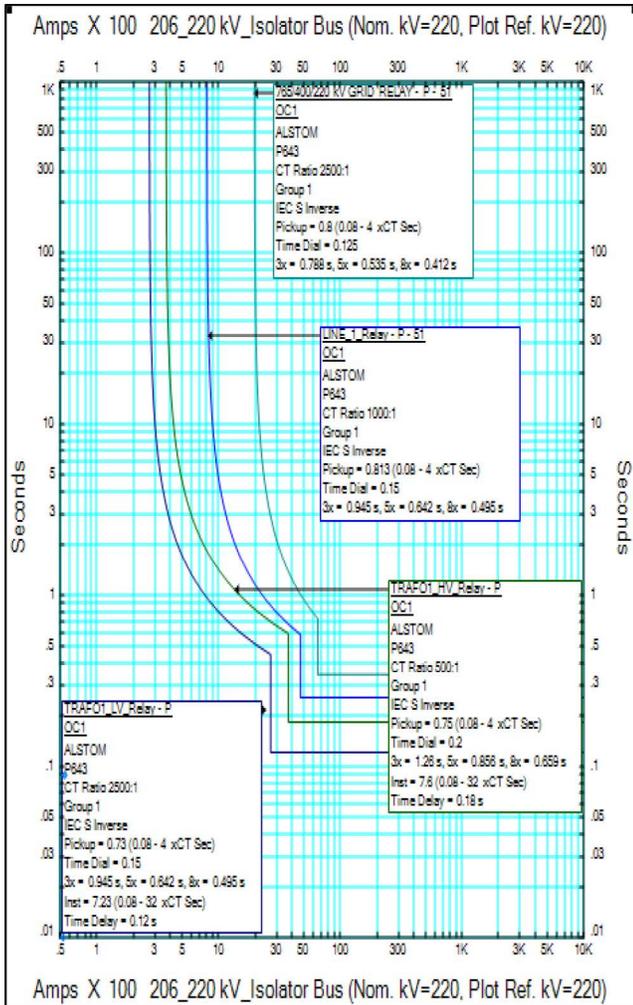


Figure 10. Case- (b): Phase relay coordination for fault on 33 KV feeder bus.

Table 4. Three Phase Fault on 33 kV Bus

Name	TMS	IP	PSM	Top
LV side Transformer	0.15	0.73	10.711	0.432
HV side Transformer	0.2	0.75	7.819	0.667
Line 1 Relay	0.15	0.813	1.859	1.684
Grid	0.125	0.8	1.512	2.109

3. Conclusion

The rating of inverters limits the short current feeding capabilities of solar farms, and typically it is hardly 15-20% higher than the loading limits. In this research article, a study has been carried out to model the short current capabilities of solar power farm inverters. This study is carried out for a 500 MW solar farm PV string inverter.

The percentage fault feeding capability of a solar farm as against the grid short current contribution is assessed. It is observed that short circuit contribution from the grid is a crucial factor in designing electrical components and switchgear. The performance of coordinated relays operation is also studied in this research papers for multiple types of faults in the solar farms, and it is found that the operation of overcurrent phase and earth relays remains stable for fault from the grid as well from inverter infeed. The operation of relays will be unreliable for seeing the fault current infeed from inverter only. This article will be helpful for the solar power generation utilities for planning and designing substation's power components and switchgear.

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