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RESEARCH ON MITIGATION OF ARC FLASH FOR MICROGRID WITH PHOTOVOLTAIC POWER PLANT CONNECTED

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ABSTRACT

The paper presents a study of arc flash protection in a PV power plant connected to distribution network. It first put forward an approach applying relay protection and coordination to reduce arc flash hazard. An example of micro-grid with PV power plant connected is then proposed to verify the effectiveness of the approach. In recent years, the growing concern for environment preservation has caused the sustainable power and energy system gets more attention. The renewable energy integrated with traditional power system, such as the PV power plants connected to micro-grids, turns out to be lack of stability and more vulnerable to typical faults. Among many kinds of faults, the arc fault could result in serious arc flash accident, even terrible fire and explosion, leading to casualties and huge economic losses. In order to study the hazard of an arc flash accident and the way to protect the equipment from it, the paper uses a power system analysis software, named EasyPower, to simulate an arc flash accident happens in a PV power plant inside a micro-grid and makes an assessment of the hazard. After that, the time-current curves are plotted for the purpose of protection coordination among all the protective devices. The original relay settings are adjusted to satisfy the selectivity and backup protection.

Keywords: PV power plant, arc flash analysis, protection coordination, relay settings.

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
HVCB	High Voltage Circuit Breaker
LVPCB	Low Voltage Power Circuit Breaker
TCC	Time-current Curve

1. INTRODUCTION

Arc fault[1] is formed through the process of high power discharge happens between conductors. Beside the voltage shock, it creates heat, spark, strong noise, and finally causes fire if not cleared. Even the arc fault has been cleared, it probably already damages the appliances.

The arc faults generally occur in transformers, switchgears and feeder lines in a PV power plant. Most of arc faults form due to single line-to-ground faults. A single line-to-ground fault may be caused by weather, environment, animals around or incorrect operation by personnel. If the single line-to-ground fault is not cleared in time, the voltages to ground of other two phases will be increased, which may result in electrical breakdown of the insulation parts and causes an phase-to-phase short-circuit fault, and even a three-phase short-circuit fault. Consequently, the arc fault is formed. Normally, the three-phase short-circuit fault produces the largest short-circuit current. So the three-phase

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short-circuit fault is usually simulated to do the arc flash analysis, which obtains the most conservative results.

The renewable energy has become a hot topic for a certain number of years. With the continuous growth of investment into renewable energy industry, the construction of renewable energy generation, especially for PV power generation, develops rapidly. According to Renewables 2018 Global Status Report[2] (GSR), during 2017, the global PV intalled capacity increased by about 33% and the total capacity reached 402 GW.

The new technologies accelerate the development of PV power generation industry, but at the same time bring with plenty of risks to traditional power system, including but not limited to:

(1) Since the generation capacity depends much on solar radiation quantity, the generation power varies a lot in a day. It consequently causes the voltage fluctuation and voltage flicker.

(2) The large-scale inverters adopted in PV power plant apply PMW technology, which create harmonics and lower the power quality.

(3) The conventional structure of power grid is radial with single-source. After integrated with PV power plant, it works under multi-sources feeding mode. Therefore when a fault occurs, the protective devices may refuse to trip or trip by mistake.

The fast development of PV power generation industry extremely increases the arc flash hazard as it may influence the protective devices and make them refuse to trip or not trip in time.

Due to the serious hazard of arc flash, the study of mitigation approach for it gains more and more attention these years. Many kinds of approaches[3] are being proposed, including:

(1) Installing infrared window on the switch cabinet to perform infrared inspection without opening the cabinet door.

(2) Utilizing arc flash reduction maintenance system to reduce the trip time of overcurrent protection.

(3) Installing vacuum interrupter on high-voltage switch.

(4) Using distributed control system to remotely control the circuit breaker of switchgear.

(5) Performing protection coordination to precisely adjust the relay settings.

The paper follows the last approach to apply appropriate protection strategy and protection coordination to mitigate the hazard.

In part 1 of the paper, it first introduces the definition, hazard and formation of the arc fault. Then, the paper briefly discusses the development of PV generation industry and points out its impact on arc flash hazard. Next, the paper illustrates several approaches being researched to mitigate the arc flash hazard.

In part 2, the paper put forward an approach to protect the PV power plant and mitigate the arc flash hazard according its multi-sources feeding mode.

In part 3, the paper proposes an example to verify the effectiveness of the approach.

2. APPROACH APPLIED

2.1 Directional protection

In traditional power grid, the protective devices are often installed on the side of protected line approaching the power supply. When a short-circuit fault occurs on an electrical equipment, there will be a short-circuit fault current flowing from the power supply to the electrical equipment. The protection starts with the protective device connected to the closest upstream bus of the electrical equipment. Then, the protective device connected to the second closest upstream bus of the electrical equipment will work as a back-up protection.

However, in a multi-sources feeding grid, the traditional protection mode may not applicable. For example, in Fig 1, if a fault occurs on LOCATION 4 and we regard the SOURCE A as the power supply, the trip time of SW4 would be less than that of SW3. But if a fault occurs on LOCATION 2 and we regard SOURCE B as the power supply, the trip time of SW3 would be less than that of SW4.

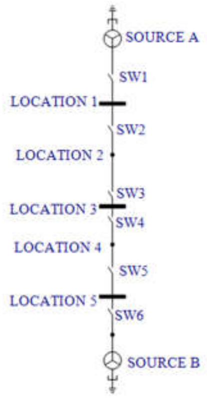

Fig 1 Example of Directional Protection

One of the approaches to avoid the contradiction is to apply directional protection. By adopting directional protection, the switches only operate if a short-circuit fault current flowing from bus to line is detected. As a result, if a fault occurs on LOCATION 4, SW4 and SW2 detect the fault current coming from SOURCE A while SW5 detects the fault current coming from SOURCE B. Similarly, if a fault occurs on LOCATION 2, SW2 detects the fault current coming from SOURCE A while SW3 and SW5 detect the fault current coming from SOURCE B. Therefore, the trip time of SW3 is not relevant to that of SW4.

2.2 Arc Flash Analysis and Protection Coordination

Basically the closer to the arc flash source, the more severely the staff gets burnt. Thus, the purpose of arc flash analysis is to obtain the flash protection boundary first. Working at the distance equaling to flash protection boundary only causes curable burn theoretically. If working inside that distance is needed, the actual working distance is taken into the calculation of incident energy to figure out the personal protective equipment required to take with.

According to the calculation formula of incident energy in IEEE 1584[4], the reduction of arcing time, which is the sum of the device trip time and the device opening time, could considerably decrease the incident energy. Thus, the way to mitigate the hazard is to reduce the trip time of protective device by doing protection coordination. The protection coordination is about adjusting the pick-up settings and delay settings at the same time to satisfy both the selectivity and the sensitivity of protective devices. After doing protection coordination, the protective devices turn out to trip faster and the pick-up settings become more accurate.

Therefore, the paper put forward an approach applying directional overcurrent protection and coordination to mitigate the arc flash hazard. An example of a large-scale PV power plant in a micro-grid is given in this paper to perform the approach.

3. EXAMPLE

The inverters in large-scale PV power plant generally have the capability of low-voltage ride through. If there is a fault occurs on the alternating current side of the inverter, the inverter will not trip immediately and continues to supply fault current to the fault point till the fault is cleared or it reaches the trip time of inverter. Thus there is a period of time when both sources supply short-circuit fault current. A large-scale PV power plant generally contains the PV modules, PV inverters, transformers, switchgears and other basic electrical components. Fig 2 is the overall one-line diagram of the example.

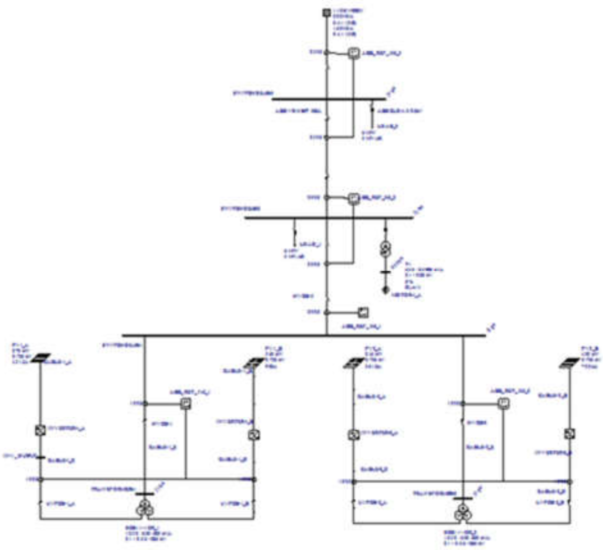

Fig 2 One-line Diagram for an Example of PV Power Plant

3.1 Configuration and Specifications

There are four parts of PV modules and each part is equivalent to certain amount of single PV modules connected in series first and connected in parallel then. The example uses monocrystalline silicon module with 270Wp rated each. The voltage under maximum power output is 31.1V and the current under maximum power output is 8.68A. The short-circuit current is 9.03A and the open-circuit voltage is 37.8V. Twenty monocrystalline silicon modules are connected in series and form a strand of modules. The four parts of PV modules in the one-line diagram are composed of 50, 100, 40, 80 strands respectively. The total capacity of PV modules is 1.458MWp. Therefore, taking the first part as an example, the total voltage and current under maximum power output are 622V and 434A. The total open-circuit voltage is 756V and the total short-circuit current is 451.5A.

The four parts of PV modules are connected to four inverters respectively. The inverters have the capacity of 630kVA. Each takes the pick-up current as 1.5 times of the rated load current.

Then, the outputs of the first and second inverter are connected to the secondary side and tertiary side of the first three-winding transformer separately. Similarly, the outputs of the third and fourth inverter are connected to the secondary side and tertiary side of the second three-winding transformer separately. The transformer ratios are 21/0.36/0.36kV.

The high-voltage sides of two transformers are connected to switchgear#1 that is used to connect or disconnect the step-up transformers. Then the switchgear#1 is connected to the upstream switchgears, with the loads and motors connected to them too. The switchgear#3 is an incoming cabinet, which is connected to a 20kV step-down substation.

The specifications for cables, current transformers, voltage transformers, loads, motors and so on are not discussed in this paper.

3.2 Protection Strategy

When a three-phase short-circuit fault occurs, the fault current on the fault point is supplied by both the grid and the PV modules. By taking the node TRANSFORMER#1 as the fault point and doing short-circuit analysis, the result comes out in Fig 3.

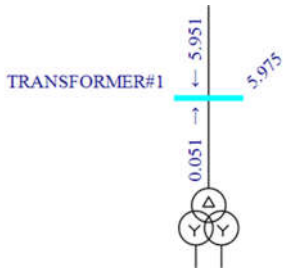

Fig 3 Result of Short-circuit Analysis for Node TRANSFORMER#1

It can be seen that the fault current on the node TRANSFORMER#1 is 5.975kA, which results from the sum of the fault current supplied by grid (5.951kA) and the fault current supplied by PV modules (0.051kA) subtracted by the losses.

Considering the node connected to the output of the inverter, the short-circuit analysis result of it is shown in Fig 4.

The fault current flowing into the node comes from the PV module, which is less than or equal to 1.5 times of the rated load current of inverter. The maximum fault current provided by inverter is often taken into short-circuit calculation for conservative results.

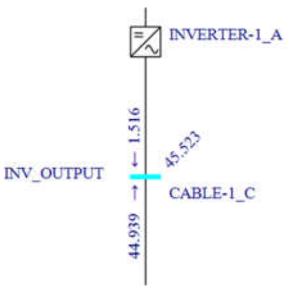

Fig 4 Result of Short-circuit Analysis for Node INV_OUTPUT

Knowing that the fault currents coming from both sides flow into the fault point, the traditional non-directional overcurrent protection may not work as expected. For example, Fig 5 presents part of the one-line diagram, including one switchgear, three relays and three HVCBs. If there is a fault occurs on bus SWITCHGEAR#1, as we can see according to the result of short-circuit analysis, the left feeder line delivers fault current of 0.051kA, which might not reach the pick-up current value of relay ABB_RET_545_1, thus the relay does not intend to trip under that case. However, as there is fault current of 5.943kA supplied by the grid, the relay might trip and the part of the system linked with the left feeder line would be disconnected.

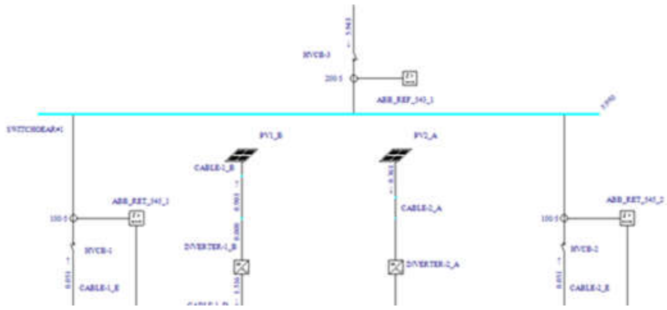

Fig 5 Result of Short-circuit Analysis for Bus SWITCHGEAR#1

The directional protection function is adopted to identify and distinguish the fault currents coming from different directions.

Considering the part (named as Part A later) of one-line diagram shown in Fig 6, the directional overcurrent relay ABB_RET_545_1 controls both HVCB-1 and LVPCB-1_A. The functions and the settings of the relay are listed in TABLE I.

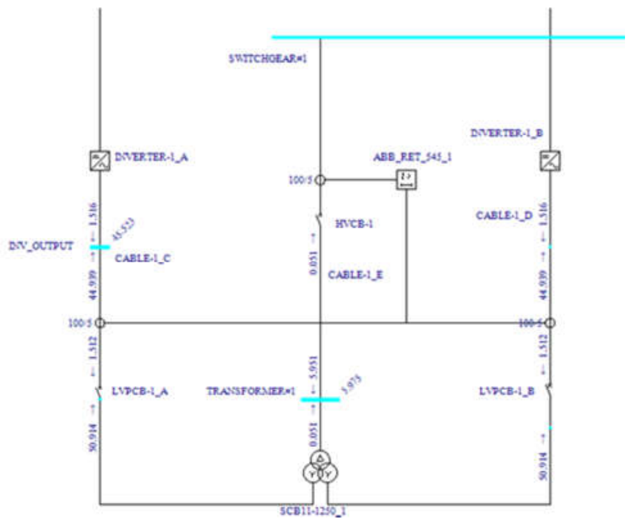

Fig 6 Directional Overcurrent Protection of Node TRANSFORMER#1

According to TABLE I, by adopting the inverse-time directional overcurrent function, HVCB-1 only detects the fault current supplied by grid while LVPCB-1_A only detects the fault current supplied by PV modules.

TABLE I Settings for Relay ABB_RET_545_1

Function	CT	Pick-up current	Time dial	Inverse-time curve type	Trip device
67 IEC	100/5	12	0.05	Very Inverse	HVCB-1
67 IEC	100/5	3	0.2	Normal Inverse	LVPCB-1_A
67 IEC	100/5	3	0.2	Normal Inverse	LVPCB-1_B

IEC indicates that the IEC standard for relay function is being applied.

When simulating a three-phase fault on the node TRANSFORMER#1, a sequence of events report can be obtained, which is shown below in TABLE II.

TABLE II Sequence of Events Report

No. of Seq.	Protective device	Fault current	Trip time	Upstream trip time difference
1	RET_545_1	5.951	0.17	0
2	RET_543_1	5.928	0.46	0.291
3	RET_543_2	5.928	0.741	0.281
1	RET_545_1	1.499	0.681	0
1	RET_545_1	1.499	0.681	0

Seq is short for sequence. No is short for number. The unit of fault current is kA. The unit of trip time and upstream trip time difference is second.

TABLE II presents the trip order of protection devices. The parameters corresponding to sequence number 1 to 3 indicates the stepped backup protection, meaning the closest upstream protection device trips first and the farthest upstream protection device trips last. The last two rows in TABLE II indicate the implementation of function no.2 and function no.3 of relay REF_545_1. The sequence of events report suggests that the relay ABB_RET_545_1 does not detect the fault current supplied by the grid when applying the function no.2 and function no.3.

3.3 Protection Coordination and Arc Flash Mitigation

The EasyPower software is able to calculate the incident energy and the flash protection boundary based on IEEE 1584[4]. The result of arc flash analysis with original settings is shown in TABLE III below.

TABLE III Arc Flash Analysis Result of Part A before Coordination

Fault Location	Upstream trip device	Arc current	Last trip time	Flash protection boundary	Incident energy
T#1	RET_545_1	5.975	0.681	130.6	21.3
SG#1	RET_543_1	5.99	0.459	202.8	51.8

T is short for TRANSFORMER. SG is short for SWITCHGEAR. The unit of arc current is kA. The unit of last trip time is second. The unit of flash protection boundary is inch. The unit of incident energy is cal/cm2. The working distance taken into calculation is assumed to be 31 inches.

Note that in TABLE III, the arc current is calculated from the short-circuit fault current on the node, which is the sum of the fault currents coming from both sides. The last trip time refers to the largest trip time for the closet upstream trip device of the fault point. According to TABLE II, compared to the trip time of 0.17s controlled by the relay RET_545_1 with function no.1, the last trip device is relay RET_545_1 with function no.2, of which the trip time is 0.681s. It protects the transformer from the fault current supplied by the PV modules.

From TABLE III, it is obviously the flash protection boundary and the incident energy is too large, making the level of hazard reaching level 3 and level 4 of HRC, which is short for Hazard Risk Category as classified in NFPA 70E[5]. In order to mitigate the arc flash hazard, the protection coordination is necessary. Fig 7 is the part of system being coordinated and Fig 7(a) is the TCC of it.

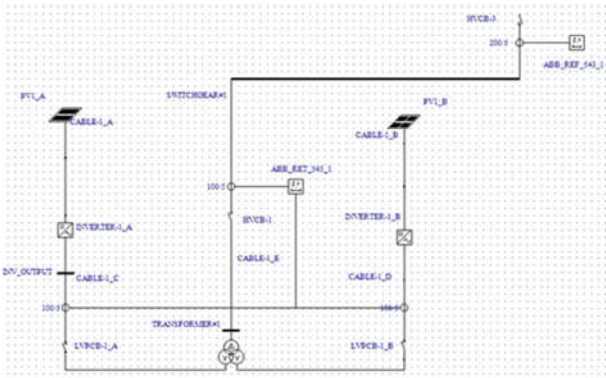

Fig 7 One-line Diagram for the Part of System Being Coordinated

Basically, there are two principles for protection coordination on TCC:

(1) The curve of protective device should always be in the left bottom of the components it protects.

(2) The coordination between protective devices should consider both selectivity and sensitivity.

Thus, the strategy to mitigate the arc flash hazard is to reduce the trip time as far as possible while satisfying the two principles for protection coordination.

For example, by looking at Fig 7(b), we can find out the transformer damage curve intersects with the curves of relay RET 545 function no.1 and REF 543. Besides, since the REF 543 is the upstream protective device of RET 545, working as a back-up protection of the transformer, the curve of RET 545 should lie on the left bottom of the curve of REF 543, suggesting that RET 545 trips earlier than REF 543. Because the curve of

CABLE-1_E lies on the top right of the curves of relays, it does not need to be adjusted.

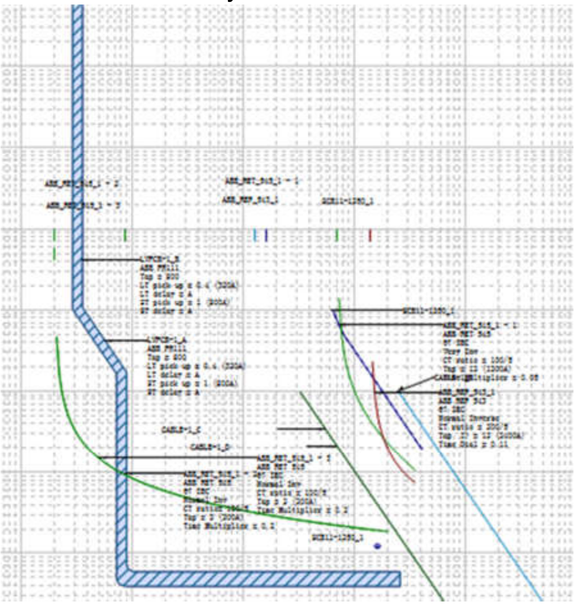

Fig 7(a) The Whole TCC for the Part of System Being Coordinated

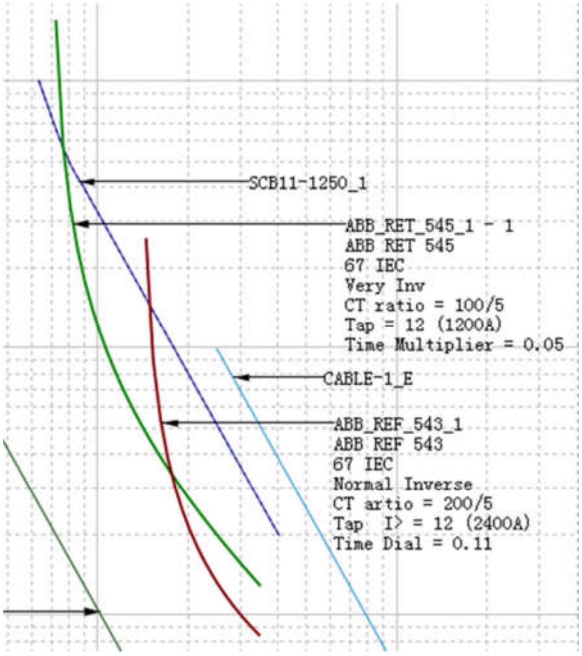

Fig 7(b) Part 1 of TCC

The curves of CABLE-1_C and CABLE-1_D are the same in Fig 7(c) because of the same type of cable being used. The curves of relay RET 545 function no.2 and RET 545 function no.3 are the same since they have the same settings. The circle with a dot in it indicates the magnetizing inrush current of the transformer. The inrush current should avoid the action of its protective devices, so the circle should be in the left bottom of the curves of relays. The curve of LVPCB-1_A does not need to be coordinated since the action of LVPCB-1_A is controlled by RET 545 function no.2.

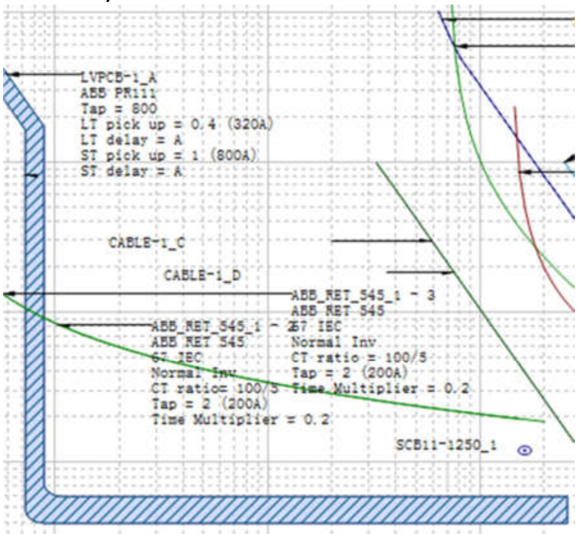

Fig. 7(c) Part 2 of TCCs

The result of arc flash analysis after coordination shown in TABLE IV indicates the successful mitigation of arc flash hazard.

TABLE IV Arc Flash Analysis Result of Part A after Coordination

Fault Location	Upstream trip device	Arc current	Last trip time	Flash protection boundary	Incident energy
T#1	RET_545_1	5.975	0.062	89.8	10.1
SG#1	RET_543_1	5.99	0.207	126.8	24.2

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