DESIGN OF A DC OVERCURRENT FAULT DETECTION AND PROTECTION SCHEME FOR DC COLLECTORS OF A PHOTOVOLTAIC PLANT

I. Holland*, P. Bokoro*, B. Paul* and E. Ndlovu**

**Department of Electrical and Electronic Engineering Technology, University of Johannesburg (Doornfontein Campus), P.O Box 524, Auckland Park, South Africa, Email: 201048892@student.uj.ac.za, pitshoub@uj.ac.za, bspaul@uj.ac.za*
***Pele Energy Group, 3 Centex close, Eastgate Kramerville, Sandton, 2196, South Africa, Email: elen@peleenergygroup.com*

Abstract: Faults in the DC collector circuits of a photovoltaic plant are a cause for major concern due to the damage they may cause to equipment. Fault protection is required for ground faults, line-to-line faults and arc faults. Typically, the magnitude of short-circuit currents of PV modules are similar to that of load currents which makes fault detection and protection difficult to carry out on the DC system. The DC collectors of a PV plant consist of combiner boxes where PV arrays are connected and inverter DC buses where combiner boxes are connected. This paper investigates the fault contribution from the PV modules on the combiner boxes and inverter DC buses in relation to typical PV module data on an isolated section of the DC network of a plant using the ETAP simulation tool. A fault detection and protection scheme for the main faults in a DC PV system is proposed based on previous research, for complete protection of the DC collector circuits.

Keywords: DC collector, fault detection and protection scheme, photovoltaic plant, combiner box, PV array

1. INTRODUCTION

The increased risk of global warming and preventive measures put in place for the burning of fossil fuels has prompted a reliance on alternative forms of energy. Photovoltaics (PV) are emerging as a leading source of renewable energy where the continued work done in this field contributes to its reliability, appeal and acceptance in both small and large scale applications. One aspect to consider is that optimal safety and reliability of a photovoltaic system is required for protection of property and personnel. In terms of PV plants in particular, their grid connection properties warrants a careful approach to electrical protection of the system. In the low voltage DC section of a PV plant, the main types of faults that cause catastrophic damage to equipment are ground faults, phase faults and arc faults [1]. The protection systems employed to protect against these faults are vital to ensure reduced risk of fires, where it is noted that although there are existing standards for fault protection in PV plants (such as the IEC standards), the risk is still apparent [2]. One of the contributing factors of this risk is that PV modules are constantly producing energy. Inherently, they cannot be turned off completely as long as there is some level of radiation incident on the cells [3]. This indicates a risk of arcing even when isolators are installed. The likelihood of arc faults causing major damage is a concern that is addressed by the design of arc fault protection systems in [4 - 6]. However, as mentioned in [1], there are also ground faults and phase faults to consider. In order to design the protection scheme, the fault levels on the combiner boxes and the inverter DC bus must be evaluated. This is to obtain a base fault level contribution which is important due to the short-circuit current of a PV module being close in magnitude to the load current of the module [7]. This small difference in magnitude requires a system of detection.

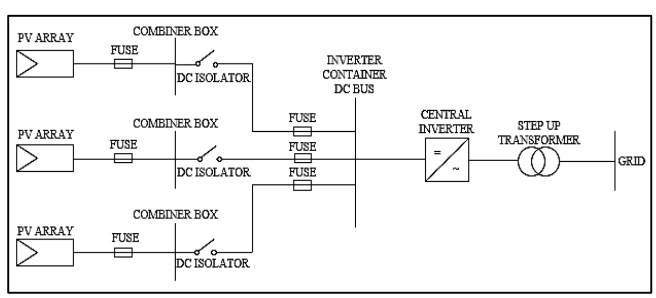

Figure 1: Basic PV plant layout

The typical PV plant layout in Figure 1 indicates the location of the DC collector circuits (combiner boxes and inverter DC bus) where faults take place the majority of the time. In a well-protected DC section of a PV plant, all three types of faults are protected against to ensure that no damage is caused and the plant continues to operate optimally. The evaluation of fault currents on the DC collector circuits will allow for the proposal of a complete protection scheme.

2. DC SECTION DATA

Before designing the protection scheme, the faults on the combiner boxes and inverter DC bus are determined by making use of ETAP software to calculate the short-circuit current on each of the applicable DC buses. A plant layout was provided, however, an isolated section is used to carry out the simulation. The given network already contains fuses as a high level fault protection system. These fuses have been considered in the population of the equipment data on the software. Typical PV modules are used in the series and parallel connections of the arrays. For the purpose of obtaining results, the PV modules in Table 1 were considered for simulation purposes.

Table 1: PV module data

Manufacturer: Yingli Solar	
Model: YL 255 P-326	
Maximum power (P_{max})	260.2W
Voltage at P_{max} (V_{mp})	32.65V
Current at P_{max} (I_{mp})	7.97A
Open circuit voltage (V_{oc})	40.57V
Short circuit current (I_{sc})	8.49A
Efficiency (η)	14.2%
Maximum system voltage	1000V

This is typical PV data where it is noted that the magnitude of the short-circuit current is approximately 6.5% higher than the maximum power current. This value differs based on the manufacturer and the construction of the panel. Another consideration is that, depending on the irradiation conditions, the maximum power point for power production of the module will shift based on its I-V characteristic curve. Consequently, the short-circuit current contribution of the module will change. However, the ratio between the load and fault current will remain more or less the same. Each combiner box used in the simulation consists of six arrays with 15 modules per string and 9 strings in parallel. The parallel connections of strings gives rise to a high current through each combiner box and due to the number of combiner boxes, a high current on the inverter DC bus, hence the use of fuses. For simpler evaluation of the fault contributions on the DC collectors, the arrays are sized uniformly. This means that each array contains the same number of modules and each combiner box contains the same number of PV array connections.

3. SIMULATION RESULTS

Due to the requirement of proposing a protection scheme for the DC collector circuits in the PV plant, simulation was done on the combiner boxes (represented by DC buses) and the DC bus of the inverter container. The ETAP network diagram, indicating the basic plant layout and the fault locations on three combiner boxes and the inverter DC bus, is indicated in Figure 2. This short-circuit fault simulation will indicate the fault levels in the DC collector circuits.

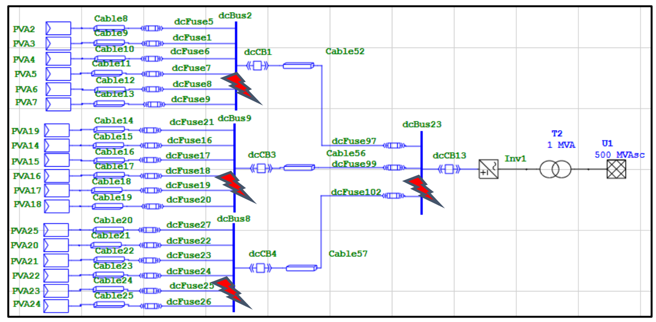

Figure 2: ETAP network diagram

Simulation results are indicated in Figure 3. The fault contributions are obtained by running a short-circuit analysis on the pre-faulted buses. The fault contributions from each array can be observed on the combiner boxes and the fault contributions from the combiner boxes can be observed on the inverter DC bus.

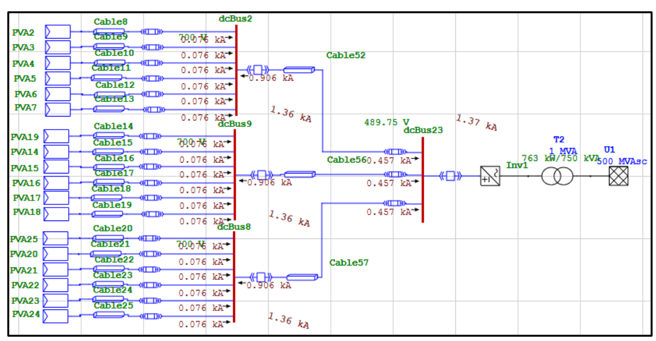

Figure 3: Short-circuit simulation results

The data obtained from the fault simulation can be represented as a step function of the load current at the instance that a fault occurs. Figures 4a, 4b and 4c indicate the ratios between the expected load current and the simulated fault currents on each of the applicable buses in the network and the expected fault current on a single PV module.

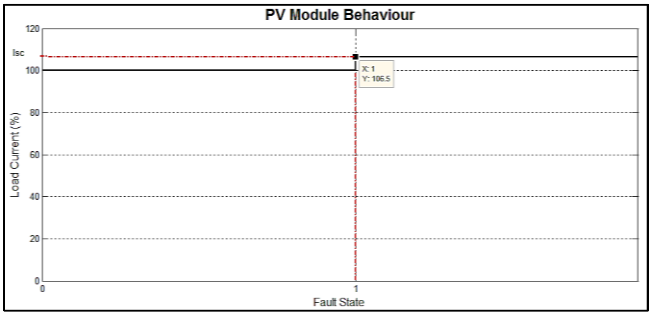

Figure 4a: PV module behaviour

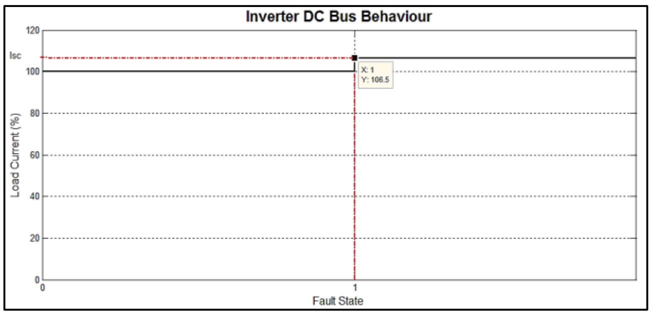

Figure 4b: Inverter DC bus behaviour

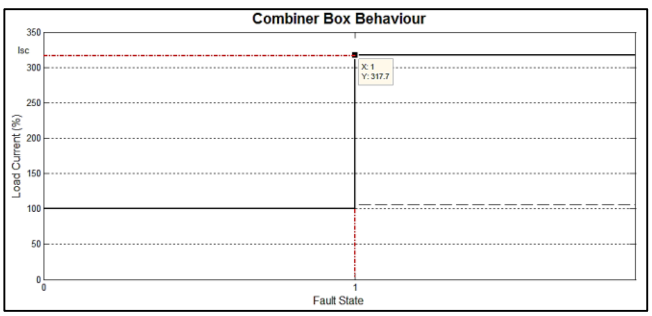

Figure 4c: Combiner box behaviour

Figure 4a and Figure 4b indicate an identical behaviour when a fault occurs. The theoretical fault current on a PV module (obtained from the module specifications) is 6.5% higher than the load current and likewise for a fault on the DC bus of the inverter container which was obtained by simulation. For a fault on the combiner box, there is a higher fault current with reference to the load current. The fault current is 217.7% higher than the load current. When one string in an array of PV modules experiences a short-circuit fault, the other strings in the array contribute to the magnitude of the fault current [3]. This statement, which is applicable to strings in an array, by simulation is also apparent for faults in combiner boxes. The 217.7% increase is indicative of the fault currents from the other combiner boxes contributing to the faulted combiner box. Hence, depending on the number of combiner boxes connected to one inverter, the fault current in one box could be of a large factor. The simulation data is summarised in Table 2.

Table 2: Fault simulation data

Fault State	0	1	**Fault Location**
I_f % of I_{load}	100%	106.5%	PV module
I_f % of I_{load}	100%	106.5%	Inverter DC bus
I_f % of I_{load}	100%	317.7%	Combiner box

Based on the above data and the given module specifications, the following can be stated for a short circuit fault on the following DC locations of the PV plant:

<u>Single PV module</u>

$$I_{fault} = I_{sc,mod} \tag{1}$$

Where:

$I_{sc,mod}$ is the short circuit contribution of the PV module

<u>Inverter DC bus</u>

$$I_{fault} = nI_{sc,array} \tag{2}$$

Where:

n is the number of combiner boxes connected to the bus

$I_{sc,array}$ is the short circuit contribution from one PV array

<u>Combiner box</u>

$$I_{fault} = nI_{sc,box} \tag{3}$$

Where:

n is the total number of combiner boxes

$I_{sc,box}$ is the short circuit contribution from one combiner box

It should be noted that although the equations for a fault on the combiner box and the inverter DC bus are the same, the fault as a percentage of the load current differs which must be considered when designing the protection scheme.

4. PROPOSED FAULT PROTECTION SCHEME

In order to design a protection scheme for the DC collector circuits of a PV plant, a number of factors must be considered. There are three proposed faults that need to be protected against which include ground faults, line-to-line faults (phase faults) and arc faults all of which have the potential to cause a fire [1]. The existing protection in the DC section of the plant consists of fuses which are not sufficient to protect against overcurrents due to their slow reaction. When a lower output is produced by the PV modules, such as at sunrise or sunset, the fuse would not be able to detect a fault current due to its low magnitude and hence will not blow [3]. This means that the location of the different types of protection in the protection scheme is important for proper coordination.

For ground fault protection, the equipment should be grounded by an EGC, Equipment Grounding Conductor, which is a physical grounding rod for the system [3]. Also, a ground fault detector can be used to measure the current between positive and negative terminals at the combiner box which works in conjunction with a GFCI (Ground fault circuit interrupter). A device such as the Littelfuse SE-601 utilises a ground reference module (resistive voltage divider network) to limit the ground fault current to 25mA. Hence, when the resistor module detects a change in measured current from positive or negative terminal to ground, it will trip an output relay to turn off the power to the system. The current setting and tripping time can be selected by the user. This device is used for an ungrounded system. For a grounded system making use of an EGC, an insulation resistance measurement device could be used [1].

For arc fault protection, series and parallel arcs exist which require a method of protection. Arcing is a consequence of equipment degradation, poor connections or damage caused by rodents [8]. A combination of an arc fault detector (AFD) and arc fault circuit interrupter at different locations in the DC network is required to mitigate arcing faults. The arc fault detector would be able to detect a fault by measuring abnormal noise levels in the system other than those produced by the inverter [1]. Arc fault protection would be based on the coordination of switches which break the connection on the respective terminal/cable in the DC section of the plant [1]. The locations of arc fault protection would determine protection against a series or parallel arc fault.

For phase fault protection, as mentioned previously, there is the persistent problem of reverse currents which, depending on the time of day that the fault occurs, might not be able to blow the fuse intended for overcurrent protection. This is due to the magnitude of the short-circuit current of a module being similar to that of the load current. The device used in [3] is a mechanical and solid state hybrid switch. The hybrid DC switch has optimised timing control for fault detection and system protection purposes. Using a solid state switch on its own provides for a fast-acting arcless mechanism with the drawback of high power loss and sensitivity to transient overcurrents and overvoltages. A hybrid switch utilises the properties of a solid state switch as well as an electromechanical contactor which has a low power on-state characteristic [3]. This is a new concept that could be used for phase (line-to-line) fault protection. The different protection schemes can be combined to form a proposed overall fault detection and protection scheme for the DC collectors as shown in Figure 5.

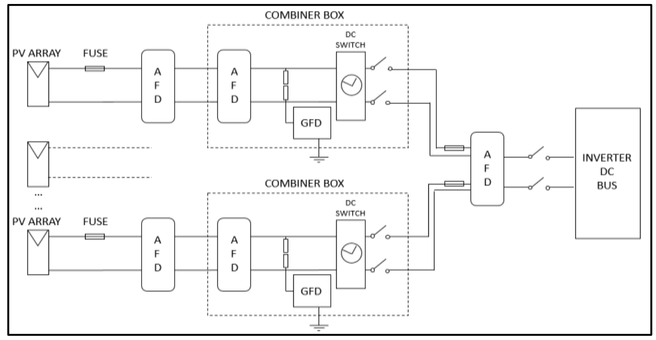

Figure 5: Proposed DC collector protection scheme

From Figure 5 it can be seen that the protection systems are integrated to protect against the main types of faults in the DC section. Arc fault detection is required on the PV array, combiner boxes and inverter DC bus to extinguish any arcs resulting from faults throughout the DC network. Arc fault protection on the strings of the array would protect against series arc faults while the protection on the combiner box would protect against parallel arc faults. A ground fault detector could be used for ungrounded systems to detect ground fault levels and operate a relay tripping scheme. Incorporating a grounded system would incur costs and would also require the use of insulation resistance measurement devices. Fuses are used for high level fault protection under normal operating conditions in the originally allocated locations. The DC switch is a connotation for a combined electromechanical and electronic switch with timing control. This type of switch will be used to monitor the phase fault and would probably require a microcontroller based algorithm for monitoring short-circuit current at the specific time of day based on measured data patterns in the form of incident solar irradiation. This will reduce risk of nuisance blowing or non-blowing of the fuse due to different irradiation conditions and hence varying current flow from the PV modules. Also, the DC breakers in the network could be configured with all the above mentioned protection equipment so that if any of the fault conditions occur, power in the DC network will be cut. Based on the fault simulation results, fault detection on the combiner boxes should be a simpler task due to the high n-multiple fault current contribution from the other combiner boxes. A fault in any of the arrays or at the inverter DC bus input would require a more careful approach through the use of an active component intelligence device for differentiating between load and fault currents.

5. CONCLUSION

The design of a fault detection and protection scheme for DC collector circuits of the low voltage DC section of PV power plants must adhere to the following key principle: Protection compliance with standards while taking into account the optimal performance of the plant. The evaluation of the fault current through the combiner boxes and through the inverter

DC bus indicates that an inverter DC bus fault produces a fault current equal to the total number of combiner box array fault currents. The fault on the combiner box on the other hand produced a fault current of a multiple of the number of combiner boxes connected to one inverter. This is a consequence of the reverse current characteristic due to the parallel connections of strings in each array. The protection scheme used for total DC side protection would consist of arc fault detectors, ground fault detectors and a possible active component intelligence system used for monitoring phase faults. These three systems would work cohesively to provide the fault detection and protection requirements for minimal risk of faults that could produce damaging results. Future work on the proposed design of the protection scheme will include the modelling of the different types of protection systems and the simulation of faults for evaluation of the effectiveness of the proposed DC collector protection scheme.

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