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PROTECTION ANALYSIS OF HYBRID MICROGRID: UNDER VARIOUS CONDITIONS

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ABSTRACT. The number of renewable and decentralized power plants is rising globally, due to the need to minimize emissions that have an impact on the climate. The hybrid distribution network has recently attracted much attention since it combines the best features of AC and DC microgrids (MGs). Despite the several benefits of integrating a hybrid MG into the distribution network, it also offers some challenges. The development of a reliable protection system generalized for both AC and DC sub-MGs and the coordination between them is one of the most important challenges facing hybrid MG technology. Even though they both have a substantial mutual influence, most recent studies only concentrate on one side DC or AC. This study thoroughly analyzes the system under various conditions and discusses some recent protective strategies that can be applied to such a system. The study also outlines the benefits of the hybrid AC/DC network and some of the protection challenges that the hybrid MG faces. The research also compares the system behavior under both disturbance and fault conditions. Additionally, a thorough illustration is provided of how a fault in the AC-microgrid (MG) affects the DC-MG and vice versa.

KEYWORDS: Fault analysis; hybrid distribution network; islanding condition; protection challenges; protection strategies.

1. INTRODUCTION

Conventional power systems were designed and built for their centralized generation from large-scale, mainly fossil-fuel-based power plants. So, it requires a complex rather expensive long-distance transmission system. The conventional grid faces various problems from several aspects, including security, reliability, poor overall efficiency, large voltage dips for far-end load, and economic problems. The most serious problem with the conventional grid is the pollution it causes to the environment. With the emergence of renewable energy resources (RES), energy storage systems (ESS), and power electronic technologies, a new improved system, known as a hybrid distribution system, was introduced. The benefits of both AC and DC microgrids are combined in a hybrid microgrid. The primary benefit of such a configuration is that it reduces the need for multistage AC-DC and DC-AC conversion.

The hybrid MG combines the best characteristics of AC and DC networks while needing minimal modification to the existing distribution network and minimizing the power conversion process losses [1]. Despite the many benefits of AC/DC hybrid MGs, one of the difficult issues facing MG technology is creating a reliable protective system.

The distribution network has changed due to the integration of (DGs), going from a passive distribution system with power flowing only in one direction to an active network with power flowing in both directions. Numerous technological studies have been carried out to establish protective strategies for DC MG and even more so for AC MG [2]. There have been few studies, nevertheless, on the operation of the hybrid AC/DC system, particularly on developing a reliable protective system.

Most of the studies related to the hybrid AC/DC network focus on system planning, control, simulation, and energy management. However, only a few research focuses on developing protection schemes that cover both sides. In [3]–[5], protection schemes based on feature extraction and discrete wavelet analysis, these three scheme utilized different artificial intelligence techniques for fault detection.

However, these systems do not consider the protection of both AC and DC MGs, the cooperation between both sides and the effect of both sides on each other's, and the different disturbances that can affect the protective relays in the system. Ref. [6] proposes a protection scheme for DC-MG integrated on a low-voltage hybrid network. The scheme is based on three strategies which are: unbalanced-current, and overcurrent, differential protection.

The hybrid MG adopted is thoroughly examined in this study. the modeling and analysis of various healthy and fault events are conducted. For the objectives of this analysis, a variety of fault types on both AC and DC MGs are considered. In addition, the effect of each sub-MG on the other is considered under fault and non-fault situations. Finally, a review of the most common protection strategies during the past decade is conducted.

2. AC AND DC MG PROTECTION CHALLENGES

Several protection challenges face the hybrid network. These challenges may be caused by different reasons as follows [2], [7], [8]:

- The connection of DGs at different nodes in the system especially the inverter-based DGs.
- The interconnection between different characteristic systems AC and DC.
- Different disturbances that can impair the protection scheme like changing system irradiation and load switching.
- Changing the grid mode of operation from grid connected to islanding. Which causes a change in current distribution through different lines in the system.

Fig. 1 summarizes the most common challenges [9], [10] facing the protection scheme of a hybrid distribution system. In addition to these challenges, the coordination of the two connected systems considers very challenging. Since both systems have different characteristics and different time bases. To design a reliable protection that can cover all faults in both AC and DC MG and be stable against different disturbances all these challenges must be taken into consideration. In addition, an extensive analysis of the system behavior during different types of faults helps create a robust resilient protection scheme for the hybrid network.

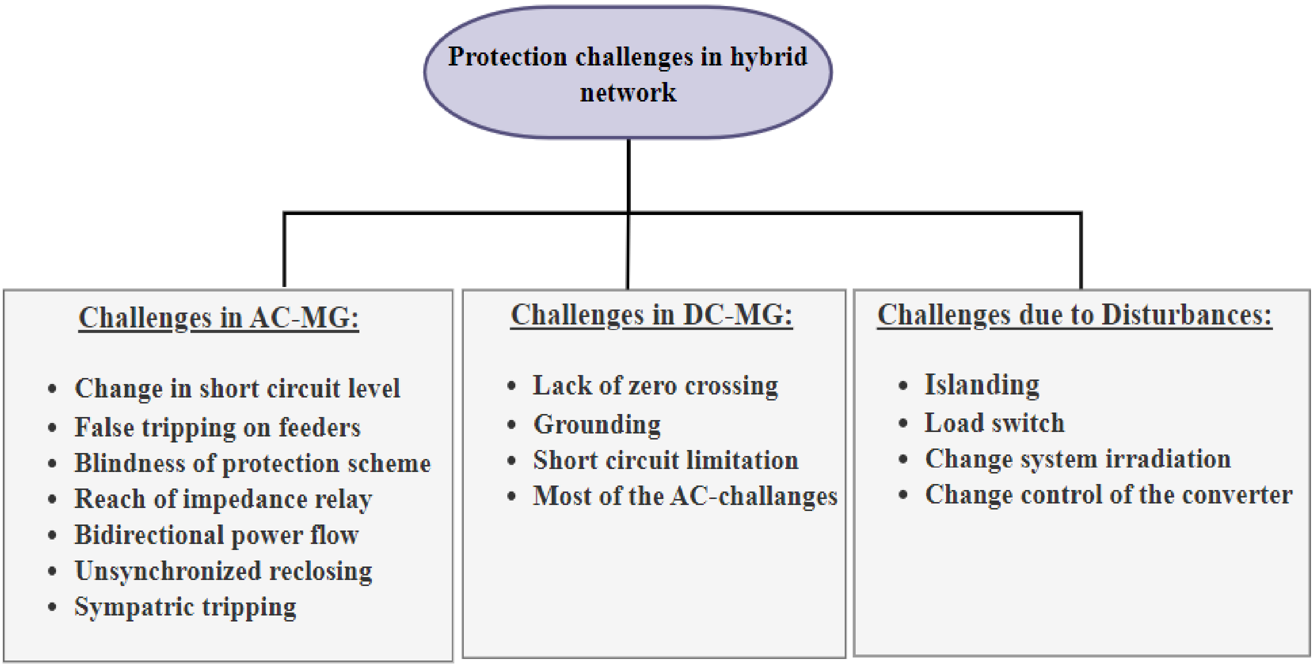

Fig. 1. Protection challenges of both AC and DC system.

3. Protection Strategies Of Both AC & DC MG

Several protection strategies adopted for both AC and DC MG are shown in this section. In addition, the advantages and drawbacks of each strategy are mentioned.

3.1. Protection schemes for AC-MG

As previously discussed, traditional overcurrent-based techniques are incapable of protecting AC microgrids and sub-grids due to the large difference in the amplitude of fault currents in grid-connected and islanded modes and the challenges mentioned before. Several techniques for overcoming this difficulty have lately been offered in scientific literature.

3.1.1. Adaptive protection scheme

An online system that adapts the preferred protective reaction to a change in system conditions via an externally generated signal is referred to as adaptive protection [11], [12]. The adaptive protection schemes are divided into two main categories: computational-based schemes and intelligent-based schemes.

A. Overcurrent-based adaptive scheme

As mentioned before the conventional overcurrent-based protection scheme is unsuitable for the protection hybrid network. Several studies are focusing on developing such schemes. In [13] adaptive overcurrent scheme continuously updates the relay set according to the grid operating condition. In order to accurately apply such a scheme, all the operating conditions and disturbances that may affect the relay must be recorded in a table called an event table. The event table shows all possible network configurations together with the associated position of DG sources. And then according to each configuration, the fault current is calculated from the relevant relay for the entire fault site and saved in the fault current table. After studying all possible system configurations, the relay setting is recorded in the action table. The advantage of this scheme is that it can cover most of the previously stated challenges and operate during both modes of operation. However, this approach is very complex and requires numerous simulations since all system arrangements must be covered. Finally, since the scheme requires communication then it's not cost-efficient.

Another simpler approach for an adaptive overcurrent scheme which basically based on the dual-setting relay. The relay has two main settings for both grid connecting and islanding modes of operation [14]. And in [15] a scheme for duel setting relay based on both current and voltage in a non-communication scheme is presented.

B. Adaptive protection based on a differential scheme

Conventional differential protection techniques work by comparing the measured currents of relays located at both ends of a protected component (such as a bus bar, line, and transformer). Due to the dynamic conditions of the network with DG, conventional differential protection suffers from fixed-setting problems. In [16], [17] different suggestions for an adaptive setting differential scheme. The main disadvantages of such a scheme are the requirement for a communication system, the requirement for a secondary protection scheme, and the difficulty of handling disturbances and high-impedance faults.

3.1.2. Distance protection

Another method for protecting AC microgrids and sub-grids is to use a distance protection strategy that offers great selectivity. The installed distance relays in the scheme are simply calculating impedance based on measured voltage and current at their position to detect fault occurrences. There are several issues facing conventional distance protection when applied to DG-based networks such as the reach of distance relays, sensitivity to fault impedance, the effect of system disturbances and changes in grid configuration like islanding, and dependency of integrated DGs type and the interfacing converters [9]. In [18] offers solutions for different challenges facing distance protection schemes used in hybrid networks. However, the scheme only considers AC-lines protection and is not valid for DC-feeders.

3.1.3. Multi-agent protection scheme

A multi-agent system is made up of several decision-making agents that work together in a shared environment. The network is divided into different zones and the agents are distributed in these zones. The protection scheme consists of different levels or layers and each layer consists of several intelligent agents. The agents can utilize different detection and artificial algorithms. Several studies have adopted the multi-agent approach, especially on MG applications [19], [20]. And since it's a centralized scheme it requires communication infrastructure to connect all agents together. The agents gather the necessary network information, use it to implement the necessary network protection system, and transfer it across network equipment via a communication structure. The main disadvantage of this strategy is that, in the event of a fault, due to its dependency on the central control unit, it requires considerable data transmission between the main and backup relays.

3.2. Protection scheme for DC-MG

Due to the intermittent nature of RES and the dependence of fault current on various parameters, including the kind of ground system, and various component modelling, the protection of DC-MG is rather difficult. Over the last decade, there have been countless studies in the field of DC MG protection and despite that, there are still challenges in the development of a reliable fast-acting protection scheme. Following is the discussion of the most popular schemes which have been adopted by scientific research regarding this topic.

3.2.1. Current-based protection scheme

Based on the local measurement of the relay point current, different protection algorithms based on such schemes were developed in different studies. In [21], [22] presented schemes based on the current derivative technique where the rate of rise of current with time (di/dt) is calculated. Most of the current derivative protection schemes are usually based on threshold setting and when $\left(\frac{di}{dt}\right) > \left(\frac{di}{dt}\right)_{sett}$, a trip signal is generated. However, the scheme offers faster and better performance than traditional overcurrent relays [23]. The scheme has serious sensitivity limitations due to fault resistance. And the scheme is unreliable during changing conditions like islanding, load switch, changing battery status from charging to discharging, and vice versa, and changing system irradiation.

3.2.2. Impedance-based protection scheme

In [24] a protection scheme based on impedance calculation is introduced. Each scheme offers an addition to the conventional impedance-based scheme (distance protection). Since the distance protection concept for a DC system differs from that of an AC system because the inductance of the DC cable is much lower, and the present fundamental frequency is absent. In [25] another scheme is based on calculating the power electronic impedance and comparing it with their suggested specifications. A resistance estimation-based protection technique for a ring-bus DCMG is addressed in ref. [26]. This scheme's operation is not dependent on fault resistance and can detect high resistive faults (HRF) up to 50 times. While in [27] a protection scheme based on line inductance estimation is used.

3.2.3. Voltage-based protection scheme

Several protection schemes based on voltage variation, drop, and rate of change of voltage during fault conditions are introduced [28]. The voltage-based protection scheme requires no communication infrastructure since it depends on local measurement of single-end line voltage during fault. Still, the main limitation of this scheme is fault resistance which deeply affects the voltage value.

4. System Model Description

The simulated model [29] is divided into three MGs, two of which are AC sub-MGs and one of which is a DC MG. As shown in Fig. 2, both types of MGs are connected to the utility via a single distribution network. Furthermore, power converters are used to connect the DC and AC sides of the system, allowing power to flow between the two grid sides. Table 1 displays data of the connected loads. This table displays the connected load bus numbers, power factor, and rated power. There is one DC load powered by the DC bus, five AC loads in AC-MG2, three AC loads in AC-MG1, and nine AC loads in total.

Various types of (DGs) are connected to the system, together with the utility grid. When the grid is unavailable and the islanding mode is in use, these DGs are designed to deliver the necessary power to the associated loads. These DGs are of different ratings, types, and interface with the network. The data of the connected DG in the system is shown in Table 2. The DG used in the model is distributed among the three MG as shown in Fig. 2.

In addition, different types and topologies of converters are used to connect the different parts of the system, and a proper control algorithm is used for each converter.

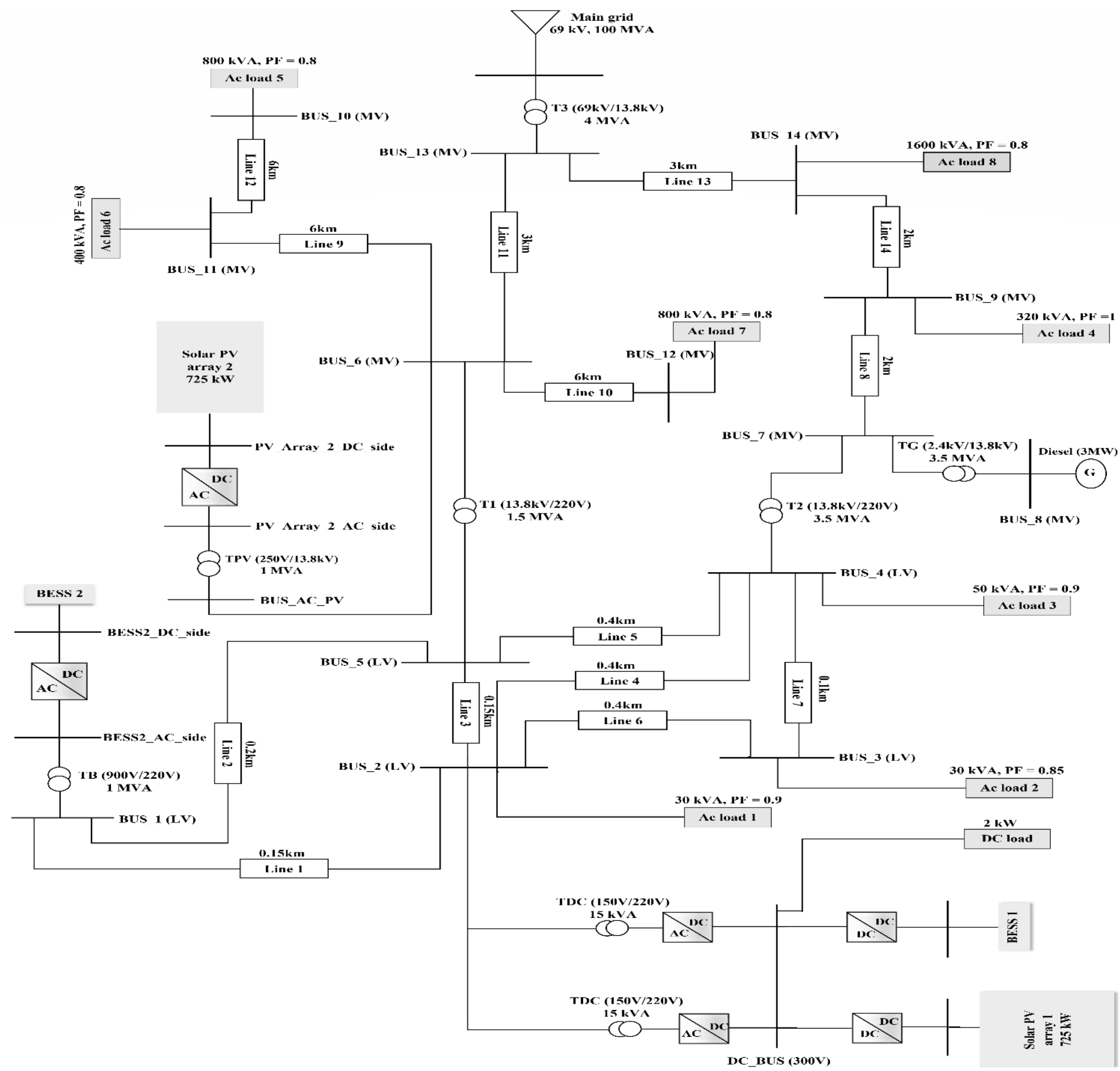

Fig. 2. Single line diagram of the adopted hybrid network.

Table 1. Load data

Load No.	Data of the connected load	
	S (kVA)	Location
Load 1	40	AC-MG1
Load 2	30	
Load 3	50	
Load 4	320	AC-MG2
Load 5	800	
Load 6	400	
Load 7	1000	
Load 8	1600	
DC load	2 kW	DC bus

Table 2. DG data

DG	Source data		
	S (kVA)	Base voltage	Connected bus
PV array 1	10.5 kW	120 V	DC-BUS
PV array 2	725 kW	480 V	BUS 6
BESS 1	800 Ah	120 V	DC-BUS
BESS 2	1.5 Ah	650 V	BUS 1
Desiel	3 MVA	2.4 kV	BUS 8

5. System Analysis Under Normal Conditions

The MATLAB/Simulink simulation platform is used to simulate the adopted hybrid distribution network. Different operation scenarios are discussed to examine the system's performance under the prementioned challenges. The distribution of current through the AC line fluctuates along with the system's operational conditions. The change of the interface converters also significantly affects the magnitude of DC current.

5.1. Islanding

The transition from grid connected to islanding significantly affects the network. Where the distribution throughout the entire network changes and not in a predicted way. The current increased in some lines decreased in others and remained constant in most of the others.

Fig. 3 to Fig. 5 shows the effect of islanding on the current of different parts in the AC MG. As shown in these figures, the current increases in line (5) 2.8 times, in line (8) increased 4.3 times, and in line (14) increases 6.1 times. The change of the current level through these lines is due to non-fault condition (islanding). If this is not taken into consideration, will cause a mal operation of the conventional current-based protection scheme as it will be seen as a fault by the relay. While as shown in Fig. 6 the effect of islanding on the DC side is barely noticeable compared to the AC side. Since the PV is controlled by MPPT during both operating modes. In addition, the power from the battery does not change significantly since it depends mainly on the used controlling algorithm.

In addition, a comparison between the behavior of the current during a fault condition and islanding (as a normal disturbance) is shown in Fig. 7. And as shown in the figure the current at fault value is way higher than the change in current due to islanding. However, if a resistive fault is considered the two currents are very close. In addition, the time response of the islanding condition is slower than the fault condition.

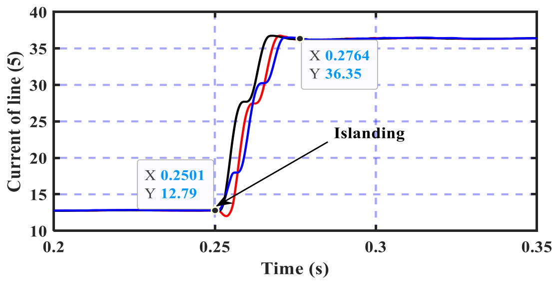

Fig. 3. Current of line 5 during the transition from grid connecting to islanding

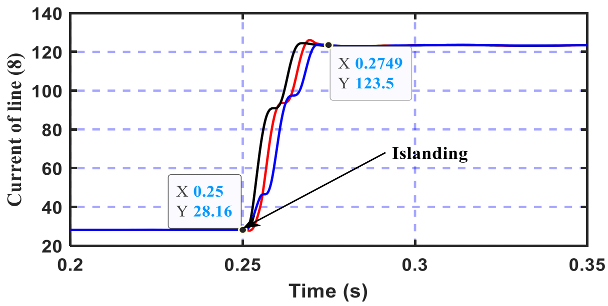

Fig. 4. Current of line 8 during the transition from grid connecting to islanding

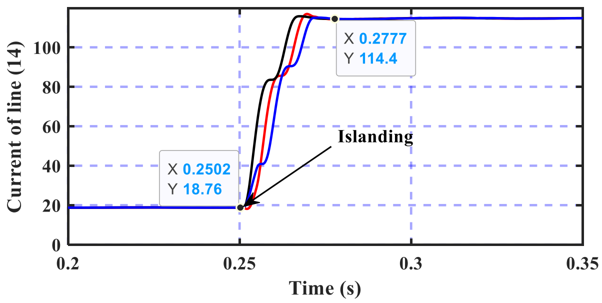

Fig. 5. Current of line 14 during the transition from grid connecting to islanding

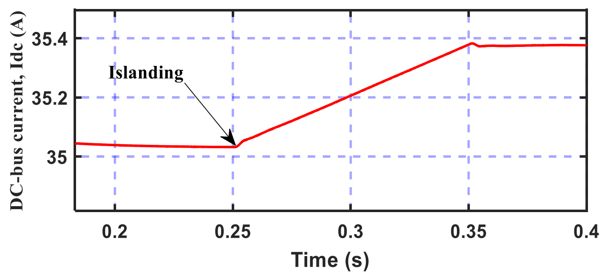

Fig. 6. Current of the DC bus under changing from grid-connected to islanding modes.

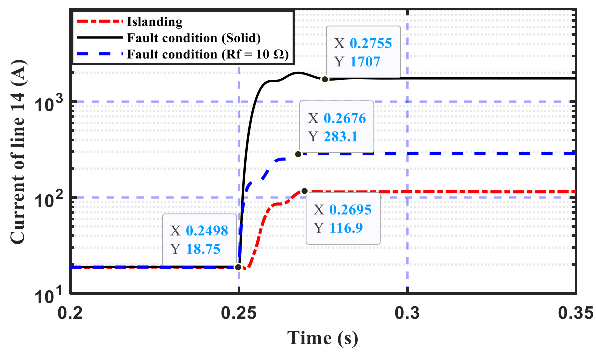

Fig. 7. RMS current of phase (a) for line 14 during a symmetrical fault condition and normal operation (islanding condition).

5.2. System Irradiation Change from 1000 to 500 W/m²

Fig. 8 to Fig. 11 shows both AC and DC MG behavior during the drop in solar irradiation to half. And as shown in the figures this disturbance affects the DC side more than it affects the AC one. In addition, it has been concluded that not all disturbances cause the same effect. Since as shown in the previous discussion islanding affects the AC side greatly not the DC side while changing system irradiation affects DC side more AC.

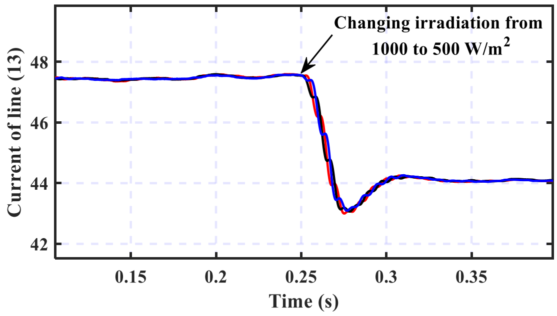

Fig. 8. Current of line 13 during changing irradiation from 1000 to 500 W/m²

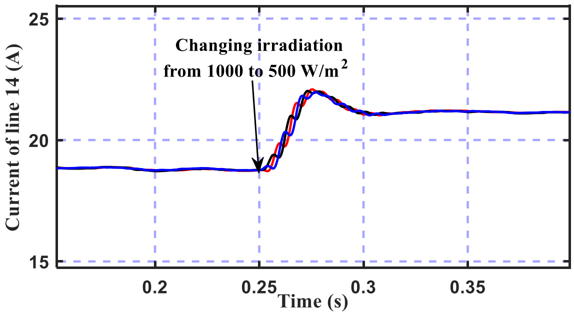

Fig. 9. Current of line 14 during changing irradiation from 1000 to 500 W/m².

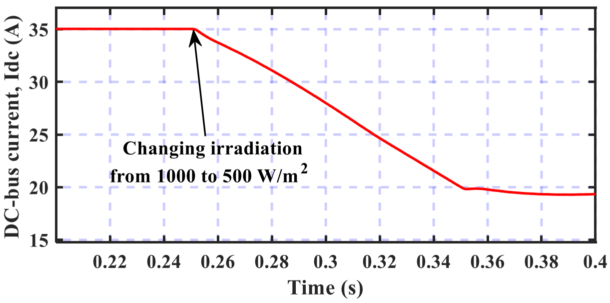

Fig. 10. Current of DC-bus under changing irradiation.

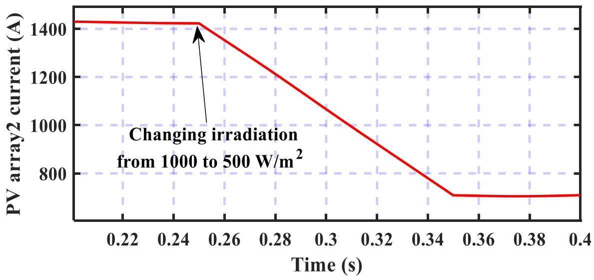

Fig. 11. Current of the PV array 2 under changing irradiation.

6. FAULT ANALYSIS OF BOTH AC AND DC SYSTEMS

This section studies the behavior of the adopted model during the fault conditions in both AC and DC MG. In addition, an investigation of the effect of a fault in one sub-MG on the other is shown. Accordingly, multiple measurements are taken at various points during each fault.

6.1. DC-MG FAULT ANALYSIS

To create an adequate protection strategy for a DC microgrid, an analysis of fault current is required. There are two types of DC microgrid faults: pole-to-pole (P-P) faults and pole-to-ground (P-G) faults. To comprehend and analyze DC fault characteristics, the system is handled by identifying three distinct stages of the fault current. When a fault occurs in the DC MG the fault current passes through three stages known as capacitor discharge, freewheeling diode stage, and AC-side/grid feeding stage [30]. The second and third stages are current from both the energy stored in line inductance and current feeding from the AC side. When a fault occurs on the DC side first the capacitor of the connected converter starts to discharge. Resulting in a very high current change in small time due to the low time constant. And then comes the second and third stage, where the current is fed from line inductance stored energy and AC-side. In addition, the protection system in the DC MG is required to clear the fault during the first stage (capacitor discharge) and before the second stage. This time constraint comes from the fact that most of the power converters can withstand an overcurrent of range 2:3 times the normal current [30], [31].

For the analysis of such a system, different protective relays and circuit breakers are assumed at different locations of the DC-MG. Since the most common fault locations in the DC system are either the DC-bus or DC feeders an optimal location of the protective relays is significantly important. Fig. 12 shows a suggested allocation of protective relays and DCCB.

For a fault on the DC MG the system behavior is studied. Fig. 13 to Fig. 15 shows the current and voltage response during a P-P fault on DC-bus. Fig. 14 shows the current contribution to the fault point from all the connected feeders. The current contribution from the PV array (I_{sc}) is almost the same. While the current from BESS1 contributes most of the fault current.

In addition, as can be seen in Fig. 13 and Fig. 15 the system is very sensitive to fault resistance. Finally, Fig. 16 shows the AC-side responses for a P-P fault on the DC side. Which is very important during the coordination of the AC and DC sides.

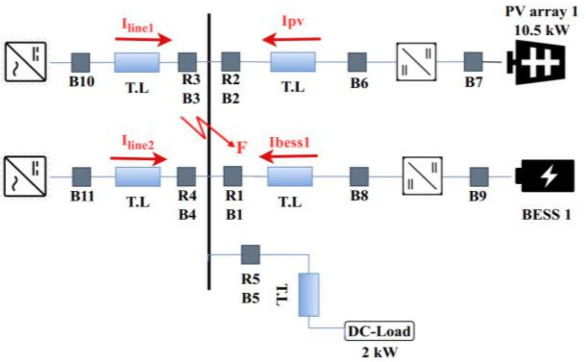

Fig. 12. Fault case utilized on the DC-MG showing the current behavior of all the connected feeders the connected feeders.

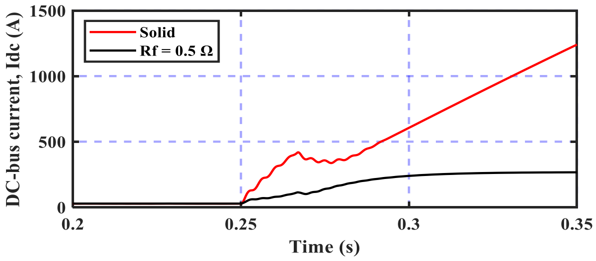

Fig. 13. Fig. 13. Current of DC side during a fault on the DC bus.

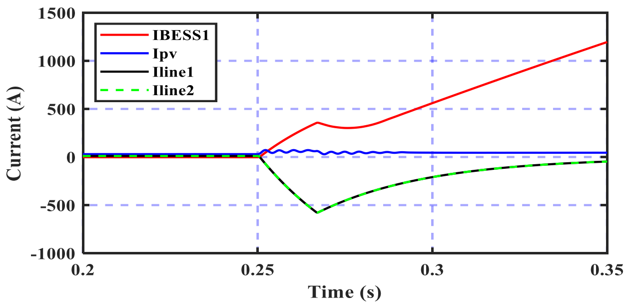

Fig. 14. Fig. 14. Current of the connected feeders connected to DC-bus during a fault on the DC-bus.

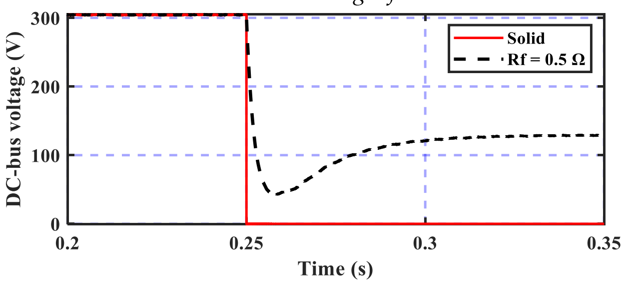

Fig. 15. Fig. 15. Voltage of DC bus during a fault on the DC bus for solid and resistive fault.

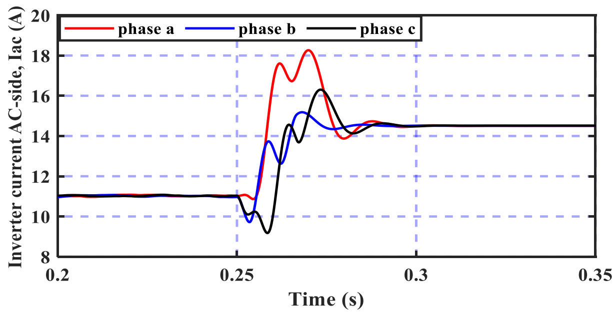

Fig. 16. Current of the AC line after inverter under pole-to-pole fault on DC bus.

6.2. FAULT ANALYSIS ON AC SUB-MG

Symmetrical and unsymmetrical faults are the two main types of AC faults. Both types of fault conditions are studied for the AC sub-MG, and the related measurements are taken. Fig. 17 shows the corresponding current measurement at both ends of line 3 during a symmetrical fault, during both grid-connected and islanding modes. During a fault in any line of the AC network, the current contribution from the two ends is significantly different. Furthermore, Fig. 18 and Fig. 19 show the current behavior during unsymmetrical faults. For the ground fault shown in Fig. 19, the current in phase B (which is a healthy phase) approximately doubled. The reason for that is the feeder is close to an earthed star-connected transformer that affects the impedance during the fault and, by extension, affects the value of the symmetrical components (0, +ve, and -ve). In addition, the location of the feeder near inverter-based sources makes the contribution of these sources (through converter topologies) during the fault condition unconventional.

Furthermore, the current of phase A is 5.2 times the normal current.

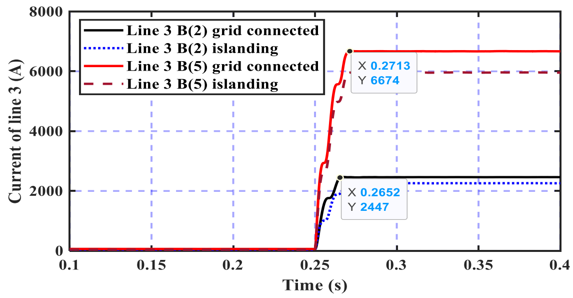

Fig. 17. RMS current of phase (a) during a symmetrical fault in line 3 at both ends of the line.

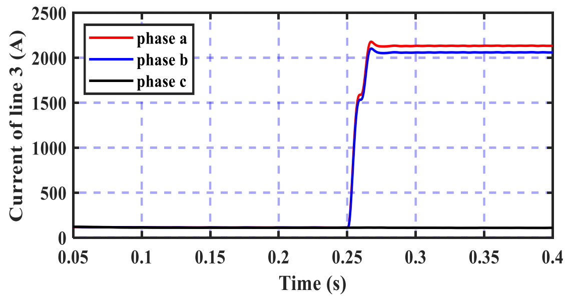

Fig. 18. RMS current of line 3 for unsymmetrical (AB-G) fault.

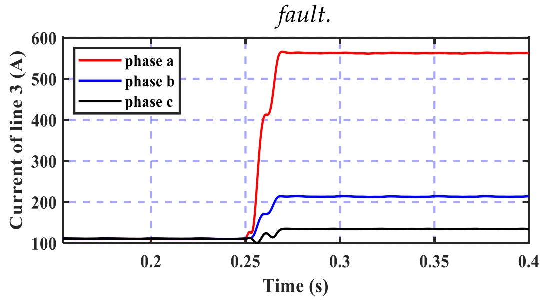

Fig. 19. RMS current of line 3 for unsymmetrical (A-G) fault.

7. Conclusions

The research investigated the different issues of hybrid system protection and conducted a complete analysis under different scenarios. Different operating conditions are modeled to study the system's reaction under different settings. Some of these illnesses are discovered to have a greater influence than others. In addition, the system is tested under various fault scenarios to explore its behavior and discuss the effect of DC MG on AC MG during fault and vice versa. As a result, protection solutions based on a single-setting relay are no longer appropriate, and dual-setting relays are insufficient.

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