Investigating the performance of an R-Criterion based protection method when applied on PV Solar microgrid

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Performance Analysis of an R-Criterion based Solar-PV Microgrid Protection scheme

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***Abstract*—Microgrids have become an attractive way of integrating several distributed generators to the utility network via a common point of coupling (PCC) to minimize network complexity and improve stability, amongst other attributes. Africa receives an abundance of solar radiation. Solar PV has, rightly, become a popular alternative clean energy. However, because of the nature of solar radiation, the produced power is intermittent. Furthermore, power electronics used to integrate PV solar systems into the grid have limited maximum allowable current. These attributes negatively impact the capability of existing protection systems and thus the call to find effective protection solutions. R-Criterion was identified as a potential fault detection system; however, it is unable to differentiate a balanced 3-phase fault from a switched load in the network. All simulations were done in MATLAB/ Simulink.**

Keywords—microgrid, solar PV, protection, R-criterion.

I. Introduction

Microgrids have been viewed as a game-changer in minimising the negative impact of distributed generators on the network which they impose when a large number of them are integrated into the network individually [1].

Since inception, the interest in microgrids has grown exponentially. With the world becoming more conscious about the viability of renewable energies, a large number of countries are criticised for not implementing renewable energies to contribute towards minimising emissions. It is important to note that, due to the high solar influx Africa receives, solar PV systems are becoming a key power solution in many corners of the continent [2], [3]. These units are generally installed at the distribution level. However, the existing electrical network systems were never built to integrate power generating units within the LV distribution end of the network system [4]-[6]. This is because the network was always designed with the idea of power flowing from a region of high voltage to a region of low voltage [3], [7]. High voltage end being the generation side and low voltage the load end side of the network.

However, as more renewable energy sources are integrated at the load end of the network system, the network structure changes and so does its dynamics [8]. The more renewable energy sources penetrate the more complex the network system becomes [9]. Thus, instead of easing power demand and emissions, the complexity of the network increases, thus negatively affecting the network integrity and reliability. Therefore, in a bid to see the benefits of bringing in renewable sources, a new technology that would allow the integration of these renewable resources without compromising the network integrity was necessary. The result of this was the microgrid [4], [10].

A microgrid is a power system with different interconnected components forming a fully functional low scale power network system. The interconnected components in this always include distributed generators, DGs, (mainly renewable energy source based such as wind turbines, photovoltaic (PV) arrays and fuel cells), the power electronic interface (DC/DC and AC/DC/AC converters), the local loads and storage (optional) [1]-[4], [11], [12].

Although microgrids have now eased the management of renewable distributed generation, protection has remained a challenge. Solar PV systems, in particular, impose challenges due to their operating nature. Firstly, their intermittent nature which results from the intermittent nature of solar radiation produces variable power. Secondly, these systems use power electronics to integrate into the network. The power electronic systems used for this purpose rely heavily on the insulated gate bipolar transistors (IGBTs) switches which have limited capability to supply high fault currents [4]. Power electronics can only allow up to three times their rated current during a fault [13].

In this paper, the effectiveness of R-criterion scheme in protecting Solar PV based microgrids is evaluated. The results obtained show that this scheme can complement other protection systems.

II. PV Solar Characteristics

PV generation systems convert sunlight directly into electricity. They, however, produce DC power and this is inverted to AC power through inverters before being integrated into the grid. The general schematic diagram for the inverter of a PV grid-connected system is shown in Fig. 1.

To further comprehend the effects of solar radiation and actual array temperature on PV solar system behaviour, a study was conducted in MATLAB Simulink.

The solar photovoltaic array model was developed using fundamental approaches. The model is based on a Simulink implementation of a photovoltaic cell using a single diode mathematical model, as per equation (1).

$$I = I_{ph} - I_0(e^{\frac{q(V+IR_s)}{kT}} - 1) - \frac{V + IR_s}{R_{sh}} \tag{1}$$

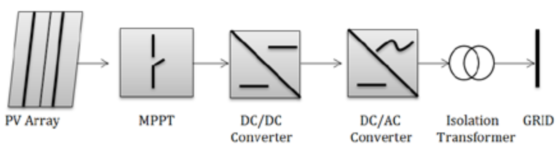

Fig. 1. A schematic diagram of a PV system for a grid-connected operation.

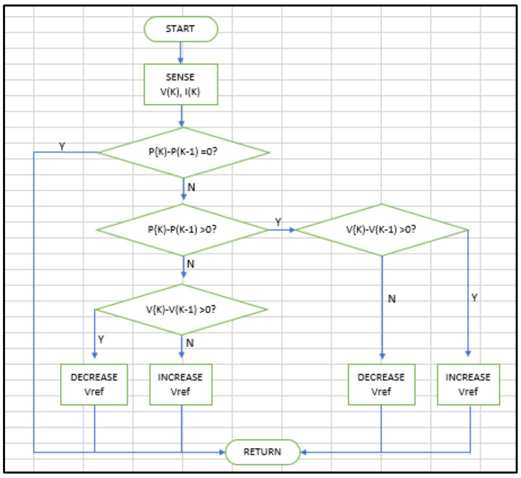

Fig. 2. Perturb & Observe methodology algorithm.

A Solar PV module system is a combination of several solar PV cells connected in series and parallel to give the desired output terminal voltage and current. The solar PV system is characterized by a non-linear I-V characteristic, mathematically expressed by equation (2). This equation shows a simplified expression describing the relationship between voltage (V) and current (I) for a module [1], [14].

$$I = n_p\left[I_L - I_S\left[e^{q\left(\frac{V}{n_S}+\frac{IR_S}{n_P}\right)/AKT} - 1\right] - \frac{\frac{V}{n_S}+\frac{PR_S}{n_P}}{R_P}\right] \quad (2)$$

To keep the array operating at or as close to the region of maximum power point as possible, a Maximum Power Point Tracking (MPPT) system, Perturb and Observe (P&O) is applied for this study. MPPT allows maximum efficiency operation of the array [1], [2], [15].

P&O is the most common MPPT methodology and it is simple to implement. This methodology depends on voltage and power measurements. The controller for P&O adjusts the voltage by a small amount from the PV array and measures the relative power [16], [17]. Depending on the direction in which the perturbation leads into, a positive change in V is applied if the perturbation leads into an increased output power and a negative change in V is applied if the perturbation results in a decreased output power [18], [19]. Fig. 2 shows the algorithm for P&O methodology [18].

A. *Impact of Solar irradiation on output power*

The model is implemented using the mathematical blocks available in Simulink. The impact of solar irradiation at a fixed output voltage is an increase in the output current with increasing irradiation. Fig. 4 shows the obtained output current-voltage and power-voltage curves as the solar irradiation varied from 600 to 1400 in steps of 200. The output power of the Solar PV is highly dependent on solar radiation and array temperature. The effects of these two variables on I-V and P-V characteristics are studied independently and relevant family of curves shown Fig. 3 and Fig. 4. From these two families of curves, it is clear that although these variables affect the output power, they have little effect on the voltage at maximum power. Vmax is almost invariant regardless of changes in solar irradiation and array temperature. However, the current varies as either of the two variables vary and thereby varying the output power.

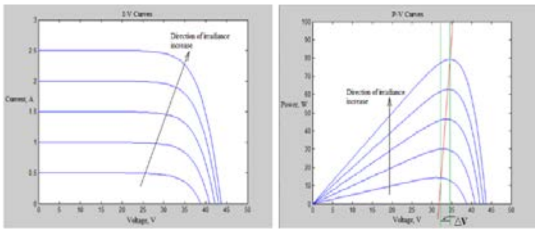

Fig. 3. The effect of changes in solar irradiation on I-V and P-V characteristics of a solar module.

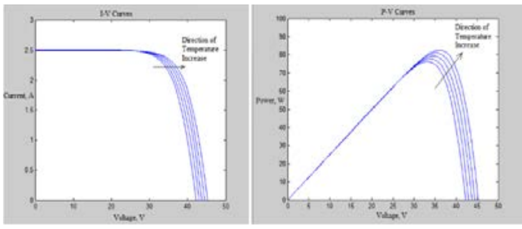

Fig. 4. The effect of changes in the array temperature on I-V and P-V characteristics of a solar module.

The curves highlight the intermittent nature of PV solar systems which results directly from the varying solar radiation. The time of the day, the season of the year all greatly influence this intermittent nature.

B. *Impact of array temperature on output power*

Another variable that greatly impacts the output power of a PV solar is the temperature of the solar array. Solar array temperature directly influences output voltage at fixed current. An increase in temperature results in an increase in output voltage as shown in Fig. 4.

As observed in the previous section, the current-voltage and power-voltage curves obtained highlight on the intermittent nature of PV solar systems resulting directly from the varying solar array temperature. Therefore, the time of the day and season of the year greatly influences this PV solar behaviour.

III. Solar PV Microgrid Protection

The Solar PV microgrid considered for this study consists of a 5 kW solar PV system as the source, 1.5 kVA inductive load as load 1, 2 kW resistive load as load 2, a 100m low voltage distribution line in zone 2 of impedance of 5,52 Ω/km and voltage drop of 9,561 mV/A/m shown in Fig. 5.

Two different protection strategies are applied in this study. The first strategy isolates the microgrid from the main grid via a point of common coupling, PCC, whenever there is a fault detected. This isolation is true for both internally detected and externally detected faults. The second strategy only isolates the microgrid whenever a fault is detected in the main grid. For internal faults, the microgrid remains connected to the grid and receives high-level current flow which is essential for detecting faults using fault current detection methods [16].

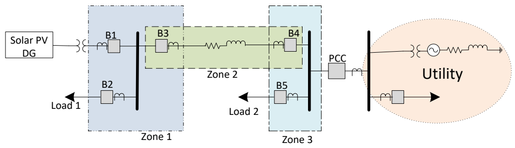

Fig. 5. A microgrid system consisting of one generating unit and two different loads, and is connected to the main grid through a PCC.

The microgrid is implemented such that it operates in a grid-connected mode and it can only go into a healthy island operating mode during certain scheduled times e.g. for maintenance purposes. The aforementioned strategies are described in detail in the following subsections.

A. *Strategy I*

In this strategy, the relays in the microgrid send signals to the static switch, SS, (embedded at point of common coupling, PCC) to open the switch whenever there is a fault detected. This is the first step of any protection system based on this strategy. This strategy eliminates the possibility of experiencing high fault currents in the microgrid that can be detected by the conventional fault detection protection systems unless a high current source is implemented in the microgrid to provide this high current during faults. The addition of a high current source can be an alternative; however, this approach is not commonly adopted due to complications it can bring to the entire operation of the microgrid. Therefore, when this strategy is adopted, protection systems based on network parameters other than the fault current magnitude will be of most importance. The fault current level is expected to be low due to the type of DG used in the microgrid, solar PV in this case. Although the absence of transmission lines in microgrid networks substantially reduces losses, it negatively impacts on the selectivity attribute of the protection system [13], [19] The voltage drop across the whole microgrid network is small such that it would be difficult to differentiate different positions within a microgrid using the voltage drop approach.

B. *Strategy II*

This strategy takes advantage of the high fault current that is injected into the microgrid by the utility grid during an internal fault. It only uses the protection system during grid-connected periods. When an internal fault occurs during the grid-connected mode, the microgrid experiences an overall high fault current. This is because this fault current becomes a combination of the local DG fault current and that of the utility grid. The traditional fault current protection systems can pick-up this fault current and immediately take action [18].

However, the existence of distributed energy resources, DERs, at any point in the network system disrupts the radial structure of the conventional network system and as such can cause incoordination within the conventional protection system [19], [20].

When there is an external disturbance, the SS operates quickly to isolate the microgrid from the utility grid and the microgrid continues to operate in islanded mode until the external disturbance is cleared, and the utility network is stable. At this moment, the microgrid is connected back to the utility [18]. If an internal fault occurs during autonomous mode (i.e. before the external fault is cleared and the microgrid is not connected back to the utility grid), all the micro-sources in the microgrid are isolated, so that the microgrid does not stay energized. This means total blackout.

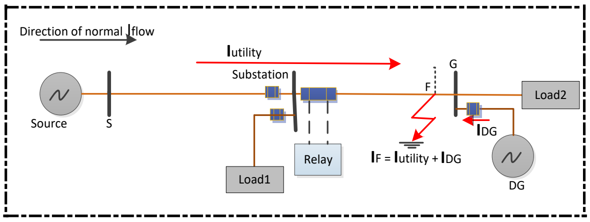

Fig. 6. Fault current flow during a fault in a microgrid.

Literetaure shows that there has been a lot of research around protection of microgrids. In [21], Z C Li, et-al propose a protection method that is based on information sharing. This system relies on communication which has its own draw backs such as vulnerability to cyber-attacks and thus cannot be relied upon. In [22] Sachit Gopalan, et-al propose two protection approaches; however, their performances were only evaluated for phase to ground and phase to phase faults and not for a balanced three phase fault. Several other proposed protection schemes reviewed fell short of capable to effectively protect the microgirds in study.

IV. The R-Criteria

The R-criterion is a symmetrical sequence component-based fault detection method. This method performs the ratio of the difference between the positive and negative sequence current magnitudes to the sum of the two given by equation (3) below:

$$R = \frac{|I_1| - |I_2|}{|I_1| + |I_2|} \tag{3}$$

The principal approach used to detect the symmetrical current sequence components in this R-criterion method is described in the steps below.

This R-criterion analysis is highly effective when detecting asymmetrical faults in which the negative sequence component is considerably high such that $|I_1| \cong |I_2|$ which leads to $|I_1| - |I_2| \cong 0$ the numerator and, thus, the value of R approaching zero. This criterion function is also essential for discriminating fault from non-fault switching conditions. In the switching case, the negative component is very small and R thus R approaches 1. The sequence current magnitude components used in the R criterion equation are calculated from the amplitude of the fundamental harmonic of the phasor values I_a, I_b, and I_c.

The two asymmetrical faults studied are LG and LLG. The obtained results are compared with those obtained during load connection to and load disconnection from the network.

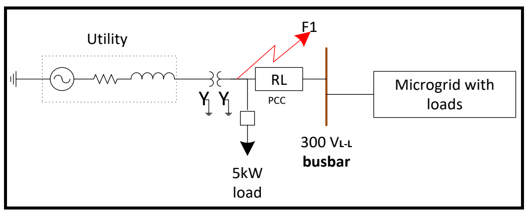

Fig. 7. Fault, F1, in the utility grid section.

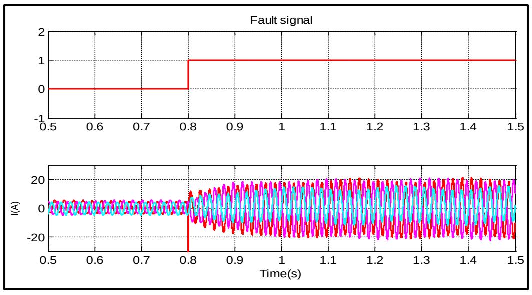

Fig. 8. Three-phase current, detected at the PCC, due to fault L-G at position F1 at time 0.8s.

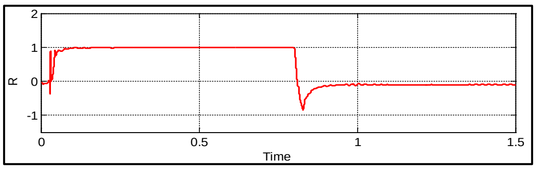

Fig. 9. Value of R vs. time, detected at the PCC, due to fault L-G at position F1.

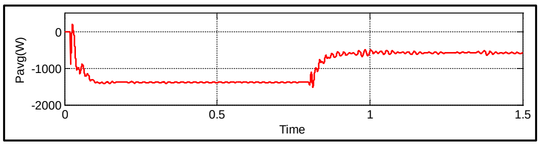

Fig. 10. Power flow detected at the point of common coupling (PCC).

The injected faults at fault point F1 indicated in Fig. 7, are LG and LLG faults

A. L-G Fault

The first fault analysis is done for a single-phase to ground fault type that is induced into the network at 0.8s mark. Fig. 9 shows the simulation results of the current supplied to the fault by the microgrid. The fault current from the microgrid is not expected to be as much as that contributed by the utility itself.

Fig. 9 represents the obtained R-value. Notably, the value of R is close to 1 during normal operating conditions, in which the negative sequence component of the current is almost zero. However, R-value drops drastically in the presence of a fault and this value turns to settle at values just above zero as a result of the present negative sequence component in an asymmetrical system. The R-value calculated is based on the current sequence components supplied by the microgrid during asymmetrical external faults and they are measured at the point of common coupling.

Fig. 10 shows the power flowing through the PCC. The negative power shows that the power is flowing from the main utility to the microgrid, according to the implemented circuit. The results suggest that the overall power detected at the PCC still flows into the microgrid at reduced magnitudes. This suggests that the microgrid is not contributing towards the total fault current which is experienced when the single-phase fault occurs in the utility grid. However, it is the power contributed by the utility to the microgrid that is affected. It is for this reason that the microgrid should be disengaged from the utility during external faults.

B. L-L-G Fault

In this case, a double-phase to ground fault is induced at F1 under the same operating conditions as in the previous case. The obtained simulation results are given in Fig. 11.

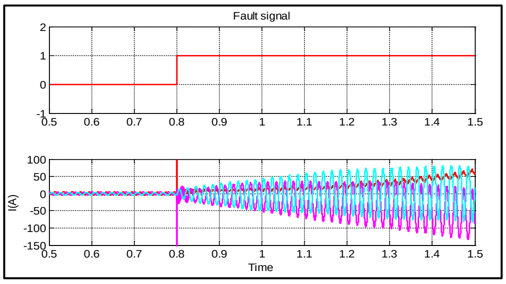

Fig. 11. Three-phase current, detected at the PCC, due to fault L-L-G at position F1 at time 0.8s.

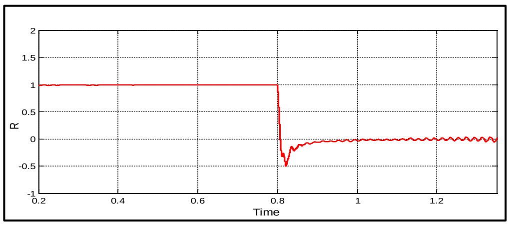

Fig. 12. Value of R vs. time, detected at the PCC, due to fault L-L-G at position F1.

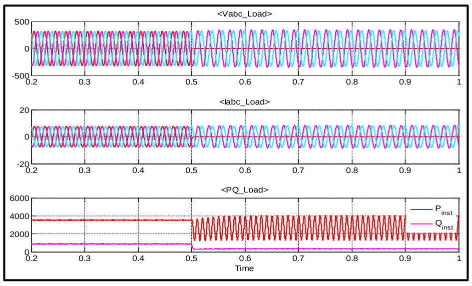

Fig. 13. Load parameters before and during a single-phase external fault.

As observed above, in the single-phase to ground fault detection, a similar response is noticed for the double-phase to ground fault. In both cases, there is a high presence of the negative sequence current component during the fault. [16], [17] thus, the resultant drop on R-value as indicated.

C. Effects of the external faults on the microgrid load power

A single-phase external fault affects the total power distributed to the internal load. The average power falls below the load demand and it also causes oscillations in the load instantaneous power, as shown in Fig. 13.

The current and voltage of the faulted phase drop to zero, leaving the other two phases unaffected, shown in the simulation results of Fig. 13, hence the power oscillations. Also, the total average power, P_{avg}, decreases.

D. Impact of connecting and disconnecting an external load on the microgrid

This test was done to conclude that the external grid normal operation of switching loads on and off does not affect the microgrid protection system. Protection systems must be able to differentiate between normal operation and a fault condition.

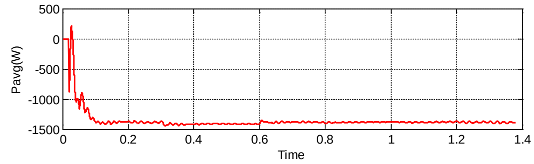

Fig. 14. Microgrid average power profile at PCC during normal operation.

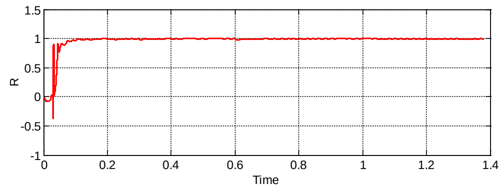

Fig. 15. Value of R vs. time, detected at the PCC during normal operation. An external load was disconnected from the network at tim0.4s and re-connected at time 0.6s.

External load switches do not affect the power supplied to the microgrid by the utility as clearly observed in Fig. 15.

V. Conclusion

The method used above effectively detected the different types of asymmetrical faults based on unbalanced fault currents in both operating modes (islanded and grid-connected). Both single-phase to the ground and the double-phase to ground faults response curves were observed to settle at a new R criterion value after the faults occurred. This is because the network becomes unbalanced during these two fault conditions and thus the negative sequence current component persists for the duration of the fault existence.

However, a different scenario happens when a three-phase to ground fault occurs. The interruption of the fault instantly causes some disturbances that create the negative and zero sequence components; however, these sequence components last for about 0.06s which is less than the time for a disturbance to be classified as a fault. As such, the R criterion value is only seen to change at the instant the fault is injected but fades and disappears once the system stabilises. A similar response is detected when a large load is either connected or disconnected from the network, a result which makes it harder to differentiate between a fault condition and a normal activity such as switching network loads. Therefore, this method fails to effectively detect balanced faults and cannot effectively protect a microgrid.

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