DEVELOPING PROTECTION SCHEMES FOR LOW VOLTAGE MICROGRID WITH HIGH PENETRATION OF PHOTOVOLTAIC GENERATION

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ABSTRACT

The high integration of inverter-interfaced distributed generation, in particular photovoltaic systems into the conventional low voltage distribution network has imposed several challenges on the operation of the existing protection system which is mainly based on overcurrent principle. In order to take the advantage of distributed generation, the network that is so called microgrid should be able to operate in both modes named grid-connected and islanded. However, the low level of fault currents in islanded mode of operation is not sufficient for the present overcurrent based protective devices to operate. Moreover, the delay in fault clearance degrades the voltage level of the network, resulting in the undesired disconnection of PV systems in unaffected areas. This, in turn, will inversely affect the possibility of islanding. Thus, the paper proposes a new protection strategy that can ensure the safety operation of microgrid in both operation modes and also revises the anti-islanding protection of the connected PV systems so as to prevent them from unnecessary tripping.

INTRODUCTION

As indicated in a lot of research publications, a high integration of photovoltaic (PV) units into conventional low voltage (LV) distribution networks may transform this kind of network into a new one called LV microgrid [1]. This new kind of distribution network might be required to be able to operate in both modes namely grid-connected and isolated and should be protected against all kinds of faults. However, the existing normally overcurrent-based protection system fails to deal with the significant differences in fault currents when the networks change from one operational mode to another and vice versa [2]. In fact, in the isolated mode, the extremely high fault current contributed by the utility network is not present. The low level of the fault current contributed by the PV systems and the Battery Energy Storage System (BESS) is not sufficient for the responsible protective devices to operate within a permissible time delay.

Recently, various advanced protection strategies dedicated for microgrid have been developed [3-4]. In [3] a relaying scheme that is able to protect the LV microgrid in both operation modes is presented. This scheme is mainly based on overcurrent and undervoltage functions. However, due to the lack of communication facility, the relays have to be coordinated by time, resulting in a significant large operating time of the relay closed to the utility. Paper [4] presents a protection system that has the same protection strategies for both isolated and grid-tied mode of operation. However, this paper does not consider the compatibility of the developed system with the anti-islanding protection of distributed generation. Currently, in most countries in Europe the PV systems coupled to the grid have to meet the standard VDE-0126-1-1 which requires the PV systems to trip from the utility network in less than 0.2 s if the terminal voltage falls below 0.8 p.u. However, with a high penetration of PV systems into the grid, a disconnection of PV systems on a large scale will affect the post-fault active power balance, resulting in the instability of the whole network. Moreover, as presented in [5] the disconnection of a large amount of the connected PV systems may cause the remaining PV systems to disconnect unnecessarily. Therefore, the study on the capability of PV systems to remain connected in an event of fault (FRT capability) is of significant importance. There are several research conducted on developing the FRT capability of the PV systems [6-7].

As aforementioned, although a variety of research focusing on protection issues of microgrid with high proportion of PV generation has been published, some studies do not consider the operation of the anti-islanding protection of the connected PV systems while some only concentrate on FRT capability of the PV systems itself.

Therefore, in this paper, a complete protection scheme for LV microgrids with a consideration on FRT capability of the connected PV systems is proposed. In order to demonstrate the effectiveness of this protection scheme, its performance is verified by applying for protecting a typical LV microgrid as shown in **Figure 1** under various scenarios of fault using Matlab/Simulink software environment.

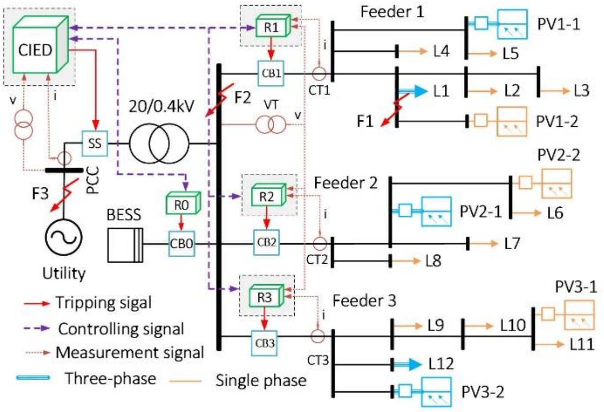


Figure 1 - The single-line diagram of the studied microgrid

THE PROTECTION SYSTEM OF A LV TRADITIONAL DISTRIBUTION NETWORK

Normally, LV distribution network consists of several feeders originating from the secondary busbar of a step-down MV/LV transformer. PV units are installed along the feeders. These feeders and the step-down transformer are often protected against faults by fuses or overcurrent relays that have fixed melting curves [8]. The simulation analyses conducted in the study have shown that although these fuses offer proper protection for the grid-connected microgrid, they fail to cope with the fault occurring inside the stand-alone microgrids due to the limited fault currents contributed by the installed PV units. This is due to the thermal limit of the PV inverters that restricts their fault current to about 2 times their rated currents. Even though it is assumed that we are able to change to fuses with lower melting characteristics when the microgrid is transferred into isolated mode, the new fuses will face with the bi-directional characteristic of fault currents. In particular, due to the lack of a directional element, feeder fuses cannot determine if a fault is in forward or reverse direction. Thus, the fuse of a sound feeder may operate for a fault on an adjacent feeder, resulting in the collapse of the microgrid. Besides, there are some cases in which the conventional fuse-based protection scheme may be totally lost, for instance, if fault arises on the secondary bus-bar of the step-down transformer.

THE DEVELOPED PROTECTION SCHEME

Due to numerous drawbacks of the fuse-based system mentioned above, this study suggests replacing all the feeder fuses by circuit breakers (CBs) with integrated digital relays as shown in **Figure 1**. A fast-operating static switch (SS) controlled by a CIED (Central Intelligent Electronic Devices) will take place of step-down transformer fuse. The current anti-islanding protection of the PV systems are based on the standard VDE-0126-1-1 However, in order to ensure the FRT capability of the connected PV systems, their protection units will be modified based on the FRT curve require by ENTSO [9].

The simplified diagram and coordination of protective devices of the developed protection system can be observed in **Figure 1**. The particular functions of each protective devices as well as the operating strategy of the whole protection scheme are as follows. There will be two predefined different sets of operating parameters for each out of two operation modes of the studied microgrid. When a transition between these two modes happens, the CIED will send a signal to each relay to change their group of setting values to a new corresponding mode of operation. A locking command is also produced by the CIED to all PV protecting devices (PVC), preventing all PV units from unintentional islanding by their active anti-islanding protection and ensuring the power balance for newly formed isolated microgrid.

The protection algorithm for grid-tied mode

For detecting three-phase fault, the paper proposes the use of phase definite time overcurrent element (51P, ANSI). Besides, a positive-sequence directional element (32P, ANSI) is integrated with the 51P function of the feeder relays in order to assist them in distinguishing whether a fault occurs on its own feeder or on the neighbouring branch. The 32P element calculates a torque-like product in order to determine the direction of the fault current using the equation (1) [10]:

$$T32P = |V_1| \cdot |I_1| \cdot \cos\left[\angle V_1 - \left(\angle I_1 + \angle \varphi_L\right)\right] \qquad (1)$$

where V_1 and I_1 are the positive-sequence polarizing voltage and positive-sequence current respectively and φ_L is the positive-sequence line angle. A positive torque indicates a fault in the forward direction and a negative value of the torque declares a reverse fault. For faults closed to the voltage transformer, the measured voltage may drop to a very low value or even zero, thus a positive-sequence memory polarizing voltage V_{1mem} is deployed instead of V_1. Similarly, a combination of a negative-sequence overcurrent element (51Q) and a negative-sequence directional element (32Q) is applied for dealing with two-phase fault. Finally, zero-sequence overcurrent element (51G) and zero sequence directional element (32G) is for ground fault [10].

For the busbar fault, all the feeder relays will trigger tripping signals to their corresponding CBs after a delay time period of 0.3s if all their directional elements simultaneously sense a reverse fault and the CIED detects a forward fault. In case of feeder breaker failure to operate for fault on its own feeder, the CIED will play a role as a back-up protection to isolate this fault. For fault happens in the main grid, the CIED will operate to clear this fault within less than 0.1s in order to ensure the safe transition of microgrid into the islanded mode. Information exchange between the relays can be achieved by utilizing one of the possible wireless media such as IEEE-802.11-based wireless local area network (WLAN) protocol [11].

The protection algorithm for islanded mode

Due to the weak voltage stability and the short length of LV distribution feeders, a fault anywhere inside the microgrid is likely to cause a voltage decrease widely propagating across the network. Thus, three-phase faults can be detected by a drop in the positive-sequence component of the phase voltage (27P) while all unbalanced faults can be detected by measuring an increase in the negative-sequence component (27Q) or zero-sequence one (27G). Consequently, a combination of an under-voltage element and a directional element is adequate to deal with all kinds of fault on feeders.

THE STUDIED SYSTEM

The single-line diagram of the studied network is illustrated in **Figure 1**. The studied microgrid consists of a step-down 20/0.4 kV transformer with a rating of 240 kVA, Δ/Yn winding connection. Three feeders originate from the secondary side of the transformer. Three-phase and single-phase loads as well as PV systems are connected along the feeders. A master unit (BESS) rated 120 kVA is used for controlling the system frequency and voltage in islanded mode.

SIMULATION RESULTS AND ANALYSIS

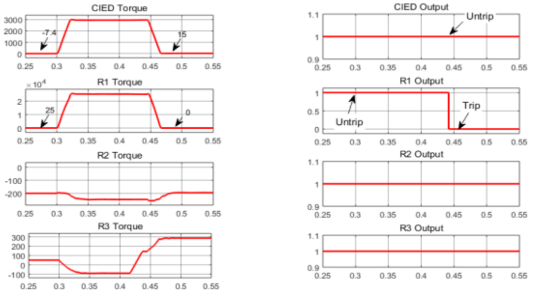
There are three types of fault simulated in the paper including feeder fault (F1-type), busbar fault (F2-type), and grid fault (F3-type. Various locations of fault have been studied (**Figure 1**), but due to the limited space, only several scenarios have been illustrated in detail.

Grid-connected operation mode

In this operation mode, let us assume that the fault happens at t=0.3s.

Case 1: Three-phase F1-type fault

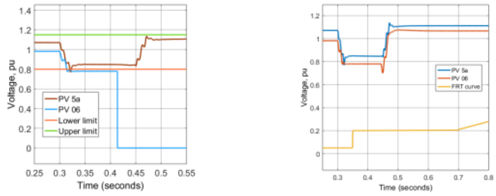
As indicated in **Figure 2a**, the positive values of the torque calculated by the 32P elements of R1 and CIED have correctly indicated that the fault is forward and the 51P function of R1 is allowed to send a tripping signal to open CB1 after the time delay of 0.142s (**Figure 2b**). The 51P element of CIED has a longer time delay by 0.3s and therefore does not generate any signal.



(a) (b)

Figure 2 - Torques determined by 32P (a) and relay outputs (b)

Also, as can be observed from the **Figure 2**, the 32Ps of R2 and R3 have detected a reverse fault and thus blocked their corresponding 51P elements.



(a) (b)

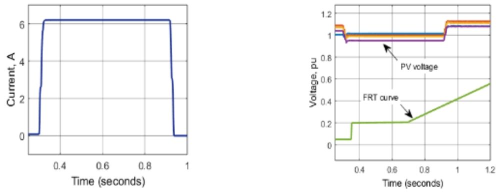
Figure 3 - Voltage variation at the terminals of the PV systems connected to feeder 3 in case of (a) VDE and (b) ENTSO

On the other hand, if the anti-islanding protection of the connected PV systems is still based on the standard VDE-0126-1-1 then some of PV systems connected to unaffected feeders are disconnected unnecessarily as shown in **Figure 3a**. Thus, the anti-islanding protection of PV systems are modified. As a result, **Figure 3b** shows that all PV systems in the unaffected area stay connected to the grid after fault has been cleared.

We hereby can point to a conclusion that the proposed protection system has accurately detected and isolated the three-phase feeder fault in the grid-tied microgrid.

Case 2: Two-phase F1-type fault

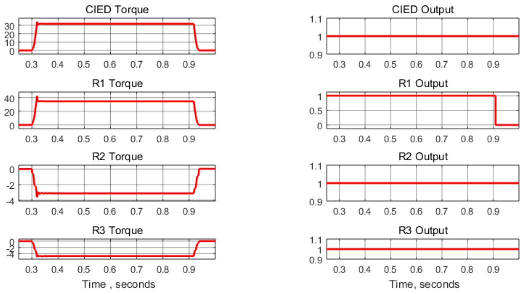
For this kind of fault, the 51Q element of R1 has properly detected an unbalanced fault thanks to the increase of the negative sequence current (**Figure 4a**).



(a) (b)

Figure 4 – Negative-sequence current measured by R1 (a) and terminal voltage of PV connected to un-faulted feeders (b)

The positive value of the torque computed by the 32Q element of R1 **(Figure 5a)** has allowed its 51Q element to open the CB1. R2 and R3 have been blocked (**Figure 5b**). All PV systems connected to feeders 2 and 3 still continue to operate as shown in **Figure 4b**.



(a) (b)

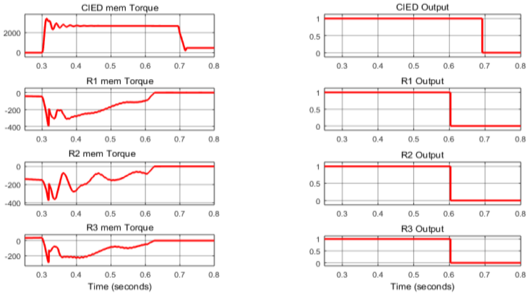
Figure 5 - Torques determined by 32Q (a) and relay outputs (b)

Case 3: Single-phase F1-type fault

Similar to the two-phase fault, thanks to the increase of zero-sequence current flowing feeder 1, R1 has detected a fault in forward direction and tripped CB1 in 0.525s.

Case 4: F2-type fault

In this case, the measured voltage drops to nearly zero, however; thanks to the memorized technique all the 32P elements of feeder relays simultaneously correctly detect a reverse fault (**Figure 6a**), thus all open their CBs in 0.3s. The CIED also trips after about 0.399s (**Figure 6b)**.



(a) (b)

Figure 6 - Torques determined by 32P (a) and relay outputs (b)

Case 5: F3-type fault

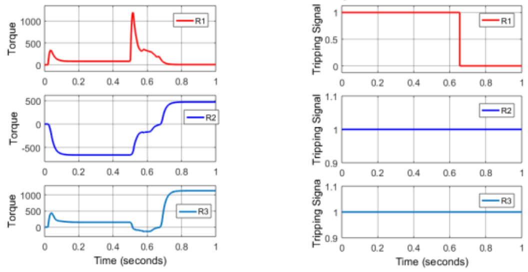
In this case, the 27P or 27Q elements of CIED has operated in 0.15s from the moment of fault inception, safely transforming the microgrid into isolated operation mode.

ISLANDED MODE OF OPERATION

In this mode, the fault is assumed to happen at t=0.5s.

Case 1: Three-phase F1-type fault

The 27P elements of all relays have detected a considerable voltage drop (below 0.2 p.u.), however; only R1 has observed a forward fault (**Figure 7a**), therefore is allowed to trip CB1 (**Figure 7b**).



(a) (b)

Figure 7 – (a) Torques determined by 32Q and (b) relay outputs

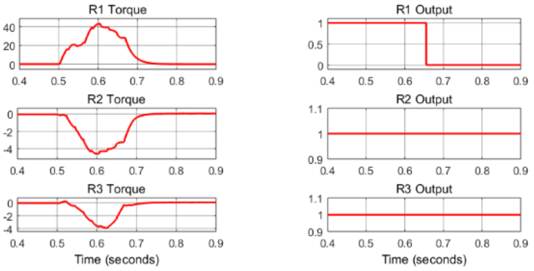
All PV systems connected to sound feeders remain connected with the network after fault isolation.

Case 2: Two-phase F1-type fault

An increase of negative-sequence voltage is an effective indicator for this kind of fault which is cleared in 0.183s. Moreover, all PV systems connected to sound feeders keep their normal operation (**Figure 9a**).

Case 3: Single-phase F1-type fault

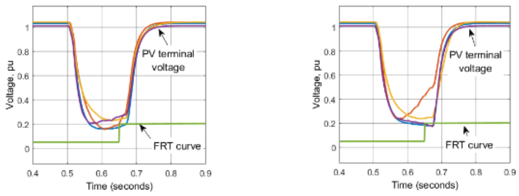
An increase of zero-sequence voltage and a positive value of zero-sequence torque (**Figure 8a**) have permitted R1 to open CB1 in 0.156s (**Figure 8b**).



(a) (b)

Figure 8 - Torques determined by 32G (a) and relay outputs (b)

All PV systems connected to sound feeders continue to supply power to the load after fault isolation (**Figure 9b**).



(a) (b)

Figure 9 - Terminal voltage of PV connected to sound feeders for (a) two-phase and (b) single-phase feeder faults

CONCLUSION

The study conducted in this paper has developed a complete protection scheme for a typical LV microgrid with high penetration of PV systems. Various case studies were carried out so as to demonstrate the effectiveness of the proposed protection system. This protection system can detect and isolate all kinds of fault including balanced and unbalanced faults in both operation modes in a selective and timely manner. The time delay of feeder relay are compliant with the FRT requirements for PV systems, preventing the PV systems in un-affected zone from unnecessary tripping.

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