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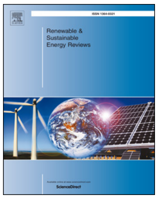

Establishment of fault current characteristics for solar photovoltaic generator considering low voltage ride through and reactive current injection requirement

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ABSTRACT

Fault current studies are often required to determine the proper settings for the overcurrent relays. The conventional synchronous generators are known to exhibit high current magnitude during fault, which present an ideal scenario for fault isolation using the cost-effective overcurrent relays. On the other hand, the fault current magnitude from renewable based generation such as solar photovoltaic (PV) is intentionally limited due to the constraints in the power electronic components. Therefore, dispute pertaining to the feasibility of overcurrent relay in inverter based distributed generations (IBDG) applications arises. These disputes mainly arise due to the unavailability of firm understanding of the fault current characteristics from the IBDGs. The problem is further compounded with the availability of numerous possible fault current controls, where various fault current characteristics can be obtained from the IBDGs. In light of this problem, this paper aims to establish the various possible IBDG fault current characteristics, with special attention paid to compliance to the latest grid codes requirements such as low voltage ride through (LVRT) with reactive current injection (RCI). Five different types of RCI controls are analyzed as follows: variable active current control, constant active power control, constant reactive power control, constant active current control, and maximum current control. From the established fault current characteristics in this paper, the disputes pertaining to the feasibility of overcurrent relay for IBDG applications can be resolved and the suitable types of RCI control that allow satisfactory performance of overcurrent relays can be identified.

1. Introduction

Owing to the increasing global demand for clean and renewable energy, rapid increase had been observed in the integration of renewable distributed generations (DG) like solar photovoltaic (PV) and wind turbine into the power grid. However, the introduction of such renewable DG into the power system constitutes both positive and negative effects. The advantages of these renewable DGs include improving the voltage profile and reducing power losses [1]. Whereas the negative effects include harmonic distortions, voltage fluctuations, voltage rise, and changes in fault current which led to mal-operation of existing relay coordination [2]. This project will solely concentrate on the changing fault current characteristics from the DG.

Generally, most of the renewable distributed generations (DG) require power electronics interface to interconnect with the existing electrical power system. To achieve an economical design, the power electronic components commonly have a lower fault current rating as compared to its synchronous machine counterparts. Consequently, the fault currents contribution from such inverter based distributed generations (IBDG) are limited. Several studies had shown that the fault currents response from IBDG are generally constraint to around 1–2 pu of its rated current due to limitations in the rating of power electronic interface [3–5]. However, another detailed report presented that most of the commercial PV inverter generates fault current up to 120% of the rated current only [6]. Thus, majority of literatures had concluded that the widely used overcurrent relays are not suitable for microgrid protection with IBDG [7–12]. The main reason being cited is due to the low fault current from the IBDG, which led to failure in triggering the traditional protection equipment such as overcurrent relays and fuses. Despite the reported problem of low maximum fault current from the IBDG to trigger the overcurrent relay, few literatures had disputed the previous findings and instead claimed successes in using directional overcurrent relays for microgrid protection [13–17].

However, regardless of the stand on the use of overcurrent relay in

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microgrid protection from these literatures, it must be noted that all presently available literatures had failed to pin-point yet another problem in the fault current from IBDG, which can have equally severe consequences to the grading of overcurrent relays. This problem is due to the uncertain fault current trend from the IBDG, and will be discussed in depth in this paper.

Thus, it can be generally summarized that, in contrast to the well-known fault current characteristic from a synchronous generator [18], the fault current characteristic from an IBDG has yet to be firmly established. The fault current from an IBDG is first influenced by a wide range of control methods that can be used to inject the fault current [19,20]. In addition, the latest grid codes also require that the PV generator provides ancillary services such as low voltage ride through (LVRT) with reactive current injection (RCI) during undesirable conditions [21]. The injected fault currents under these control schemes are dependent on the terminal voltages of the IBDG, which will further complicate the fault current analysis under dynamic voltage conditions.

In view of the unestablished fault current characteristics, a review of the PV inverter controls followed by subsequent studies are conducted in this project to establish the fault current characteristics from an IBDG. From the identified fault current characteristics in this paper, disputes pertaining to the feasibility of overcurrent relay for IBDG applications can be resolved and the suitable types of RCI control that allow satisfactory performance of overcurrent relays can be identified.

This paper will first provide an insight into the evolution of Grid Codes. From these grid codes, requirements such as LVRT with RCI controls in the inverters will be identified. Next, the various LVRT with RCI controls that have previously been proposed by other authors will be studied. Finally, the multiple possible fault current characteristics will be established based on the previously proposed LVRT and RCI controls. Subsequent discussions will then concentrate on resolving the disputes pertaining to the feasibility of overcurrent relay for IBDG applications and the suitable types of RCI control that allow satisfactory performance of overcurrent relays.

2. Evolution of grid codes: from anti islanding to low voltage ride through (LVRT) and reactive current injection (RCI)

Conventionally, the electric power distribution systems are designed to operate with the assumption that the source of power originates solely from the primary/main power plant [22]. It is not intended to accommodate any active generation at the distribution network level. However, with the proliferation of DG, this assumption is no longer valid. The direct connections of DG in the low/medium voltage distribution network are new operating scenario that may adversely impact the power quality and stability of the grid [23,24]. Therefore, grid codes are required to ensure smooth integration of PV system with the distributed network [25]. Among these grid codes, one of the most relevant requirements is the response of PV system towards abnormal grid conditions. According to most of the standards, a PV system is required to be disconnected during grid disturbances [26–28]. This is also known as the anti-islanding protection and it is done to ensure personnel safety and to avoid equipment damages [29,30].

At the moment, as most of the PV systems are used for residential applications with low power ratings, the amount of solar generation only constitute a relatively small portion of the total generation capacity [31,32]. As such, the impacts due to disconnection of PV system as required by the existing grid codes are negligible. However, as the PV system capacity increases to a substantial level, any loss of large PV system can lead to voltage and frequency instability issues [33–36] which have been frequently associated to wide scale blackouts [37,38]. For instance, the authors in [39] presented that the severity of voltage sags caused by disconnection of PV system will increase when more PV system are connected to the distribution network. On the other hands, case studies shown in [40] indicate that large scale PV trip off during fault will cause severe drop in dynamic frequency. Thus, it is necessary to reconsider the appropriateness of anti-islanding grid codes with respect to the PV penetration level [41].

As a result, countries with significant PV penetration such as Germany had proposed new requirements to prevent the disconnection of PV system during short-term and recoverable disturbances, which is also known as LVRT [42,43]. Due to its success in mitigating blackouts, the other renewable energy sources (RES) intensive countries had also revised their grid codes to include the LVRT requirements [44,45]. Furthermore, the recent amendments in IEEE 1547a had proposed extended RES disconnection time during abnormal grid conditions for LVRT to take place [46,47]. In addition to LVRT, the role of PV system had also been extended to provide dynamic grid support, similar to the behavior of the conventional synchronous generator based power plant [48–50]. This grid support is achieved by injecting reactive current concurrently with LVRT during under-voltage situations (inductive loads) to minimize the voltage drop during fault and ensure a fast voltage recovery after fault [42,51–55]. In contrast, if over-voltage occurs during grid disturbances (capacitive loads), the PV system is required to absorb reactive current to maintain the voltage stability [56]. The requirements for LVRT and RCI, according to German grid codes, are shown in Fig. 1 and Fig. 2 respectively [21,57]. The RCI and LVRT requirements for all other countries show similar pattern, but with only some variations incorporated to suit the different grid orientations as discussed in [25,58].

Referring to Fig. 1, borderline 1 indicates the fault ride through requirement for a synchronous generator. For voltage drop above borderline 1, the synchronous generator must remain connected. This requirement has also been adopted as the minimum fault ride through standard for IBDG as well. In addition, a higher fault ride through capability is also proposed for IBDG applications, which is indicated as borderline 3. This curve indicates that for voltage drop below borderline 3 the IBDG can disconnect from the grid; while the IBDG must remain connected if the voltage drop is above borderline 1. However, compliance to this higher capability curve is optional and is subjected to prior consultation and agreement with the distribution network operator. In other words, utility operators are offered some flexibility in the fault ride through curve for voltage drop between borderline 1 and borderline 3. Example of such flexibility is shown as borderline 2 in Fig. 1.

The RCI requirement is shown in Fig. 2. When the voltage variation is within the deadband (± 10%), reactive current injection is not necessary. Otherwise, as the voltage exceeds the deadband region, the PV generator must supply reactive current by satisfying the slope or also known as droop (k), with requirement of $k \geq 2p.u.$ It must be noted that, for voltage drop of more than 50%, the reactive current is required to supply at least 100% of the rated current. Alternatively, the RCI requirement can be represented by the following equation:

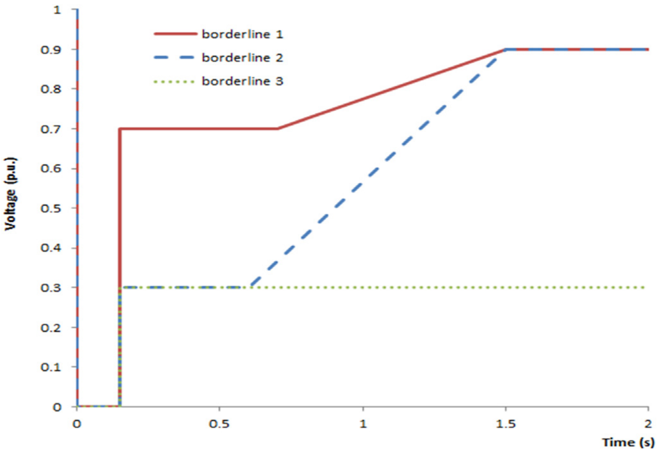

Fig. 1. LVRT requirement.