Electric Power Systems Research 106 (2014) 21–28

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Fault response of inverter interfaced distributed generators in grid-connected applications

Cornelis A. Plet*, Timothy C. Green

Control & Power Research Group, Imperial College London, SW7 2AZ London, United Kingdom

ARTICLE INFO

Article history:
Received 27 March 2012
Received in revised form 10 June 2013
Accepted 27 July 2013
Available online 7 September 2013

Keywords:
Distributed generation
Inverter
Fault current
Protection

ABSTRACT

Inverter-interfaced distributed generation is prominent in some distribution networks because of the growth of PV and other new sources. In order to ensure that protection system design remains effective in this environment, it is essential to be able to accurately represent inverters in fault current calculations. Calculating the fault current contribution is complicated because of the nature of the transition into current limiting mode and because the current produced is a function of control choices as well as physical components. The desire is for a simple source plus impedance model for incorporation into network studies. Based on knowledge of the control strategy and the details of the method of current limiting, linear analytical equivalent models are proposed whose source and impedance values (at fundamental frequency) can be expressed as a function of the inverter's hardware parameters and controller gains. The dependence of the entry into current limit on the nature and location of other generators in the network leads to a proposal for a load flow based fault analysis incorporating the new models. This iteratively determines which inverter experiences current limiting. The proposed inverter fault models and their use in a network fault analysis have been verified against experimental results in a 3-inverter network.

1. Introduction

A changing energy mix has led to an increased amount of electrical generators being connected to the distribution network. The connection of any additional so-called 'distributed generation' generally increases the amount of energy or fault current that can be dissipated in faults, which are (temporary) low Ohmic connections amongst phases or between phases and earth. This low Ohmic connection typically results in the rapid release of the energy stored in the inertia of the connected generators in the form of large currents that in turn can lead to excessive heat dissipation, undesirable mechanical forces in network components, and potentially dangerous rise of neutral, phase and earth voltages. Therefore, the distribution network protection system is tasked with disconnecting the smallest possible portion of the network that contains the fault in the shortest possible time in order to protect equipment and personnel. The accurate calculation of this fault current in various branches and at various times is crucial to the proper determination of the protection relays settings for guaranteed discrimination of faults and operation of the correct circuit breakers. It is well known that inverter-interfaced distributed generation contributes less fault current than a traditional rotating machine of similar rating but that its contribution can not be ignored and has to be accurately represented. When inverter interfaces were rare and were known to disconnect under fault conditions, ignoring their fault current was plausible but when PV and other non-traditional sources proliferate in a local network, they can significantly affect the overall fault response of the network.

In traditional fault analysis, the fault response of generators is represented by simple linear equivalent models whose parameters reflect the machine excitation and winding impedances [1]. The transient nature of a fault response is accounted for by using different parameters depending on the time period under study. If multiple generators are present in the power system, then they are each represented in the same way, regardless of the type of fault and their distance from it.

The fault response of an inverter interfaced distributed generator (IIDG) depends mostly on its control system rather than its physical parameters. In turn, an inverter's control system is specific to its application. Moreover, depending on its method of current limiting, an inverter's fault response depends on whether the fault is symmetric or asymmetric. An additional complication in calculating fault currents in networks containing multiple IIDGs arises in determining which inverters experience current limiting and which ones do not. The objective in this paper is to demonstrate the factors important in determining the current produced by an inverter under fault conditions and to provide a simple model for

---

* Corresponding author. Tel.: +31 026 356 2370.
E-mail addresses: cornelis.plet02@imperial.ac.uk, cornelis.plet@gmail.com (C.A. Plet), t.green@imperial.ac.uk (T.C. Green).

0378-7796/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.epsr.2013.07.013

the current which is suitable for inclusion in a traditional fault study. This requires exploration of the control system of an example inverter and a description of the methods available for current limiting.

A method then needs to be developed that can determine which inverters in a network are electrically close enough to the fault to enter a current limiting state and which remain under power control. The models and fault study method proposed in this work will then be tested against a wide variety of fault conditions in an experimental test network of three 10 kVA IIDG and a branched network structure.

2. Background

In anticipation of a substantial rise in IIDG, a number of attempts to characterise inverter fault response have been published in the technical literature. The impact of PQ-controlled inverters on fault levels is investigated in [2] through full time-domain simulations in which current limiting is implemented by instantaneous hard limits on the inductor current references in the control system. It is concluded that the low fault-current contribution of IIDG compared to conventional generators allows a larger amount of DG to be connected to a feeder. However, no attempt is made to incorporate the IIDG into a conventional fault analysis technique which can be applied to large networks.

In [3], a comparison is made between the fault response of PQ-controlled IIDGs that either use an inner voltage or an inner current control loop. A distinction is made between subtransient and transient components of the fault response of these two cases. Based on analysis of the control system and time-domain simulation results, an analytical equivalent fault model of the PQ source IIDG with an inner voltage control loop for use in systematic fault studies was proposed. The IIDG is represented as a constant voltage source in series with the filter inductor. This representation can be used in both analytical fault studies and in time-domain simulations to obtain an approximated fault response. The phase and magnitude of the voltage source are adapted at each time step in order to take into account controller dynamics. No current limiting was implemented, instead the inverter is assumed to disconnect when a certain overcurrent threshold is exceeded. The analysis and proposed method were verified through time-domain simulation.

In [4] the authors investigated the short-circuit behaviour of grid-connected photovoltaic inverters by assuming that they disconnect when an overcurrent threshold is exceeded and conclude that therefore inverter fault-current contribution is insignificant. No attempt was made to characterise inverter fault behaviour or discuss the need for inverters to possibly ride through a fault if IIDG represents a significant share of the generation mix. The discussion was supported by results from time domain simulations.

Experimental fault response results of commercially available grid-connected inverters were presented in [5]. However, no details were given about the factors that shape an inverter's fault response or how this fault response might aid the fault ride-through of a distribution system containing IIDG. A need for accurate, experimentally verified inverter fault models that are compatible with existing fault analysis techniques is highlighted.

In [6] a methodology is proposed for modelling an IIDG based on the transfer function of its inverter's control system and its output filter components. This methodology is used to develop and experimentally verify fault models of stand-alone voltage controlled inverters in [7]. In [8], the methodology is applied to grid-connected inverters and how to calculate the fault response of multiple inverters.

The existing relevant technical literature focusses on describing the fault response of inverters by describing that of example inverters or with time-domain simulations. Neither of these methods is suitable for use in protection studies, which are analytical calculations. Hence there is a need to understand the factors that govern an inverter's fault response in order to determine an analytical fault model which can be verified against experiment.

In this paper, the modelling approach presented in [8] is expanded with the grid-connected inverter fault recovery and a statistically based experimental validation of the proposed fault analysis method for multiple grid connected inverters.

The modelling approach from [8] is reviewed in Section 3 and its application in fault analysis reviewed in Section 4. Section 5 then introduces an extensive set of experimental tests on a branched distribution feeder similar to the Cigre test case and equipped with three 10 kVA IIDG. Statistical analysis of the errors between the experimental observations and the proposed fault flow calculation method is used to verify the methodology and models.

The key modelling tasks are to identify the impact of the control system and method of current limiting on the shape of the fault current. These topics are addressed in the following sections.

2.1. Review of control of a typical grid-connected inverter

Grid-connected inverters control the magnitude and angle of their output current to regulate for example their DC-link voltage (active rectifier) or to regulate real and/or reactive power flows (PQ source). Several approaches towards achieving control of real and reactive power exist. In this paper the approach discussed in [9] has been adopted for its simplicity and high inductor current quality. The inverter system is shown in Fig. 1 and comprises a three-phase three-leg inverter bridge, a LCL-filter, and a multi-loop control system. The neutral wire, which is often present in LV

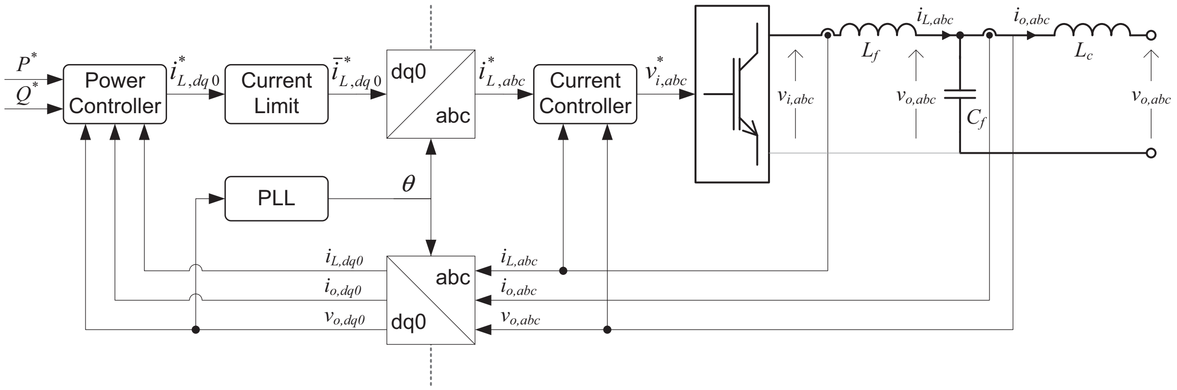

Fig. 1. Grid-connected inverter system.