# FAULT BEHAVIOUR IN ISLANDED MICROGRIDS

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## ABSTRACT

*This paper investigates the fault behaviour of inverter-supplied microgrids for the purpose of proposing alternative approaches in the design of suitable protection schemes. First, the different inverter interfaces between the Distributed Generation (DG) units and the distribution network and their control strategies are described. Then two case studies of two identical microgrids supplied by a single inverter interfaced DG with different control features are considered and their fault behaviour simulated in PSCAD. The study shows that the response of the system in the event of a fault is strongly dependent on the inverter control which actively limits the available fault current and therefore the choice of an alternative protection scheme for an islanded microgrid is strongly dependent on the type of control implemented. On the basis of the results obtained from the simulations, alternative voltage based protection schemes are suggested.*

## INTRODUCTION

A microgrid can be defined in outline as a cluster of loads and Distributed Generation (DG) sources capable of operation as a single controllable unit [1]. Although the shape and size of a microgrid can vary quite a lot, it is usually considered to be a small part of the MV or LV distribution network where the power is supplied by local sources including storage. It can be operated either in grid-connected mode or in islanded mode depending on factors like planned disconnection, grid outages or economical convenience. Studies have shown the benefits of microgrid applications such as improved local supply reliability, losses reduction, local voltage support and economic benefits [2]. However, the operation of a microgrid poses a series of technical challenges regarding its operation and control. Among these technical issues, the protection of islanded inverter-only supplied microgrids is considered to be challenging because of the reduced fault current supplied by inverter-interfaced DG units.

Traditionally the existing protection schemes used in LV distribution networks are based on the detection of high fault current. However, inverters are designed to supply a fault current that is typically only twice the nominal load value. This reduced fault current environment increases the detection and clearing times of over-current based protection devices and reduces the selectivity of the protection scheme [3].

A possible approach to this problem is to increase the available fault current either by up-rating the inverter [4] or by introducing energy storage devices capable of supplying a large current in the event of a fault [5]. Other approaches are based on the use of alternative fault detection methods and protection strategies [3]. However, much research work is still needed, in particular on the analysis of the fault response of islanded inverter-dominated microgrids in order to understand the behaviour of network voltages and currents. Some recent studies in this direction have focused on the behaviour of grid-connected inverters during grid faults [6], [7].

This paper shows how different inverter control strategies can influence the response of islanded microgrids to different types of fault. An overview of inverter topologies and control strategies is given. Two case studies are then built in PSCAD and their fault behaviour analyzed. The models use identical microgrid topologies supplied by a stand-alone inverter but in the first case the inverter is controlled in *dq0* coordinates and in the second controlled in phase coordinates. Different responses are compared and then alternative fault detection strategies are suggested.

## INVERTER TOPOLOGIES AND CONTROL

A typical microgrid is formed by a small part of an LV distribution network supplied by local DG units, as shown in Fig. 1. An inverter-interfaced DG unit can be connected in various ways depending on how the existing network is operated. Usually, LV distribution networks are designed with four wires in order to be able to supply three-phase and single-phase loads.

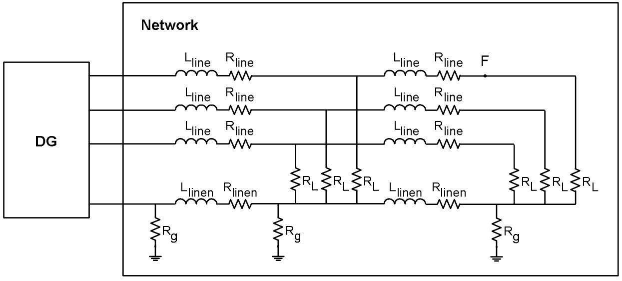

Fig. 1: Microgrid network.

There are three different ways in which inverters can be connected to three-phase four-wire systems [8]:

- Through a Delta/Wye grounded transformer;
- Using split dc-link capacitors and connecting the mid-point of the dc-link to the neutral point;
- Using a four-leg topology and connecting the mid-point of the fourth (neutral) leg to the neutral point.

The approach of the split dc-link capacitors is not very convenient because it does not sufficiently utilize the available dc-link voltage. Moreover, the large unbalanced current flowing through the dc-link capacitors requires high capacitance. As a result of these drawbacks, the most common way of interfacing the DG source to the network is via a three-phase inverter with a transformer or via a three-phase four-leg inverter. Fig. 2 shows the model of the inverter used in this work which is a stand-alone three-phase four-leg voltage source inverter with a low-pass LC filter and coupling impedance, supplying the microgrid network in Fig. 1.

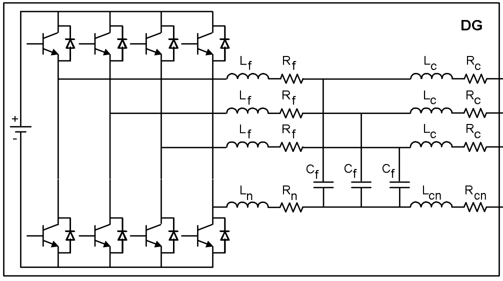

Fig. 2: Three-phase, four-leg, four-wire voltage source inverter.

The primary role of a stand-alone inverter is to maintain a regulated voltage and frequency supply to loads and this is done through a multi-loop control strategy. Fig. 3 shows a single-phase diagram of this control structure for an inverter supplying a local network through an LC filter. The outer loop is a voltage control loop which regulates the output capacitor voltage $v_0$ and sets the reference for the inner current control loop. Blocks $G_V$ and $G_C$ are the voltage and current regulators. The output voltage reference $v_0^*$ is kept constant (in magnitude and frequency) but can also vary if an additional outer droop control loop is used, as it is done in parallel connected inverters. The multi-loop control of a stand-alone voltage source inverter can be implemented in *dq0* coordinates, phase coordinates and *αβγ* coordinates. In this study, controls in *dq0* and phase coordinates are considered and their influences on the microgrid fault behaviours are analyzed in the next two sections.

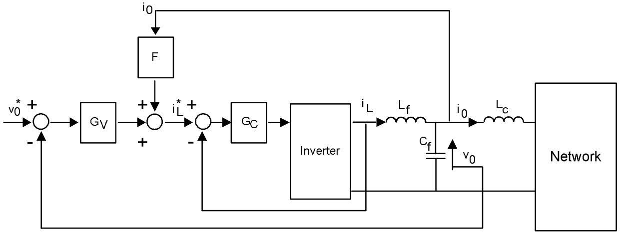

Fig. 3: Multi-loop control of a stand-alone inverter.

As the microgrid increases in size, it is not convenient to supply power with a single highly rated inverter because of factors like heat dissipation, reliability and costs. Instead, a modular approach is preferred with inverters connected in parallel as shown in Fig. 4. Control methods which are implemented in parallel connected inverters are based on some form of communication (master-slave approach) or on the mimicking of the operation of synchronous machines (droop method).

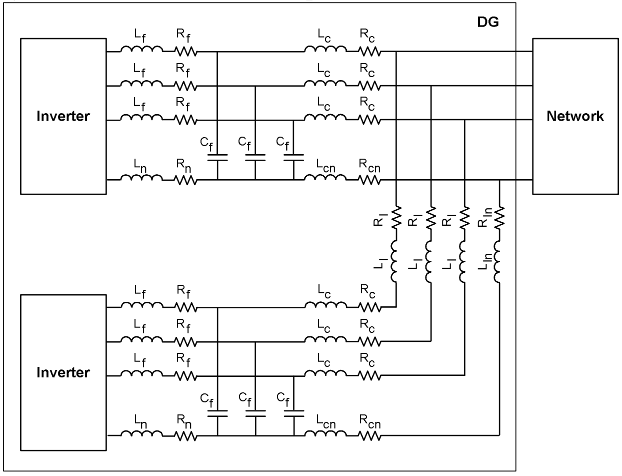

Fig. 4: Parallel operation of two inverters.

## CASE STUDIES

Following the introduction of various inverter topologies and control strategies, this section describes the fault behaviour of two islanded microgrids. The microgrid network (of Fig. 1) is a 240 V (phase-neutral), 50 Hz, four-wire multi-grounded system with two resistive loads each of 6.9 kW connected along the line. The network is supplied by a single stand-alone inverter-interfaced DG source as shown in Fig. 2. The microgrid parameters are given in Table 1. The models with their respective controls in *dq0* and *abc* coordinate were built and simulated in PSCAD.

Table I: Microgrid parameters

| *Parameter* | *Value* | *Parameter* | *Value* |
|---|---|---|---|
| $L_f$ | 1.35 mH | $R_c$ | 0.03 Ω |
| $C_f$ | 50 µF | $L_{line}$ | 0.35 mH |
| $R_f$ | 0.1 Ω | $R_{line}$ | 0.36 Ω |
| $L_c$ | 0.35 mH | $R_g$ | 10 Ω |

### A. Case 1: microgrid supplied by a stand-alone four-leg inverter with control in *dq0* coordinates

The control system in Fig. 3 when implemented in *dq0* coordinates becomes equivalent to three multi-loops, one for each coordinate. The current loop is designed to have a high bandwidth (around 1.6 kHz) while the voltage loop is slower with a smaller bandwidth (around 400 Hz). PI regulators are used in the *dq* loops while a P+Resonant and a PI regulator are used in the zero sequence voltage and current control loops respectively. The P+Resonant controller is used here as zero sequence components are sinusoidal in form and common PI regulators cannot achieve zero steady-state error with a sinusoidal excitation.

Under balanced operation, the *dq* components are dc terms and there is no *0* component. However, as soon as a fault is present, the *dq* components contain a $2\omega$ ripple added to the dc term and if the fault involves ground, then also a zero sequence component is present. The available inverter fault current is limited to two times the nominal value $I_n$ by placing three saturation blocks after the voltage loop controller in order to limit the reference inductor current.

A single phase-to-ground (A-G) and then a phase-to-phase (B-C) fault are simulated at time t = 1 s at point F in the network. Fig. 5 and Fig. 6 show the response of the microgrid under study in terms of phase voltage and current at the fault point.

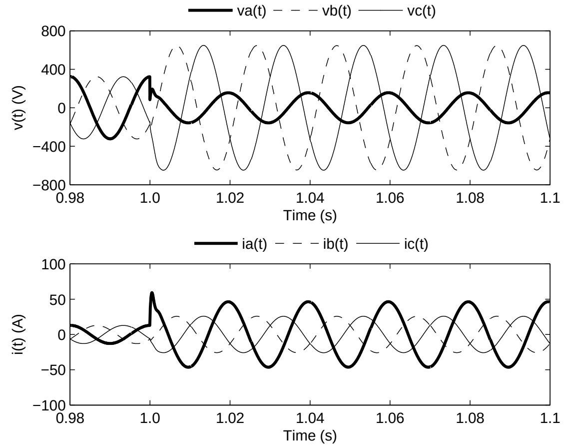

Fig. 5 Response of a four-leg inverter with control in *dq0* coordinates during a single phase-to-ground (A-G) fault: phase voltage and phase current at fault point.

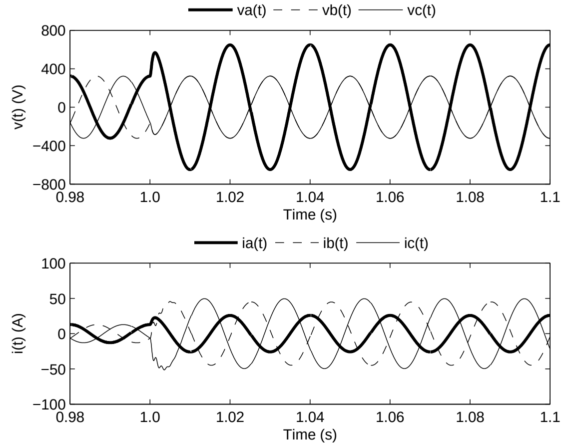

Fig. 6 Response of a four-leg inverter with control in *dq0* coordinates during a phase-to-phase (B-C) fault: phase voltage and phase current at fault point.

**Discussion**

The behaviour of the microgrid is explained by considering how the control of the inverter limits the current. As soon as the current reaches its limit, the control loop in Fig. 3 is broken and a constant (saturation limit) reference is used such that the inverter becomes a constant current source. The microgrid can be then represented as a current source with a parallel impedance whose value depends on the type of fault. As expected, the value of the fault current is quite small and therefore traditional over-current based protection schemes cannot be used.

However, the presence of a fault can still be detected by using some alternative features which are produced by the fault. The voltage sequence components are a good candidate for use in detecting the faulty operation of the system. Because the theory of the interconnection of equivalent sequence networks in the event of a fault is applicable here, it is possible to calculate the values of the voltage sequence components for different types of fault and then be able to make a distinction between normal and faulty operation.

### B. Case 2: microgrid supplied by a stand-alone four-leg inverter with control in *abc* coordinates

The inverter in this case is controlled by three equivalent multi-loop controllers, one for each phase. A simple proportional controller with a constant gain $K_C$ is used in the current loop. The value of $K_C$ is set to achieve a closed loop bandwidth of around 1.6 kHz. Similarly, the voltage control loop uses a proportional controller with a closed loop bandwidth of 400 Hz. For this type of control there are several current limiting options. The strategy implemented here is such that as soon as the current reaches its limit, the voltage control of faulty phases is switched to current control while keeping unchanged the control of fault-free phases. As a result, the current is actively limited in the faulty phases while the control of the voltage is kept unchanged over the healthy phases.

Fig. 7 and Fig. 8 show the response of the microgrid to a single phase-to-ground (A-G) fault and a phase-to-phase (B-C) applied at the same point F in the network at time t = 1 s. As it can be seen, the response of the system is quite different from the one of the previous model.

**Discussion**

The main advantage of control in phase coordinates is the ability of the inverter to control the voltage of each phase independently. In this way, in the event of a fault, the supply of power is kept unchanged in the healthy phases while the current is only actively limited in the phases affected by the fault. This behaviour could be particularly advantageous when the number of disrupted customers has to be kept to a minimum. However, under normal operating conditions, the control in *dq0* coordinates is preferred over the control in phase coordinates because of the better performance of PI regulators with dc control variables. Possible solutions to this problem can be the use of P+Resonant regulators or the implementation of a double control strategy: control in *dq0* coordinates under normal operation and switch to control in phase coordinates under faulty conditions.

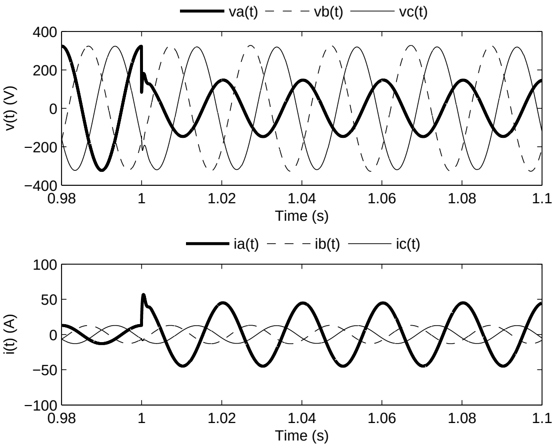

Fig. 7 Response of a four-leg inverter with control in phase coordinates during a single phase-to-ground (A-G) fault: phase voltage and phase current at fault point.

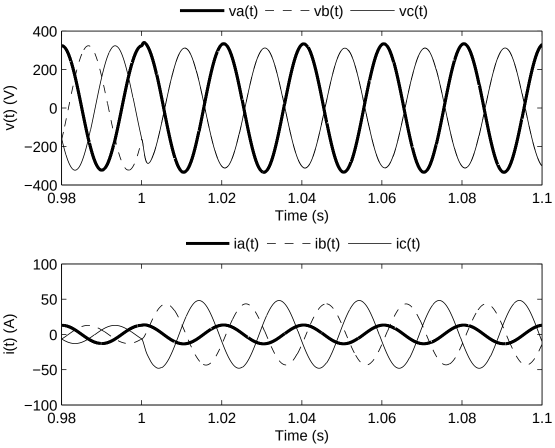

Fig. 8 Response of a four-leg inverter with control in phase coordinates during a phase-to-phase (B-C) fault: phase voltage and phase current at fault point.

As the available fault current is rather small, the voltage can be used instead to detect the presence of a fault. It is important to understand how the voltage behaves for different types of fault and how a distinction can be made between normal and faulty operation in order to design an effective fault detection technique based on voltage magnitude. Conventional network analysis based on symmetrical components cannot be used here as the power source of the system (the inverter) is unbalanced. Therefore alternative circuit analysis techniques which can handle unbalanced systems have to be used to study the system.

## CONCLUSION

The study of fault behavior in an LV distribution network and the following fault management strategies forms a much consolidated field of studies. However in recent years, the traditional passive role of distribution networks is experiencing a radical change with the introduction of DG and microgrids. This poses a series of technical challenges which need to be addressed in order to guarantee an effective integration of DG into the existing network.

Among these technical issues, the protection of islanded microgrids is considered to be challenging because of the limited fault current contribution of DG with inverter interfaces. This paper has shown how the control of the inverter deeply affects the response of the system in the event of a fault. This is completely different from the traditional response of a network with a synchronous generator which is capable of supplying very large fault currents while keeping constant its output voltage. As a result, any alternative protection system design should start from an analysis of the inverter control system and current limiting strategy. Advantages and disadvantages of two possible control strategies have been presented and alternative fault detection methods suggested.

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