Evaluation of Fault Characteristic in Microgrids Dominated by Inverter-Based Distributed Generators with Different Control Strategies

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***Abstract*—This paper presents a comprehensive study of the fault current characteristics of microgrids dominated by Inverter-Based Distributed Generators (IBDGs) with different control strategies, with a view to identifying protection challenges and potential future solutions. Different combinations of control strategies, (i.e. PQ, V/F and droop control strategies) are deployed within different IBDGs, to represent typical microgrid operating scenarios and to investigate the impact of these strategies and types of IBDGs on the fault behavior of microgrids under islanded mode of operation. Various controllers are also deployed on the IBDGs at different physical locations in the system to investigate locational impact on microgrid's fault behavior. Extensive simulation results will be presented and the impact of different control strategies and IBDG locations on the protection systems performance will be evaluated based on the results. Recommendations of how protection systems should take the various control strategies and locational impact into account to ensure reliable operation will also be discussed and future work will be outlined.**

***Index Terms*—Microgrids, protection, control, fault analysis, inverter-based distributed generator (IBDG).**

I. INTRODUCTION

Microgrids are considered as promising solutions for operating future power system with distributed generation. Compared with conventional centralized power systems, microgrids offer, among other advantages, more efficient and flexible approaches for operation of power systems incorporating renewables and energy storage, along with potentially enhanced reliability and resilience of supply [1]. Microgrids can operate in both grid-connected and islanded modes. While these modes offer flexibility, they also bring operational challenges. The nature of the system (e.g. fault levels, control of IBDGs, etc.) could be completely different for each mode, which could introduce significant issues to protection schemes [2]. Furthermore, it has been recognized that the control systems of IBDGs could also have significant impact on the fault behavior (e.g. limited current contribution and different characteristics), thus further challenging the protection systems [3].

Existing work has been concerned with modelling and characterizing fault behavior of the control schemes [4]; however, these studies are limited and demonstrate characteristics where only a single IBDG is considered. The contribution of this paper is to evaluate and analyze microgrid's fault current characteristics with multiple IBDGs using various combinations of different controllers, which represents more realistic future scenarios that can input to the design and development of new future microgrid protection scheme.

The rest of the paper is organized in the following way: section II will present review of IBDGs' control schemes, section III will depict the suggested protection schemes of the microgrids, section IV will discuss various scenarios of fault studies in microgrids with different control strategies and finally, section V will conclude the paper with proper recommendation of protection schemes.

II. REVIEW OF CONTROL SCHEMES IN MICROGRIDS

There are three major control strategies for IBDGs available and discussed in the literature [5]: (1) Grid feeding (PQ control); (2) Grid forming (V/F control) and (3) Grid supporting (droop control). This section will discuss a short review of each scheme. Two reference frames can be used to implement each controller scheme- stationary ($\alpha\beta$ domain) reference frame and rotational or synchronous (dq domain) reference frame but later one is most popular [6] and used to model the controllers in this paper. A current limiter is used before the inner current control loop to restrained the fault current injected into power electronic devices within 1.5 times of rated value.

A. Grid Feeding Control Scheme

Grid feeding control scheme is also known as real and reactive power (PQ) control scheme. This type of inverter control has the ability to supply a constant current to loads based on the real and reactive power through reference value. Fig. 1 shows the typical model of a grid feeding controller. There are two sections in this controller- the first section calculates the reference current, and the second section contains the inner current control loop. The controlled signal is then fed to the inverter through the pulse width modulator (PWM).

PQ controlled IBDGs can be modeled as power controlled current source with parallel impedance [5] or only power controlled current source [7]. The scheme provides better control of current while microgrid is connected to the distribution grid since voltage and frequency cannot be controlled by this type of controllers. Therefore, grid feeding controller based IBDGs cannot be operated independently during islanded mode.

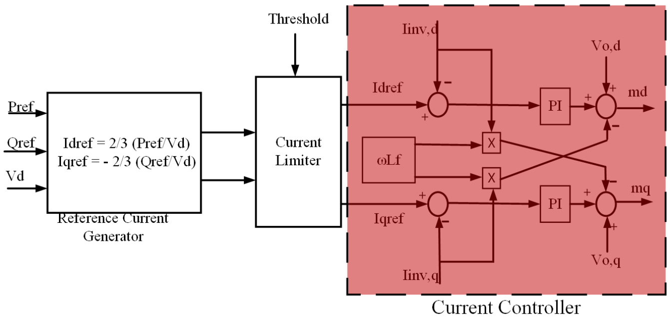


Fig. 1. Design diagram of grid feeding PQ control scheme.

B. Grid Forming Control Scheme

Grid forming or voltage/frequency (V/F) control scheme has the ability to regulate the output voltage and frequency of the IBDGs. Fig. 2 shows the general model of the grid forming V/F controller. Similar to the PQ controller, it also has two main sections, voltage control loop and current control loop. Voltage control loop regulates the microgrid voltage according to the reference value and fed the reference current to the current controller. The output current and power of V/F controlled IBDGs are determined by the microgrid loads. The equivalent circuit model of the V/F controlled IBDGs can be presented as a constant voltage source in series with impedance [3, 4], like the conventional synchronous generator. The drawbacks of the scheme are: it only can be used during islanded condition, and only one unit of the IBDGs of islanded microgrid can be V/F controlled.

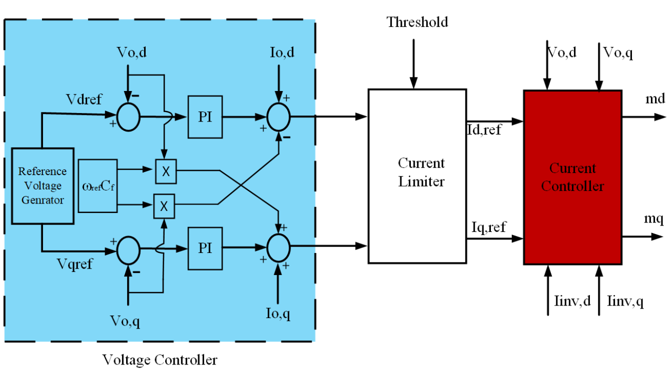


Fig. 2. Design diagram of grid forming V/F control scheme.

Power sharing in microgrid involving PQ and V/F controlled IBDGs is possible through the master-slave power sharing strategy with communication where grid forming IBDG works as master controller and grid feeding controllers work as slave [8]. However, the strategy is expensive and absence/loss of master IBDG due to communication failure or fault isolation might cause all the generators in microgrid to shut down.

C. Grid Supporting Control Scheme

The shortcomings from the grid feeding and grid forming control scheme can be mitigated through the grid supporting or droop control scheme. The operation strategy of this scheme is like, a combination of the other two types of control schemes. It can support the microgrid during islanded condition by controlling the voltage and frequency (similar to grid forming), and at the same time during grid connected mode, it supplies constant power (similar to grid forming). The design of the droop controller is shown in Fig. 3.

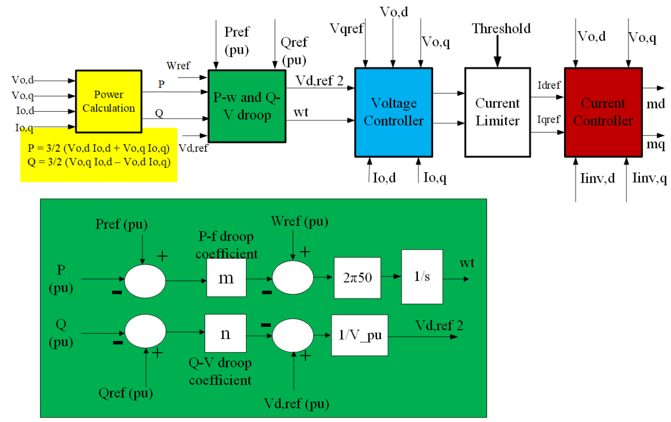


Fig. 3. Design diagram of grid supporting droop control scheme.

The positive attribute of the droop controller is, it either can be operated with other droop controlled IBDGs (plug and play) or can be operated with grid feeding controllers based IBDGs. It also ensures smooth operation during the transfer of grid connected mode to islanded mode. The scheme is most popular in microgrid as it does not require communication [9]. However, since a trade-off between voltage and frequency standard, and real and reactive power sharing has to maintain in droop controller, power quality is not satisfactory [10].

III. Review of Protection Schemes for Inverters Dominated Microgrids

Several protection schemes are proposed by different researchers to address the protection issues in microgrids. However, there are some limitations with each of the schemes and this creates a scope of further research to develop a protection scheme that can operate in both modes of operation in microgrid. Some of the schemes discussed in the literature are presented in Table. I with their limitations.

IV. Fault Studies in Microgrids Dominated by IBDGs with Different Control Strategies

Due to limited page allocation, only four different fault scenarios during islanded condition are demonstrated in this paper with the inverter control strategies that are discussed in section II. Fig. 4 shows one section of the Simulink model that is used to exemplify the scenarios and Table. II explains the controller position for each scenario.

Fault currents are measured from both ends of the line (R1 and R2) to evaluate and understand the fault contributions from

TABLE I
CRITICAL REVIEW OF THE PROTECTION SCHEMES FOR MICROGRIDS

Protection Schemes	**Referenced Article**	**Descriptions**	**Limitations**
Conventional Schemes	[11, 12]	Overcurrent, differential and distance protections are considered as traditional schemes.	Due to low fault level, overcurrents in the islanded mode are not possible. Distance or impedance based protection is also not suitable for short length microgrids and differential scheme with communication is expensive for microgrids.
Adaptive protection	[13, 14]	Changes the protection coordination and settings with the variation of grid topologies and DGs capacity.	Depended on communication and intelligent electronic devices and therefore, expensive. Also, complicated design or algorithm with large amount of real time data managements.
Harmonic contents based	[15]	Fault is identified based on the total harmonic distortion of the voltage. Type of fault is identified through the FFT and variation of the fundamental frequency.	Since IBDGs with DC sources produces harmonics during normal operating condition the scheme might mal-operate. Furthermore, variation of DGs capacity might affect its performance.
Voltage based	[16]	The scheme transforms the bus voltage to the d-q frame to detect the voltage dips during fault. Communication between the relays are suggested to locate the fault properly.	Discrimination issues (between load change and fault) might not detect properly. Locating faults through communication is expensive for microgrids and the scheme cannot detect high impedance faults (HIFs).

both IBDGs. A three phase to ground low impedance (0.001Ω) fault has been injected in the microgrid and therefore, voltages at R1 and R2 collapses to zero. Fig. 5 shows the fault current at R1 and R2 for all scenarios.

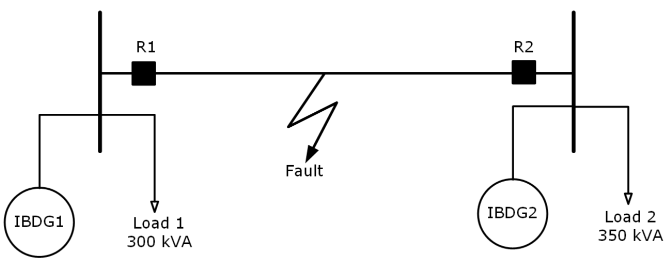


Fig. 4. Line diagram of simulated microgrid.

TABLE II
SIMULATION SCENARIOS WITH CONTROLLERS POSITION

Number of Scenarios	**Controller Position**		**Power Contribution (kVA)**	
	IBDG1	***IBDG2***	***IBDG1***	***IBDG2***
#1	Grid forming	Grid feeding	450	200
#2	Grid feeding	Grid forming	300	350
#3	Grid supporting	Grid feeding	450	200
#4	Grid supporting	Grid supporting	350	350

Reference power for IBDG1 and IBDG2 is set to 300 kVA and 200 kVA respectively (i.e. referenced power will be produced during grid connected mode). Grid forming IBDGs are responsible to produce additional power to support the loads in islanded microgrid as can be seen from scenario #1 and #2. Again. since grid feeding controller based IBDG cannot participate in power sharing, the characteristics of Fig. 5(a) and 5(c) (characteristic of scenario #1 and #3) are almost similar although droop controller is used in IBDG1. In case of scenario #4, power is equally shared by the IBDG1 and the IBDG2 because both are controlled by droop controller, and droop coefficients are set in a way that they can share power equally.

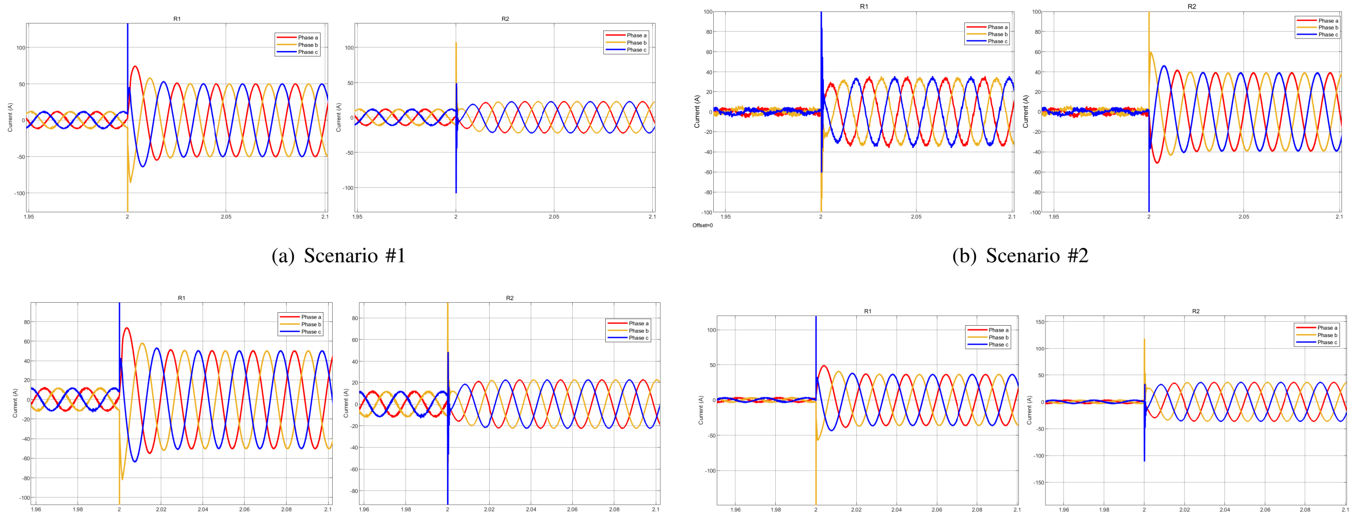
From the simulation results, it can be observed that the transient fault current behavior of grid forming and grid supporting controllers are similar to the conventional synchronous generators. However, during steady-state, each IBDG behaves as dependent current source, controlled by the controller's fault current limiter. In case of V/F and droop controllers, reference current follows the eq. 1, where, $I_{dref} > I_{th}$ and causes the voltage control loop to brake. Again, broken voltage control loop of V/F or droop controller causes reference current of the PQ controller to increase as it can be seen from eq. 2.

$$I_{dref} \propto (V_{ref} - V_g) \tag{1}$$

$$I_{dref} \propto \frac{1}{V_g} \tag{2}$$

V. CONCLUSIONS

The paper presents study of IBDGs' fault characteristics in islanded microgrid with V/F, PQ and droop controllers. Several conclusions can be drawn based on the simulation results and discussed scenarios: (1) During fault each IBDG behaved as a constant current source, (2) Capacity of the IBDGs and current limiters in the controllers determine the fault current magnitude in the microgrid, (3) Location of the controller does not have impact on the fault current and most importantly (4) Fault detection and coordination of the relay is very difficult to achieve in islanded microgrid. Hence, active protection scheme based on the inverters control might be a solution for islanded microgrid protection issues.



(a) Scenario #1

(b) Scenario #2

(c) Scenario #3

(d) Scenario #4

Fig. 5. Simulation Results

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