FAULT ANALYSIS OF INVERTER-INTERFACED DISTRIBUTED GENERATORS WITHIN A LOW-VOLTAGE MICRO GRID USING DIFFERENT CONTROL SCHEMES

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Abstract: Power electronic devices like inverters are employed as the interfaces to improve the controllability of DGs and ensure the power quality. The increasing penetration of Inverter-Interfaced Distributed Generators (IIDGs) has significantly challenged the distribution network in terms of intermittent power generation, bidirectional power flow, limited overcurrent capacity, etc. control schemes adopted by IIDGs in a microgrid that leads to the complexity on fault estimation. The system under study in a microgrid consists of two DGs. The step-up transformer is used to connect a microgrid to the utility grid. When circuit breaker is open the microgrid will operate in islanded mode operation. PQ-IIDG and V/f IIDG controllers will be used in the system to control current, voltage and frequency of the system. PQ controlled IIDGs deliver preset power to the utility grid. V/f-IIDG is a group of controlled voltage sources, which can handle different types of faults flexibly while achieving current limiting. This paper can be extended by using Fuzzy controller which controls current, voltage and power so that the negative sequence signals are filtered out and only positive sequence signals are delivered into control systems. Fuzzy control strategy is widely used in a microgrid for its advantages of fuzzy logic controller, is that, it generally has a nonlinear transfer function, simple, robust solutions that convert a wide range of system parameters and can cope up with major disturbances.

1. Keywords

IIDG- Inverter-interfaced distributed generator, PQ-IIDG- PQ controlled IIDG, V/f-IIDG- Voltage controlled IIDG, FRT- Fault ride through, PC- Point of connection, DER- Distributed energy resource.

2. Introduction

Distributed generation (DG) including renewables like solar/photovoltaic and wind power, hydel power plants are being increasingly installed by several industries to meet their environmental footmark and sustainability goals. DG is a vital issue for the development of modern power systems. Technical constrains, mainly related to voltage stability and power flow limitations, decreases reliability of such generation schemes. The DG systems are normally connected at the distribution networks, they are closer to the end consumers when compared with large-scale power plants, which permits reducing the overall transport losses. Many of the DGs use power electronic inverters for energy conversion process to equal the grid voltage and frequency. The DGs are having a great impact on the stability and protection of distribution system[1-3].

Microgrid (MG) is a single controlled unit in a power system that can be operated as a single aggregated load. The unit is made up of generators, energy storage, load controller and power electronic interfaces like inverters. The MG has two critical components a static switch and micro source, which consists of generator, storage and an inverter. Microgrid (MG) is a concept which involves the utilization of distributed energy resources by using the energy generated by small power generators which are located near the customers' site. Microgrids are dynamic entities where DGs, loads, storage devices etc. are constantly connected and disconnected. Operating conditions vary rapidly since the inertia of the system is much less than that of conventional networks. Weather conditions, resource availability and consumption affect the operating conditions of the equipment. In order to ensure safe operation of such a system, it is required to monitor all elements and make the necessary changes in their settings as the operating conditions of the microgrid change. Reliability and quality of power received by a customer is greatly enhanced by setting up a MG. Cost per unit of energy is greatly reduced by setting up a MG with locally available renewable energy source in the remote locations and with combined heat & power generation at load centers in the cities. In long term, MG structures will be attractive for small business which will eventually enhance local economy and bring about more local jobs[3-4].

In grid connected mode the MG operates at the grid frequency. The grid being a stiffer voltage source than the MSs the voltage of the MG is regulated by it. In islanded mode, one or more MSs are required to maintain the MG voltage and frequency. Both voltage and frequency are maintained in an acceptable range. In case the frequency drops below the minimum acceptable value, loads are shed to restore the MG frequency to the nominal value. Microgrids are set up to provide quality power to sensitive loads. It is required to have adequate reactive power compensation to ride through voltage sags and faults. Further adequate harmonic reduction capability is provided so that the harmonics generated by the nonlinear loads on the MG do not reach the sensitive loads. Grid connected mode is the normal operating mode of a MG with no power quality disturbance on the main grid to which it is connected. In this mode the MG may cater to its entire local load or may either import or export power to the main grid, depending on the total power generation of the local DG. The MG may also maintain a predetermined load mix determined by the market policies. The MG can separate from the main grid whenever a power quality disturbance occurs on the main grid[4-5].

3. GRID FAULT CONSIDERATIONS

A) Balanced fault: when all three grid voltages register the same drop/swell amplitude but the system remains balanced. The occurrence of this type of fault is extremely rare in power systems.

B) Unbalanced fault: when the three grid voltages register unequal drop/swell amplitudes. Usually, phase shift between the phases also appears in this situation. This type of fault occurs due to one or two phases that are shorted to ground or to each other[6].

4. CONTROL SCHEMES OF POWER CONVERTERS IN AC MICROGRIDS:

The local controllers used in different types of power converters in a microgrid will be described. Low level voltage and current controllers are responsible of regulating locally the power converter output variables. These controllers should have a high bandwidth and performance in order to guarantee a fast time response under generic operating conditions[7].

The inner controller of grid-feeding power converters lays on fast current control loops that regulate the current injected into the grid. Another external controller sets the reference current to regulate the power delivered to the grid. This reference current is usually provided as a feed-forward signal calculated as a function of the reference powers, P^* and Q^*.

Grid-Forming Power Converter: **(Voltage and Current Control Loop)** Grid-forming power converters are in charge of setting the voltage that will be supplied to loads, the main control structure of a grid-forming power converter consists of two cascaded loops. The external loop is in charge of regulating the output voltage. In this loop, the error between the reference and the measured voltage is the input to a controller whose output establishes the current reference i^* to be injected by the converter. It should be pointed out that the voltage control loop of the grid-forming power converter will be enabled only when the microgrid is disconnected from the main network and works in the island mode. On the other hand, the inner current loop regulates the current supplied by the power converter, tracking the reference current provided by the outer voltage loop.

Grid-Supporting Power Converter: **(Active and Reactive Power Control Loop)** Techniques for controlling power sharing in microgrids have previously been used in applications dealing with paralleled UPS. Different current sharing strategies have been proposed for small rated paralleled inverters, such as centralized controllers, master–slave, average-load sharing, or circular-chain control. However, these solutions are conceived for paralleling systems which are close to each other and interconnected through high-bandwidth communication channels used for control purposes. These communication-based solutions are not the most suitable choice for controlling microgrids, since distributed generators and loads in microgrids may be separated several kilometers. To overcome this problem, droop control algorithms are used to control the power sharing in microgrids without using communication channels, thereby eliminating the limits imposed by the physical location and improving the microgrid performance. The droop regulation techniques are implemented in grid-supporting power converters to regulate the exchange of active and reactive powers with the grid, in order to keep the grid voltage frequency and amplitude under control. The main idea to support the droop control comes from mimic the self-regulation capability of the synchronous generator in grid-connection mode, decreasing the delivered active power[21].

5. Control Strategies: Inverter Control Strategies Usually two control strategies are used to control inverters of the microsources connected to microgrid[9].

5.1 PQ IIDG controler: A microsources may be controlled so that its real and reactive powers output are constant. The inverter functions by supplying the active power available at its input. The reactive power injected corresponds to set point, which has been derived locally or downloaded by the central controller like MGCC[22].

The MS along with the inverter behaves like a current-controlled voltage source converter. The terminal voltage is measured and its direct and quadrature components are extracted. The direct and quadrature components of the PCC current are computed from the 3 phase current and required real and reactive power output generated. This control can be adopted when the inverter is grid connected like in power compensation of generation system.

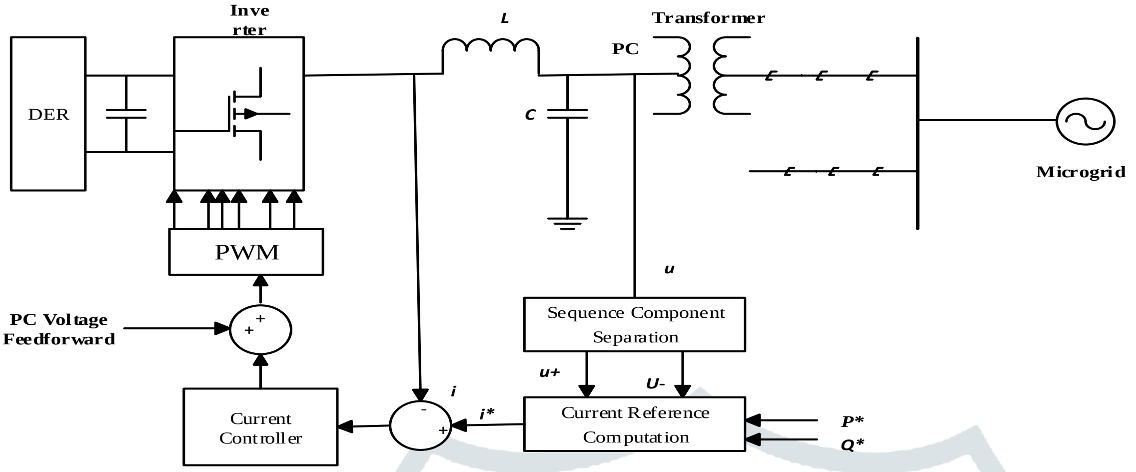

Fig.5.1.1 PQ IIDG Controller

The PQ controlled inverter operates by injecting into the grid the power available at its input. There active power injected corresponds to a pre-specified value, defined locally (using a local control loop) or centrally from the MGCC. The PQ inverter control is implemented as a current-controlled voltage source. Current components inphase and quadrature with the inverter terminal voltage are computed based on a method presented in [9] for power calculation in single-phase inverters. Power variations in the MSinduceadc-link voltage error, which is corrected via the PI-1 regulator by adjusting the magnitude of the active current output delivered to the grid. The reactive power output is controlled via the PI-2 regulator by adjusting the magnitude of the inverter reactive current output. This inverter can be operated with a unit power factor or receive a set-point (locally or from the MGCC) for the output reactive power.

5.2 V/f - IIDG CONTROLLER[23-24]: The loads are likely to be unbalanced in low-voltage microgrid. The V/f-IIDG discussed in this paper utilizes three phase four-leg inverter [20] to regulate three-phase voltages separately. When fault occurs in microgrid, V/f-IIDG will attempt to maintain the PC voltages within their normal range.

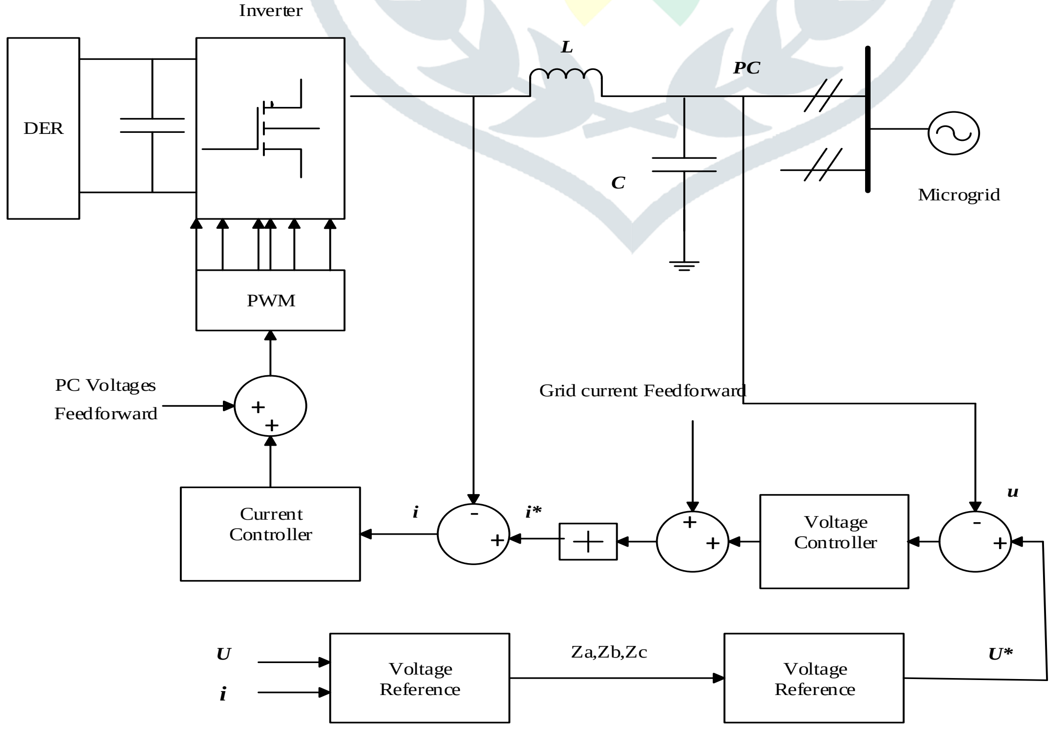

Fig.5.2.1 V/f IIDG Controller

However, if the fault is far too severe, V/f-IIDG should modify its voltage references actively to avoid overcurrent. Subsequently, the critical issue of V/f-IIDG's fault control is to calculate the maximum allowable voltage references of V/f IIDG with consideration of current limiting V/f-IIDG, where u and i represent PC voltages and output currents, u^* and i* represent the corresponding references of u and i . The control system first calculates the equivalent impedances of each phase, which are denoted as x Z (x=A,B,C), based on V/f-IIDG's output currents and PC voltages. Then, V/f-IIDG's voltage references can be determined by its phase current limitation and the measured equivalent impedances. If both the current controller and voltage controller are designed properly, and appropriate feed forwards are adopted, then it can be assumed that u=u*. The fault model of V/f-IIDG preserves the nature of voltage source, which is useful to maintain the stability of microgrid under fault conditions[10]

4.3 Fuzzy controller: Fuzzy controller which controls current, voltage and power so that the negative sequence signals are filtered out and only positive sequence signals are delivered into control systems. Fuzzy control strategy is widely used in a microgrid for its advantages of fuzzy logic controller, is that, it generally has a nonlinear transfer function, simple, robust solutions that convert a wide range of system parameters and can cope up with major disturbances[25].

Δe \ e	**PB**	**PM**	**PS**	**Z**	**NS**	**NM**	**NB**
PB	**NB**	**NB**	**NB**	**NB**	**NM**	**NS**	**Z**
PM	**NB**	**NB**	**NB**	**NM**	**NS**	**Z**	**PS**
PS	**NB**	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**
Z	**NB**	**NM**	**NM**	**Z**	**PM**	**PM**	**PB**
NS	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**	**PB**
NM	**NS**	**Z**	**PS**	**PM**	**PB**	**PB**	**PB**
NB	**Z**	**PS**	**PM**	**PB**	**PB**	**PB**	**PB**

Table 5.3.1 Rule Base

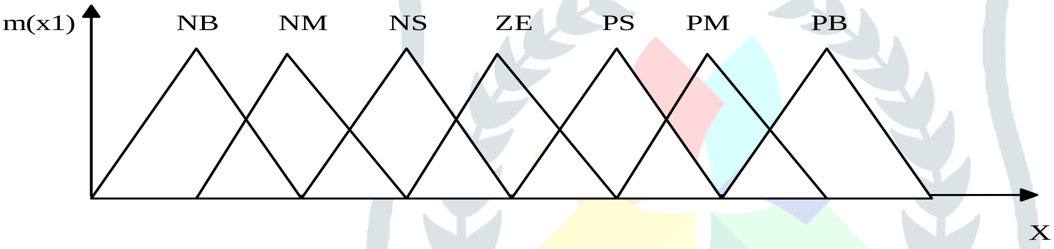

Fig.5.3.1 Rule base

6. Problem formulation: Single line to ground fault (SLGF): Single line to ground fault (SLGF) is also known as short circuit fault. It occurs when one phase of transmission line makes contact with ground or neutral wire. Some of the reasons for SLGF are wind, falling trees or any other incident. Three types of SLGF are shown in Fig.5.1 where a–c represent the phases and Rf represents fault resistance. 70% of faults in network are classified under this category.

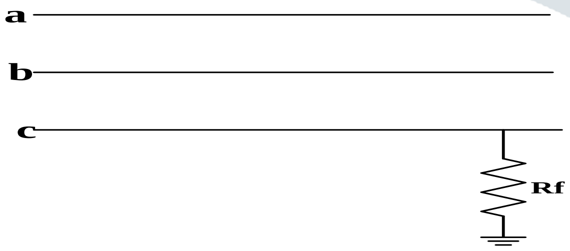

Fig.6.1. Single line to ground fault

Line to line fault (LLF): Line to line fault occurs due to high winds or when two conductors are short circuited. It may occur at overhead or underground transmission systems. Fig.5. 2 represents line to line fault on three phase line conductors. One of the characteristics of LLF is the magnitude of fault impedance may vary over a wide range, resulting it difficult to predict its lower and upper and limit. 15% of faults in network are considered as line to line fault.

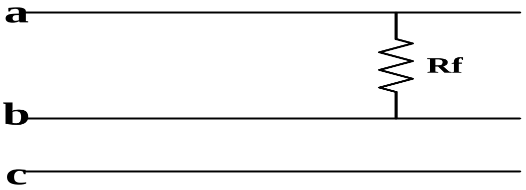

Fig.6.2. Line to line fault

Double line to ground fault (DLGF):

Double line to ground fault will occur when a falling tree connects two phases with the ground. Fig. 3 represents double line to ground fault on three phase conductors. A DLGF is a serious event, which results in a significant asymmetry and it may become a three-phase fault if it is not cleared in a certain time. 10% of faults are classified as DLGF

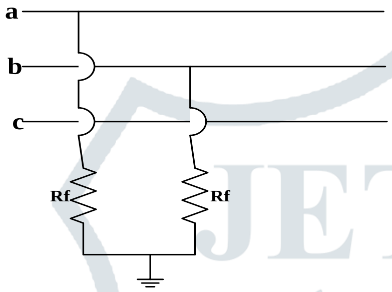

Fig.6.3. Double line to ground fault

Three-phase to ground fault (LLLGF): Three-phase to ground fault (LLLGF) is also known as symmetrical fault. It may occur due to an equipment failure, falling tower or a line connecting the remaining phases. In real scenario, LLLGF does not often exist and occupies only 5% of line faults. It is the most dangerous fault although it is the least fault occurrence. Fig. 4 shows a general representation of three-phase to ground fault. The characteristics of three-phase to ground fault are voltage level equals to zero and the fault current is very large. The percentage occurrence of each fault type and its severity are shown in Table 1. The fault severity can be expressed in terms of the fault current magnitude and its potential of resulting in damage. In power systems, a three-phase to ground fault is the most severe and is caused due to simultaneous short circuit between all three lines while the least severe fault is a single line to ground fault. Also, the percentage occurrence of fault due to other elements of power systems is shown in Table 2. Fault current analysis of IIDG when subjected to asymmetrical faults.

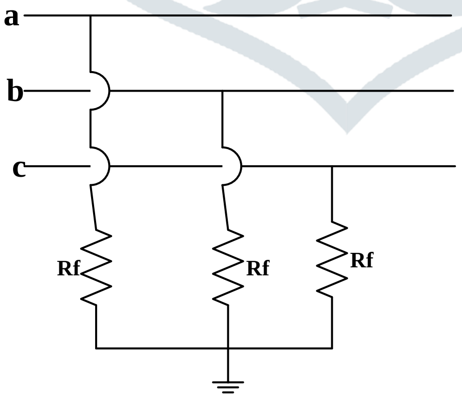

Fig.6.4 Three phase to ground faults

Voltage

$$\boldsymbol{u} = \boldsymbol{u}^{+} + \boldsymbol{u}^{-}$$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = (1/3) \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

<u>Current</u> $\boldsymbol{i = i^{+} + i^{-}}$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = (1/3)\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\mathbf{1I\angle 120}$$

$$\boldsymbol{S = \dot{U}_A \dot{\bar{I}}_A + \dot{U}_B \dot{\bar{I}}_B + \dot{U}_C \dot{\bar{I}}_C}$$

$$\begin{cases} \boldsymbol{P = u.i^{+} + u^{-}.i^{-}} \\ \boldsymbol{Q = u^{+}_{\perp}.i^{+} + u^{-}_{\perp}.i^{-}} \end{cases}$$

$$\begin{cases} \boldsymbol{i^{+} = i^{+}{}_{P} + i^{+}{}_{Q}} \\ \boldsymbol{i^{-} = i^{-}{}_{P} + i^{-}{}_{Q}} \end{cases}$$

7. SYSTEM UNDER STUDY: The system under study is a 0.4kV microgrid. A step up transformer is used to connect a microgrid to the utility grid. The microgrid can operate either in grid connected or in islanded mode.

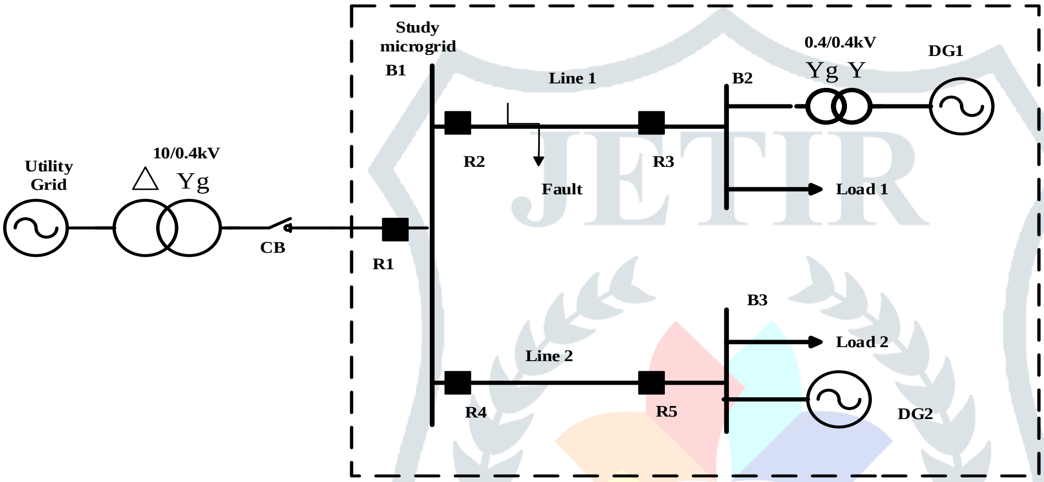

Fig.7.1 Low Voltage Microgrid

DG1 is controlled in current control mode, like constant current control and PQ control, in order to provide a preset power to the utility grid & DG2 is connected to V/f controller to control voltage to maintain system stability. DG1 is a 10kVA PQ-IIDG, whose peak current limitation is 40A. DG2 is a 20kVA V/f-IIDG, whose peak current limitation is 80A. The length of Line1 and Line2 are both 0.2km with the impedance per unit length being 0.642+j0.083Ω/km. The pre-fault active and reactive power references of DG1 are 7kW and 2kvar.

SI.NO	Element	Parameter
1	DG1	10KVA; peak current limitation is 40A.
2	DG2	20KVA; peak current limitation is 80A.
3	Line	The length of Line1 and Line2 are both 0.2km
4	Impedance	0.642+j0.083Ω/km
5	Pre fault active and reactive power	DG1 are 7kW and 2kVAR
6	Fault Resistance	1Ω,2Ω

Table 7.1 Parameters

8. Simulation Results

The total supplied active power and reactive power are 7kW and 6kvar.The fault resistance is 1Ω, k_p is set as 0.8 and k_q is set as 0.5. The active powers supplied from positive sequence and negative sequences are 5.62kW and 1.4kW, and the reactive powers supplied from positive sequence and negative sequences are both 3 kvar. Fault occurs at the time duration of 0.08s to 0.32s. At the time of fault duration the PQ and V/f controllers controls the currents and voltages of the system. The PQ and V/f are replaced with the fuzzy controller After the fault duration the system regains to its original values. The simulation results of the three cases, single phase fault, two phase fault and three phase faults can be observed from the below figures.

Case 1: Single phase fault

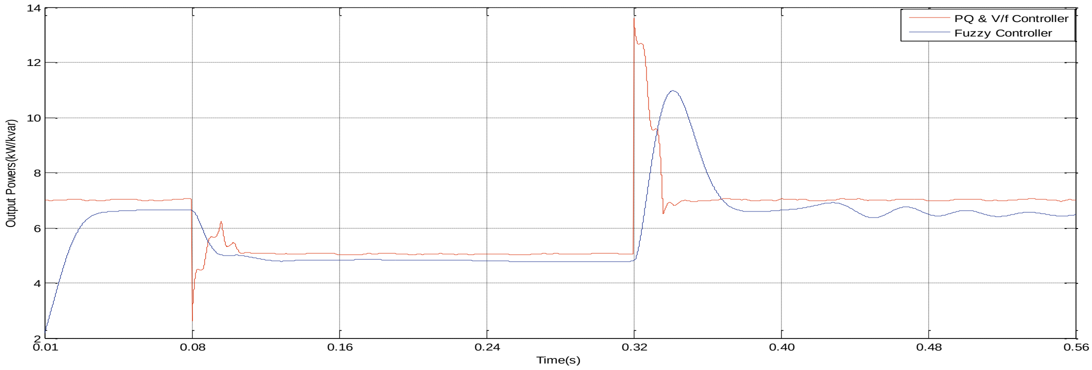

Fig.8.1.1 Simulation results of DG1 in case 1: Supplied active power of positive sequence

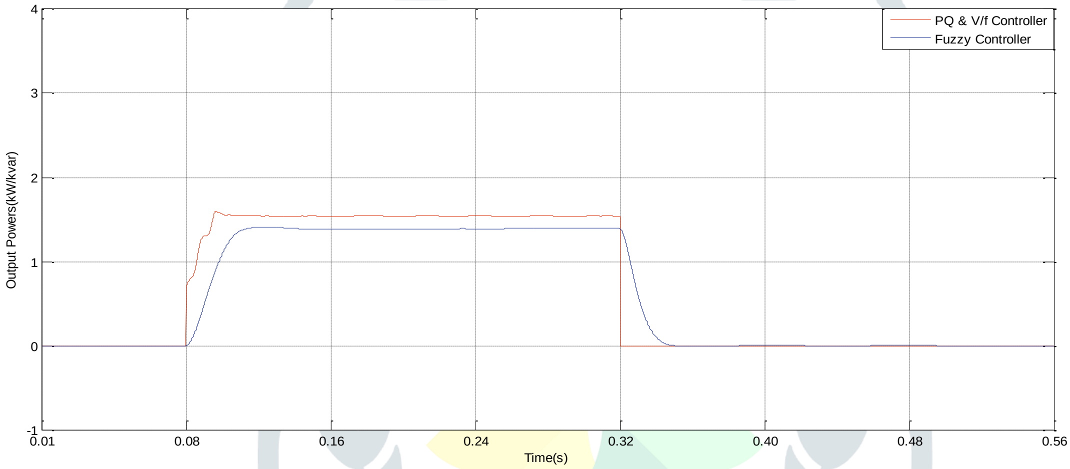

Fig.8.1.2. Simulation results of DG1 in case 1: Supplied active power of negative sequence

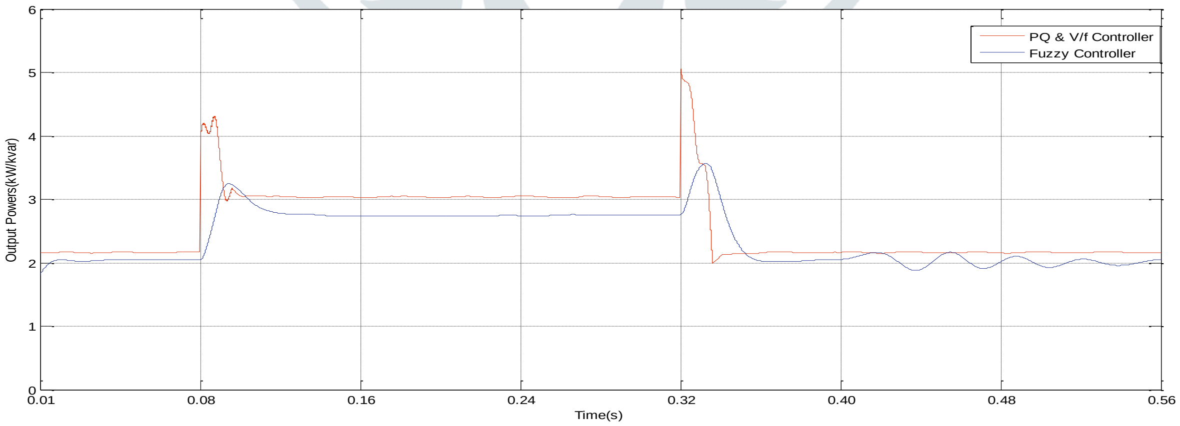

Fig.8.1.3.Simulation results of DG1 in case1: Supplied reactive power of positive sequence

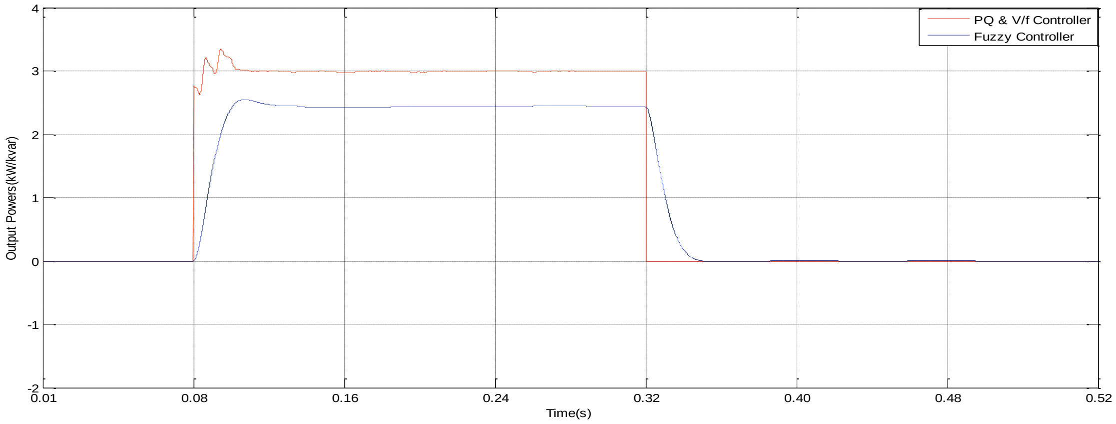

Fig.8.1.4.Simulation results of DG1 in case 1: Supplied reactive power of negative sequence

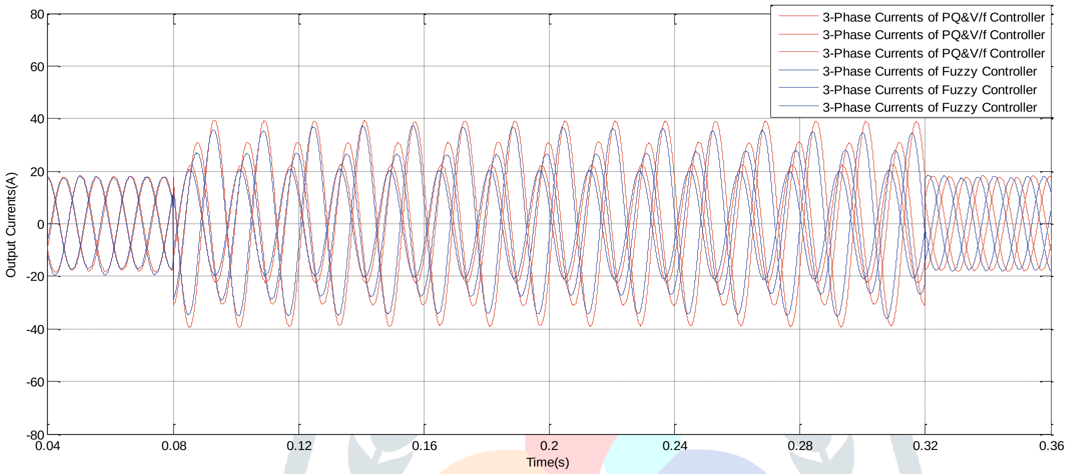

Fig.8.1.5. Simulation results of DG1 in case 1: Output Currents

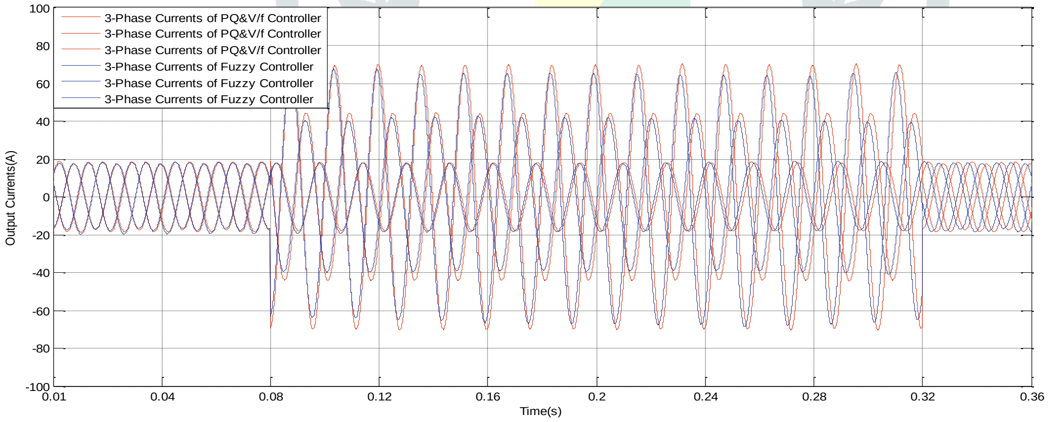

Fig.8.1.6. Simulation results of DG2 in case 1: Output Currents

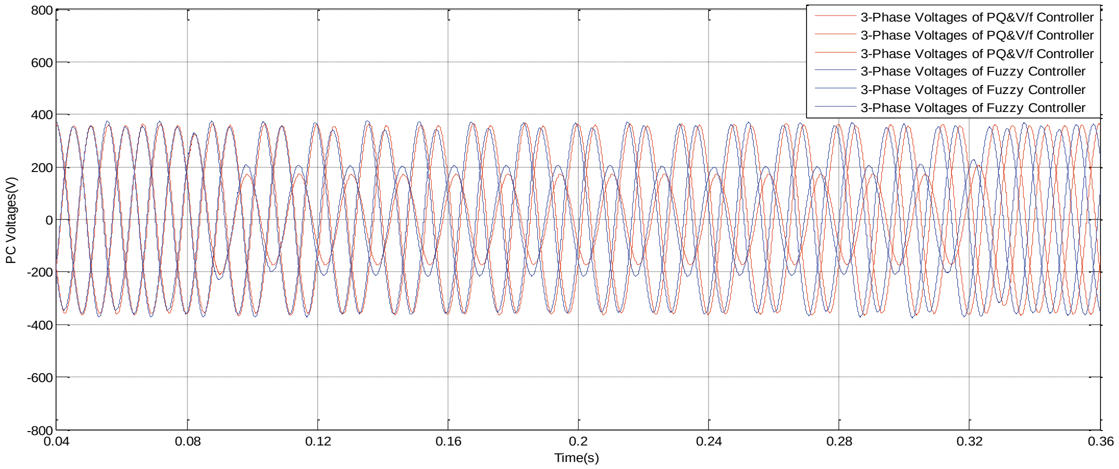

Fig.8.1.7 Simulation results of DG2 in case 1: PC Voltages

Case 2: Two-phase fault

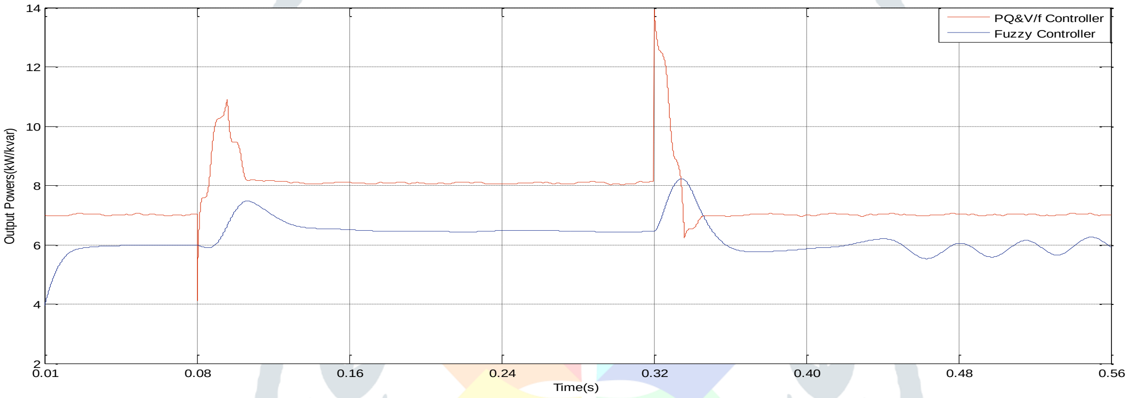

Fig.8.2.1. Simulation results of DG1 in case 2: Supplied active power of positive sequence

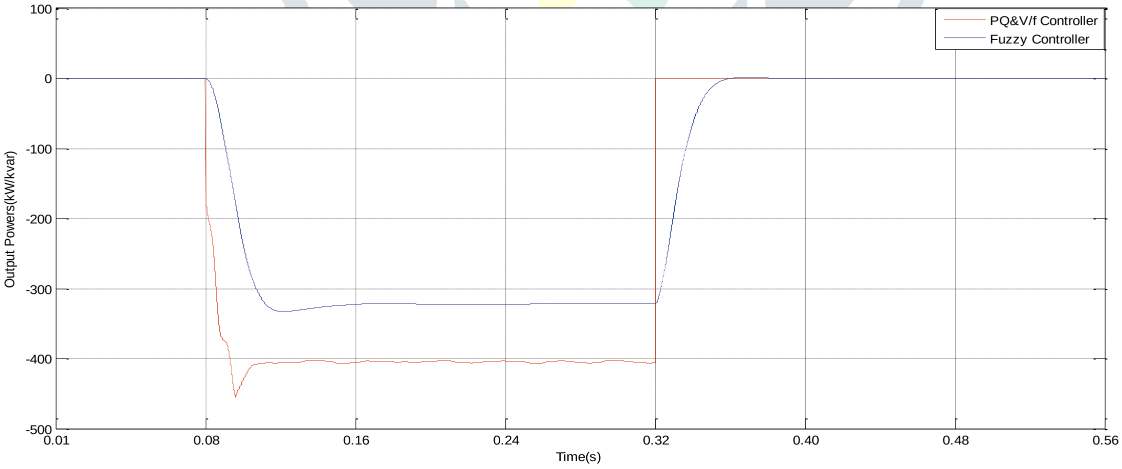

Fig.8.2.2. Simulation results of DG1 in case 2: Supplied active power of negative sequence

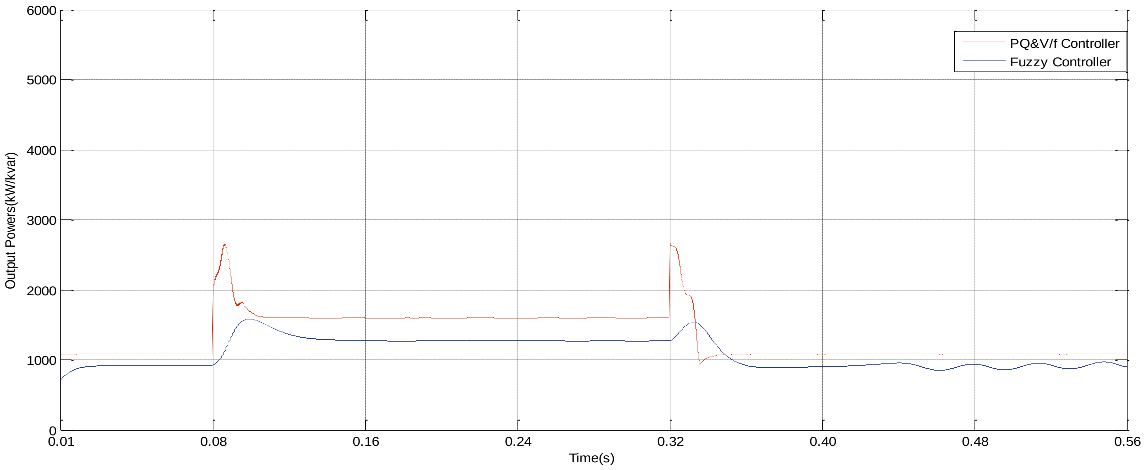

Fig.8.2.3. Simulation results of DG1 in case 2: Supplied reactive power of positive sequence

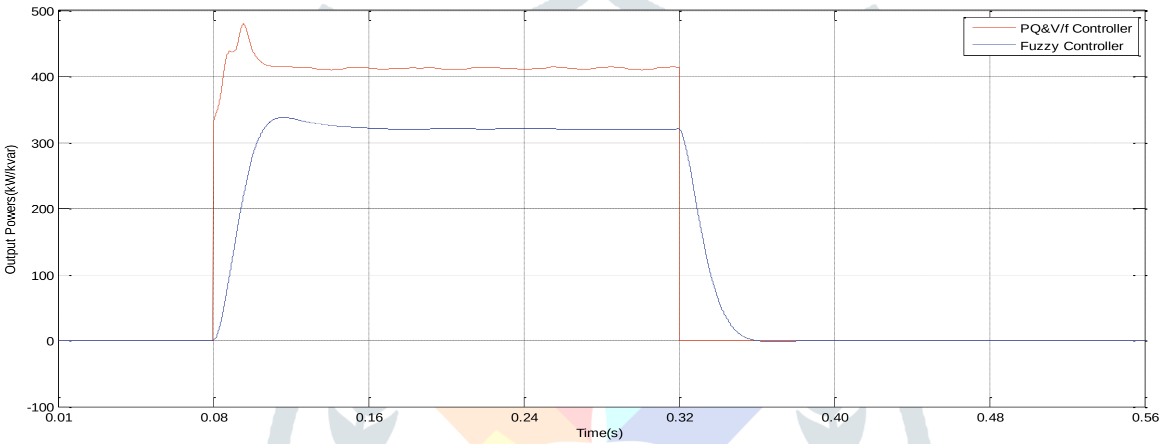

Fig.8.2.4. Simulation results of DG1 in case 2: Supplied reactive power of negative sequence

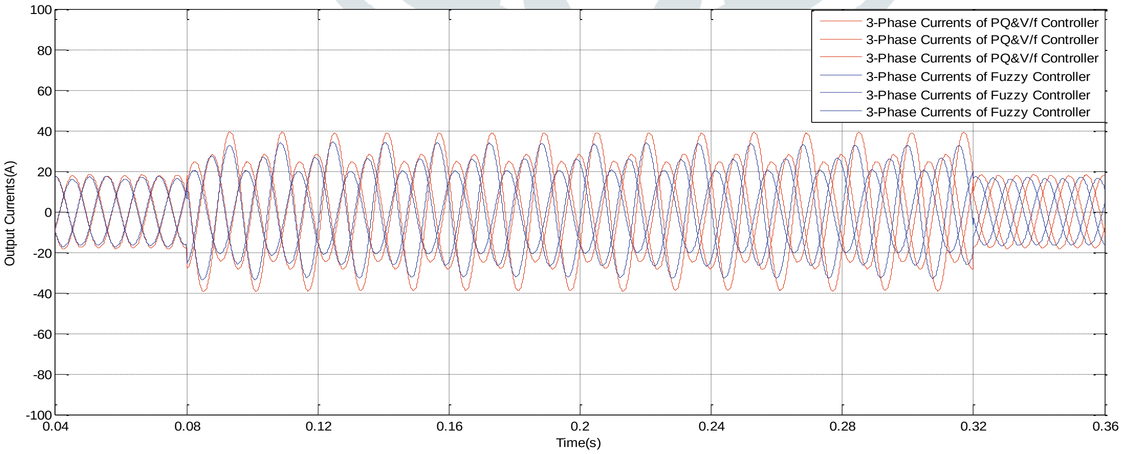

Fig.8.2.5. Simulation results of DG1 in case 2: Output Currents

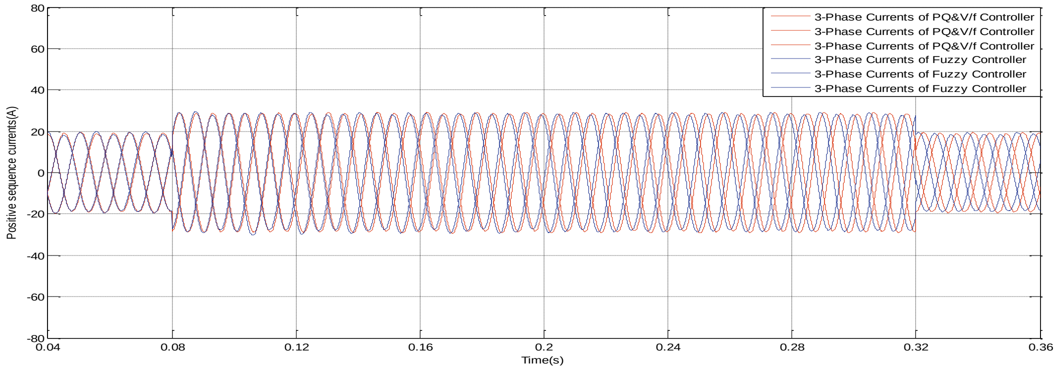

Fig.8.2.6. Simulation results of DG1 in case 2: Positive sequence component of output currents

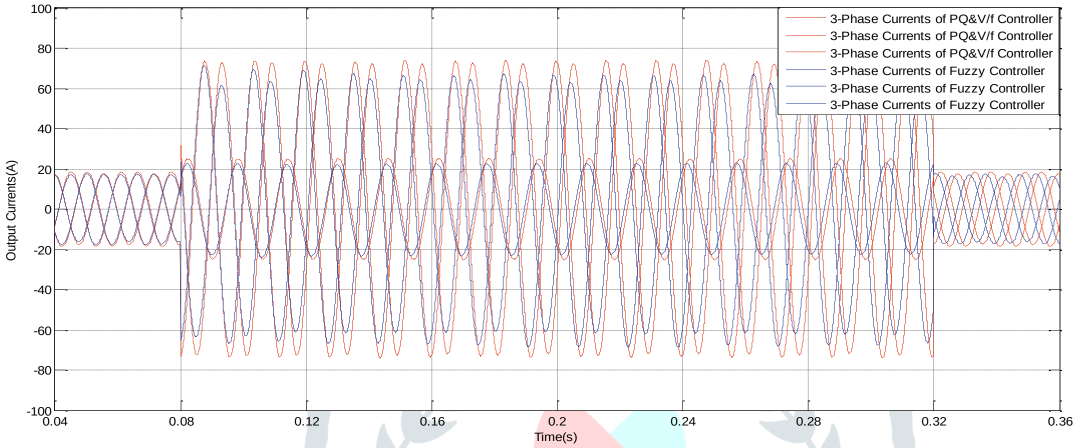

Fig.8.2.7. Simulation results of DG2 in case 2: Output currents

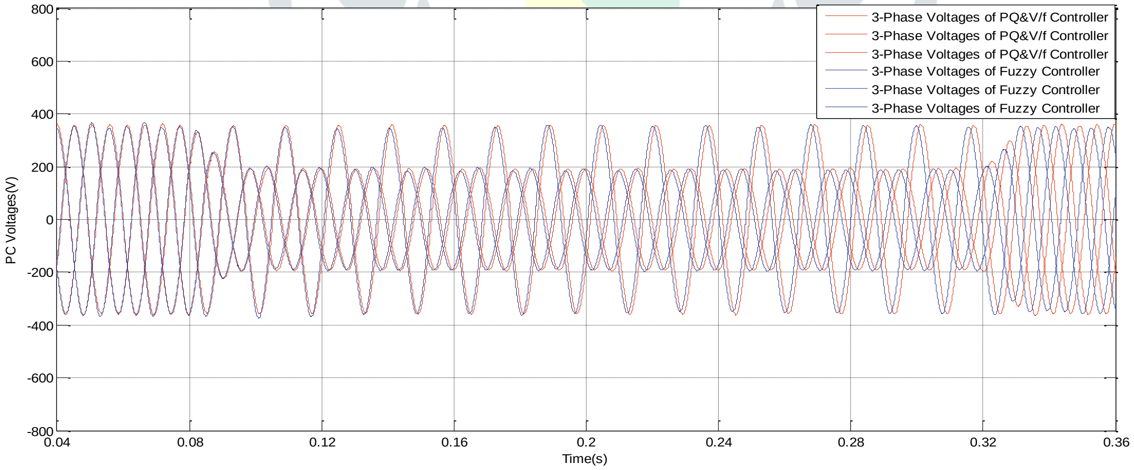

Fig.8.2.8 Simulation results of DG2 in case 2: PC Voltages

Case 3 Three phase faults

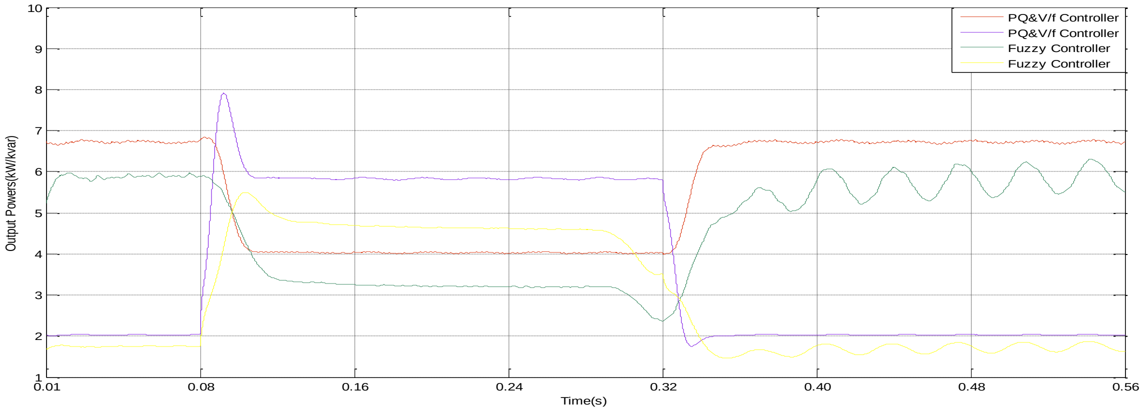

Fig.8.3.1 Simulation results of DG1 in case 3: Supplied active power of positive sequence.

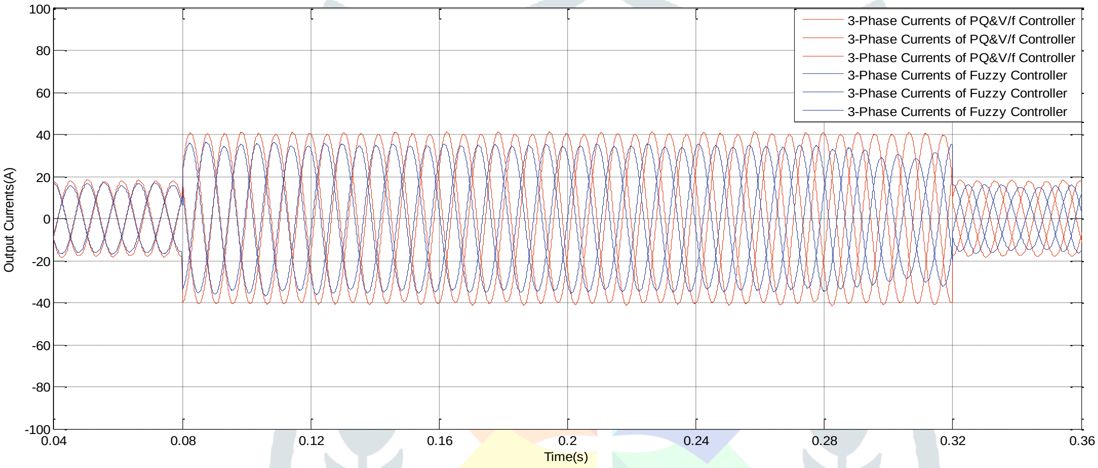

Fig.8.3.2 Simulation results of DG1 in case 3: Output Currents

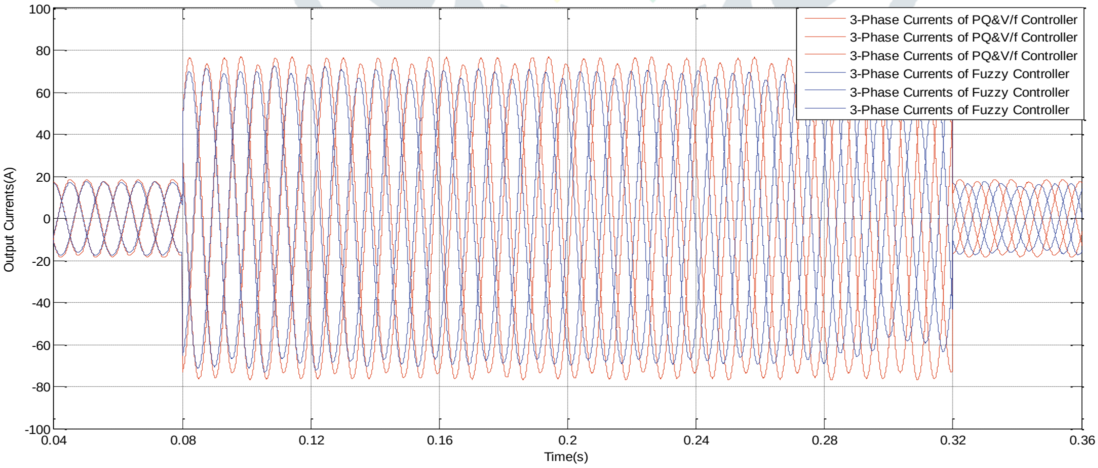

Fig.8.3.3 Simulation results of DG2 in case 3: Output Currents

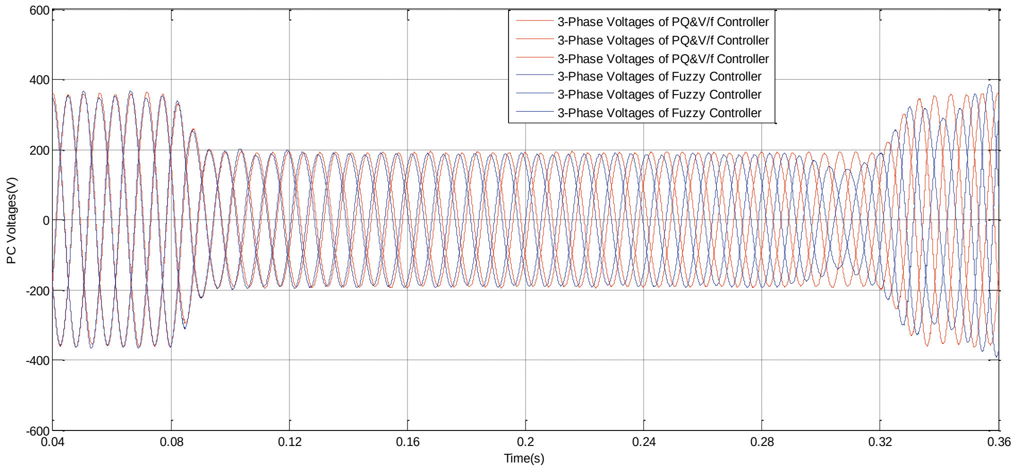

Fig.8.3.4 Simulation results of DG2 in case 3: PC Voltages

It can be observed that maximum active power, reactive powers voltages and currents in single phase, two phase and three phase faults are controlled by the fuzzy controller which has rule based conditional statements that specifies the relation between fuzzy variables. Two variables k_p, k_i are used as input signals. The rules of the fuzzy sets considered are shown in Table.4.3.1.

The comparison of maximum active power, reactive power, voltages and currents in single phase, two phase and three phase faults are shown in the above figures.

The rule-base, which holds the knowledge, in the form of a set of rules, describing the best way to control a system. The membership functions are used to quantify knowledge. The inference mechanism evaluates which control rules are relevant at the current time and then decides what input of the plant should been allowed. The fuzzification interface modifies the inputs, so that they can be interpreted and compared to the rules in the rule-base.

The control active power and reactive power of positive sequence and negative sequence is shown in Fig 7.1.1, 7.1.2, 7.1.3, 7.1.4, where the fuzzy controller limts the powers when compared with the PQ-IIDG and V/f-IIDG controllers. The increase in voltages is shown in Fig 7.1.6, 7.1.7. The decrease in currents are shown in Fig.7.1.5. Consistency, redundancy and completeness can be checked in rule base.

In the same way the two phase and three phase fault powers, voltages and currents are controlled by the fuzzy rule based controller due to its flexible knowledge base design, convenient user interface, easy computation.

7. CONCLUSION: The diversification of control schemes in microgrids makes it difficult to estimate fault current of IIDGs during transient period. This paper investigates fault characteristics of IIDGs with Three different control schemes. In summary, voltage controlled IIDGs can be modelled as a voltage source in series with output impedance while current controlled IIDGs can be seen as a current source in parallel with the filter capacitor during transient period. Fuzzy controller controls the voltage and currents by using logic rules. When systems are subjected to symmetrical faults, we assume that negative sequence signals are filtered out and only positive sequence signals are delivered into control systems. Under this assumption, fault current of current controlled IIDGs remains balanced while fault current of voltage-controlled IIDGs is balanced.

Voltage-controlled IIDGs seen to provide higher fault current peak value and less peak time than current-controlled IIDGS.

Current limiters make fault current of IIDGs similar to that of a constant current source. When modulation wave limiters are adopted. IIDGs can be modelled as ideal voltage sources.

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