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Modeling and Stability Analysis of AC and DC Microgrids

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ABTRACT-

This report mainly concentrates on modeling and stability analysis of AC Microgrid and DC Microgrid during fault conditions, sudden load variations and when connected to weak grid in real time digital simulator. An overview of real time digital simulator and hardware in loop simulation are presented in second chapter. In the third chapter, modeling of different distributed resources used in the microgrid is discussed. The different control strategies used to control the distributed energy resources are discussed in fourth chapter, which then followed by Stability analysis of AC microgrid and DC microgrid during different conditions of operation is discussed in fifth and sixth chapters. Finally seventh chapter includes my observations, conclusions and future work.

Keywords: Microgrid, Electrical Grid, Concrete, Transmission Lines, Distribution Lines, Common Coupling

INTRODUCTION

Electricity demand has been significantly increasing over the past few years due to many factors [1]. In countries such as the United States, Energy production will play an important role because of its power based civilization. Thermal, hydro and nuclear power plants are the major sources of electricity to date. But the limited availability of resources like coal and nuclear energy made us to concentrate on renewable sources such as wind and solar energy. Even though there has been a rapid development going on in wind and solar power technology to make use of renewable sources efficiently and to increase the stability of the system, there are many problems associated with these time- and environment- dependent sources. Because of the variations in parameters such as wind speed, intensity of sunlight, etc., the power extracted from these sources varies accordingly which in turn imposes series problems on the stability of the main grid system. The problems include voltage fluctuations, oscillations in frequency, harmonics, and imbalances in power generation and load demand etc. The best way to shield this problem is to move towards the smarter localized grid system which is called as a microgrid (MG). Microgrid can act as backup power when there is a shortage of supply from the main grid which in turn reduces the voltage fluctuations caused by high demand. Microgrid can also operate in an islanded mode during power blackouts to supply power to localized loads. Microgrids are connected to the main grid through the point of (PCC). Circuit Breakers are used to isolate MG from the main grid during faulty conditions.

Concept of microgrid

Microgrid is defined as the "localized grid that interconnects distributed energy resources with organized loads and normally operates connected to traditional centralized grid synchronously. During faulty conditions can act in islanded mode i.e. disconnected from the centralized grid." [17]. The sources in the microgrid are called as micro sources, which can be battery storage, Solid oxide fuel cell, wind, solar, diesel generator, etc. Each source is controlled in the respective manner to connect it to distribution network. Loads are connected to the distributed network whose power demand is met by micro sources and main grid.

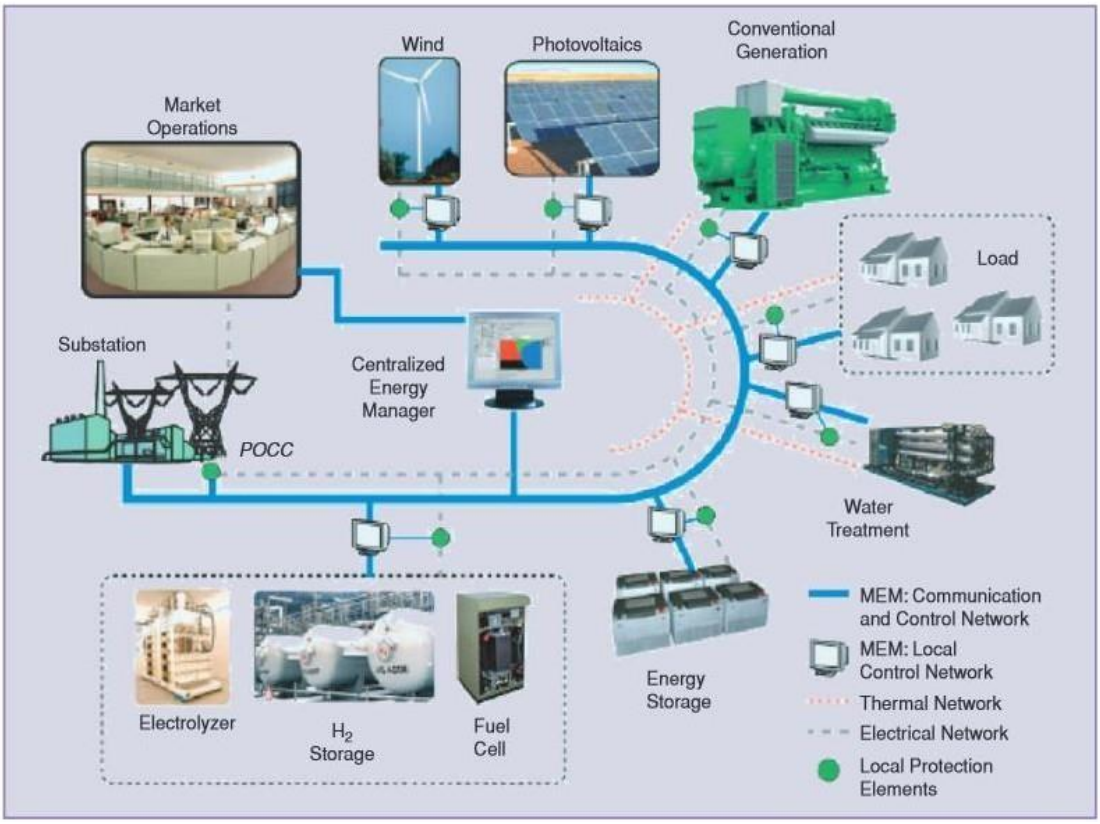

Figure 1.1 Example of Micro Grid, GE MEM framework (source: GE global research) [2].

Motivation to go for the microgrid

During the power blackout, many critical loads suffer from tremendous loss. North Eastern power blackout of 2003 is one of the major power blackouts in the history of United States, which affected 45 million people in eight US states [4]. Building the microgrids is one of the objective ways to minimize the severities caused by power blackouts which ensures to provide continuous power to critical loads by generating power at the distribution facilities.
When the power demand is high, the microgrid provide benefits to the utility by dispatching power to shave the peak loads [5]. Hence it helps to maintain system stability when generation doesn't meet demand. Cost of electricity for the end users can be reduced when the microgrid meet the load demand especially when electric prices are high [5]. Microgrid helps to reduce the transmission losses by producing power at local facilities. Moreover, any upgrades needed by the transmission system to increase its capacity can be postponed. Many of the sources used in the microgrid like solar array, wind farm, rechargeable batteries are environmental friendly, and hence there are less carbon emissions.

MODELING AND STABILITY ANALYSIS OF DC MICROGRID

DC micro grid is defined as the localized grid where the operating voltages and currents of the distribution network are in DC. Power converters are used to Convert AC or DC voltage from DER's to DC Voltage. Consumer loads are powered by the DC supply from the distribution feeder.

Modelling of the DC micro grid.

In a DC micro grid distributed energy resources such as battery, fuel cell, etc. act as a power bank to provide power to loads. Buck or boost converters are used in closed-loop control to convert DC voltages to rated DC voltage of the microgrid. If the source voltages are AC, then a three phase rectifier combined with DC-DC converter in the closed loop control is used to convert it in to DC voltages. Proportional integral controller helps DC-DC converter to maintain reference output voltage.

Stability Analysis of DC microgrid when a three phase fault occurredat the main grid side.

In grid connected mode, the microgrid shares the load along with main grid. The power shared among each distributed energy resource should not exceed its maximum power rating. When the fault occurs on the main grid immediately the microgrid enters into islanded mode to supply continuous power to the critical loads.

Case 1: In this case, A sudden three phase fault is given to the main grid side at t = 9.98. Immediately the microgrid operates in islanded mode disconnected from the grid. The non- critical loads are disconnected to ensure that the microgrid provide enough power to critical loads for required time.

Table 6.1 Load on DC microgrid before and after fault

Fault status	**Load**
Before fault	550 KW
During fault	250 KW

Table 6.1 shows the total load demand on the microgrid before and after the fault. Immediately after the fault at t=9.98, a non-critical load of 300KW is disconnected from the microgrid so that it operates in islanded mode providing continuous supply to the critical loads.

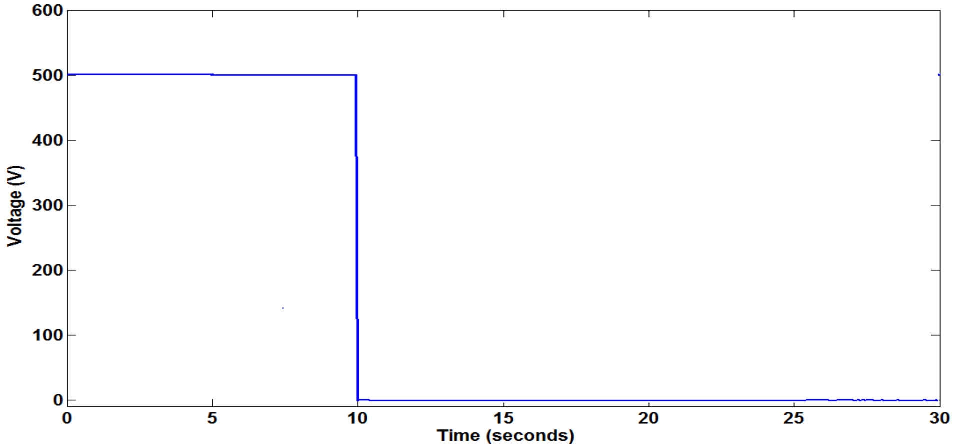

Figure 6.1 Voltage response at main grid

Voltage at the main grid drops to zero immediately after fault at t = 10 as shown in the figure 6.1. Then the Circuit breaker at PCC trips to disconnect the microgrid from main grid.

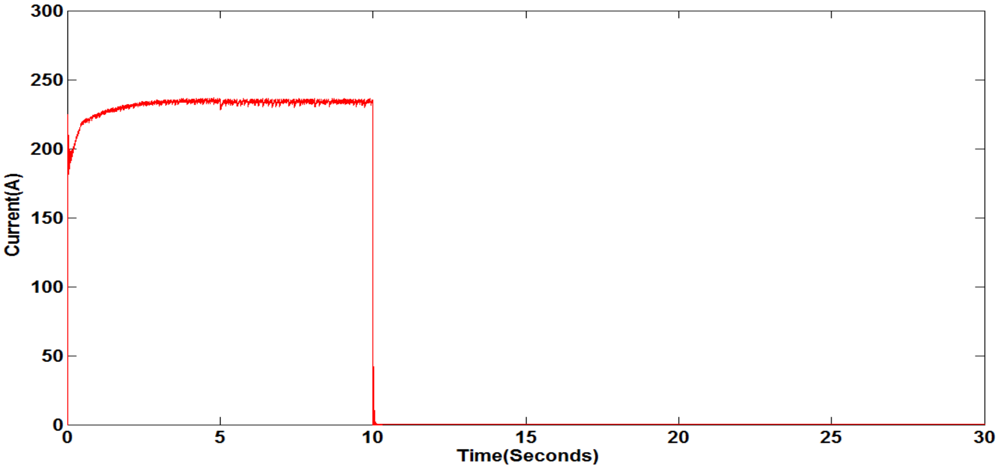

Figure 6.2 Current response from main grid

Figure 6.2 shows that after the circuit breaker trips at t=10, the current flowing from main to the microgrid is zero.

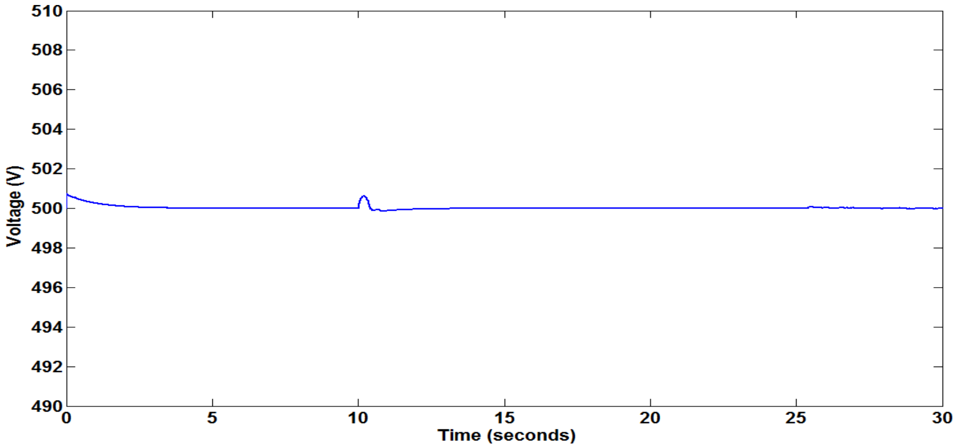

Figure 6.3 Voltage response at Point of common coupling (PCC)

After the fault on the main grid the circuit breaker trips at t=10 to isolate the microgrid from the main grid. The voltage of the microgrid is set to reference voltage by controlling converters in the closed loop. Figure 6.3 shows that immediately after the circuit breaker trips at t = 10, the microgrid operates in islanded mode maintaining rated voltage at PCC.

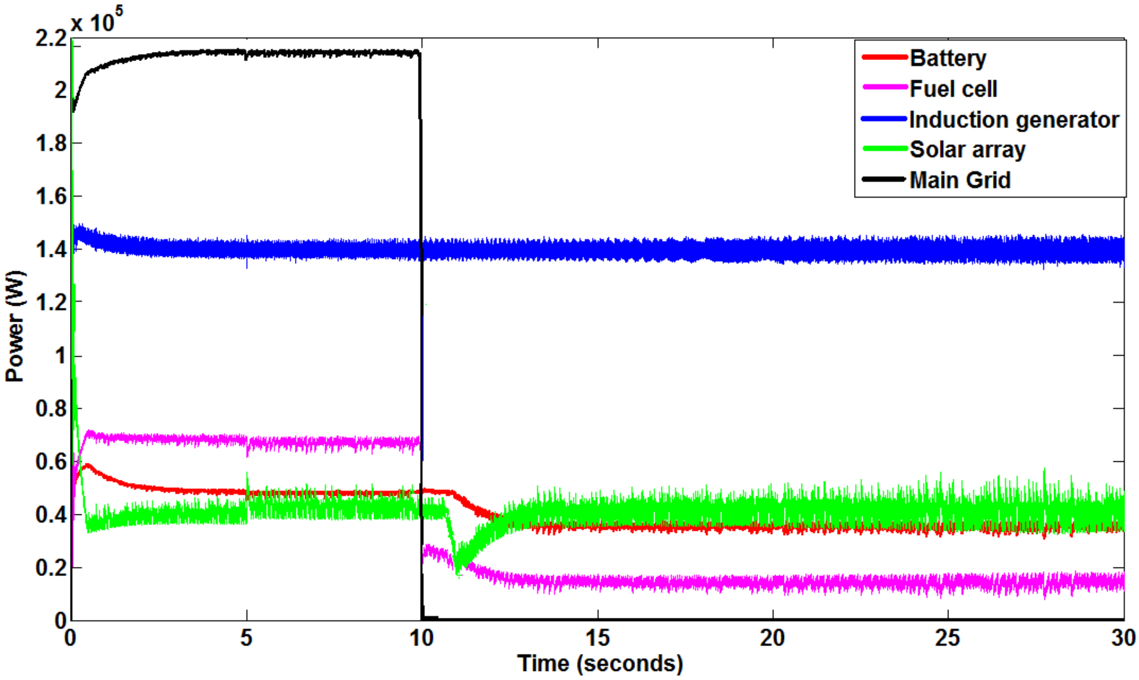

Figure 6.4 Power shard by different sources in microgrid along with main grid

When the micro grid is disconnected from the main grid, the power provided by the main grid reaches zero. Immediately all the non-critical loads are disconnected to provide continuous power to the critical loads from the isolated microgrid. Figure 6.4 shows the power shared among different sources before and after the fault. Induction generator and the solar array have constant input power, the output power provided by them before and after the fault does not vary. Because the battery and the fuel cell have the ability to vary their output power, they absorb any changes in the load by delivering required output power.

Stability Analysis of DC microgrid during sudden load variations

During sudden load variations on the microgrid, the excess load is shared among the Distributed energy resources whose output power can be varied like battery and fuel cell along with the main grid.

Case 2: A sudden load is applied on the microgrid at t=10, immediately the increment in load is shared among different sources to maintain stability of the system by balancing power demand with power generation.

Table 6.2 Load on DC microgrid before and after load variations

Fault state	Load
Before adding sudden load	437 KW
After adding sudden load	500 KW

Table 6.2 shows the load on the microgrid before and after the load variation. A sudden load of 70KW is added to the microgrid at t=10. The excess 63KW of load is shared among battery, fuel cell and the main grid.

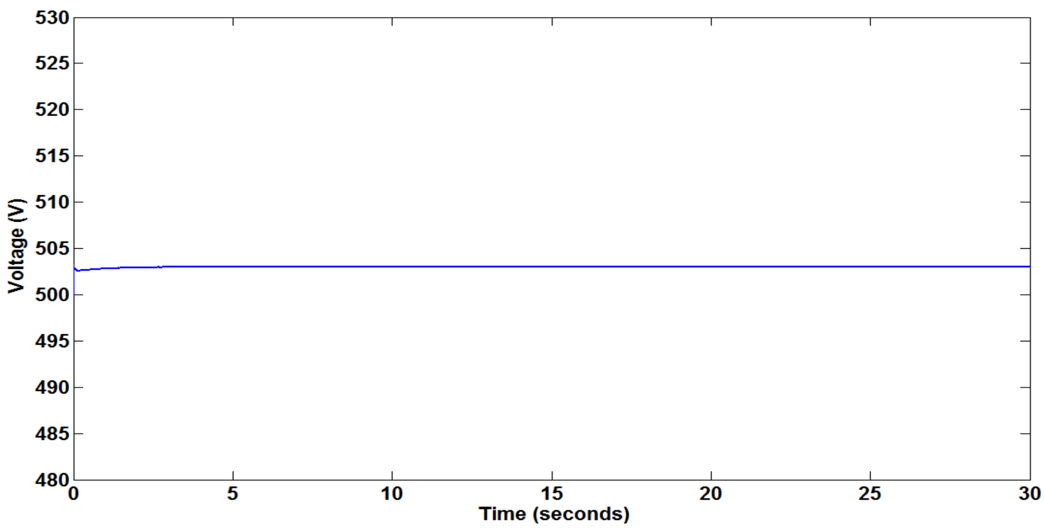

Figure 6.5 Voltage response at Point of common coupling (PCC)

Figure 6.5 shows there are no transients in voltage even after a sudden load is added tothe microgrid at t=10. The transition is stable.

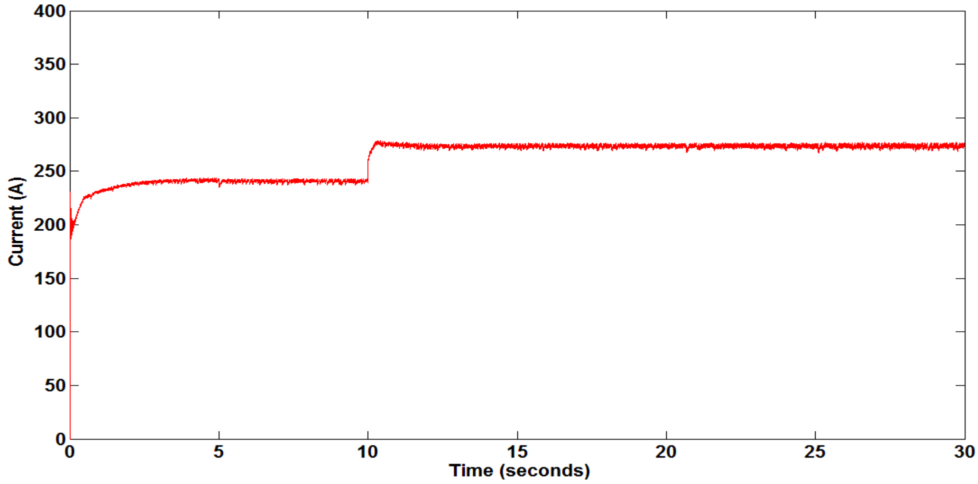

Figure 6.6 Current response from main grid

Figure 6.6 shows that the current from the main grid is increased during sudden load variation which indicates the main grid is delivering excess power to the microgrid to share increment in load.

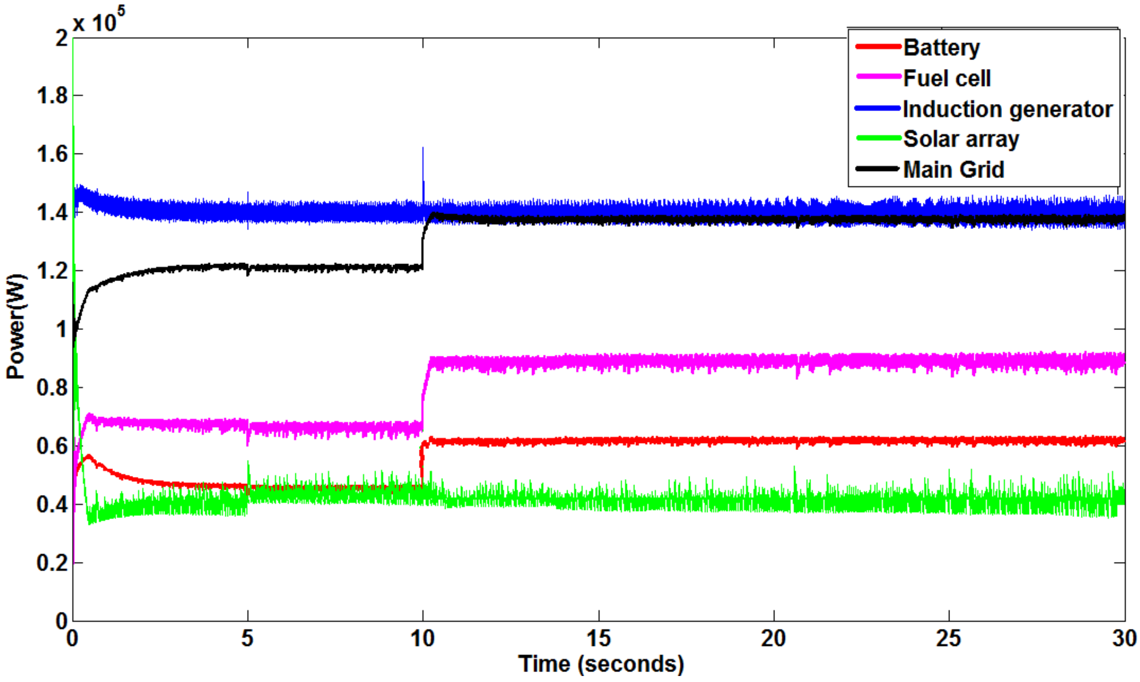

Figure 6.7 Power shared by different sources in microgrid along with main grid

Figure 6.7 shows that when a sudden load is applied at t=10, Induction generator and Solar array do not take part to share the excess amount of load. Induction generator is excited by the external supply, and it is assumed that its operating speed is constant. At constant excitation and operating speed the output power from the generator is constant. Solar array do not share the excess load because its input power is constant. Therefore, the increment in load is shared by battery, fuel cell and the main grid. There are no transients occurred during the load variation.

Stability Analysis of DC microgrid during temporary fault on the main grid

When a temporary fault occurs on the microgrid, immediately the microgrid enters into islanded mode during fault time, and the non-critical loads are disconnected from the microgrid. During islanded mode, the voltage of the microgrid is set by the closed loop controlled converters connected to the DER's. When the fault is cleared the microgrid again operates in the grid connected mode providing power to the critical and non-critical loads along with the main grid.

Table 6.3 Load on DC microgrid before, during and after temporary fault

Fault status	Load
Before fault	530 KW
During fault	250 KW
After fault	530KW

Case 3: In this case main grid suffers from a temporary fault for 200ms starting at t=9.98. During fault time the microgrid enters in to islanded mode by disconnecting non-critical loads from it. Table 6.3 shows that when the fault occurred on the micro grid a non-critical load of 280KW is disconnected from the supply. Immediately after the fault all non-critical loads are reconnected to the microgrid.

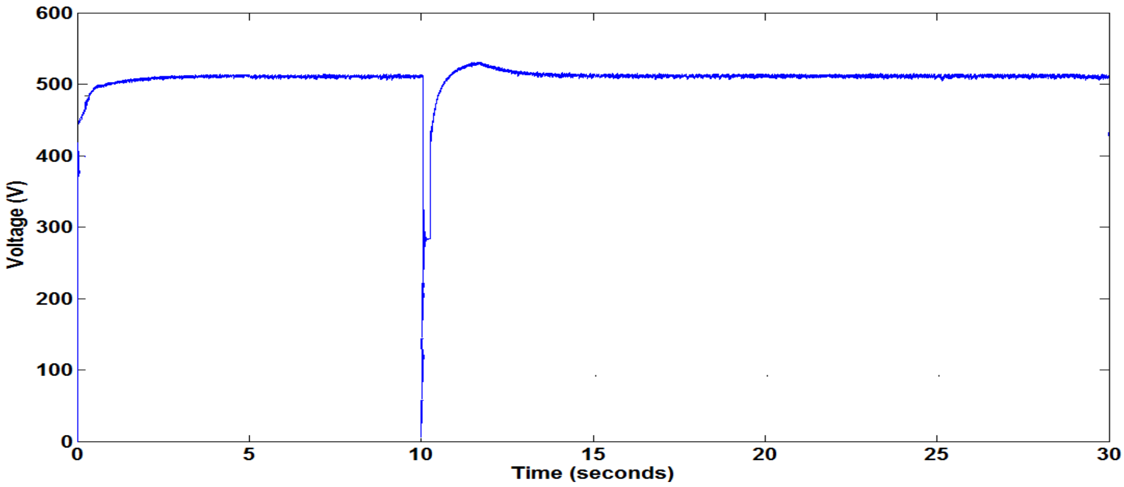

Figure 6.8 Voltage response at main grid

Figure 6.8 shows that when temporary fault occurred on the main grid its voltage drops to zero. Immediately after the fault is cleared at t = 10.2 grid gets back rated voltage.

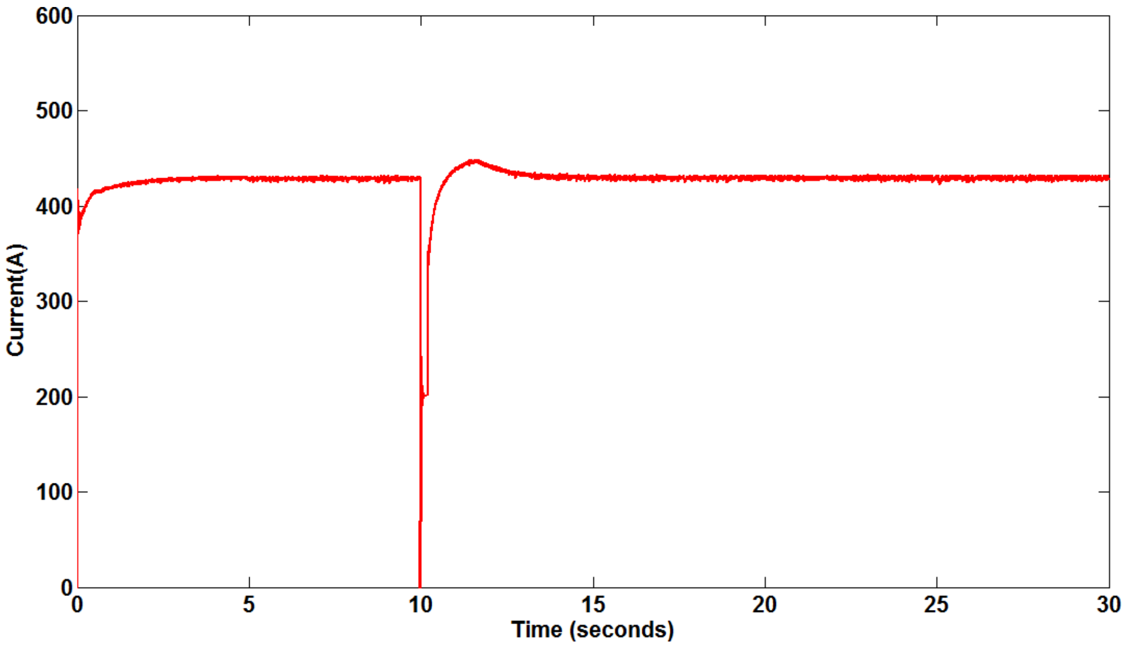

Figure 6.9 Current response from main grid

Figure 6.9 shows that whenever the fault occurred on the microgrid the circuit breaker trips at t = 10. Immediately grid current drops to zero. Current increases to normal value immediately after the fault is cleared.

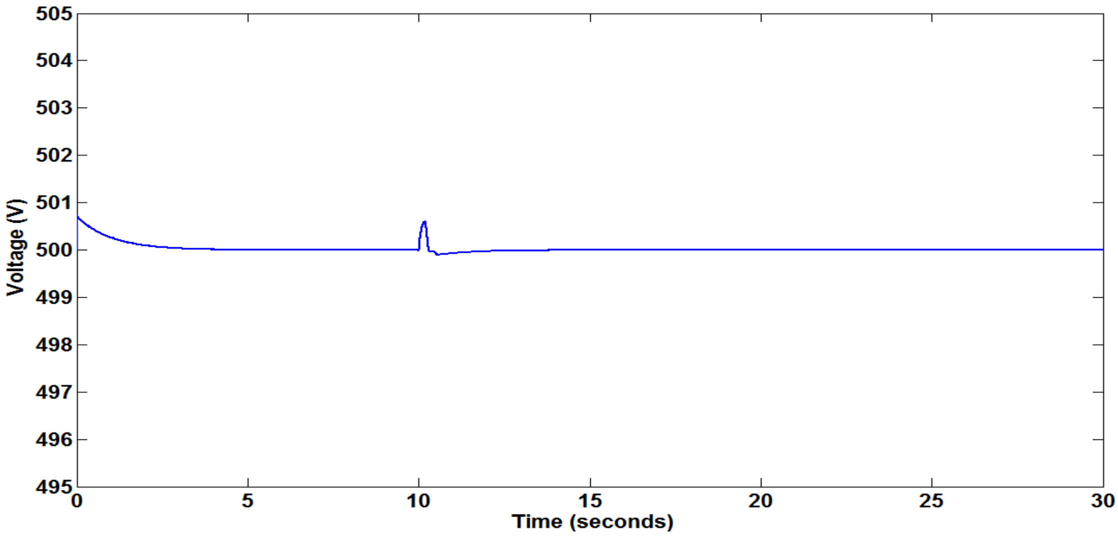

Figure 6.10 Voltage response at Point of common coupling (PCC)

Figure 6.10 shows when the micro grid enters in to islanded mode at t=10 the voltage at PCC is maintained by DER's using the closed loop feedback converters. Once the fault is cleared the micro grid enters in to grid connected mode without undergoing any fluctuations.

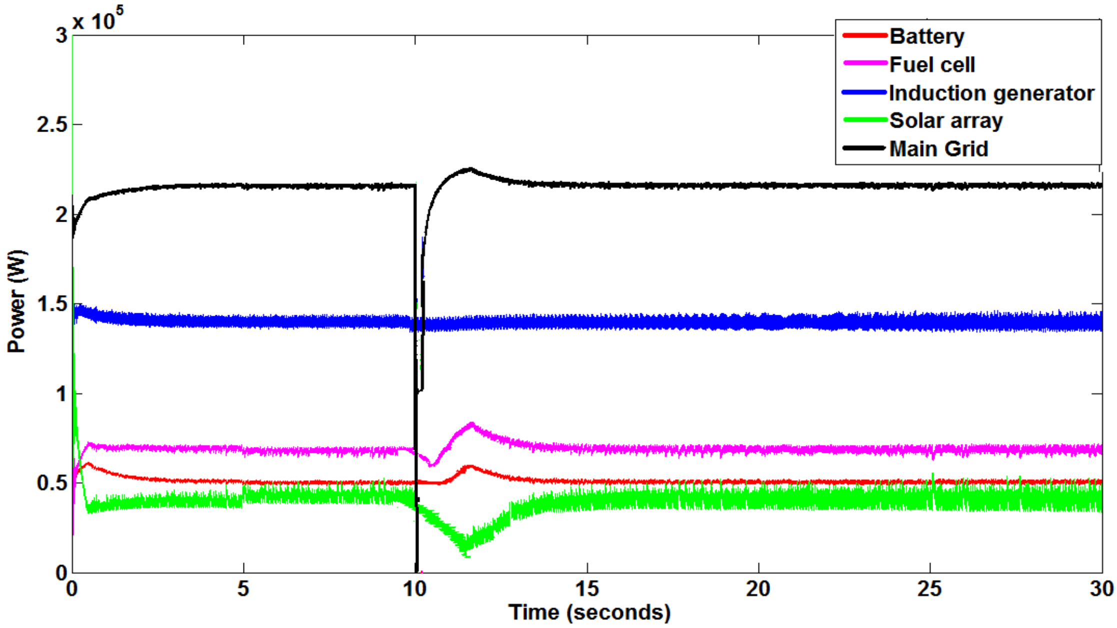

Figure 6.11 Power shared by different sources in microgrid along with main grid

During the fault, the power delivered by the main grid is zero. All the non-critical loads are disconnected from the microgrid to ensure critical loads get continuous power supply from the DER's. Figure 6.11 shows that immediately after the fault is cleared power delivered by the solar array goes down. Which indicates that solar array is not operating in MPPT mode just after the clearance of the fault.

Stability Analysis of DC microgrid during temporary fault on distribution line.

When a temporary fault occurs on a distribution feeder of the DC microgrid, immediately the circuit breakers across the fault trips and divides the micro grid in to two parts.

Case 4:

A temporary fault for 10 cycles is given on the distribution feeder at t=9.98. Immediately the microgrid divides in to two parts one part consisting the battery connected to the grid and other part has Induction generator, fuel cell and the solar array. The isolated part voltage is maintained by fuel cell.

Table 6.4 Load on DC microgrid before, during and after fault

Fault status	Load
Before fault	480 KW
During fault	437.5KW
After fault	480 KW

Table 6.4 shows that total load before fault on the microgrid is 480 KW. Immediately after the circuit breaker across the fault trips, a load of 42.5 KW which is near to the fault is disconnected from the microgrid. When fault is cleared after 10 cycles the load of 40 KW is re-connected to the microgrid.

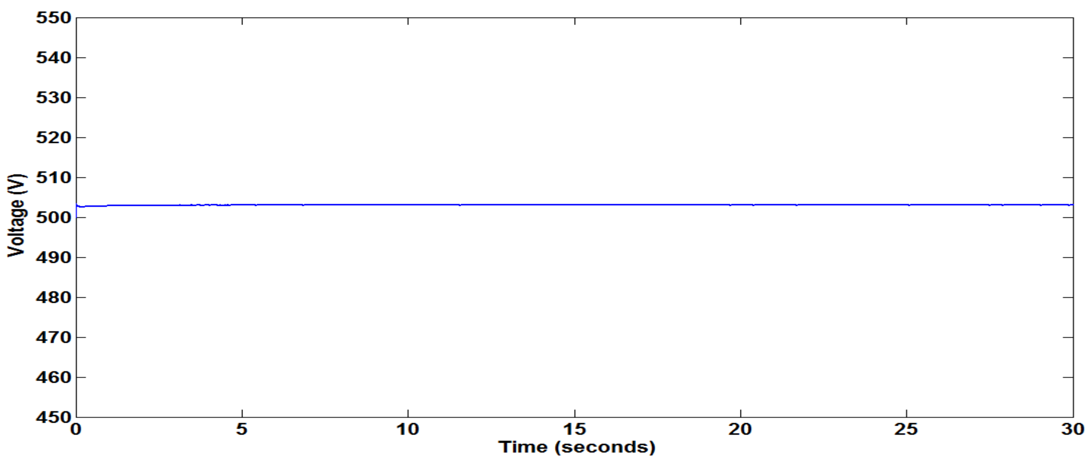

Figure 6.12 Voltage response at PCC

Figure 6.12 shows that when fault occurs at t=9.98, there are no transients in the voltage at the point of Common coupling.

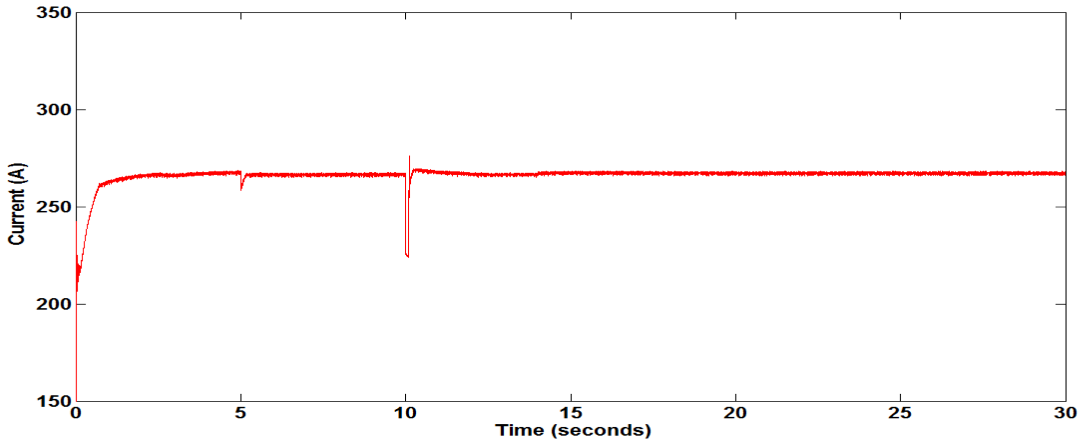

Figure 6.13 Current response from main grid

When a temporary fault occurred on the system, one part of the microgrid grid is isolated. The grid connected part of the microgrid shares small load with battery. Figure 6.13 shows that there is a decrement in the power shared by the main grid during the fault. It is because the net load on the battery and grid has decreased during the fault.

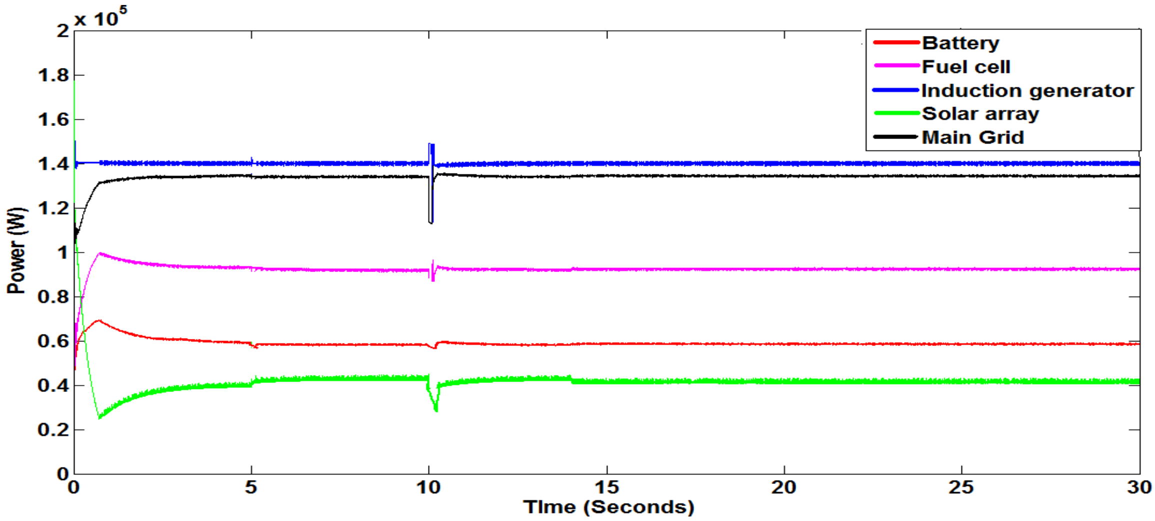

Figure 6.14 Power shared by different sources in microgrid along with main grid

Figure 6.14 shows that immediately after the fault clears, the micro grid attains its stability to operate in normal conditions. During the fault the load is shared by the battery and the main grid is less due to decrease in load demand across the grid connected part.

Any load across the isolated part is shared by the Fuel cell. The power shared by induction generator and the fuel cell is constant.

Effect of weak grid on DC micro grid

AC main grid is connected to the DC micro grid through AC to DC converter. This converter is controlled in the closed loop feedback system with a standard reference voltage signal. Any voltage variations in the input don't affect the converter output voltage because controller maintains the output voltage to be constant irrespective of the input voltage. Hence DC micro grid is not affected by the weak grid.

Effect of weak main grid on DC micro grid when SCR = 5

Table 6.5 Weak grid system parameters for SCR =5

Parameter	Value
Open circuit grid voltage	11KV
Short Circuit Power	200KVA
Rated micro grid voltage	500V DC
Short circuit ratio	5

Table 6.6 Voltage fluctuations Versus Nominal power when SCR = 5

Power flow	Vgrid side (ph-ph) (Volts)	V dist side (ph-ph) (Volts)
$0.8P_n$	8873	500
$0.9\ P_n$	8666	500
P_n	8270	500
$1.1\ P_n$	8110	500
$1.2\ P_n$	7873	500

Table 6.6 shows that even though weak grid results in grid voltage fluctuations at SCR = 5, the voltage on the microgrid is not effected.

Effect of weak main grid on DC micro grid when SCR = 2

Table 6.7 Weak grid system parameters for SCR =2

Parameter	Value
Open circuit grid voltage	11KV
Short Circuit Power	200KVA
Rated micro grid voltage	500V DC
Short circuit ratio	2

Table 6.8 Voltage fluctuations Versus Nominal power when SCR = 2

Power flow	Vgrid side (ph-ph)	V dist side (ph-ph)
$0.8P_n$	6244	500
$0.9\ P_n$	6104	500
P_n	5912	500
$1.1\ P_n$	5862	500
$1.2\ P_n$	5798	500

Table 6.8 shows that even though weak grid results in grid voltage fluctuations at SCR = 5, the voltage on the microgrid is not effected. Hence the DC microgrid is not effected for any SCR value of the main grid

OBSERVATIONS AND CONCLUSIONS

Observations

Effect of weak grid on AC/DC microgrids.

DC microgrid is not affected by the weak grid as in case of AC microgrid as discussed in chapter 5 and chapter 6. In a DC microgrid the closed loop feedback AC-DC converter is used to convert AC voltage from main grid to DC voltage. It helps to maintain steady reference DC output voltage even though the AC input voltage is fluctuating.

Harmonic Effects on AC/DC microgrid

The battery and the fuel cell deliver power according to the load demand, i.e. the current from these sources varies with the load demand. As the net load is not constant for these sources, it is difficult to design an LC filter to eliminate higher harmonics in AC microgrid system. Hence there will be harmonics present in the AC microgrid system. In a DC system, microgrid do not have harmonics.

Selection of DC source voltages in AC/DC microgrid

As discussed in chapter 4, the peak value fundamental frequency component of the PWM controlled DC to AC converter output voltage (VA0)1 is given by:
(VA0)1= ma *(Vd/2) for ma<=1

From above equation, the output voltage of the converter depends on ma and input DC voltage for DC to AC converters. But the range of ma is between 0 to 1. Hence to get the rated output voltage input DC voltage should be at least greater than twice the output voltage. Moreover, as the load current increases voltage drops across the inductor in LC filter increases. Hence magnitude of VA0 should be increased in order to keep the filtered output voltage constant. As VA0 depends on modulation index and input DC voltage, one among these parameters should be increased. But modulation index can have a maximum value of one. Hence Input DC voltage should be large in order to keep the load current high. This condition holds good for DC sources used in AC microgrid. Whereas in DC microgrids there are no source voltage limitations because the buck or boost converters are as per the output voltage requirements.

Output power limits for DC sources in AC/DC microgrid.

As seen earlier, to increase the output maximum current flow from PWM controlled DC to AC converter its input DC voltage needs to be increased. For a source with fixed input voltage, there will be a maximum power associated with it to operate in modulation index limits. Hence maximum power extracted from DC sources in AC microgrid is limited and depends on Input source voltage.

Voltage drop due to line impedance in AC and DC microgrid.

In AC system, voltage drop on line with impedance Z is given by

$$V = IZ \quad (7.1)$$

$$Z = R + j(X) \quad (7.2)$$

$$V = IR + j(IX) \quad (7.3)$$

Where R is the resistance of the line and X is the reactance of the line. For DC system voltage drop on a line is given by

$$V = IR \quad (7.4)$$

From equation 7.3 and equation 7.4 it can be said that voltage drop on the line in AC system is more than the voltage drop on the line in DC system.

Conclusions

This paper discusses on control of Distributed energy resources to integrate them to form a microgrid. AC and DC Microgrid models have been developed in MATLAB, Simulink environment. Steady state and transient stability analysis is performed on both AC and DC microgrid during permanent faults, temporary faults and sudden load variations in real time using OPAL-RT real time digital simulator.

Results indicate that DC microgrid is not affected when connected to a weak grid. It attains stability faster than the AC microgrid immediately after a fault is cleared. There are no harmonic effects present in the DC microgrid. Because of the absence of the PWM controlled DC to AC converters the output power extracted from these sources is not limited by input DC source voltage or the modulation index limitations. Moreover, voltage drop in DC system is not affected by the reactance of the line. Controllers for the converters in the DC system are simple as they do not need to have control over the frequency of the converter output signal. Practically the DC microgrid systems do not suffer from skin effect or Ferranti effect. The above mentioned advantages of the DC microgrid system might play an important role in the future to make a transition from AC to DC microgrid systems.

Future work

Stability and transient analysis during faults and sudden load variations of the microgrid were performed assuming the main grid is strong. In future work, these analyses can be performed when connected to the weak main grid.

In DC microgrid, the circuit breaker considered as an ideal breaker with no arc formation and zero crossing tripping. Practically it is not possible. So in future work a more practical circuit breaker needs to be designed to perform the stability analysis on the DC microgrid

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