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Challenges to voltage and frequency stability of microgrids under renewable integration

Lahiru Aththanayake
School of Engineering, SEBE, Deakin University
Melbourne, Australia
laththanayakead@deakin.edu.au

Nasser Hosseinzadeh
Centre for Smart Power and Energy Research
School of Engineering
Deakin University
Melbourne, Australia
http://orcid.org/0000-0002-8755-1176

Apel Mahmud
Centre for Smart Power and Energy Research
School of Engineering
Deakin University
Melbourne, Australia

Ameen Gargoom
Centre for Smart Power and Energy Research
Deakin University
Melbourne, Australia

Ehsan M. Farahani
Operational Analysis & Engineering
Australian Energy Market Operator (AEMO)
Melbourne, Australia

***Abstract*— Renewable energy have become an abundant source of power in microgrids. As the conventional synchronous generators are being replaced with Inverter Based Resources (IBRs), frequency and voltage stability of microgrids are at risk. This is because characteristics of IBRs and intermittent nature of renewable generation poses challenges to operation and control of microgrids. This paper describes how voltage and frequency stability is affected in the presence of renewable integration. A comparison is made between voltage and frequency stability of microgrids under supply of power from synchronous generators and wind generation using IEEE 9 bus system. Finally, a synchronous condenser is used to mitigate the issue of voltage variation of the IEEE 9 bus system under wind integration.**

I. Introduction

A microgrid is a "group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" [1]. A micro grid can either operate in an islanded mode or a grid connected mode. Grid connection of a micro grid is mainly for the reliability purposes. If the power generation within the micro grid can supply its demand, grid connection is not necessary [2]. Microgrids have become an attractive solution for renewable energy applications and supply of critical loads such as hospitals and universities. Advantages of microgrids are being able to operate in an islanded mode in the event of a system blackout (Ex : A micro grid system in a brewery in South Australia was continuously functioning in a blackout), less reactive power consumption in transmission lines as power is locally produced and consumed and easy integration of renewable energy which are located far from the main grid. Disadvantages of microgrids can be divided into three sections as economic, technical and policy [1].Under economic disadvantages maintenance, operational and interconnection costs can be identified. A need for an advance control structure for operation and control can be identified under technical disadvantages. Policy related disadvantages include resistance from environmental activists and local people as microgrids are usually build in rural areas.

II. Challenges to Voltage and Frequency Stability in Microgrids

A. IBRs characteristics

IBRs have become an abundant feature in modern microgrids. Percentage of IBRs in the microgrids increased over the years due to large increase in Solar and Wind power penetration. Even at the load side IBRs are increased due to usage of devices such as adjustable speed drives, power supply to computers, lighting, electrical cooking etc …etc… [2] It is expected that future microgrids will consist only 100% IBRs.

IBRs do not behave same way as conventional synchronous generators in the system. They show very fast dynamic response for faults. In static operation, there can be power quality issues from harmonic distortion.

Therefore, behavior characteristics of IBRs are critical for operation and control of microgrids.

B. Reliability and storage requirement

Reliability is an essential factor in microgrids. Power system reliability is defined as "the ability of an electrical system to deliver electricity in the quantity and quality demanded by energy users" [3]Reliability of power supply in a grid tied microgrid is high while it is low in islanded microgrids. One of the main reasons for unreliability in an islanded microgrid is intermittent nature of variable renewable generation.

C. Weather Forecast

Since most microgrids consist of wind and solar generation, weather forecasting is an essential step in microgrid operation. Unexpected reduction in power can cause severe impacts in islanded microgrids. Intermittency in generation can cause frequency and voltage fluctuations inside the microgrid. Usually day ahead forecasting has been used in the past but it is prone to error. Hour ahead forecast or real time forecast is necessary for determining uncertainty in wind and solar generation.

D. *Fault ride through capability*

All generators inside the microgrid must exhibit required fault ride through capability by the power system operator for any fault inside the microgrid or main grid [4]. When there is a fault in the power system, low voltages are expected in bus bars close to that fault. Low terminal voltages can be harmful since large currents are drawn from IBRs which can damage the power electronic devices inside them. But disconnecting from the grid during a fault is not an option since it affects recovery of the microgrid after the fault. Therefore, all generators in the microgrid should ride through these faults successfully.

E. *System strength and system inertia*

Lack of system inertia and system strength is one of the main issues in operation of a microgrid since it can lead to frequency and voltage stability issues.

System strength is directly related to the size of a voltage change in a bus bar after a disturbance [5].If the system strength is high, voltage change is less for a given disturbance and vice versa. The indicator for the system strength is the short circuit ratio, which is directly proportional to a three-phase fault level at a bus. Equation for short circuit ratio is as follows,

$$SCR = \frac{three\ phase\ fault\ level\ (MVA)}{power\ injection\ (MVA)} \tag{1}$$

According to equation 1, three phase fault level at a bus is proportional to its SCR.
Higher fault levels contribute to higher short circuit ratios and eventually to higher system strengths. Having less system strengths can lead to voltage collapses under low reactive power supply in that area.

F. *Requirement for an advance control structure*

Voltage and frequency stability of a microgrid depends upon the advance control structure as well.

The hierarchical control structure of a micro grid is divided into three sections as primary, secondary and tertiary. Following diagram shows the combination of these three.

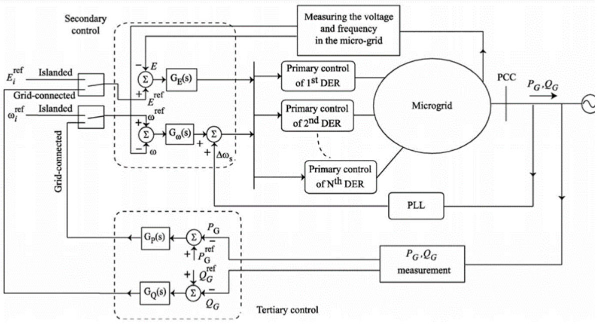

Figure 1: Hierarchical control of a microgrid [10]

There are basically two control techniques for microgrid control as, droop-based control and droop free control.

A droop-based control does not require communication between IBRs. But there have been few issues related to droop based control as Load dependent frequency/voltage deviation, handling non-linear loads [16] and poor reactive power sharing in the presence of unequal buses [17]. Droop free control requires a very healthy communication between IBRs. Communication failures can affect the voltage and frequency stability of the microgrid. [12,15,18,19,20,21]

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III. Voltage and Frequency Stability Analysis

A static analysis and a dynamic analysis are carried out in this section with three different operations scenarios in each analysis. Operation scenarios were selected such that synchronous generators in the system are replaced by wind power plants to analyze the impact of renewable energy.

A. *Static analysis*

In this section, a static PV analysis is carried out under following three operation scenarios.

1. Scenario 1 - IEEE 9 bus system original configuration
2. Scenario 2 – System in scenario 1 modified by replacing synchronous generator in bus 9 with a 85 MW wind power plant (islanded mode)
3. Scenario 3 – System in scenario 2 modified by replacing synchronous generator in bus 9 with a wind power plant (grid tied mode)

1) *Scenario 1*

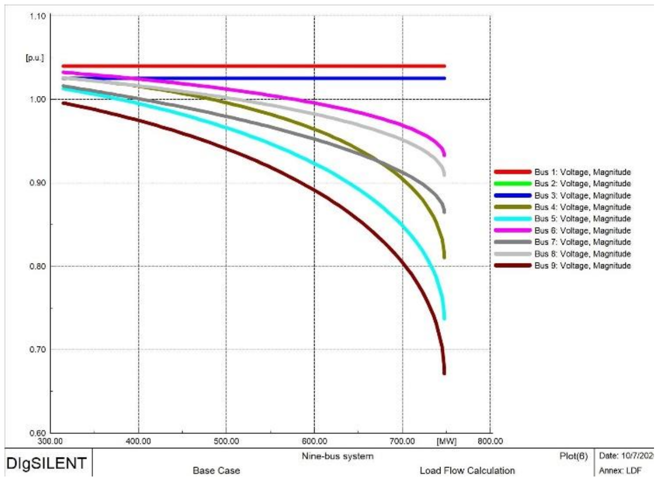

Figure 2: PV analysis of the system in scenario 1

According to the above diagram, buses 5 and 6 seem to be the two weakest buses in the system. This is because, when active power is increased in these two buses, voltage begins to reduce drastically. Also buses 1,2,3 shows flat PV curves since these three are generator buses. Bus 9,7 shows a very strong response to the PV analysis. Bus 4 initially shows a strong response but then its voltage is decreased at a higher gradient than others at the end. As seen from the diagram, voltage collapse point of the system is nearly around 750 MW.

2) Scenario 2

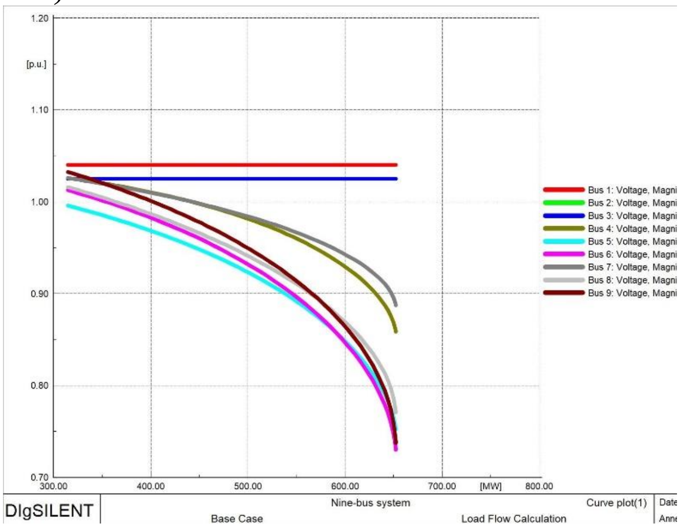

Figure 3: PV analysis of the system in scenario 2

As seen from the above diagram, when the synchronous generator is replaced with a wind power plant with same load flow characteristics (active and reactive power injection was matched), voltage stability of bus 9 is drastically reduced. This is because system strength of bus 9 is reduced by replacing synchronous generator with wind power plant. Even in bus 6, there is a steeper decrease in voltage compared to scenario 1. Voltage collapse point of this configuration is reduced to 650 MW.

3) Scenario 3

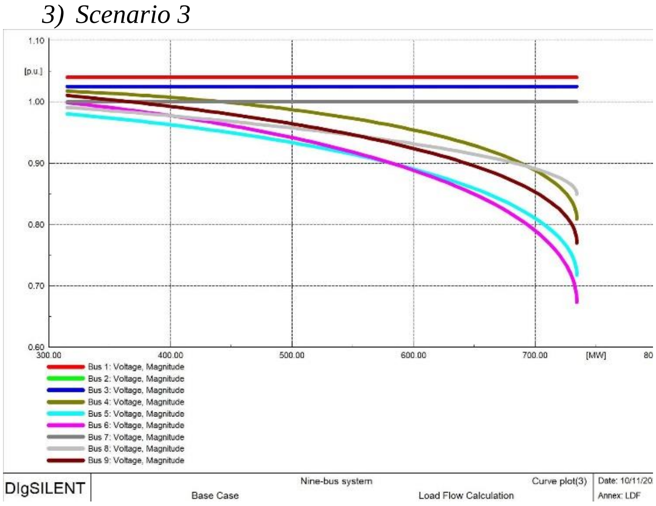

Figure 4: PV analysis of the system in scenario 3

Scenario 1,2 can be considered as an islanded microgrid. In this scenario, 9 bus system is connected to the main grid via bus 7.

As seen from Figure 3, PV characteristics of bus 7 has changed. It shows flat a PV curve like buses 1,2,3 as external grid acts like a generator. Voltage stability of bus 6 is also improved.

As seen from the diagram, voltage collapse point is 735 MW. Therefore, overall stability of the system is also increased.

B. Dynamic analysis

Dynamic analysis for voltage stability in IEEE 9 bus system was simulated in three operation scenarios as follows.

1. Scenario 1 - All three generators in IEEE 9 bus system with synchronous generators
2. Scenario 2 - Generators connected to buses 2 and 3 replaced with wind power plants of 110 MW each.
3. Scenario 3 - A synchronous condenser is added at bus 9 for operation scenario 2.

1) Scenario 1

Only synchronous generators were used for generation of power in buses 1, 2 and 3. Machine MVA ratings used for this analysis are 915 MVA, 170 MVA and 85 MVA respectively for buses 1, 2 and 3. A higher value was selected for MVA rating of generator 1 to represent it as a slack bus.

Then a fault is simulated at bus 5 of the system at 4s for a period of 0.5 s. This fault was self-cleared. Voltage and frequency variation of bus 6 was observed under this fault as show below.

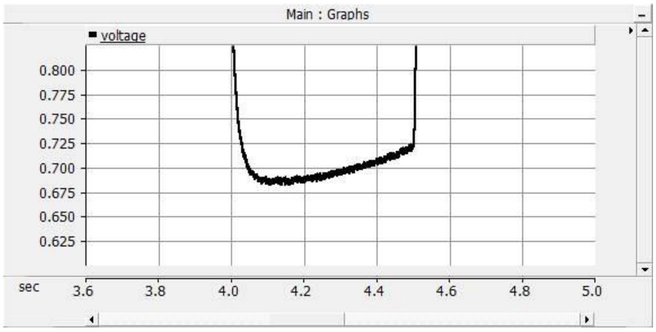

Figure 5: Voltage dip at bus 6 during a fault in scenario 1

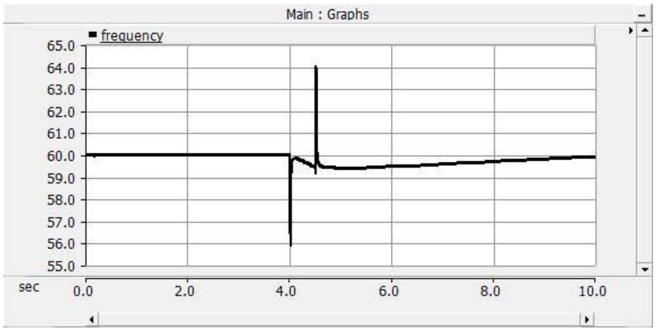

Figure 6: Frequency variation at bus 9 under a fault in scenario 1

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2) Scenario 2

Synchronous generators connected to buses 2 and 3 are replaced with two identical wind power plants consisting of doubling fed induction generators. The size of a wind power plants is estimated be 110 MW each. Then same fault is simulated as in scenario 1 is simulated to observe the voltage and frequency variation at bus 6. Graphs which were obtained for this scenario are shown below.

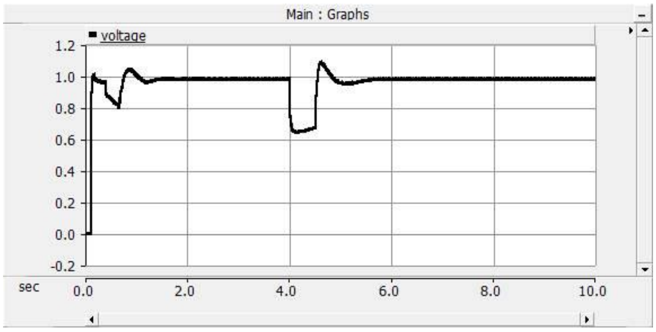

Figure 7: Voltage variation at bus 6 for a fault in scenario 2

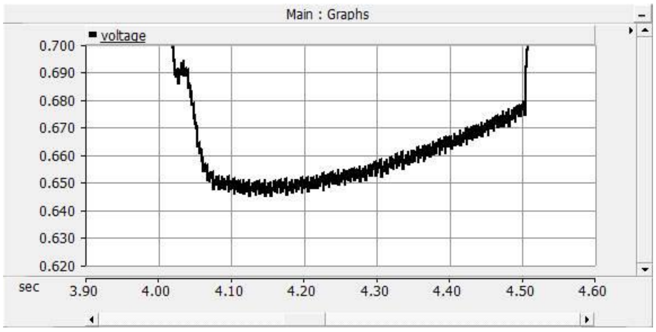

Figure 8: Voltage dip at bus 6 for a fault in scenario 2

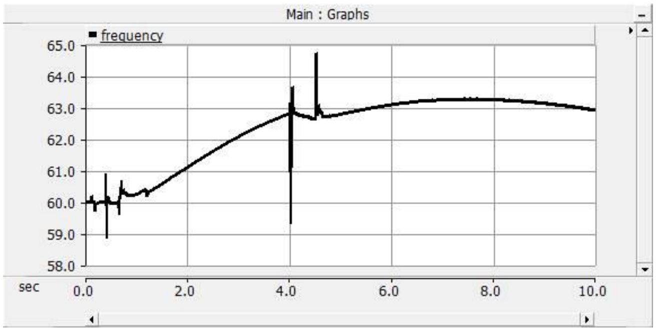

Figure 9: Frequency variation at bus 6 for a fault in scenario 2

As seen from figure 8, voltage at bus 6 initially oscillates until it settles at 1 pu. From Figure 9 it is seen that voltage dip at the fault has gone nearly below 0.65 pu. During the fault, bus bar voltage is raised from 0.65 puto 0.68 pu. In this scenario, microgrid has been unable to maintain the frequency at 60 Hz.

3) Scenario 3

A synchronous condenser of 17 MVA is connected to bus 6 in the above scenario.

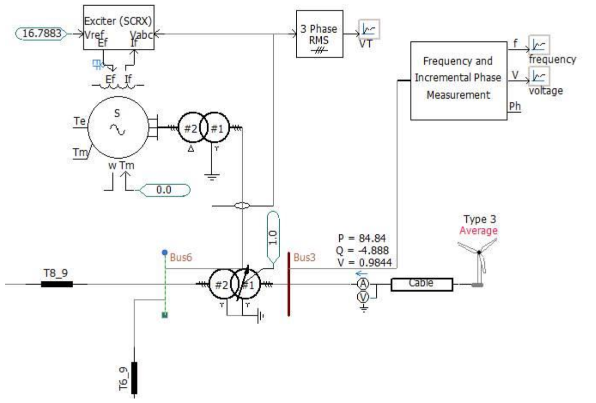

Figure 10: Synchronous condenser connected at bus 9(only a section of the system is shown)

Then the same fault is applied as above scenario to observe the voltage and frequency variation at bus 6. Obtained results are shown below.

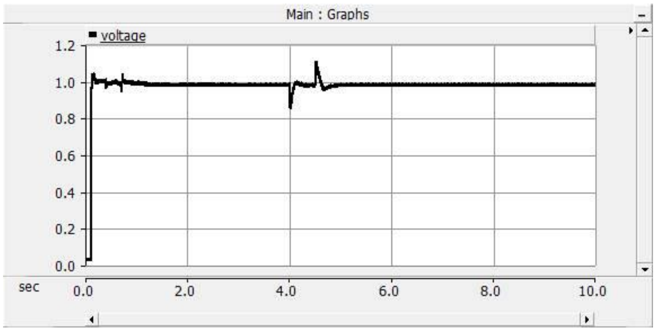

Figure 11: Voltage variation at bus 6 for a fault in scenario 3

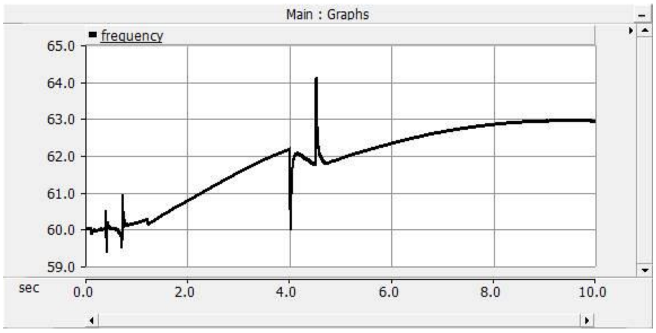

Figure 12: Frequency variation at bus 6 for a fault in scenario 3

Voltage variation at bus 6 is below 2 pu as seen from Figure 8. At the time of the fault, voltage is dipped to 0.85 pu. During the fault, voltage is settled back to original value. At the time of clearing the fault, a sudden overvoltage is noticed. Then it is quickly restored back to original value within in less than 1 second.

C. A gust of wind

Synchronous generator at bus 3 of IEEE 9 bus system is replaced with a single wind turbine generator system of 2 MVA. Then a gust of wind (3 m/s peak velocity) is simulated from this machine at 4 second for a period of 2 seconds. Voltage and frequency of bus 6 was observed for this disturbance as show below.

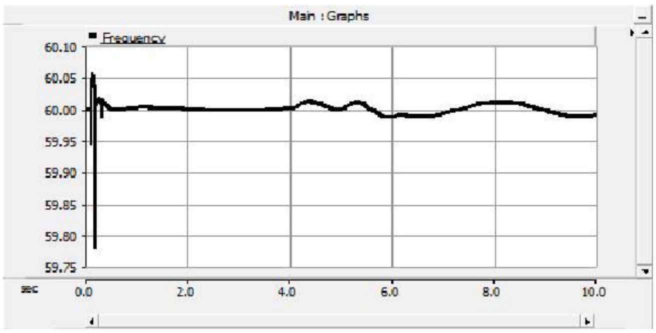

Figure 13: Frequency response at bus 6 for a gust of wind at 4 second

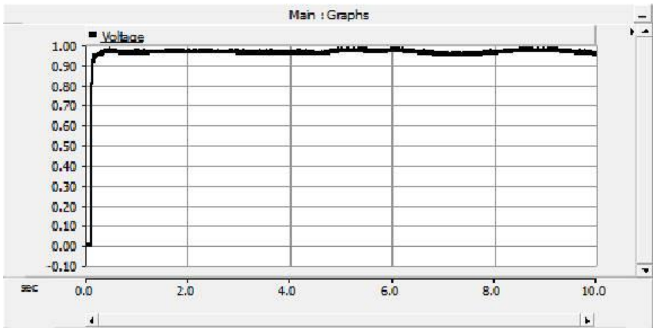

Figure 14: Voltage response at bus 6 for a gust of wind at 4 seconds

From figure 11 it is observed that for a gust of wind at 4 seconds, frequency initially starts to increase and then oscillate for the rest of simulation time. And the voltage in Figure 12 slightly oscillates too for this gust of wind.

D. Fault ride through capability in wind power plants turbines

Scenario 2 in dynamic analysis is used to observe the voltage dip at terminal of the wind power plant. Obtained graph is shown below.

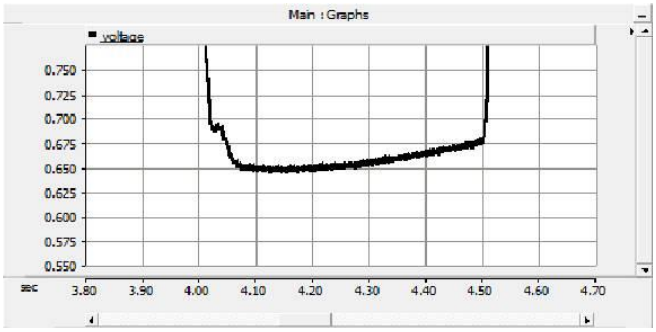

Figure 15; Voltage dip at wind power plant terminal voltage for a fault in the system

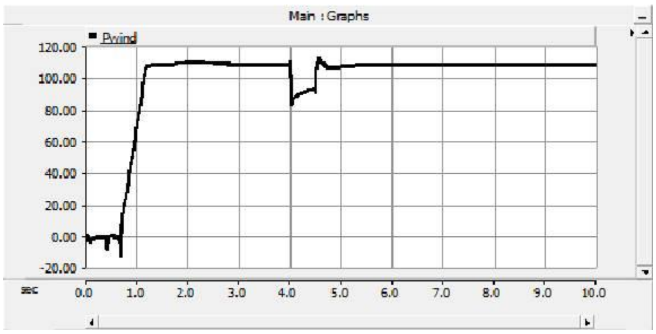

Figure 16; Active power output of the wind power plant for a fault in the system

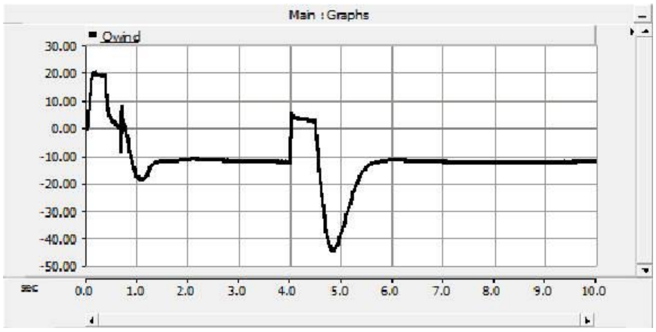

Figure 17; Reactive power output from wind power plant for a fault in the system

From figure 18, it is seen that active power output of the wind turbine is instantly reduced at the time of the fault and returns to nominal value after the fault is cleared. From figure 19, it is observed that reactive power output is suddenly increased at the event of the fault and it oscillates to come back to nominal value when the fault is cleared.

IV. DISCUSSION

In PV analysis results, voltage is decreased when real power demand of a particular bus is increased because, reactive power consumption in transmission lines are increased too as they become heavily loaded. As seen from scenarios 1 and 2, voltage stability at buses 9 and 6 were largely reduced by addition of a wind power plant. This is due to the reduction of system strength in those buses.

Unlike synchronous generators, IBRs provide limited fault level. Therefore, replacement of synchronous generators in the system with IBRs reduces the system strength [22]

Since integration of a wind power plant reduces the fault level at bus 9, strength of that bus is deprived. This causes the voltage to drop quickly for the same fault in first two operation scenarios.

However, when the microgrid is connected to the main grid via bus 7, three phase fault level in the microgrid is again increased as a main grid is modelled using synchronous machines (Scenario 3).

By comparison of results in scenarios 1 and 2 of dynamic analysis part, it is understood that replacement of synchronous generators at buses 2 and 3 of IEEE 9 bus system causes a higher voltage dip for the same fault (0.68 pu for scenario 1 and 0.65 pu for scenario 2). Also voltage oscillations were observed at the start of the simulation in scenario 2. Deprivation of system strength in bus 9 due to replacement of synchronous generators causes this higher voltage dip and oscillations. This is verified from analysis of results in static PV analysis as well.

Frequency increase in scenario 2 of Dynamic analysis is due to having no control structure in the microgrid. Unlike synchronous generators, IBRs do not have internal droop controls. As a result, output from the wind power plants causes an excess generation in the system which causes frequency to settle above 60 Hz. This arises the need for an advance control structure of the microgrid.

Scenario 3 in dynamic analysis shows how the integration of a synchronous condenser can mitigate the voltage oscillations in the presence of renewable energy. Both the start-up transient and fault voltage dip is greatly reduced in scenario 3. But main purpose of a synchronous condenser is to provide reactive power. Therefore, they do not have an active power output or mechanical power input. As a result frequency deviation issue is not fixed by this. Synchronous condenser is simply a synchronous machine which consists only an excitation control system. They can either absorb/supply reactive power by controlling excitation. By installation of synchronous condensers, short circuit ratio of the point of common coupling is increased and hence the system shows very high fault currents for a fault in that area.

In the simulation results for a gust of wind, frequency is suddenly risen at first due to sudden increase of power from wind power plant. Output of the wind power plant is proportional to the square of the wind speed. Sudden increase of power causes reactive power losses in transmission lines as well. As a result with respect to variation in real power generation is reflected in the voltage as well. This oscillation continues as the wind turbine tries to adjust the power out back to its nominal value after the gust of wind.

This simulation result identifies the need for having a storage requirement or grid connection to handle intermittent generation of power output.

In the result from fault ride through simulation identifies the risk of voltage dip at the terminal of a wind turbine which can be detrimental for sensitive power electronic converters. In the wind power plant used in this simulation, a fault ride through capability was implemented. During the fault, active power output was reduced while the reactive power output is increased. This is required by some of the grid codes. Therefore, it is crucial for the wind power plant to both ride through the fault and increase reactive power output too.

V. CONCLUSION

This paper discusses main challenges caused by renewable integration in microgrid applications. From simulation results of this paper it is identified that replacement of synchronous generators with IBRs threatens the voltage and frequency stability of a microgrid. A comparative dynamic and static analysis of IEEE 9 bus system in the presence of synchronous generators and wind power plants proves that, both voltage and frequency stability is deprived by the presence of IBR of wind power plants. Even in the presence of IBRs, voltage stability is improved in grid tied operation (scenario 3) in compared to islanded operation (scenario 2). From dynamic analysis results it can be concluded that addition of a synchronous condenser improves voltage stability of the microgrid. It shall be concluded that, a highly sophisticated control structure is required to maintain stringent voltages and frequencies in all bus bars of the microgrid.

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