Evaluation of Power Quality Indices in Stand-alone Hybrid Micro-grid System

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***Abstract*: Due to issues like depletion of fossil fuel resources, exponential growth in power demand, electrification in rural areas, peak load demand, quality and reliability of electric power supply has laid to Micro-grids deployment with golden opportunity in the Indian context. Reason for key catalysts for the installation of the Micro-grids in India are, attractive subsidies from Indian government, regulations on fossil fuel usage, and recent energy missions in India. In Micro-grid operation, most important parameter is quality of the power supply i.e. Power Quality.motives for the work are reducing losses due to poor quality of power supply and thereby reducing cost and improving efficiency in the Micro-grid operation, expanding access to electricity by renewable usage, etc. For the reasons mentioned, in this work, Power Quality Analysis of standalone hybrid Micro-grid Power System is tried. In this work, Micro-grid is designed with integration of Solar, Wind (Double Fed Induction Generator) and Diesel Generator units. This integrated Micro-grid model is simulated and analyzed by using MATLAB software. In this work, various power quality issues such as Total Harmonic Distortion, Voltage imbalance, Under-voltage and Over-voltage, Voltage Sag and Swell are analyzed.**

Keyword: *Microgrid, photovoltaic array, wind energy system, battery storage system, MPPT.*

I. INTRODUCTION

In recent years, due to commercial and industrial revolutions, that demands more and more electricity to meet their needs. Due to this, conventional utility grid gets overloaded and creates problems of poor energy transmission efficiencies, environmental pollutions, high installation and operational costs, etc. and constant evolution of the functional and regulatory changes of electric utilities have led to a new trend of micro power plants at distribution called Micro-grids.[1]
Renewable Energy System is connected to the DC bus through the local controller. Local controller consists of isolation switch and DC to DC / AC to DC converter to fulfill the rating of the DC bus. Local controller takes control signal from Energy Management Control Unit and controls Renewable Energy System connection to the DC bus. Design of Energy Management Control Unit is such that to get optimum operation by checking the load availability at each instant and managing Renewable Energy System or Load or utility link to Micro-grid. Output of the DC bus is given to the micro-grid through a three phase inverter. Interfacing of micro-grid with utility is done through the Grid Exchange Unit. Grid Exchange Unit consists of a transformer with High Voltage side maintained at 11 kV and low voltage side maintained at 440 V and performs bidirectional action of power importing and exporting based on deficit or excess conditions. [2]
Due to issues like depletion of fossil fuel resources, exponential growth in power demand, electrification in rural areas, peak load demand, quality and reliability of electric power supply has laid to Micro-grids deployment with golden opportunity in the Indian context. Reason for key catalysts for the installation of the Micro-grids in India are, attractive subsidies from Indian government, regulations on fossil fuel usage, recent energy missions in India. In Micro-grid operation, most important parameter is quality of the power supply i.e. Power Quality. [3]
Motives for the work are reducing losses due to poor quality of power supply and thereby reducing cost and improving efficiency in the Micro-grid operation, expanding access to electricity by renewable usage, etc. For the reasons mentioned, in this work, Power Quality Analysis of standalone hybrid Micro-grid Power System is tried. In this work, Micro-grid is designed with integration of Solar, Wind (Double Fed Induction Generator) and Diesel Generator units.[4]

2. Power quality issues in Micro grid

End users and electrical utilities are becoming more and more concerned about power quality. The power quality has become important in the power sector industries since the late 1990s. Engineers are now solving the power quality issues using system approach rather than handling them as individual problems. The reasons for the increased concern are as follows:
More and more use of power electronics based devices and microprocessor based controls which are more sensitive to power quality variations than that the equipment used in the past. The increased importance on overall power system efficiency has resulted in use of more and more application of devices such as higher efficiency, adjustable speed motor drives and shunt condensers for improving the power factor to reduce losses in power system. This leads to increased harmonic levels in the power system.

Now we are having the integrated network which means the failure of one of the device leads to much more consequences due to possibility of cascaded failures.

End users are better informed about power quality issues such as interruptions, sags, swells, switching transients, etc. are challenging the power utilities to improve the delivered power quality.

Power quality is defined as either voltage quality or current quality. It is aimed at maintaining the system voltage or current as pure sinusoidal with 1 per unit magnitude at 1 per unit frequency and the phase shift of 120 degree between the adjacent phases in a three phase system of voltages. The term power quality aims at maintaining unity power factor always in a system. [5]

3 Characterization of Electric Power Quality:

1. Transients
2. Short duration and long duration voltage variations
3. Voltage imbalance
4. Waveform distortion
5. Voltage fluctuations
6. Power frequency variations

1) Transients

Transients is a kind of short duration phenomenon. The causes of Transients are sudden load throw, sudden switching ON of large loads, due to external disturbances that cause the shift of operating point of the system. Transients are present in the system for a very short duration up to few cycles of the input voltage. This will lead to increase or decrease in magnitude of the voltage or current. There are two categories of transients that are
Impulsive Transients
Oscillatory Transients

2) Short Duration and Long Duration Variations

The disturbances in the voltage that lasts for the duration less than 1 minute fall under this category of short duration variations. It is classified as sag, swell, voltage fluctuations.
The disturbances in the voltage that lasts for the duration more than 1 minute fall under this category of short duration variations. It is classified as under-voltage, over-voltage, voltage fluctuations.
Sag: The reduction in the RMS voltage from 0.1 to 0.9 per unit for the duration less than a minute is called as Sag.
Swell: The increase in the RMS voltage from 1.1 to 1.9 per unit for the duration less than a minute is called as swell.
Interruptions: If the RMS voltage falls below 0.1 per unit for the duration less than a minute is called momentary interruption. [6]

Under-voltage: The reduction in the RMS voltage from 0.1 to 0.9 per unit for the duration more than a minute is called as Under-voltage phenomenon.
Over-voltage: The increase in the RMS voltage from 1.1 to 1.9 per unit for the duration more than a minute is called as Over-voltage phenomenon.
Interruptions: If the RMS voltage falls below 0.1 per unit for the duration more than a minute is called as sustained interruption.

3) Voltage Imbalance

Voltage Imbalance is the phenomenon in a three phase system where the three phases are not balanced. This phase imbalance can be in either phase angle or the magnitude. This will result in unbalanced current even when the load is balanced. Due to the imbalance, neutral current starts flowing and its magnitude is increased. Any imbalance in phase angle or magnitude or both results in unbalanced currents and neutral overloading in the system.

4) Waveform Distortion

Waveform Distortion is the characterization in which the voltage or current waveforms are not purely sinusoidal. This non-sinusoidal voltage or current will increase the system losses and heating of the loads. Further it may cause voltage fluctuations, flickering, etc.

5) Voltage Fluctuations

Voltage fluctuations is the characteristic in which only the magnitude of the system voltage is not equal to 1 per unit in any of or all of the phases in a three phase system. This will result in unbalanced current and neutral overloading. It also results in overheating of the load equipment. The causes may be due to varying loads, unsymmetrical faults, climatic conditions, etc.

6) Power Frequency Variation

Power Frequency Variation means the frequency of the system is not equal to 1 per unit.This may be the problem due to sudden load variations on the system. A sudden load throw will cause the system frequency to increase beyond 1 per unit, similarly a sudden loading will cause the system frequency to dip below 1 per unit.The variation in frequency will result in speed changes in AC drives, malfunctioning of the load equipment such malfunctioning of triggering of thyristor converters. [7]

4. Power Quality Problems

1. Poor load power factor.
2. Non-linear and unbalanced loads
3. Power quality indices
4. Modelling of harmonic distortion- Total Harmonic Distortion and Total Demand Distortion.

Non-Linear Loads
Loads are classified in two categories based on the terminal voltage and current relation via, linear loads and non-linear loads.
Linear loads are defined as the loads in which the load voltage and load current are sinusoidal and in phase with each other. The power factor is always unity in this case.
Non-linear loads on the other side, in which the load voltage and load current are not in phase with each other. The waveforms may be sinusoidal or non-sinusoidal. All practical loads comes under this category.

Total Harmonic Distortion
It is the measure of the closeness of a waveform with respect to its fundamental component. Fourier series is the mathematical tool used to extract the fundamental and harmonic components from its distorted waveform. [8]

5 Modelling of Hybrid Micro-grid System

In this work, practical data of Solar Irradiance (Monthly Average Value), Temperature, Wind speed in Agartala City is taken as input for the Solar PV Array, which is shown in the tabular and graphical form as below: [9]

Monthly Average	
JAN	4.06
FEB	5.11
MAR	5.30
APR	4.87
MAY	4.49
JUN	2.73
JUL	2.95
AUG	3.54
SEP	3.87
OCT	4.83
NOV	5.86
DEC	4.93

Table 5.1 Solar Irradiance (Monthly Average Value)

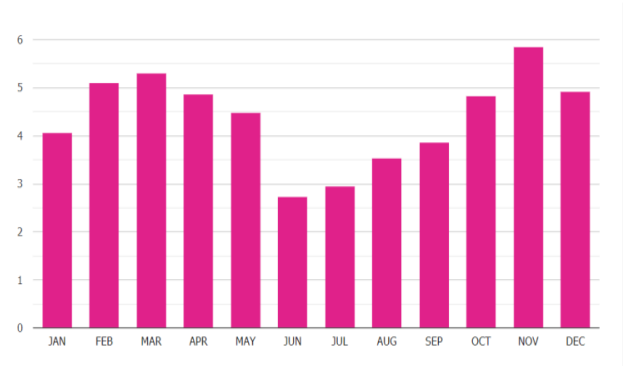


Fig. 5.1 Solar Irradiance (W/m^2)

Month	Ambient temperature (%)	Wind speed (m/s)
May 2012	33.9	2.6
June 2012	32.5	3.2
July 2012	32.4	3.8
August 2012	32.4	1.7
September 2012	32.4	1.3
October 2012	31.2	1
November 2012	28.6	1.1
December 2012	24.1	1.7
January 2013	21.2	1.2
February 2013	22.4	1.6
March 2013	35	4.3
April 2013	35.8	3.2

Table 5.2 Ambient Temperature (^{0}C) & Wind Speed (m/s)

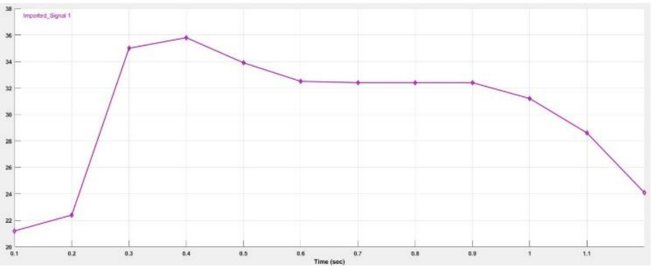


Fig. 5.2 Ambient Temperature (%)

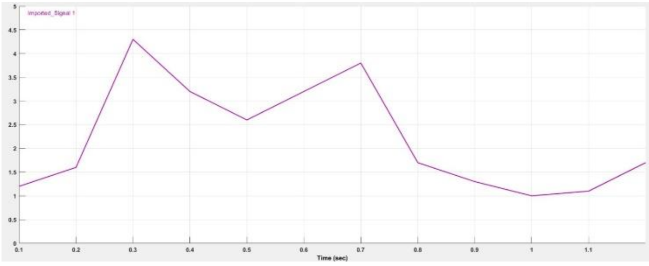


Fig. 5.3 Wind Speed (m/s)

5.1 MPPT INC Algorithm:

Incremental conductance MPPT algorithm is used to solve the disadvantages of perturb and observe MPPT technique. Incremental conductance method computes the maximum power point by comparing the incremental conductance to the instantaneous conductance of solar PV array, when this two are equal the output voltage chooses the MPPT voltage. The controller maintains this voltage till their radiation changes and process is repeated. The Incremental conductance MPPT algorithm is based on the observation that is the maximum power point, change in power with respect to the change in voltage is equal to zero.

$$\frac{I}{V} = \frac{dI}{dV};$$

Where $\frac{I}{V}$ is the instantaneous conductance and $\frac{dI}{dV}$ is the Incremental conductance.

$$\frac{dP}{dV} = 0;$$

According to rules of derivative we can express –

$$\frac{dP}{dV} = \frac{d(V*I)}{dV} = I*\frac{dV}{dV} + V*\frac{dI}{dV}$$

$$= \mathrm{I} + V*\frac{dI}{dV}$$

Maximum power point is reached when $\frac{dP}{dV} = 0$ and

$$0 = I + V*\frac{dI}{dV}$$

$$\frac{dI}{dV} = -\frac{I}{V}$$

If $\frac{dP}{dV} > 0$ then $V_p < V_{mpp}$

If $\frac{dP}{dV} = 0$ then $V_p = V_{mpp}$

If $\frac{dP}{dV} < 0$ then $V_p > V_{mpp}$

The above equations can be explained by using Power v/s Voltage characteristics of solar PV Array-

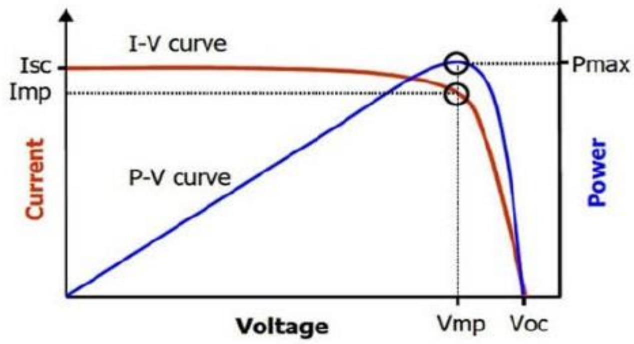
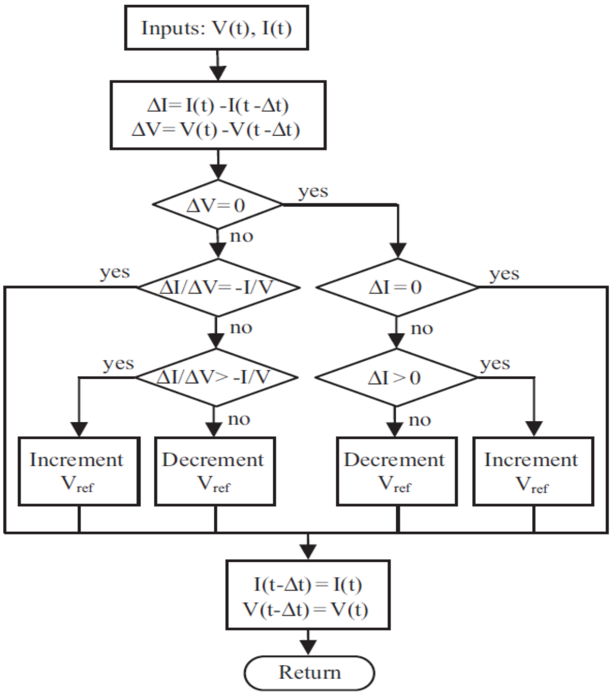


Fig. 5.4 MPPT Characteristics

If $\frac{dP}{dV} > 0$ that is the slope of Power v/s Voltage characteristics is positive this means that PV voltage is less then the MPP voltage, in this case we have to increase the duty cycle of the controller. If $\frac{dP}{dV} = 0$ that is the slope of Power v/s Voltage characteristics is zero this means that PV voltage is equal to M PP voltage, in this case dV and dI will be zero and this voltage must be maintained till their radiation changes. If $\frac{dP}{dV} < 0$ that is the slope of Power v/s Voltage characteristics is negative this means that PV voltage is greater than the MPP voltage, in this case we have to decrease the duty cycle of the controller. [10]

5.2 Flowchart for Incremental Conductance (MPPT) Algorithm:



5.3 Boost Converter:

Boost Converter is one of the type of chopper or DC to DC Converter. It is also called as step-up regulator. In Boost Converter, the input DC voltage can be stepped up by varying the firing angle of the switch (any device such as thyristor, IGBT, MOSFET can be used as switch, in case of chopper). Switch is represented with 'S' in the below figure. [11]

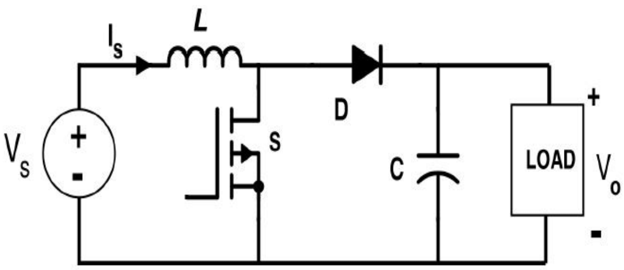


Fig. 5.5 Circuit Diagram of boost converter

Where, V_s is the Source Voltage / input DC voltage I_s is the source current, L is the Inductor (used to limit the ripples in the current), C is the Capacitor (used to maintain the steady DC output voltage)

D is the Diode (used to oppose the reverse current flow, V_o is the DC output voltage.

Operation of the Boost Converter consists of two modes:
On-State
Off-State

The output voltage of the Boost Converter is given by the equation:

$$V_o = \frac{Vs}{1-\alpha};$$

Where, α is called as duty ratio, which is given by

$$\alpha = T_{on} / T_{off}$$

T_{on} is called as Turn ON time and T_{off} is called as Turn OFF time.

The circuit diagrams in ON state and OFF state are shown below:

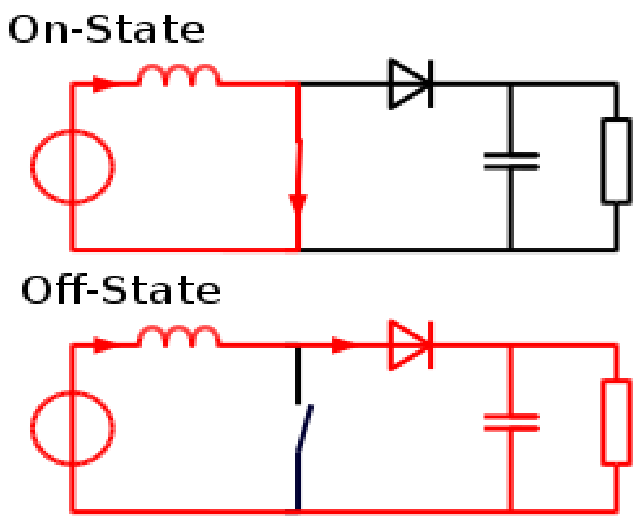


Fig. 5.6 Circuit Diagram of boost converter in ON and OFF state

5.4 Three Phase inverter:

Three phase inverter converts input DC voltage into three phase AC voltage. V_{dc} is the input DC voltage. It consists of six switches (i.e. Power Electronic Devices like MOSFET, IGBT, SCR, etc. can be used as switch). At a time, only two switches are ON.
When S_1, S_2 are ON then the output voltage is equal to the V_{ac}. When S_3, S_4 are ON then the output voltage equal to the V_{ab}. When S_5, S_4 are ON then the output voltage equal to the V_{bc}.

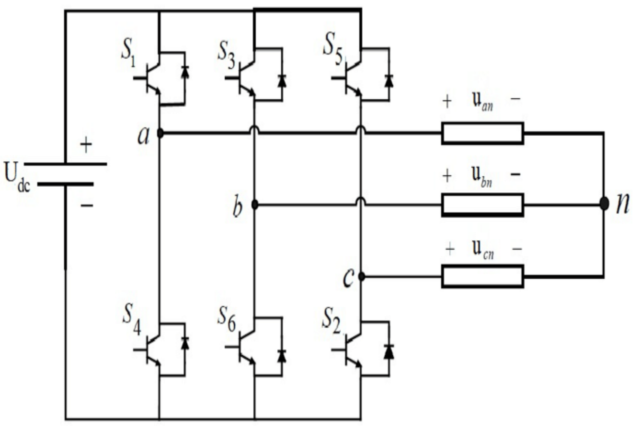


Fig. 5.7 Circuit Diagram of three phase inverter

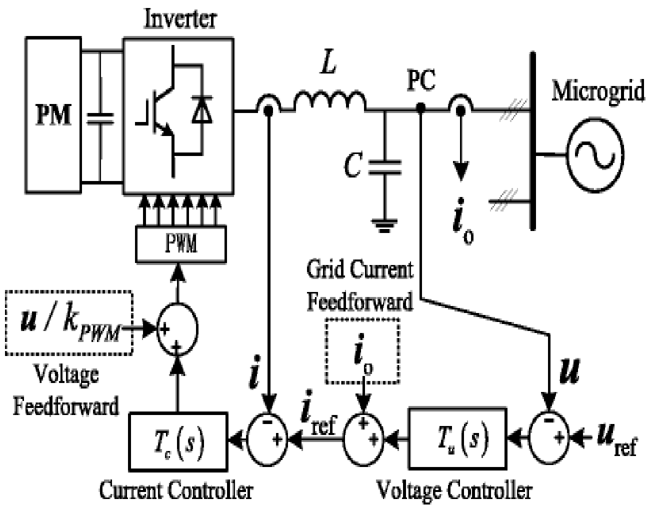


Fig. 5.8 Block diagram of inverter Control

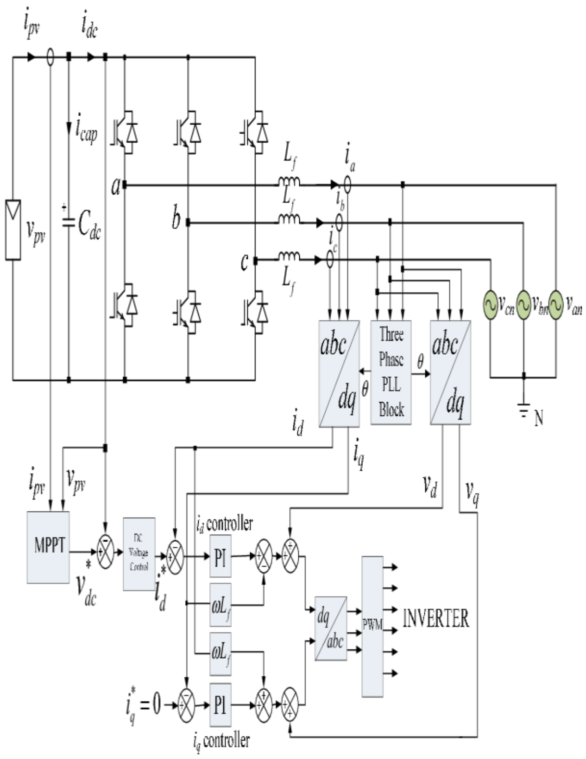


Fig. 5.9 Detailed inverter control in micro-grid

v_{pv} is the output DC voltage of the Solar PV Array, i_{pv} is the output current of the Solar PV Array. v_{pv} and i_{pv} are provided as input to the MPPT controller. MPPT Controller tracks the maximum power point voltage and gives the v_{dc}^* as the output of the MPPT Controller. This voltage is compared with v_{pv} and the error i.e. (v_{dc}^* - v_{pv}) signal is given to the DC Voltage Control which converts the voltage into corresponding current i.e. i_d^*. The three phase currents i_a , i_b , i_c are converted into abc to dq transformation. The output current i_d is compared with i_d^* and the error signal i.e. (i_d^* - i_d) is provided as input to the PI Controller (i_d controller). I_q^* is set to zero and current i_q is compared with i_q^* and the error signal i.e. (i_q^* - i_q) is provided as input to the PI Controller (i_q controller). Again these i_d and i_q currents are transformed into abc frame and given as input to the PWM, which provides the required pulses for the inverter operation.

Simulation Results

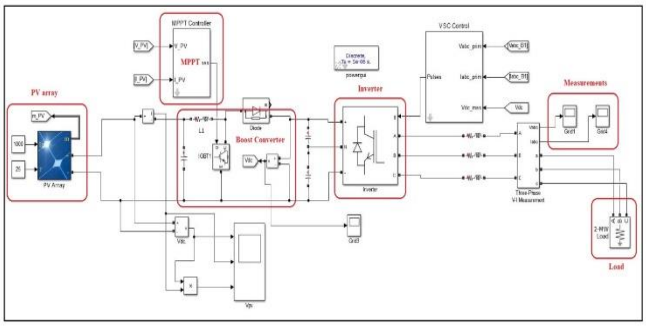


Fig. 6.1 Solar PV MATLAB Model

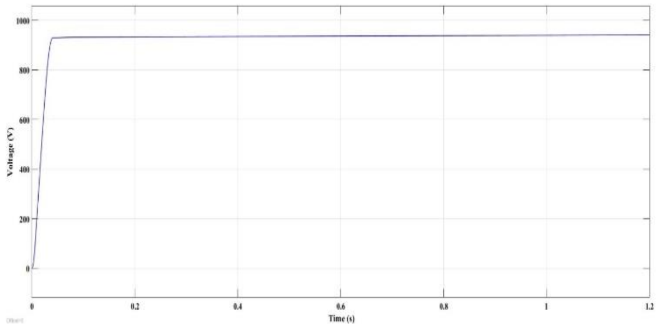


Fig. 6.2 Boost Converter Output

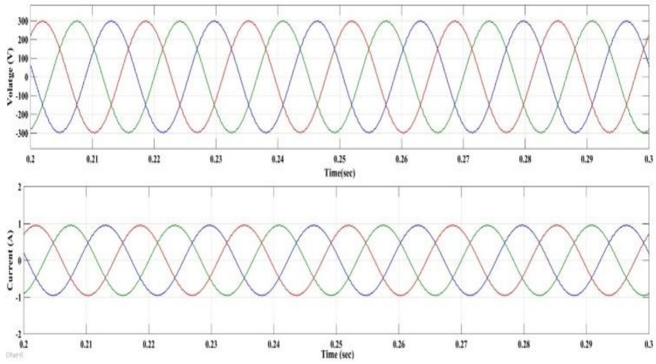


Fig. 6.3 Output Voltage and Current

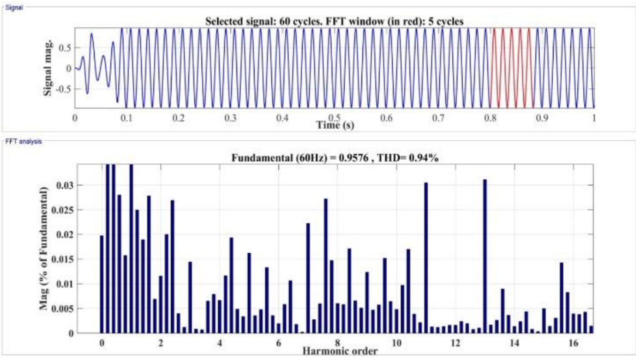


Fig. 6.4 Fourier Analysis

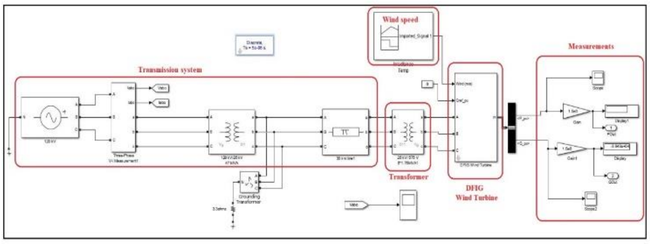


Fig. 6.5 Wind Farm MATLAB Model

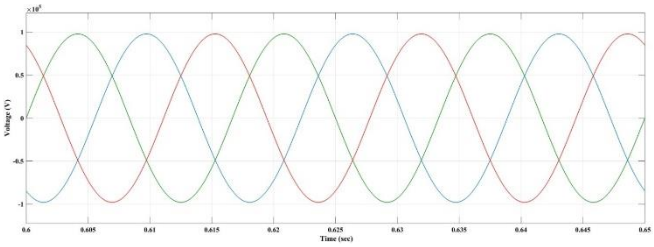


Fig. 6.6 Voltage Output

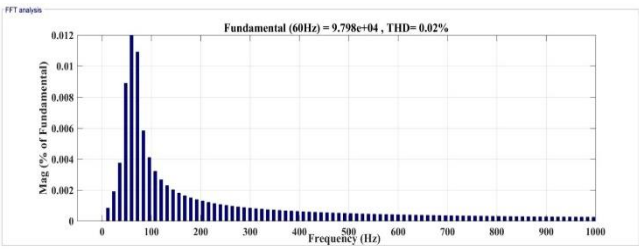


Fig. 6.7 Fourier Analysis

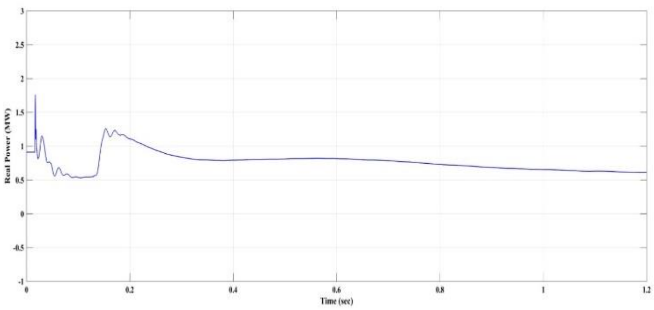


Fig. 6.8 Real Power Output (MW)

Output Reactive Power is almost zero, which can be observed from the output figure shown below, because we have kept $I_{q,ref}$ equal to zero.

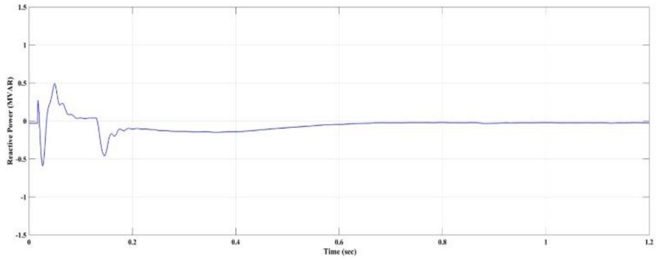


Fig. 6.9 Reactive Power Output (MVAr)

6.1 Overall Hybrid micro-grid Model

In this MATLAB Model, Solar PV model, Wind Turbine (Double Fed Induction Generator), Diesel Generator are integrated along with that distribution load is connected and simulated, analysed.

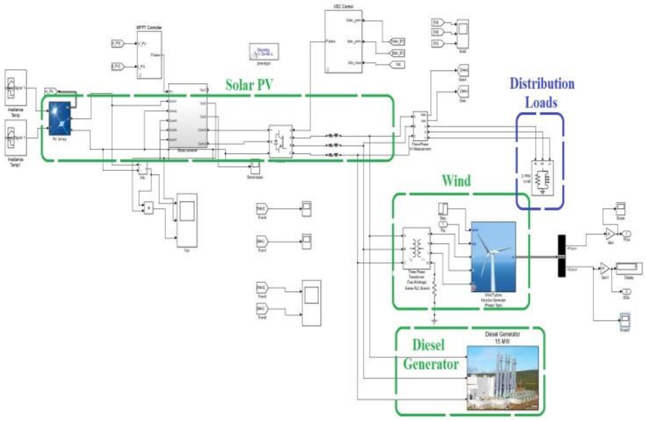


Fig. 6.10 Hybrid Micro-grid MATLAB Simulink Model

The Output Voltage and Current:

The output voltage is 20 kV, which can be observed from the output voltage figure shown below, obtained after running the simulation.

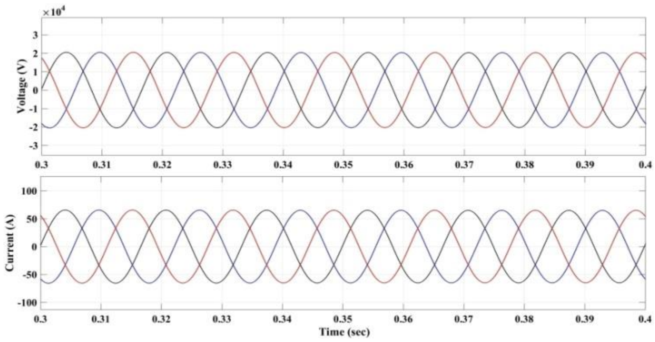


Fig. 6.11 The output voltage and current of Hybrid Micro-grid System

Active Power:

In MATLAB Simulink model shown above, we have connected 2 MW load. After simulating this model, we have got the output Active Power to be 2 MW, which can be seen from the below figure.

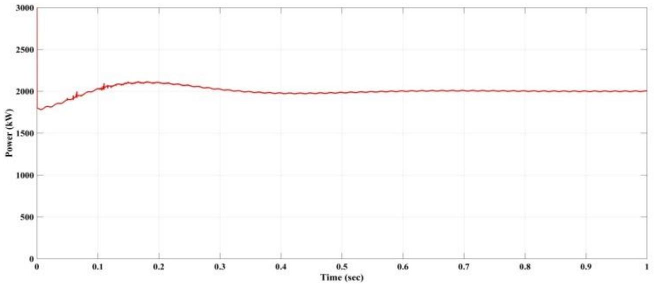


Fig. 6.12 Active Power Output of Hybrid Micro-grid System

Reactive Power:

Output Reactive Power is almost zero, which can be observed from the output figure shown below, because we have kept $I_{q,ref}$ equal to zero.

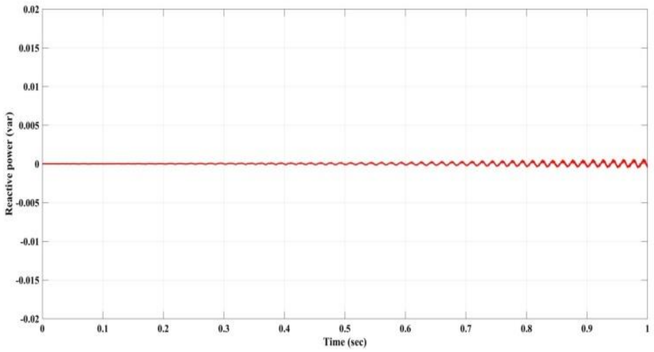


Fig. 6.13 Reactive Power Output of Hybrid Micro-grid system

6.2 Total Harmonic Distortion:

Standards EN 50160 and IEC 61000-2-2 specifies that the Total Harmonic Distortion (THD) of the supply voltage including all harmonics up to 40th order should be less than 8 %.

To analyze the THD of the system, in this work a non-linear load is connected to the system at 0.5 seconds as shown in the MATLAB model below. Fast Fourier Transform (FFT) analysis is carried out with maximum and power frequencies of 1 kHz and 60 Hz respectively.

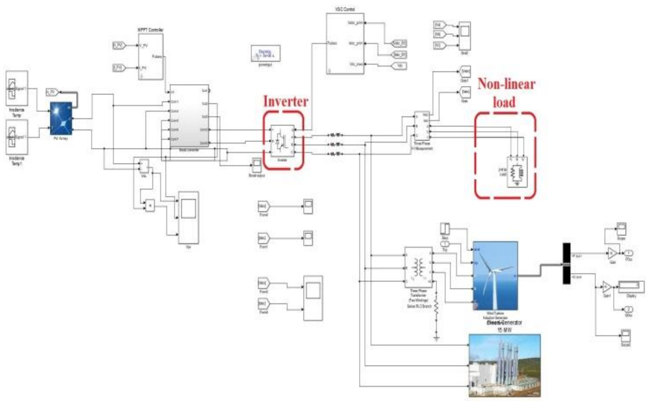


Fig. 6.14 MATLAB Model for simulating THD

Current THD:

Current THD for the above MATLAB model comes out to be 0.44%, which can be observed from the below output figure.

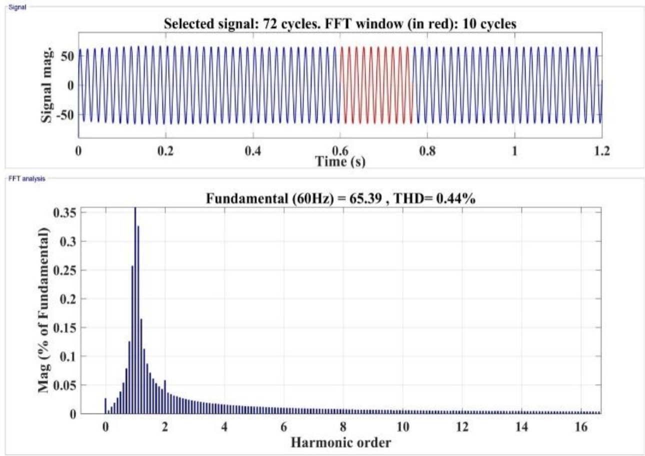


Fig. 6.15 Fourier Analysis Window for Current THD

Voltage THD:

Voltage THD comes out to be 0.70% which is under the specified limits according to the standards EN 50160 and IEC 61000-2-2, which can be observed from the below figure shown.

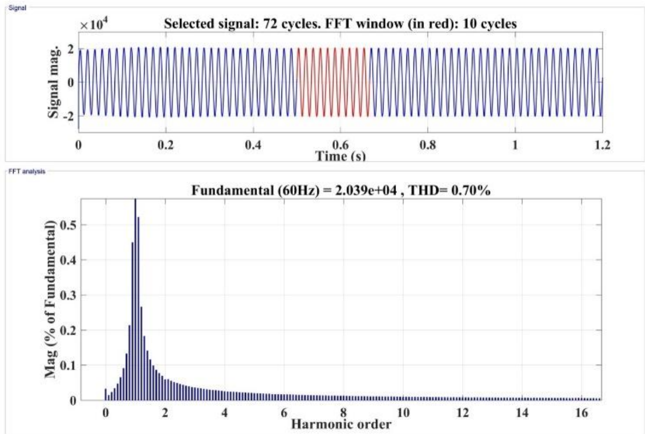


Fig. 6.16 Fourier Analysis Window for Voltage THD

6.3 Voltage Imbalance or Unbalance:

To analyse the voltage imbalance or unbalance, in this work a single-phase load is turned ‘ON’ on a three-phase line at specific time and sequence voltages are noted is shown in the MATLAB model below. The corresponding voltage imbalance can be calculated as-

$$\% \text{ Imbalance} = \frac{-ve\ sequence\_voltage}{+ve\ sequence\_voltage} * 100.$$

Utility grid failure, single phase short circuit faults i.e. Line to Ground Fault, Double Line to Ground Fault or Line to Line Fault results in the voltage imbalance in the three phase system, then the Micro-Grid voltage transfers to imbalance.

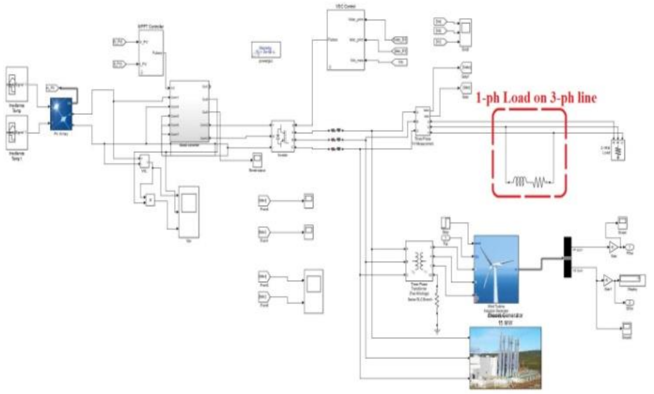


Fig. 6.17 MATLAB Simulink Model for simulating Voltage Imbalance

According to the simulation model, single phase load is connected on the three phase line i.e. in this work, single phase load is connected between the lines 'b' and 'c'. Due to this, voltages of three phases is not same, voltage at 'a' phase is increased and that of 'b' and 'c' phases is same but reduced, which can be observed from the output Voltage figure shown below. As voltage at phase 'a' is increased, current reduces and voltages at phases 'b' and 'c' is reduced, so current is increased, which can be observed from the output current waveform as shown below.

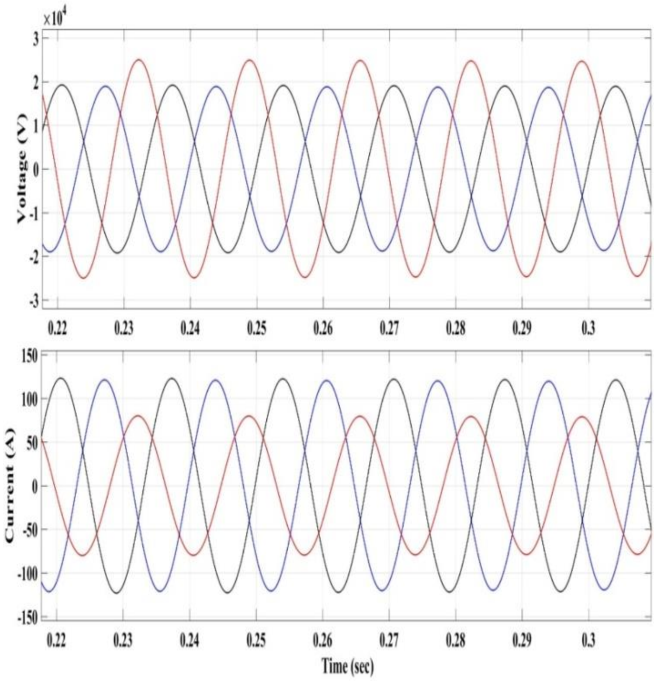


Fig. 6.18 Output showing Voltage Imbalance in the Micro-grid system

6.4 Over-voltage and Under-voltage:

In this work, Over-voltage and under-voltage phenomenon are analyzed by starting large inductive and capacitive loads switched ON and OFF simultaneously, which is shown in the MATLAB model as below.

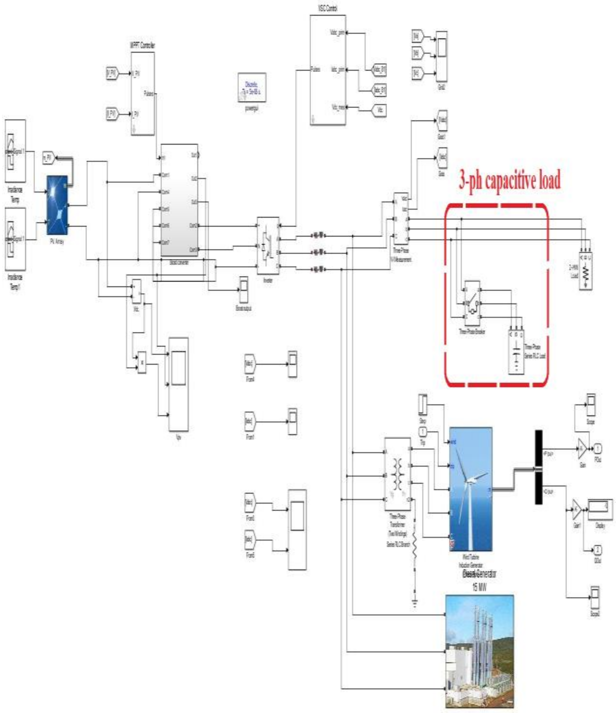


Fig. 6.19 MATLAB Simulink Model for simulating Over-voltage and Under-voltage

Due to capacitive load, whether it may be single phase or three phase, voltage is increased and due to inductive load, whether it may be single phase or three phase, voltage is decreased.

Overvoltage due to 1-phase capacitive load:

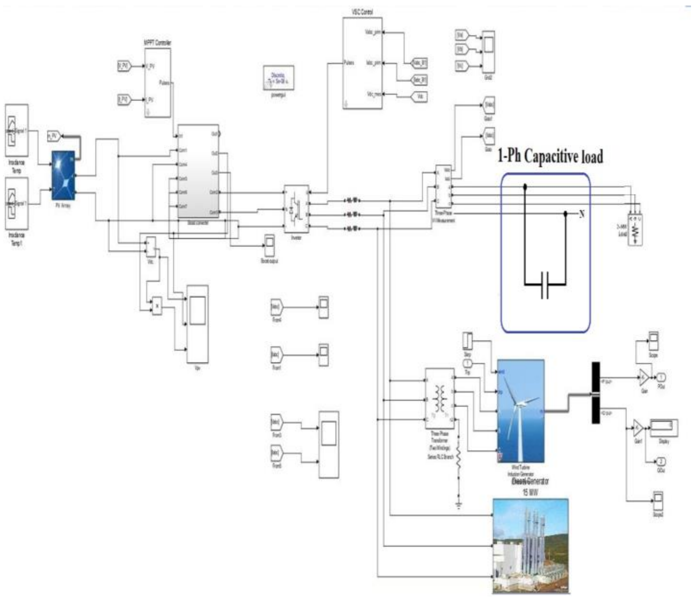


Fig. 6.20 MATLAB Simulink Model for simulating Over-voltage phenomenon due to 1-phase capacitive load

In this case, single phase capacitive load is connected across 'b' and 'c' phases, so current in 'a' phase is almost zero. Due to this voltages at 'b' and 'c' phases is increased, which can be observed from the figure given below.

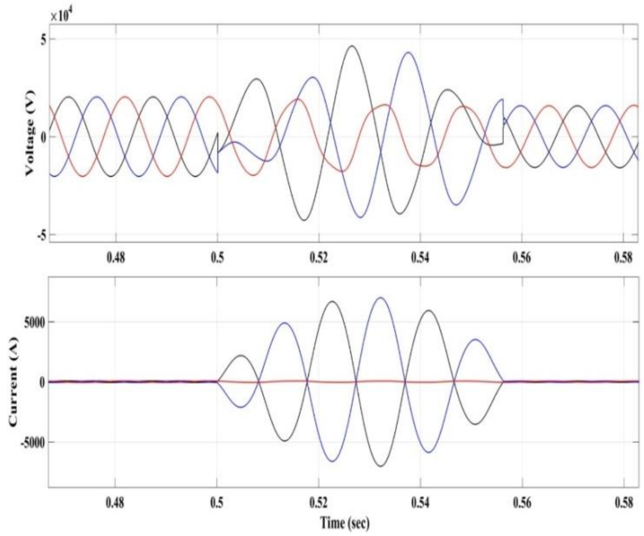


Fig. 6.21 Output voltage and current waveform representing Over-voltage phenomenon due to 1-phase capacitive load

Overvoltage due to 3-phase Capacitive load:

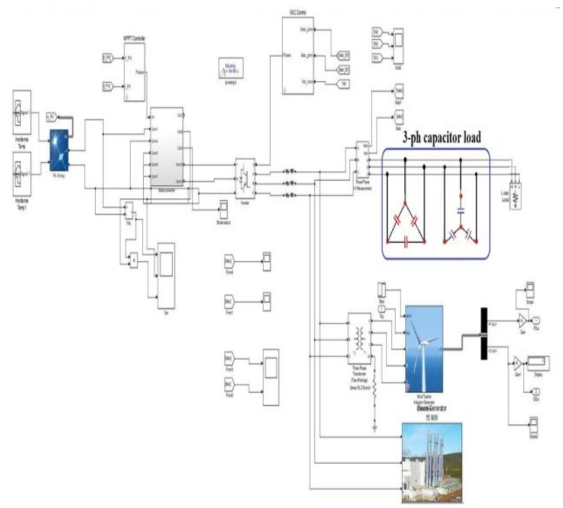


Fig. 6.22 MATLAB Simulink Model for simulating Over-voltage due to 3-phase capacitive load

In this case, three phase capacitive load is connected at 0.4 sec. Due to which over-voltage is exhibited in all the three phases, which can be observed from the below output figure shown below.

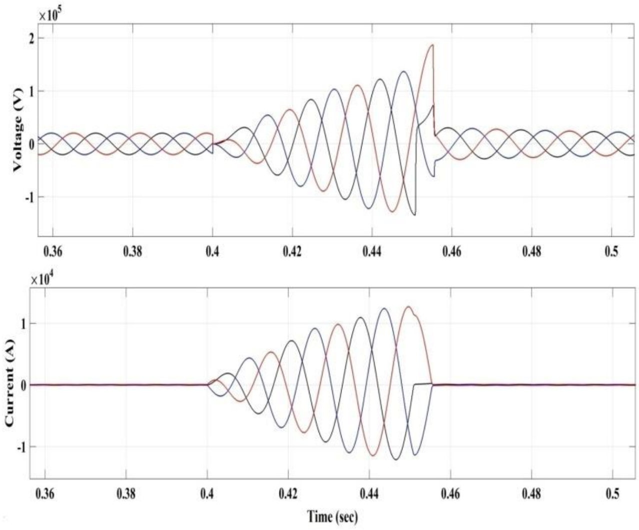


Fig. 6.23 Output voltage and current waveform for over-voltage phenomenon due to 3-phase capacitive load

Under-voltage due to 1-phase inductive load:

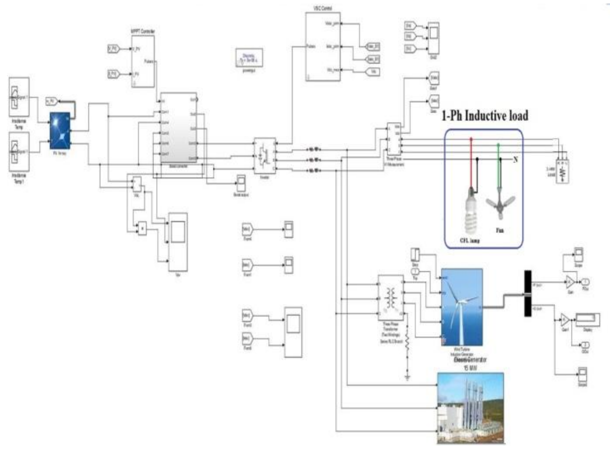


Fig. 6.24 MATLAB Simulink Model for simulating Under-voltage phenomenon due to 1-phase inductive load

In this case, single phase inductive load is connected at 0.5 sec across the phases ‘b’ and ‘c’, due to which under-voltage is observed.

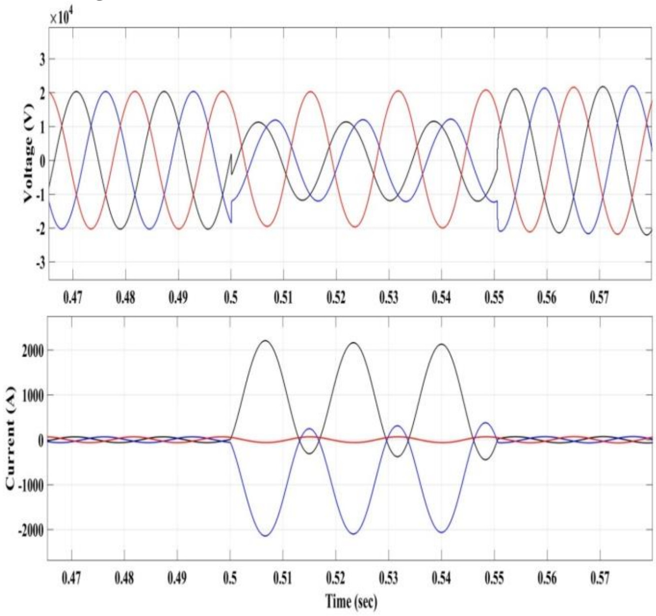


Fig. 6.25 Output voltage and current waveform for under-voltage phenomenon due to 1-phase capacitive load

Under-voltage due to 3-phase inductive load:

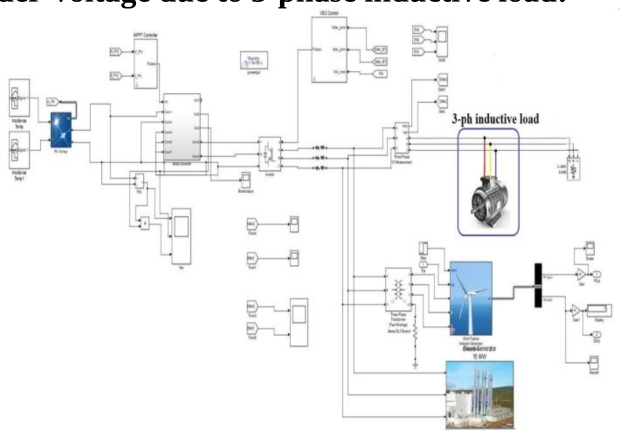


Fig. 6.26 MATLAB Simulink Model for simulating under-voltage phenomenon

In this case, three phase inductive load is connected at 0.4 sec., due to which under-voltage is observed in all the three phases as shown in the output figure shown below.

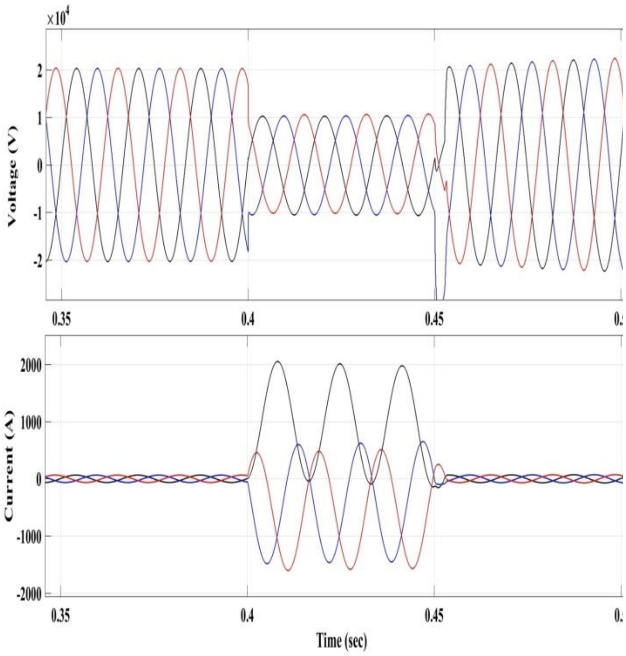


Fig. 6.27 Output voltage and current waveform for under-voltage phenomenon due to 3-phase inductive load

6.5 Voltage Sag and Swell

Causes of voltage sag are short circuit faults, abrupt increase in load, starting of motors, turning ON of electric heaters, sudden increase in source impedance due to loose connection.
Causes of voltage swell are damaged or loose connection of neutral wire, abrupt decrease in load on a circuit.
In this work, to analyze the voltage sag and swell, the single line to ground fault is applied on 'b' phase as shown in the MATLAB model below. The drop in the line voltage between 'a' and 'b' phases and swell in un-faulted phases i.e. 'b' and 'c' phases are recorded.

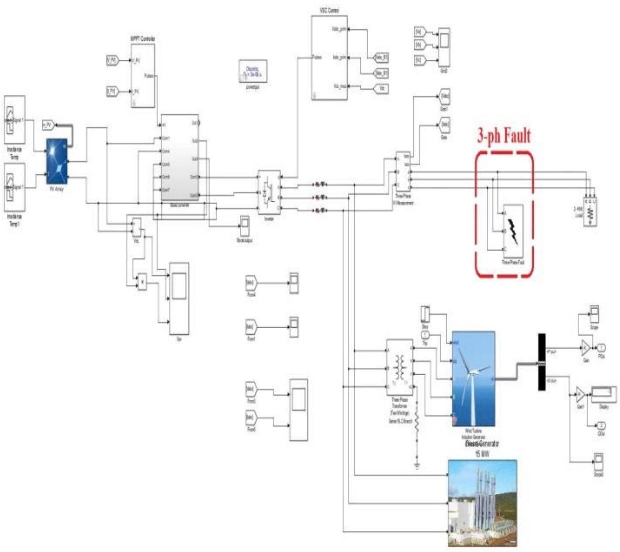


Fig. 6.28 MATLAB Simulink Model for simulating voltage sag and swell phenomenon

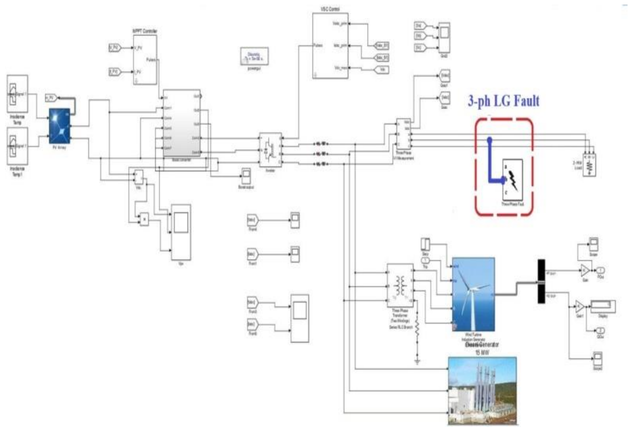


Fig. 6.29 MATLAB Simulink Model for simulating Line to Ground Fault

In this case, single line to ground fault is applied on phase 'b' at 0.8 sec., so $V_b=0$ and swell in voltage is observed on the remaining phases i.e. phases 'a' and 'c', which can be observed from the figure given below.

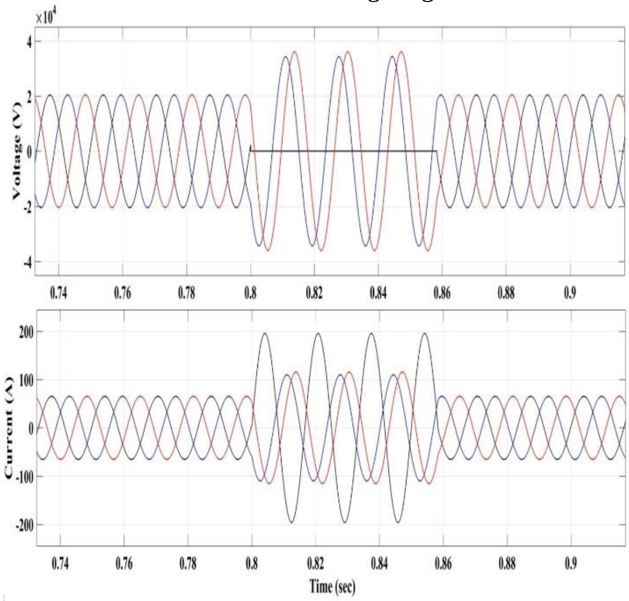


Fig. 6.30 Output voltage and current waveform due to Line to Ground Fault and exhibiting Sag and Swell

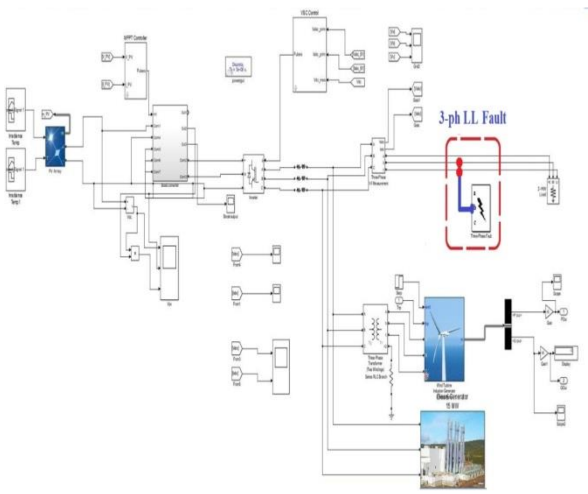


Fig. 6.31 MATLAB Simulink Model for simulating Line to Line Fault

In this case, Line to Line fault is applied on the phases 'b' and 'c' at 0.8 sec, due to which $V_b = V_c$ and sag is observed in these phases and $I_a = 0$, $I_b = -I_C$, which can be observed as shown in the output figure shown below.

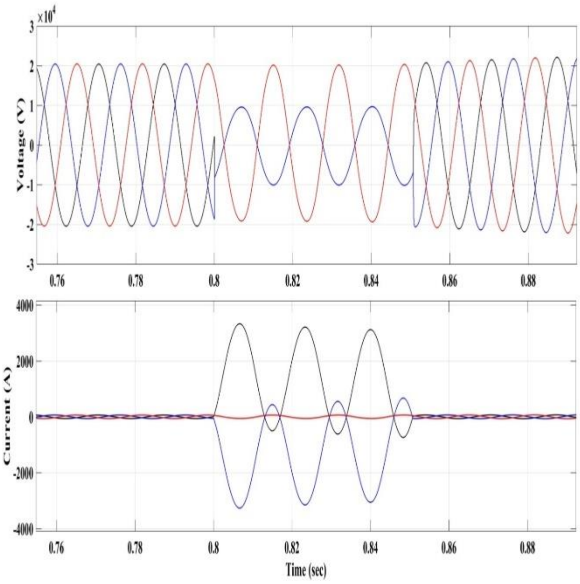


Fig. 6.31 Output voltage and current waveform due to Line to Line Fault and exhibiting Sag and Swell

7. Conclusion and Future scope

Due to ever increasing demand of electricity and depletion of fossil fuel resources, now a days we are moving towards more and more renewable energy resources. By the use of renewable energy resources we can provide the electricity to the local loads and also the problem of rural electrification can be solved.

For the renewable energy resources and also for the conventional energy sources, while providing electricity to the loads main problem faced is the quality of that provided electricity also called power quality issues, which are discussed as in the above chapters.

In this work, renewable energy sources such as Solar PV, Wind Turbine and Diesel Generator are integrated and simulated along with the loads, which forms the Micro-grid. These models are simulated by using required inputs which are Solar Irradiance, Temperature, Wind Speed, etc. and these inputs are taken considering agartala city. After simulating, we can analyze this for THD (Voltage THD, current THD), Voltage imbalance, Over-voltage and Under-voltage, Sag and swell, etc.

This work can be extended such that we can simulate Micro-grid installed in various cities, considering inputs like Solar Irradiance, Temperature, Wind Speed, etc. for the respective city and then analyze this model for various power quality issues and after analyzing this we can take the necessary actions so that we can provide the best quality of power to the loads which leads to reduced losses and increased efficiency of the system.

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