Power System Laboratory-II

B.Tech. (Electrical Engineering)

Department of Electrical Engineering
Veer Surendra Sai University of Technology Burla

Contents

Vision

To be recognized as a center of excellence in education and research in the field of Electrical Engineering by producing innovative, creative and ethical Electrical Engineering professionals for socio-economic development of society in order to meet the global challenges.

Mission

Electrical Engineering Department of VSSUT Burla strives to impart quality education to the students with enhancement of their skills to make them globally competitive through:

1. M1. Maintaining state of the art research facilities to provide enabling environment to create, analyze, apply and disseminate knowledge.
2. M2. Fortifying collaboration with world class R& D organizations, educational institutions, industry and alumni for excellence in teaching, research and consultancy practices to fulfil 'Make in India' policy of the Government.
3. M3. Providing the students with academic environment of excellence, leadership, ethical guidelines and lifelong learning needed for a long productive career.

Program Educational Objectives

The program educational objectives of B.Tech. in Electrical Engineering program of VSSUT Burla are to prepare its graduates:

1. To have basic and advanced knowledge in Electrical Engineering with specialized knowledge in design and commissioning of electrical systems/renewable energy systems comprising of generation, transmission and distribution to become eminent, excellent and skillful engineers.
2. To succeed in getting engineering position with electrical design, manufacturing industries or in software and hardware industries, in private or government sectors, at Indian and in Multinational organizations.
3. To have a well-rounded education that includes excellent communication skills, working effectively on team-based projects, ethical and social responsibility.
4. To have the ability to pursue study in specific area of interest and be able to become successful entrepreneur.
5. To have broad knowledge serving as foundation for lifelong learning in multidisciplinary areas to enable career and professional growth in top academic, industrial and government/corporate organizations.

List of Experiments

1. Determination of transient and sub-transient reactance of a 3-phase alternator.
2. Parallel operation of two alternators and effect of its load sharing.
3. Characteristics and performance of induction generator.
4. Perform load flow, optimal power flow and economic dispatch in power systems.
5. Measurement of power quality.
6. Fault analysis and determination of transient stability of power systems.
7. Calibration of different surface gaps for measurement of high voltage (Sphere-sphere, Pin-pin, Disc-disc) and Dry flash over test on different types of insulators by 100 kV AC and 280 kV DC
8. Study of impulse generator and generating standard impulse wave shape.
9. Measurement of loss tangent and dissipation factor using high voltage Schering bridge. Testing of insulating oil.

Course Outcomes

1. Evaluate dynamic performance parameters of alternators and demonstrate parallel operation and load sharing.
2. Evaluate the characteristics and performance of induction generators.
3. Compile and implement computer code for load flow, optimal power flow and economic dispatch ,
4. Compile and implement computer code for fault analysis and transient stability analysis of power systems and demonstrate power quality measurement.
5. Demonstrate calibration process of surface gaps, flash over test on insulators, measure dissipation factors.

Experiment 1

Three Phase Short Circuit of Alternator

1.1 Aim of the Experiment

To determine of transient and sub-transient reactance of a 3-phase alternator by performing three phase short circuit on alternator.

1.2 Apparatus Required

Refer Table 1.1 and Table 1.2.

Table 1.1: Apparatus for short circuit on alternator

SL.	Equipment	Rating	Quantity
1	Resistance	220 Ω, 7.9 A	01
2	Resistance	50 Ω, 10 A	01
3	Resistance	0.01 Ω, 50 A	01
4	Voltmeter	0.01 Ω, 50 A	01
5	Ammeter	0-5 A, DC	02
6	Ammeter	0-15 A, AC	02
7	Storage Oscilloscope	Three phase, 230 V	01
8	Contactor	32 A, 415 V	01
9	SPST Knife Switch	-	01

Table 1.2: Machine Specifications

SL.	Machine	Rating	Quantity
1	DC Compound Motor	16 HP, 220 V, 58 A, 1500 RPM	01
2	Three Phase Alternator	8 kVA, 400/231 V; 11.5 A, 1500 RPM	01

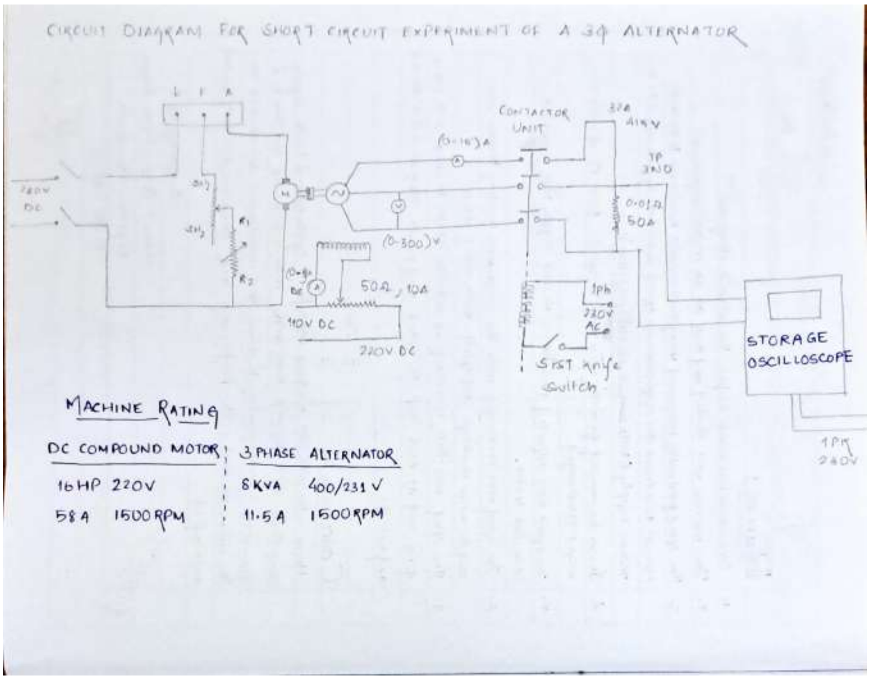


Figure 1.1: Circuit Diagram for Sudden Short Circuit Test of Alternator

1.3 Theoretical Background

In three phase short circuit test of an alternator, the flux linkages vary and therefore the source is of varying magnitude. This being a three phase short circuit, the switching angles in different phases are 120^0 apart. So there is a good chance that the conditions of 90^0 phase shift may occur where the decaying component have its maximum value at origin and the total current in some phases may be twice the peak value of the steady state current. Whenever a three phase short circuit occurs at the terminals of the alternator, the current in the armature circuit increases suddenly to a large value and since the resistance of the circuit is small as compared to reactance, the current is highly lagging and the power factor is approximately zero. Due to this sudden switching, there are two components of the current.

1. AC component,
2. DC component (decaying).

The rotor rotates at zero speed with respect to the field due to AC component of current in the stator where as it rotates at synchronous speed with respect to the field due to the DC component of current in the stator conductor. It is to be noted that the machine behaves like a transformer with the stator winding as primary and the rotor winding as secondary. The transformer action is there with respect to the DC component of current only. The AC component of current being highly lagging tries to demagnetize and reduce the flux in air gap. This reduction of flux from the instant of short circuit to the steady state operation cannot take place instantaneously because of the large amount of energy stored in the inductance of the corresponding system. In order to balance the

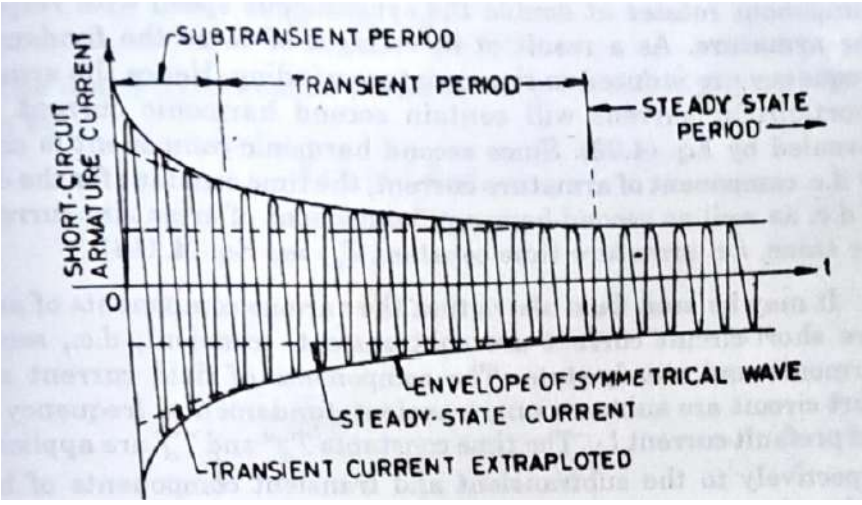


Figure 1.2: Typical short circuit current waveform of alternator

sudden increase in demagnetizing mmf of the armature current, the exciting current, that is, the field winding current must increase in the same direction of flow as before the fault. This happens due to transformer action.

At the instant of short circuit, there is mutual coupling between stator winding, rotor winding and damper winding. The reactance due to these three is called **sub-transient reactance**. The reactance due to coupling of stator winding and rotor winding is called **transient reactance**. The steady state reactance is called the **synchronous reactance**. The time constant of the damper winding is smaller than the rotor field winding since the equivalent resistance of the damper winding when referred to the state is more as compared to the rotor winding. It can be observed that the inductance increase from initial stage to final steady state. Thus $X_d'' > X_d' > X_s$.

1.4 Procedure

1. Firs the DC motor is started and is made to run at rated speed of the alternator.

2. The generator voltage is monitored and continuously adjusted to 200 V by varying the field current.

3. Then the speed of the alternator is changed to maintain the frequency to 50 Hz. This is done by varying the field rheostat of the DC motor (prime mover).

4. A storage oscilloscope is connected across a small resistance value of 0.01 ohm.

5. The three-phase alternator is short-circuited for a few seconds by means of a connector.

6. The connector works on the principle of magnetic induction and short-circuits the three phases simultaneously.

7. At the time of short-circuit, the transient, sub-transient and steady-state currents are stored in the storage oscilloscope.

Figure 1.3: Experimental Setup for Sudden Short Circuit Test of Alternator

Figure 1.4: Experimental Setup for Sudden Short Circuit Test of Alternator (cont.)

Table 1.3: Tabulation for Three phase short circuit on alternator

$V_{pre-fault}$	I_{SC}	No of cycles	Volts/div	Time/div	Frequency	V_{p-p}

8. Trace the waveforms in the storage oscilloscope. Note the Volts/division and Time/division in the panel. Tabulate results in the format provided in Table 1.3.
9. Since the oscilloscope measures only voltages, it can be converted into current by dividing with the resistance (0.01 ohm).
10. From the current values and the pre-fault voltage (200 V), the sub-transient, transient and steady-state reactances are computed using equations (1.1) to (1.6).

$$I''(\texttt{subtransient}) = \frac{V_{p-p}(\texttt{first cycle})}{\sqrt{2}\times 0.01} \tag{1.1}$$

$$I''(\texttt{transient}) = \frac{V_{p-p}(\texttt{fourth cycle})}{\sqrt{2}\times 0.01} \tag{1.2}$$

$$I(\texttt{steady-state}) = \frac{V_{p-p}(\texttt{last cycle})}{\sqrt{2}\times 0.01} \tag{1.3}$$

The values of reactances are obtained by using the following formula.

$$X_d''(\texttt{subtransient}) = \frac{V_{pre-fault}}{I''} \tag{1.4}$$

$$X_d'(\texttt{transient}) = \frac{V_{pre-fault}}{I'} \tag{1.5}$$

$$X_d(\texttt{steady-state}) = \frac{V_{pre-fault}}{I} \tag{1.6}$$

1.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications.

Experiment 2

Parallel operation of alternators

2.1 Aim of the Experiment

To perform parallel operation of two alternators and investigate the load sharing.

1. To study the transfer of load between two alternators running in parallel keeping the load, frequency and voltage constant.
2. To study the variation of VAR with respect to alternator excitation keeping the power output, load and frequency constant.

2.2 Apparatus Required

Refer Table 2.1 and Table 2.2.

Table 2.1: Apparatus for short circuit on alternator

SL.	Equipment	Rating	Quantity
1	Rheostat	50Ω, 10 A, 110 V DC	02
2	Rheostat	220Ω, 2.5 A, 220 V DC	
3	Load Box	15 kW	01
4	Frequency Meter	50-60 Hz	02
5	Voltmeter	0-500 V AC	02
6	Ammeter	0-6 A AC	02
7	Voltmeter	0-300 V DC	02
8	Ammeter	0-25 A DC	02
9	Wattmeter	220 V, 15 A, UPF	02
10	Three phase wattmeter		01
11	Series Resistance		
12			

Table 2.2: Machine Specifications

SL.	Machine	Rating	Remarks
1	Three Phase Alternator (L-7)	400/440 V, 13 A, 10 kVA, 1500 RPM	Gen-1
2	DC Shunt Motor (L-7)	220 V, 58 A, 16 HP, 1500 RPM	PM-1
3	Three Phase Alternator (L-8)	400/231 V; 11.5 A, 8 kVA, 1500 RPM	Gen-2
4	DC Compound Motor	220 V, 58 A, 16 HP, 1500 RPM	PM-2
5	3-phase Induction Motor (R-6)	400 V, 7.8 A, 3.73 kW, 1000 RPM	Load
6	DC Shunt Generator (R-6)	220 V, 13.6 A, 3 kW, 1000 RPM	Load
7	DC Shunt Generator (L-10)	110 V, 20 A, 4.4 kW, 1500 RPM	Exciter
8	DC Shunt Motor (L-10)	110 V, 20 A, 6 hp, 1500 RPM	Exc-PM

2.3 Theoretical Background

When the load demand on the alternator increases beyond the capacity of the existing alternator, two or more alternators have to be operated in parallel. The conditions of successful parallel operation of alternators are:

1. The terminal voltage magnitude of both the alternators must be same.
2. The phase sequence of the two alternators must be same.
3. The frequency of both the alternators must be same. The load output of an alternator is governed by the input power from its prime mover (here is DC motor). Variation of excitation gives rise to a change in KVAR output, not the kW output.

2.4 Procedure

1. Make connection as per the circuit diagram in Fig. 2.1. The experimental setup is depicted in Fig. 2.2, 2.3 and Fig. 2.4.
2. The DC shunt motors are started and the alternators are brought up to rated speed.
3. Adjust the voltage and the frequency of the machine to 400 V and 50 Hz.
4. Synchronize the alternator using two bright one dark lamp method. Close the synchronizing switch.
5. The alternators should now be working in parallel, but they should not be delivering any load, that is, floating condition. Also, if the voltage and speed have been previously adjusted, there should be no interchange of current between the alternators and the ammeter should read zero.
6. The load on the alternators is a three phase induction motor coupled to DC generator. Load is varied by means of load box.
7. For a particular load output at constant frequency and voltage, input to the DC machine is varied and the outputs shared by each alternator are noted from the wattmeter reading. Input to the DC side is also noted.

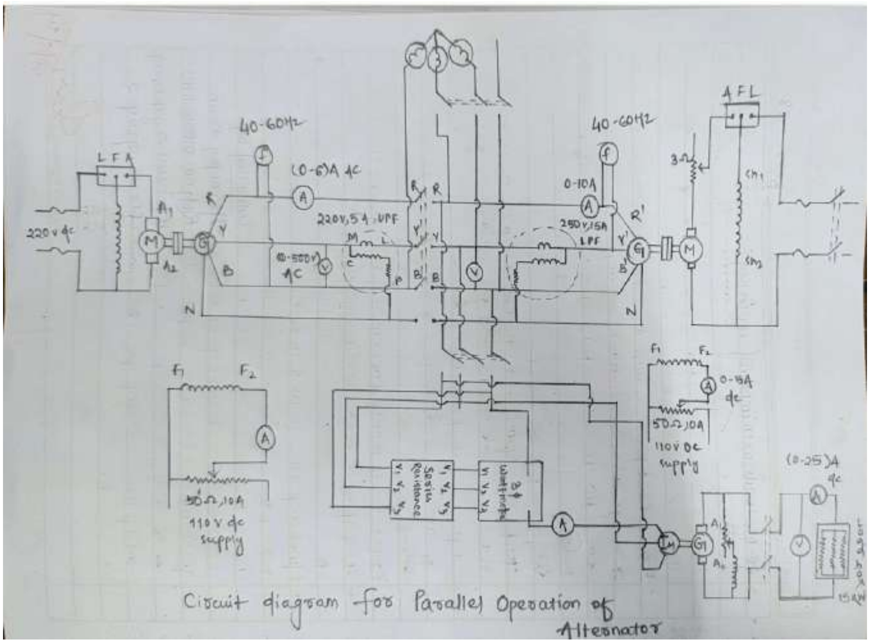


Figure 2.1: Circuit Diagram for Parallel Operation of Alternators

Table 2.3: Tabulation for Parallel Operation on Alternators

Sl.	Condition	I_{f1}	I_{f2}	I_{l1}	I_{l2}	V_{l1}	V_{l2}	W_1	W_2	W_3	V_{line}	I_{line}
1	After Syn											
2	No Loading											
3	Loading (i)											
4	Loading (ii)											
5	Changing Exc A1											
6	Changing Exc A2											
7	Changing Speed A1											
8	Changing Speed A2											

8. Graph is plotted between input power and load shared by each machine.
9. Keeping the input power, output load terminal voltage and frequency constant, the current given by each alternator for different excitation is noted.

2.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications.

Figure 2.2: Experimental Setup for Parallel Operation of Alternators (Alt-1)

Figure 2.3: Experimental Setup for Parallel Operation of Alternators (Alt-2)

Figure 2.4: Experimental Setup for Parallel Operation of Alternators (Load)

Experiment 3

Induction Generator

3.1 Aim of the Experiment

To obtain characteristics and performance of induction generator

3.2 Apparatus Required

Refer Table 3.1 and Table 3.2.

Table 3.1: Apparatus for induction generator experiment

SL.	Equipment	Rating	Quantity
1	Ammeter	0-10 A (AC)	02
2	Ammeter	0-20 A (AC)	01
3	Voltmeter	0-300 V (DC)	02
4	Rheostat	13 Ω, 7.9 A	02
5	Wattmeter	300 V, 10/20 A, LPF	02

Table 3.2: Machine Specifications for Induction Generator Experiment

SL.	Machine	Rating	Quantity
1	DC Motor	7 kW, 220 V, 1500 RPM	01
2	Squirrel Cage Induction Machine	7 kW, 400/231 V, 63/33/21 A, 960 RPM	01

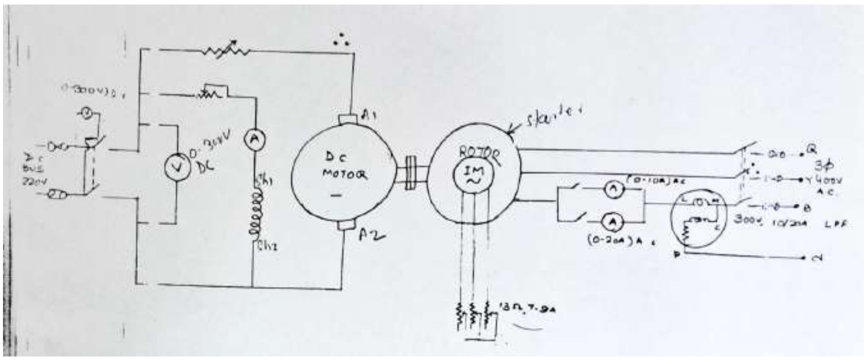


Figure 3.1: Circuit Diagram for Induction Generator

3.3 Theoretical Background

For an induction machine with synchronous speed N_s and rated speed N_r,

$$\texttt{Slip}\ s = \frac{N_s - N_r}{N_s} \tag{3.1}$$

When the slip is $0 < s < 1$, the machine operates in motoring mode. In this mode, the rotor rotates in the same direction of the rotating magnetic field. By convention, the torque developed is taken to be positive. However, when the induction machine is moved by a prime mover and the speed is increased such that $N_r > N_s$, the value of slip becomes negative. The negative slip results in negative torque. Therefore, the power developed ($P_d \alpha(-T_d N_r)$), also becomes negative. This means that the machine will provide real electrical power from its terminals to the grid. The necessary mechanical power to the machine is provided by the prime-mover to operating in this generating mode. The torque-slip characteristics is provided in Fig. 3.2.

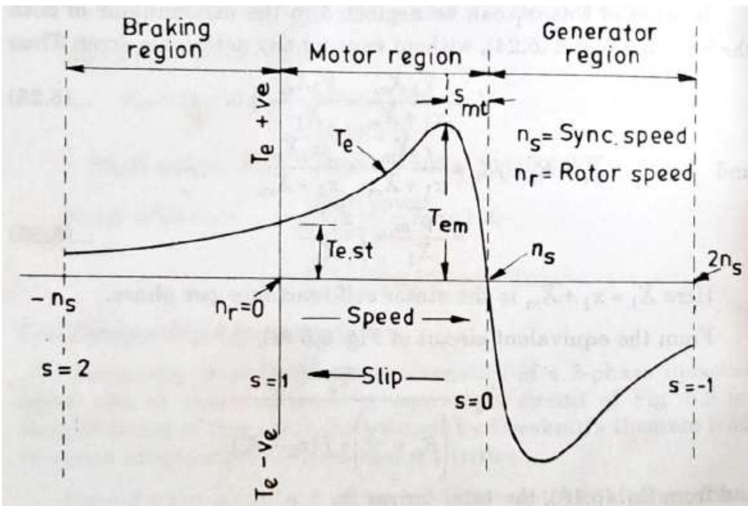


Figure 3.2: Torque-slip characteristics of an induction machine

Figure 3.3: Experimental Set for Induction Generator

Figure 3.4: Experimental Set for Induction Generator (cont.)

3.4 Procedure

1. The connection was set up as per the circuit diagram as shown in Fig. 3.1.
2. The machine was started and run as an induction motor.
3. The speed was gradually increased using the variable resistance to motor circuit to achieve synchronous speed.
4. Then the induction machine was synchronized the the mains supply (by ensuring voltage magnitude and polarity).
5. The induction machine was then disconnected from the mains terminals.
6. The current coil of the wattmeter were interchanged to register negative flow of power (generating mode).
7. The speed was adjusted just below the synchronous speed and the supply was connected to the induction motor.
8. The speed was increased until the wattmeter reading become zero. The meter readings and speed were noted down.
9. The machine speed was then increased in suitable steps to about 1.5 times the synchronous speed.
10. At each step, the speed and power outputs were noted.
11. From the observations, plot the torque-slip characteristics.

3.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications.

Experiment 4

Load Flow and Economic Dispatch

4.1 Aim of the Experiment

To perform load flow, optimal power flow and economic dispatch in power systems.

4.2 Tools Required

1. MATLAB/OCTAVE software
2. MATPOWER Toolbox
3. SCILAB, XCOS

4.3 Theoretical Background

4.3.1 Load Flow

Power Flow Equations

Since the real and reactive power at a given bus is given by $P_i + jQ_i = V_i I_i^*$, the power flow equations are give by

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad j \neq y \tag{4.1}$$

The power injected by the source into the i^{th} bus of a power system is

$$S_i = P_i + jQ_i = V_i I_i^* \quad i = 1, 2, \cdots, n \tag{4.2}$$

Since it is convenient to work with I_i instead of I_i^*, we take complex conjugate of the above equation and substituting for I_i

$$P_i - jQ_i = V_i^* I_i = V_i^* \left(\sum_{k=1}^{n} (Y_{ik} V_k) \right) \tag{4.3}$$

Equating the real and imaginary parts and considering $V_i = |V_i|e^{j\delta_i}$, $V_k = |V_k|e^{j\delta_k}$, $Y_{ik} = |Y_{ik}e^{\theta_{ik}}|$

$$P_i = |V_i| \sum_{k=1}^{n} |V_k||Y_{ik}|\cos(\theta_{ik} + \delta_k - \delta_i) \tag{4.4}$$

$$Q_i = -|V_i| \sum_{k=1}^{n} |V_k||Y_{ik}|\sin(\theta_{ik} + \delta_k - \delta_i) \tag{4.5}$$

Gauss-Seidel method of solution

The iterative formula (in terms of Y_bus matrix elements is given by

$$V_i^{k+1} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^{*(k)}} + \sum_{j\neq i} Y_{ij}V_j^{(k)}}{Y_{ii}} \tag{4.6}$$

The real and reactive power becomes

$$P_i^{(k+1)} = \Re\{V_i^{*(k)}[V_i^{(k)}Y_{ii} - \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{ij}V_j^{(k)}]\} \tag{4.7}$$

$$Q_i^{(k+1)} = -\Im\{V_i^{*(k)}[V_i^{(k)}Y_{ii} - \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{ij}V_j^{(k)}]\} \tag{4.8}$$

Newton-Raphson method of solution

Separating the real and imaginary parts,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4.9a}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \tag{4.9b}$$

Bus 1 is assumed to be the slack bus. The Jacobian matrix gives a linearized relationship between small changes in voltage angle $\Delta_i^{(k)}$ and voltage magnitude $\Delta|V_i^{(k)}|$ with small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{4.10}$$

For voltge controlled buses, the voltage magnitudes are known. Therefore, if m buses of the system are voltge-controlled, m equations involving ΔQ and ΔV and the corresponding columns of the Jacobian matrix are eliminated.
The elements of the Jacobian matrix can be computed as follows.

1. The diagonal and off-diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j\neq i} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \tag{4.11a}$$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)\ (j \neq i) \tag{4.11b}$$

2. The diagonal and off-diagonal elements of J_2 are

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i||Y_{ii}|\cos\theta_{ii} + \sum_{j\neq i} |V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4.12a}$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_i||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4.12b}$$

3. The diagonal and off-diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j\neq i} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4.13a}$$

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)\ (j \neq i) \tag{4.13b}$$

4. The diaonal and off-diagonal elments of J_4 are

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}|\sin\theta_{ii} - \sum_{j\neq i} |V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \tag{4.14a}$$

$$\frac{\partial Q_i}{\partial |V_j|} = |V_i||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \tag{4.14b}$$

The detailed procedure of N-R method is provided below.

1. For load buses, where P_i^{sch}, Q_i^{sch} are specified, voltage magnitude and phase angles are set equal to the slack bus values, or 1.0 and 0.0. For PV buses, where V_i and P_i^{sch} are specified, phase angles are set equal to slack bus angle or 0.

2. For load buses, $P_i^{(k)}$ and $Q_i^{(k)}$ are calculated from (4.9); $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are calculated from (4.15).

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{4.15}$$
$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{4.16}$$

3. For voltage controlled buses, $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated.

4. The elements of the Jacobian matrix are calculated using (4.11)-(4.14).

5. The linear simultaneous equations (4.10) is solved directly by optimally ordered triangular factorization and Gaussian elimination.

6. The new voltage magnitudes and phase angles are computed from

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{4.17a}$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}| \tag{4.17b}$$

7. The process is continued until the residuals $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than the specified accuracy.

$$\Delta P_i^{(k)} < \varepsilon \tag{4.18a}$$

$$\Delta Q_i^{(k)} < \varepsilon \tag{4.18b}$$

Fast Decoupled method of solution

In a typical power system, real power changes ΔP are less sensitive to changes in the voltage magnitude and are most sensitive to changes in phase angle $\Delta\delta$. Similarly, reactive power is less sensitive to changes in angle and are mainly dependent on changes in voltage magnitude. Therefore, it is resonable to set elements J_2 and J_3 of the Jacobian matrix to zero. Thus

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{4.19}$$

$$\Delta P = J_1 \Delta\delta = \left[\frac{\partial P}{\partial \delta}\right] \Delta\delta \tag{4.20}$$

$$\Delta Q = J_4 \Delta|V| = \left(\frac{\partial Q}{\partial |V|}\right] \Delta|V| \tag{4.21}$$

The detailed procedure for fast-decoupled method is as follows.

1. With the assumptions described above,

$$\frac{\Delta P}{V_i} = -B'\Delta\delta; \quad \frac{\Delta Q}{|V_i|} = -B^{''}\Delta|V| \tag{4.22}$$

   where B' and B" are imaginary parts of bus admittance matrix Y_{bus}.

2. Since the elements of the matrix are constant, they need to be triangularized and inverted only once at the beginning of iteration.

3. B' is of the order $(n-1)$. B" is of the order $(n-1-m)$, where m is the number of voltage-regulted buses.

4. For voltage controlled buses where $|V_i|$ and P_i are specified and Q_i is not specified, corresponding rows and columns of Y_{bus} are eliminated.

5. Successive voltage magnitude and phase angle changes are

$$\Delta\delta = -[B']^{-1}\frac{\Delta P}{|V|}; \quad \Delta|V| = -[B'']^{-1}\frac{\Delta Q}{|V|} \tag{4.23}$$

4.3.2 Economic Dispatch

Economic Dispatch without losses

The coordination equation without considering losses is given by

$$\frac{\partial F_T}{\partial P_{Gi}} = \frac{\partial F_i}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}} = \lambda \tag{4.24}$$

Simply stated, for economic generation scheduling to meet a particular load demand, when **transmission losses are neglected** and **generation limits are not imposed**, all plants must operate at **equal incremental production costs**. With more number of generators, the following analytical solution of λ can be used.

$$\lambda = \frac{P_D + \sum_{i=1}^{n_g} \frac{b_i}{2c_i}}{\sum_{i=1}^{n_g} \frac{1}{2c_i}} \tag{4.25}$$

Economic Dispatch with losses

For economic operation, the product of incremental fuel cost and penalty factor all units are same. The **penalty factor** of plant i is given by.

$$L_i = \frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}} \tag{4.26}$$

The **coordination equations** are

$$\lambda = L_i \frac{\partial F_i}{\partial P_{Gi}} \tag{4.27}$$

A general expression for transmission loss is

$$P_L = \sum_m \sum_n P_{Gm} B_{mn} P_{Gn} + \sum P_{Gn} B_{n0} + B_{00} \tag{4.28}$$

where B_{mn}, B_{n0}, B_{00} are called loss coefficients. A simple and commonly used expression is

$$P_L = \sum_m \sum_n P_{Gm} B_{mn} P_{Gn} \tag{4.29}$$

In general $B_{mn} = B_{nm}$. For a two-plant system

$$P_L = B_{11} P_{G1} + 2B_{12} P_{G1} P_{G2} + B_{22} P_{G2}^2 \tag{4.30}$$

Iterative method for Economic Dispatch

1. Start with an estimate of $\lambda^{(r)}$.
2. Using (4.31), solve for $P_{Gi}^{(r)}$.

$$P_{Gi} = \frac{\lambda - \lambda \left(\sum_{j=1, j \neq i}^{n_g} 2B_{ij} P_{Gj} \right) - b_i}{2(c_i + \lambda B_{ii})} \tag{4.31}$$

3. Compute transmission loss using (4.29).
4. Compute $\left(\frac{dP_{Gi}}{d\lambda} \right)^{(r)}$ for all i using (4.32).

$$\left(\frac{dP_{Gi}}{d\lambda} \right)^{(r)} = \frac{c_i + b_i B_{ii} - 2c_i \sum_{j=1, j \neq i}^{n_g} B_{ij} P_{Gj}^{(r)}}{2(c + \lambda^{(r)} B_{ii})^2} \tag{4.32}$$

5. Compute power imbalance using

$$\Delta P^{(r)} = P_D + P_L^{(r)} - \sum_{i=1}^{n_g} P_{Gi}^{(r)} \tag{4.33}$$

6. Compute change in λ from (4.34).

$$\Delta \lambda^{(r)} = \frac{\Delta P^{(r)}}{\sum_{i=1}^{n_g} \left(\frac{dP_{Gi}}{d\lambda} \right)^r} \tag{4.34}$$

$$\lambda^{(r+1)} = \lambda^{(r)} + \Delta \lambda^{(r)}. \tag{4.35}$$

7. Go to Step-2 and repeat till $\Delta P^{(r)} < \varepsilon$.

4.4 Numerical Problems

4.4.1 Economic Dispatch

1. The fuel costs of two units are given by

$$F_1 = 1.5 + 20P_{G1} + 0.1P_{G1}^2 \text{ Rs/h} \tag{4.36}$$
$$F_2 = 1.9 + 30P_{G2} + 0.1P_{G2}^2 \text{ Rs/h} \tag{4.37}$$

P_{G1}, P_{G2} are in MW. Write a program in MATLAB/OCTAVE to find the optimal schedule neglecting losses, when the demand is 200 MW.

2. The fuel cost functions in \$/h for three thermal plants are given by

$$F_1 = 350 + 7.2P_{G1} + 0.004P_{G1}^2 \tag{4.38}$$
$$F_2 = 500 + 7.3P_{G2} + 0.0025P_{G2}^2 \tag{4.39}$$
$$F_3 = 600 + 6.74P_{G3} + 0.003P_{G3}^2 \tag{4.40}$$

where P_{G1}, P_{G2}, P_{G3} are in MW. Write a program in MATLAB/OCTAVE to find the optimal schedule and compare the cost of this to case when the generators share load equally if (i) P_D=450 MW. and (ii) P_D =800 MW.

3. The fuel cost functions of two units in \$/MWh are

$$F_1 = 320 + 6.2P_{G1} + 0.004P_{G1}^2 \tag{4.41}$$
$$F_2 = 200 + 6.0P_{G2} + 0.003P_{G2}^2 \tag{4.42}$$

where P_{G1}, P_{G2} are in MW. The real power loss is given as

$$P_L = 0.0125P_{G1}^2 + 0.00625P_{G2}^2 \tag{4.43}$$

where the loss coefficients are in pu on a 100 MVA base. If the demand is 412.35 MW, find the optimal schedule using iterative technique in MATLAB/OCTAVE.

4.4.2 Load Flow

4. Write a program in MATLAB/OCTAVE to obtain the voltage at bus 2 for the simple system shown in Fig. 4.1 using Gauss-Siedel Method, if $V_1 = 1\angle 0$ *pu*.

5. Consider the power system shown in Fig. 4.2 The data for the system is given in Table 4.1 and Table 4.2. Write a program in MATLAB/OCTAVE obtain bus voltages at the end of first iteration applying Gauss-Siedel Method.

6. Write a program in MATLAB/OCTAVE to obtain the bus voltages at all buses for the three bus system shown in Fig. at the end of first iteration by NR Method. The data is given in Table 4.4 and Table 4.3.

7. Write a program in MATLAB/OCTAVE to obtain the bus voltages for the previous question using Fast-Decoupled method.

8. Fig. 4.3 shows the one-line diagram of a simple three-bus power system with generation at bus 1. The magnitude of voltage at bus 1 is adjusted to 1.05 per unit. The scheduled loads at buses 2 and 3 are marked on the diagram. Line impedances are marked in per unit on a 100 MVA base and line charging susceptances are neglected. Implement the following in MATLAB/OCTAVE.

Table 4.1: Line data pertaining to Q5

SB	EB	R(pu)	X(pu)	Bc/2
1	2	0.10	0.40	-
1	4	0.15	0.60	-
1	5	0.05	0.20	-
2	3	0.05	0.20	-
2	4	0.10	0.40	-
3	5	0.05	0.20	-

Table 4.2: Bus data pertaining to Q5

Bus	$P_G(pu)$	$Q_G(pu)$	$P_D(pu)$	$Q_D(pu)$	$\|V\|$	δ
1	-	-	-	-	1.02	0
2	-	-	0.60	0.30	-	-
3	1.0	-	-	-	1.04	-
4	-	-	0.40	0.10	-	-
5	-	-	0.60	0.20	-	-

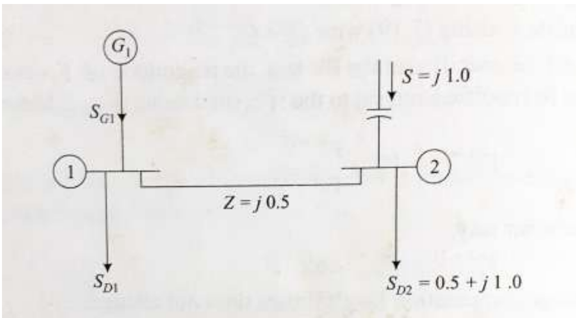


Figure 4.1: Pertaining to Q4

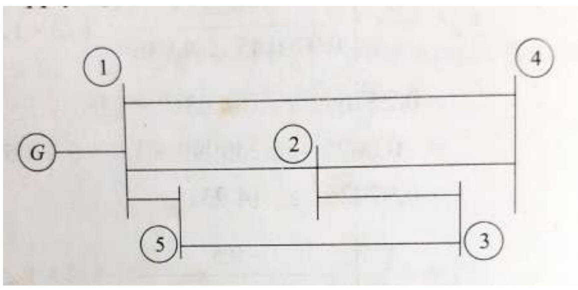


Figure 4.2: Pertaining to Q5

Table 4.3: Line data pertaining to Q6

SB	EB	R(pu)	X(pu)	Bc/2
1	2	0.0	0.1	0.0
1	3	0.0	0.2	0.0
2	3	0.0	0.2	0.0

Table 4.4: Bus data pertaining to Q6

Bus	$P_G(pu)$	$Q_G(pu)$	$P_D(pu)$	$Q_D(pu)$	$\|V\|$	δ
1 (slack)	-	-	-	-	-	1.0
2 (PV)	5.3217	-	-	-	-	1.1
3 (PQ)	-	-	-	3.6392	0.5339	-

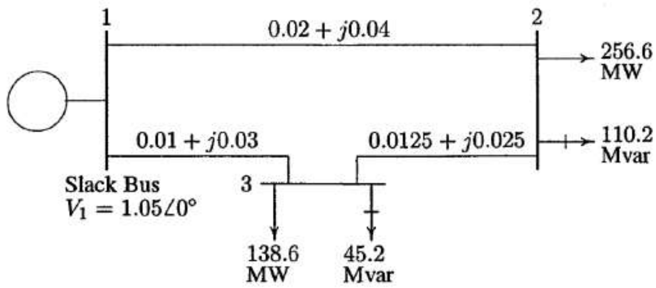


Figure 4.3: Pertaining to Q8

(a) Using G-S method, determine phasor values of voltages at load buses 2 and 3 accurate to four decimal places.

(b) Find the slack bus real and reactive power.

(c) Determine the line flows and line losses. Construct a power flow diagram showing the direction of line flow.

9. Fig. 4.4 shows the one-line diagram of a simple three-bus power system with generators at buses 1 and 3. The magnitude of voltage at bus 1 is adjusted to 1.05 pu. voltage magnitude at bus 3 is fixed at 1.04 pu with real power generation of 200 MW. A load consisting of 400 MW and 250 MVar is taken from bus 2. Line impedances are marked in per unit on a 100 MVA base, and line charging susceptances are neglected. Write MATLAB/OCTAVE program to obtain power flow solution by (i) G-S (ii) N-R (iii) F-D methods.

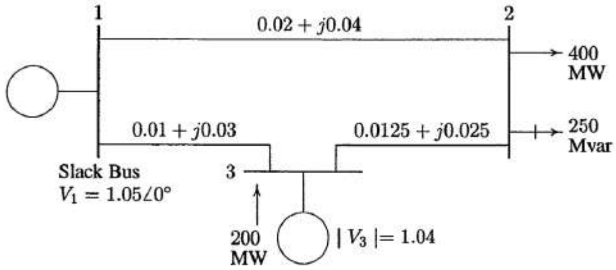


Figure 4.4: Pertaining to Q9

4.4.3 Optimal Power Flow

10. MATPOWER is a free, open-source tool for electric power system simulation.

    (a) Download `MATPOWER` software from `https://matpower.org/` and add to your OCTAVE/MATLAB workspace.

    (b) Go through `MATPOWER` manual and use `runpf` to solve the load flow problem for 9 bus, 14 bus and 30 bus system using both G-S and N-R methods.

    (c) Write the system summary and generator data. Observe the bus data and branch flows. A code segment is shown below for your reference.

```
define_constants;
mpc = loadcase('case30');
mpopt = mpoption('pf.alg', 'NR', 'verbose', 1, 'out.all', 1);
runpf(mpc,mpopt);
```

4.5 References

1. Hadi Saadat, *Power System Analysis*, McGraw-Hill.
2. D. P. Kothari, I. J. Nagrath, *Power System Engineering*
3. https://github.com/rajatkanti/Lab-Code

Experiment 5

Determination of Power Quality

5.1 Aim of the Experiment

To determine power quality measures of an AC-DC microgrid.

Detailed Objectives

1. To study the operation of a DC-AC converter (inverter) using an FPGA-based controller (WAVECT WCU200).
2. To understand the integration of the inverter into a microgrid setup.
3. To evaluate the control and performance characteristics of the DC-AC converter using an FPGA controller.

5.2 Apparatus Required

1. AC-DC Microgrid Setup
2. DC Power Supply: o Voltage Range: 0V - 30V DC (as per system requirements).
3. Inverter Setup: DC-AC converter with power rating as per the microgrid setup.
4. WAVECT WCU200 Controller: FPGA-based control module.
5. Oscilloscope: For measuring waveforms of input/output voltage and current.
6. Load (Resistive/Inductive): Select the appropriate load to test the output of the inverter.
7. Measurement Tools: Voltage and current sensors, Multimeter
8. PC/Laptop: For monitoring and programming the FPGA controller via software.
9. Cables and Connectors: To connect the power supply, inverter, load, and controller.

Figure 5.1: AC-DC Microgrid Setup

List of Components

1. Transducer
2. Three phase diode bridge rectifier
3. Brake Chopper
4. Three phase IGBT based PWM inverter
5. DC Motor
6. 230 V AC fan input
7. Thermal trip 800 NC
8. Three phase line choke
9. WAVECT FPGA controller
10. Wind Emulator

5.3 Theoretical Background

The DC-AC converter is used to convert a direct current (DC) input to alternating current (AC) output. In a microgrid, such converters are essential for enabling power flow between DC sources (like solar panels, and batteries) and AC loads. The WAVECT WCU200 controller is an FPGA-based module that allows for precise control of the

Figure 5.2: AC-DC Microgrid Setup (WAVECT and Ethernet connection to PC)

Figure 5.3: AC-DC Microgrid setup (Wind emulator)

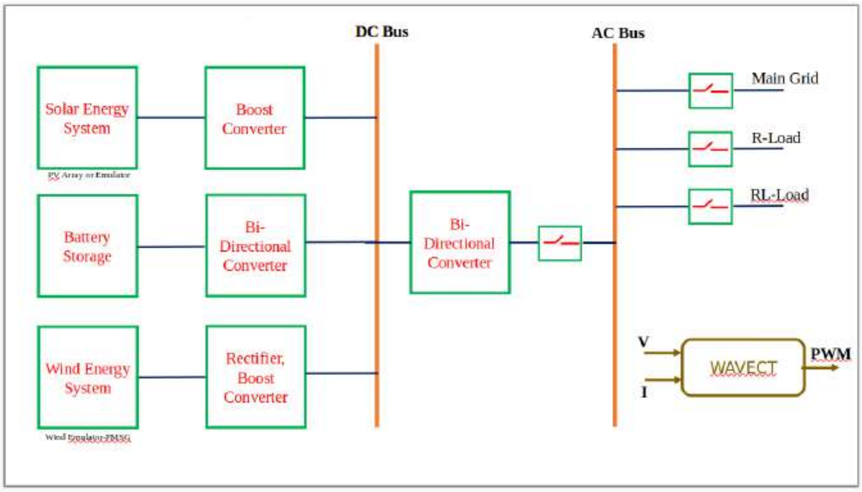


Figure 5.4: Block Diagram of AC-DC Microgrid Setup

inverter's switching to maintain the desired output voltage and frequency. Key features of the WAVECT WCU200:

1. Real-time control of the inverter using FPGA
2. Supports custom control algorithms
3. Interfaces with external sensors for voltage and current measurements
4. Adjustable switching frequency and pulse width modulation (PWM) strategies

Working Principle

The FPGA-based WAVECT controller generates PWM signals to control the switching of the DC-AC converter. By adjusting the duty cycle of the PWM signals, the output AC voltage can be modulated. The controller uses feedback from voltage and current sensors to adjust the inverter's operation, ensuring stable power delivery to the load.

5.3.1 Block Diagram

Refer Fig. 5.4, Fig. 5.5 and Fig. 5.6.

5.4 Procedure

Step 1: Pre-Setup Check

1. Ensure all the equipment (inverter, controller, power supply, and load) is in working condition.
2. Verify the DC power supply voltage matches the rating of the inverter.

Step 2: Setup Connections

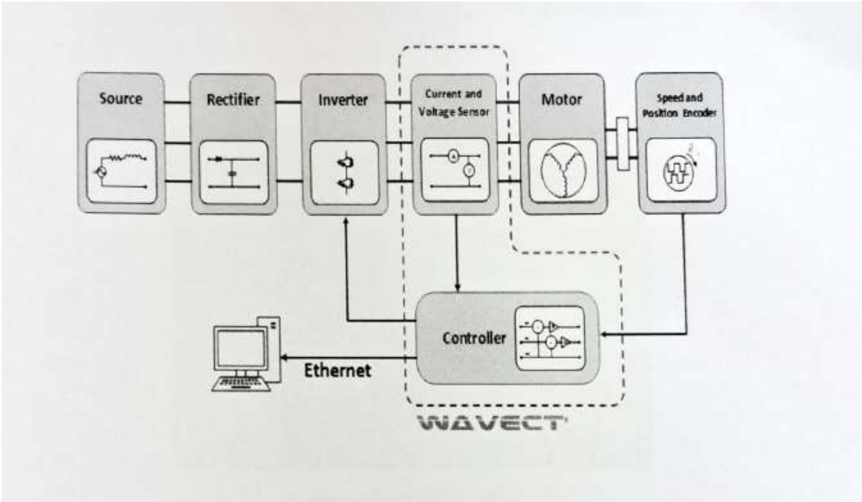


Figure 5.5: Block Diagram of AC-DC Microgrid Setup (cont.)

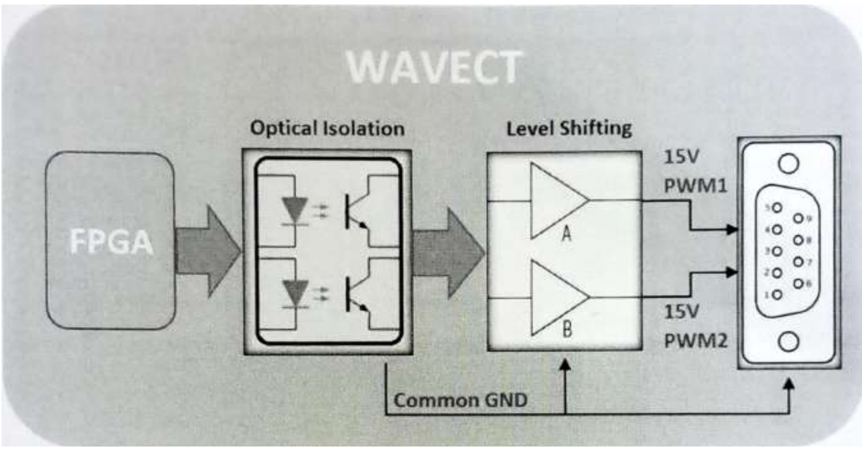


Figure 5.6: Block Diagram of WAVECT

1. Connect the DC Power Supply to the input of the DC-AC converter.
2. Connect the output of the DC-AC converter to the load.
3. Connect the WAVECT WCU200 controller to the DC-AC converter:
   (a) Interface the FPGA controller to the inverter's gate drivers.
   (b) Connect the voltage and current sensors to the controller for feedback signals.
4. Power the WAVECT WCU200 controller and connect it to a PC for real-time control and monitoring.

Step 3: Programming the FPGA Controller

1. Open the WAVECT WCU200 software on the PC.

2. Load the pre-written control algorithm or write a new control strategy.
   (a) Set the PWM switching frequency (usually between 5kHz to 20kHz depending on the inverter design).
   (b) Configure any additional parameters like modulation index, output frequency, and dead time.
3. Upload the control program to the FPGA and start the operation.

Step 4: Powering the System

1. Slowly ramp up the voltage of the DC power supply while monitoring the inverter's input.
2. Observe the output AC voltage using an oscilloscope and ensure it matches the desired waveform (usually sinusoidal).
3. Adjust the load and observe changes in the output waveform and voltage.
4. Take note of voltage sag, waveform distortions, and harmonic content.

Step 5: Data Collection

1. Measure the input and output voltage and current using the multimeter and sensors.
2. Capture the waveforms from the oscilloscope for analysis.
3. Record the switching frequency, modulation index, and output AC voltage and frequency.

Step 6: Analysis

1. Analyze the output voltage waveform for harmonic distortion (THD).
2. Evaluate the efficiency of the inverter under different load conditions.
3. Compare theoretical and practical results.

5.5 Sample Results

Refer Fig. 5.7, Fig. 5.8 and Fig. 5.9 for samples of output waveforms.

Table 5.1: Observations

SL.	Parameter	Observed Value	Expected Value
1	Input DC Voltage		
2	Output AC Voltage (RMS)		
3	Output Frequency (Hz)		
4	Switching Frequency (kHz)		
5	Total Harmonic Distortion (%)		
6	Efficiency (%)		

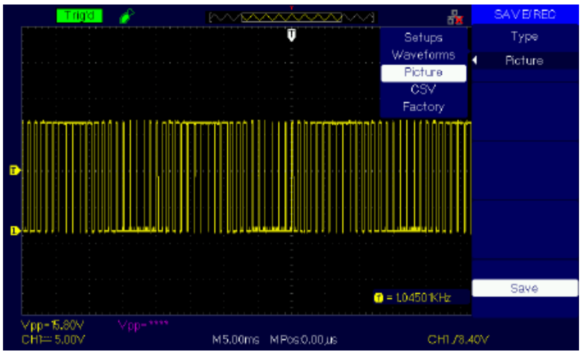


Figure 5.7: Pertaining to Microgrid Experiment

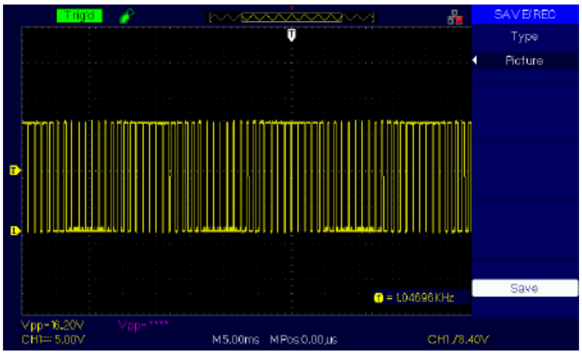


Figure 5.8: Pertaining to Microgrid Experiment (Output-2)

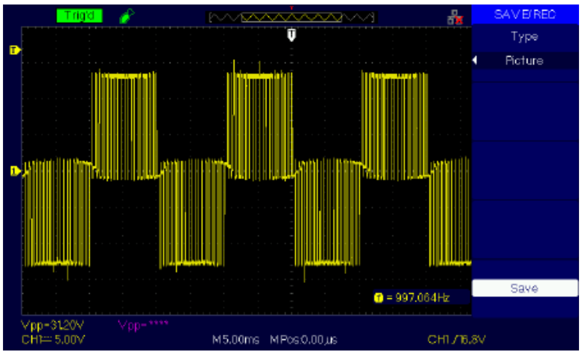


Figure 5.9: Pertaining to Microgrid Experiment (Output-3)

5.6 Discussion and Conclusion

This experiment demonstrates the use of the WAVECT WCU200 FPGA controller in regulating the operation of a DC-AC inverter within a microgrid setup. The FPGA's high-speed control and flexibility enable efficient power conversion with reduced harmonics, making it ideal for renewable energy and microgrid applications. Write the conclusions you have drawn from the experiments and their relevance.

Experiment 6

Fault Analysis and Transient Stability

6.1 Aim of the Experiment

Fault Analysis and Determination of Transient Stability of Power Systems

6.2 Tools Required

1. OCTAVE for fault computations
2. MATLAB SIMULINK for fault simulation
3. SCILAB for transient stability

6.3 Theoretical Background

6.3.1 Fault Analysis

Types of Power System Faults

- Broadly speaking, the faults can be classified as (i) shunt faults and (ii) series faults. Shunt type faults involve power conductor or conductors-to-ground or short circuit between conductors.
- When circuits are controlled by fuses or any device which does not open all three phases, one or two phases of the circuit may be opened while the other phases or phase is closed. These are called series type of faults. This can also occur with broken conductors.
- Shunt faults are characterized by increase in current and fall in voltage and frequence whereas series faults are characterized by increase in voltage and frequency and fall in current in the faulted phase.
- Shunt faults are classified as (i) Line-to-ground fault; (ii) Line-to-line fault; (iii) Double line-to-ground fault; and (iv) 3-phase fault.

- Of these, first three are unsymmetrical faults as the symmetry is disturbed in one or two phases. Three-phase fault is a balanced fault.

Derivation of sequence network for L-G fault

Since the fault takes place on phase a, $V_a = I_b = I_c = 0$. Sequence network equations are

$$V_{a0} = -I_{a0}Z_0; \quad V_{a1} = E_a - I_{a1}Z_1; \quad V_{a2} = -I_{a2}Z_2 \tag{6.1}$$

Substituting I_b,I_c in symmetrical components of currents

$$I_{a1} = I_{a2} = I_{a0} = I_a/3 \tag{6.2}$$

Also, in terms of symmetrical components,

$$V_a = 0 = V_{a1} + V_{a2} + V_{a0} \tag{6.3}$$

Substituting the values of V_{a0}, V_{a1} and V_{a2} ,

$$E_a - I_{a1}Z_1 - I_{a2}Z_2 - I_{a1}Z_0 = 0; \ \texttt{OR} \ I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_0} \tag{6.4}$$

Since the currents are equal in magnitude and phase angle, the three sequence networks must be connected in series.

Derivation of sequence network for L-L-G fault

Consider a three phase generator with a fault on phases b and c through a line impedance Z_f to ground. Assuming the generator is initially on no-load, the boundary conditions at the fault point are

$$V_b = V_c = Z_f(I_b + I_c); \quad I_a = I_a^0 + I_a^1 + I_a^2 \tag{6.5}$$

The phase voltages V_b and V_c are

$$V_b = V_a^0 + a^2V_a^1 + aV_a^2 \tag{6.6}$$
$$V_c = V_a^0 + aV_a^1 + aV_a^2 \tag{6.7}$$

Since $V_b = V_c$, from above we note that $V_a^1 = V_a^2$. Substituting for the symmetrical components of currents,

$$V_b = 3Z_fI_a^0 = V_a^0 - V_a^1 \tag{6.8}$$

Substituting for the symmetrical components of the voltages and solving for I_a^0 and I_a^2, we get

$$I_a^0 = -\frac{E_a - Z^1I_a^1}{Z^2}; \quad I_a^2 = -\frac{E_a - Z^1I_a^1}{Z^0 + 3Z_f} \tag{6.9}$$

Substituting I_a^0 and I_a^2 in (6.5), we get

$$I_a^1 = \frac{E_a}{Z^1 + \frac{Z^2(Z_0+3Z_f)}{Z^2+Z^0+3Z_f}} \tag{6.10}$$

Derivation of sequence network for L-L fault

Considering a fault through an impedance Z_f between phases b and c,

$$I_a^1 = \frac{E_a}{Z^1 + Z^2 + Z_f}; \quad I_b = -I_c = (a^2 - a)I_a^1 \tag{6.11}$$

6.3.2 Power System Stability

Steps

If we were to investigate the system as to its transient stability, we should proceed as follows

1. Determine the initial pre-fault state
2. Initiate the fault.
3. Compute the post fault transient motion of the masses and resulting forces in strings (power flow or loading).
4. If these forces do not exceed the break point of the strings, the system would be judged stable for the fault in question.

In an elastic energy system, the rotor angle position will experience transient deviations. If it can be ascertained by analysis that all the individual rotor angle will settle down to a new post-fault steady state values, corresponding to a new stable **synchronous equilibrium state**, then we conclude that the system is transient stable.

The **swing equation** can be written as

$$M\frac{d^2\delta}{dt^2} = P_m - P_e\, MW \;\; \texttt{OR} \;\; \frac{GH}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e\, MW \tag{6.12}$$

Dividing throughout by G, the MVA rating of the machine

$$M(pu)\frac{d^2\delta}{dt^2} = P_m - P_e(pu) \;\; \texttt{OR} \;\; \frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e\,(pu) \tag{6.13}$$

Numerical Solution to Swing Equation

Point-by-point method of solution to swing equation is as follows.

1. Consider the n^{th} interval, beginning at $t = (n-1)\Delta t$. The angular position is δ_{n-1}. The acceleration $\alpha_{(n-1)}$ as calculated is assumed constant from $t = (n-3/2)\Delta t$ to $t = (n-1/2)\Delta t$.
2. The change in speed during this time is given by

$$\Delta\omega_{(n-1/2)} = \Delta t\,\alpha_{(n-1)} = \Delta t\frac{P_{a(n-1)}}{M} \tag{6.14}$$

   where $P_{a(n-1)} = P_m - P_{max}\sin(\delta_{(n-1)})$.
3. The speed at the end of the interval is $\omega_{n-1/2} = \omega_{n-3/2} + \Delta\omega_{n-1/2}$.

4. The change in angular position in the n^{th} and $(n-1)^{th}$ interval is

$$\Delta\delta_n = \Delta t[\omega_{n-1/2}] = \Delta t\,\omega_{n-3/2} + \Delta t^2 \frac{P_{a(n-1)}}{M} \tag{6.15}$$

$$\Delta\delta_{n-1} = \Delta t\,\omega_{(n-3/2)} \Rightarrow \Delta\delta_n = \Delta\delta_{n-1} + \Delta t^2 \frac{P_{a(n-1)}}{M} \tag{6.16}$$

5. The process is repeated to obtain $P_{a(n)}, \Delta\delta_{n+1}, \delta_{n+1}$.

6.4 Experiments

6.4.1 Part-1: Fault Computations

For the network shown in Fig. 6.8 **write a program in MATLAB/OCTAVE** to compute the fault current for (i) three phase symmetrical fault (ii) LG fault (iii) LL fault (iv) Double line-to-ground fault. The ratings are provided below.
Generator: 11 kV, 50 MVA; $x_d^{''} = 15\%$; $X_2 = x_d^{''}$; $X_0 = 8\%$.
Grounding reactance = 2.5 ohm. T_1, T_2: 11/132 kV; 60 MVA; X=10%
M_1= 11 kV; 30 MVA; $X_d^{''} = X_2 = 20\%$; $X_0 = 8\%$ M_2= 11 kV; 15 MVA;
Transmission line: $X_1 = X_2$; 120 ohm reactance; $X_0 = 3X_1$.
In addition, graphically compute the fault using ETAP/MiPower software.

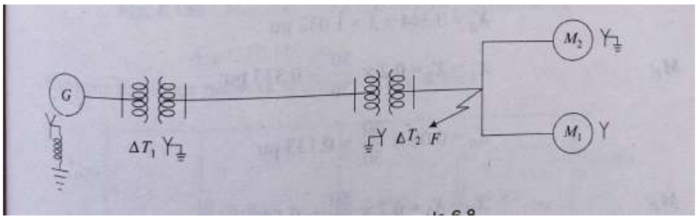


Figure 6.1: Pertaining to fault computations

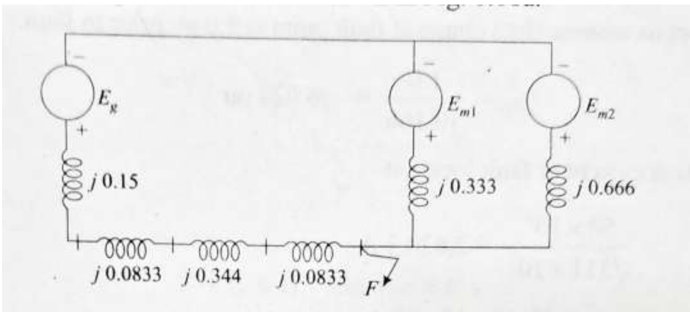


Figure 6.2: Positive sequence network

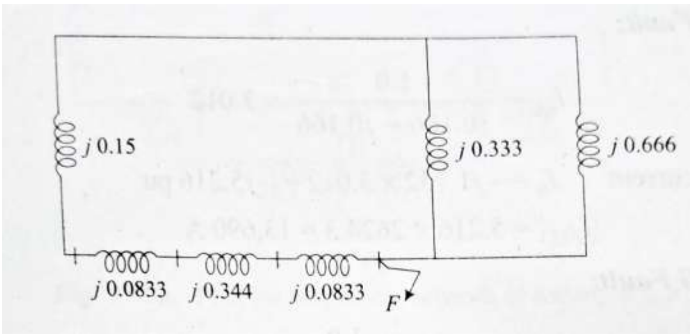


Figure 6.3: Negative sequence network

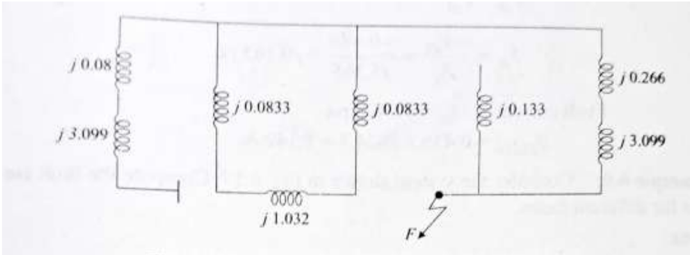


Figure 6.4: Zero sequence network

Generator:

$$X_1 = X_2 = 0.15 \text{ pu}; X_0 = 0.08 \text{ pu.}$$

$$Z_B = \frac{11^2}{50} = 2.42\ \Omega$$

$$X_n = \frac{2.5}{2.42} = 1.033 \text{ pu}$$

$$3X_n = 3.099 \text{ pu}$$

T_1 and T_2:

$$X = 0.1 \times \frac{50}{60} = 0.0833 \text{ pu}$$

Transmission line:

$$Z_B = \frac{132^2}{50} = 348.48\ \Omega$$

$$X_1 = X_2 = \frac{120}{348.48} = 0.344 \text{ pu}$$

$$X_0 = 0.344 \times 3 = 1.032 \text{ pu}$$

M_1:

$$X_1 = X_2 = 0.2 \times \frac{50}{30} = 0.333 \text{ pu}$$

$$X_0 = 0.08 \times \frac{50}{30} = 0.133 \text{ pu}$$

M_2:

$$X_1 = X_2 = 0.2 \times \frac{50}{15} = 0.666 \text{ pu}$$

$$X_0 = 0.08 \times \frac{50}{15} = 0.266 \text{ pu}$$

$$Z_B = \frac{11^2}{50} = 2.42\ \Omega$$

$$3X_n = \frac{2.5}{2.42} \times 3 = 3.099 \text{ pu}$$

Figure 6.5: Solution to Fault Calculation

(i) ***Three phase symmetrical fault:***

Let us assume the voltage at fault point is 1.0 pu prior to fault.

$$I_{F3\phi} = \frac{1.0}{j0.166} = -j6.024 \text{ pu}$$

Base current at fault location

$$\frac{50 \times 10^6}{\sqrt{3}11 \times 10^3} = 2{,}624.3 \text{ A}$$

$$\therefore \qquad |I_{F3\phi}| = 15{,}808 \text{ A}$$

(ii) ***L–G Fault:***

$$I_{a1} = \frac{1.0}{j0.166 + j0.166 + j3.365}$$

$$I_{FLG} = 3\,I_{a1} = -j0.811 \text{ pu}$$

$$|I_{FLG}| = 0.811 \times 2624.3 = 2{,}128 \text{ A}$$

(iii) ***L–L Fault:***

$$I_{a1} = \frac{1.0}{j0.166 + j0.166} = 3.012$$

Fault current $\quad I_b = -j1.732 \times 3.012 = -j5.216$ pu

$$|I_{FLL}| = 5.216 \times 2624.3 = 13{,}690 \text{ A}$$

(iv) ***L–L–G Fault:***

$$I_{a1} = \frac{1.0}{j0.166 + (j0.166 \,\|\, j3.365)} = -j3.084 \text{ pu}$$

$$V_{a1} = E_a - I_{a1} Z_1 = 1.0 - (-j3.084)\,(j0.166) = 0.488 \text{ pu}$$

$$V_{a0} = V_{a1}$$

$$I_{a0} = \frac{-V_{a0}}{Z_0} = \frac{-0.488}{j3.365} = j0.145 \text{ pu}$$

Fault current $= 3I_{a0} = j0.435$ pu

$$|I_{FLLG}| = 0.435 \times 2624.3 = 1{,}142 \text{ A}$$

Figure 6.6: Solution to Fault Calculation (Part-2)

6.4.2 Part-2: Fault Simulation Procedure

1. Refer Fig. 6.7 for the SIMULINK model to simulate LG, LLG, LL and three phase symmetrical faults.
2. The fault duration can be changed by clicking on the *Three-phase fault block*.
3. After simulating the faults, click on the Scopes to visualize various voltage and current waveforms.
4. The voltage and current on both grid and load side must be obtained.

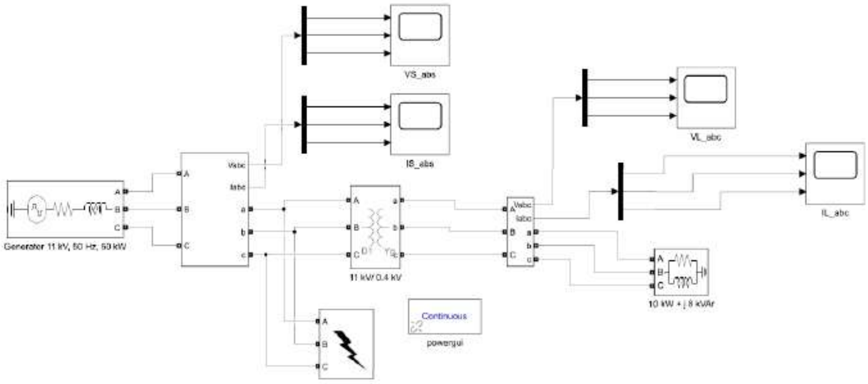


Figure 6.7: SIMULINK model for fault simulation

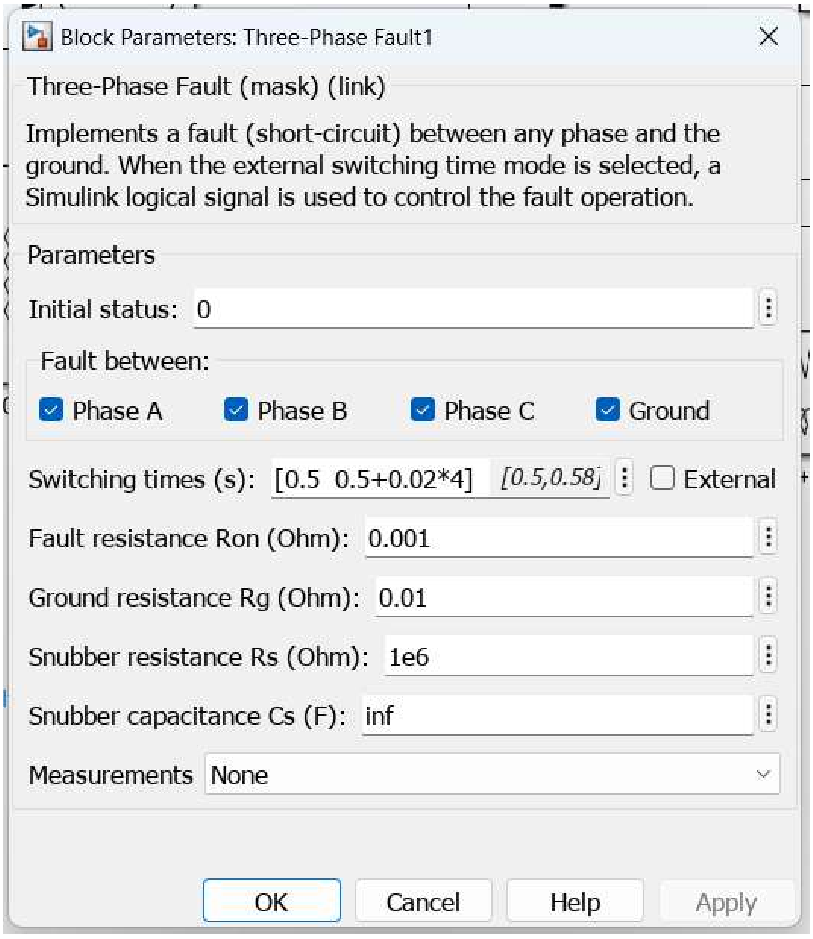


Figure 6.8: Changing the fault duration

6.4.3 Part-3: Transient Stability

A 50 Hz, synchronous generator having inertia constant $H = 5.2\ MJ/MVA$ and $x'_d = 0.3\ pu$ is connected to an infinite bus through a double circuit line as shown in Fig 6.9. The reactance of the connecting HT transformer is 0.2 pu and reactance of each line is 0.4 pu. $|E_g| = 1.2\ pu$ and $|V| = 1.0\ pu$ and $P_e = 0.8\ pu$. A three phase fault occurs at the middle of one of the transmission lines and is cleared by isolating the faulted line. Write programs in **MATLAB/OCTAVE/SCILAB** to obtain the swing curve and evalute the following using point-by-point method.

1. $\delta(t)$ for a sustained fault and the critical clearning time.
2. $\delta(t)$ when fault is cleared in 2.5 cycles.
3. $\delta(t)$ when the fault is cleared in 6.25 cycles.

In addition, plot the swing curves using **MATLAB/OCTAVE/SCILAB** software.

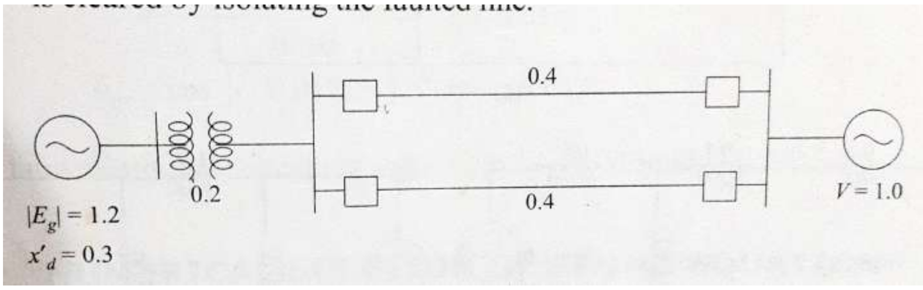


Figure 6.9: Pertaining to Transient Stability

Case (ii). Fault cleared in 2.5 cycles:

$$2.5 \text{ cycles} = \frac{2.5}{50} = 0.05\ s$$

Since, the discontinuity occurs at the beginning of an interval $P_{a(av)}$ value is calculated from $\frac{P_a(t = 0.05-) + P_a(t = 0.05+)}{2}$. The rest of computations are

Figure 6.10: Sample solution (Case-II)

Case (iii). Fault cleared in 6.25 cycles

$$6.25 \text{ cycles} = \frac{6.25}{50} = 0.125\ s$$

Since, discontinuity occurs at the middle of an interval no special method is

Figure 6.11: Sample solution (Case-III)

$$M(\text{pu}) = \frac{H}{180f} = \frac{5.2}{180 \times 50} = 5.77 \times 10^{-4}\ \text{s}^2/^\circ\text{elec}$$

Let

$$\Delta t = 0.05\ s$$

$$\frac{\Delta t^2}{M} P_a = \frac{(0.05)^2}{5.77 \times 10^{-4}} \times P_a = 4.32\ P_a$$

Case (i). Sustained fault.

$$P_e = 1.714 \sin \delta \text{ (before fault)}$$
$$= 0.63 \sin \delta \text{ (during fault)}$$

Calculations use the following formulae:

$$P_{a(n-1)} = P_m - P_{\max} \sin \delta_{n-1}$$

$$\Delta\delta_n = \Delta\delta_{n-1} + \frac{(\Delta t)^2}{M} P_{a(n-1)}$$

$$\delta_n = \delta_{n-1} + \Delta\delta_n$$

Assuming short circuit occurs at $t = 0$,

At (0^-) $P_e = 1.714 \sin \delta_0 = 0.8$

$P_a(0^-) = 0.8 - 0.8 = 0.0$ (steady state)

At (0^+) $P_e = 0.63 \sin \delta_0 = 0.293$

$P_a(0^+) = 0.8 - 0.293 = 0.507$

$$P_{av}(0) = \frac{P_a(0^-) + P_a(0^+)}{2} = \frac{0.0 + 0.507}{2} = 0.2535 \text{ pu.}$$

Figure 6.12: Sample solution (Case-I)

At $t = 0.15$, δ_{n-1} (at the beginning of the interval) = 37.43°

$$P_e = 0.63 \sin (37.43^\circ) = 0.383 \text{ pu}$$

$$P_{a(n-1)} = 0.8 - 0.383 = 0.417$$

$$\frac{\Delta t^2}{M} P_a = 4.32 \times 0.417$$
$$= 1.801.$$

$$\Delta\delta(t = 0.15\ s) = \Delta\delta(t = 0.1) + \frac{\Delta t^2}{M} P_a(t = 0.15\ s)$$
$$= 5.237 + 1.801 = 7.038^\circ$$

$$\delta(t = 0.2\ s) = \delta(t = 0.15\ s) + \Delta\delta(t = 0.15\text{s})$$

Figure 6.13: Sample solution (Cont.)

6.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications.

t	P_{max}	$\delta_{(deg)}$	$Sin\ \delta$	$P_e = P_{max}\ sin\ \delta$	$P_a = 0.8 - P_e$	$\frac{\Delta t^2}{M} P_a$ $4.32\ P_a$	$\Delta\delta$
0^-	1.714	27.820	0.466	0.800	0.000	–	–
0^+	0.630	27.820	0.466	0.293	0.507	–	–
0_{av}	–	27.820	–	–	0.253	1.095	1.095
0.05	0.630	28.960	0.484	0.305	0.495	2.138	3.233
0.10	0.630	32.190	0.533	0.336	0.464	2.004	5.237
0.15	0.630	37.430	0.608	0.383	0.417	1.801	7.038
0.20	0.630	44.460	0.700	0.441	0.359	1.550	8.588
0.25	0.630	53.050	0.800	0.503	0.296	1.281	9.869
0.30	0.630	62.920	0.890	0.561	0.239	1.032	10.901
0.35	0.630	73.820	0.960	0.605	0.195	0.842	11.743
0.40	0.630	85.560	0.997	0.628	0.172	0.742	12.485
0.45	0.630	98.050	0.990	0.623	0.176	0.761	13.246
0.50	0.630	111.29	0.930	0.587	0.213	0.920	14.16
0.55	0.630	125.46	–	–	–	–	–

Figure 6.14: Computations of swing curve for sustained fault

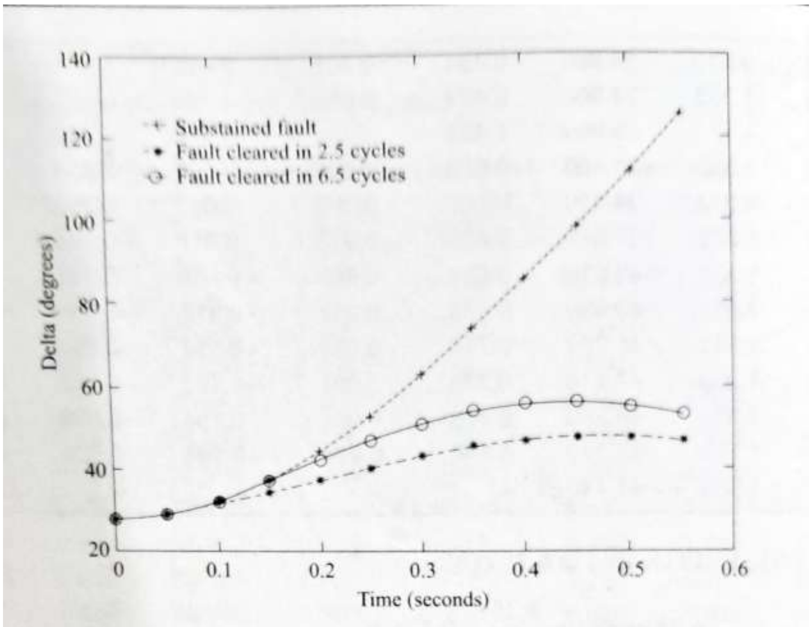


Figure 6.15: Swing curves for all scenarios

6.6 References

1. D. P. Kothari, I. J. Nagrath, *Power System Engineering*
2. K Uma Rao, *Computer Techniques and Models in Power System*
3. https://github.com/rajatkanti/Lab-Code

Experiment 7

Flashover test of insulators

7.1 Aim of the Experiment

1. Calibration of different surface gaps for measurement of high voltage (Sphere-sphere, Pin-pin, Disc-disc)
2. Dry flash over test on different types of insulators by 100 kV AC and 280 kV DC

7.2 Apparatus Required

1. LT – 400V pin insulation
2. KV Disc insulation
3. LT-400V shackle insulation

7.3 Theoretical Background

The term discharge generally denotes the phenomenon associated with the failure of insulation under electrical stress. It applies to electrical breakdown in solid, liquid and gaseous dielectric and combination of the term spark over is used when a discharge occurs in gaseous or liquid dielectric.
The term flashover is used when a discharge occurs over the surface of dielectric in a gaseous or liquid medium. The term puncture is used when a discharge occurs through a solid dielectric.
A disruptive discharge in solid dielectric produces a permanent loss of dielectric strength, but in a liquid or gaseous dielectric the loss may be only temporary. For a direct or alternating or impulse voltage, the disruptive discharge voltage is the value of the test voltage causing disruptive discharge.

TEST WITH ALTERNATING VOLTAGE:
The test voltage should be an alternating voltage having frequency in a range of 40-62 Hz or of an agreed value. The test voltage is generally supplied from a step up transformer or it may them generated by a series resonant circuit. The voltage in the

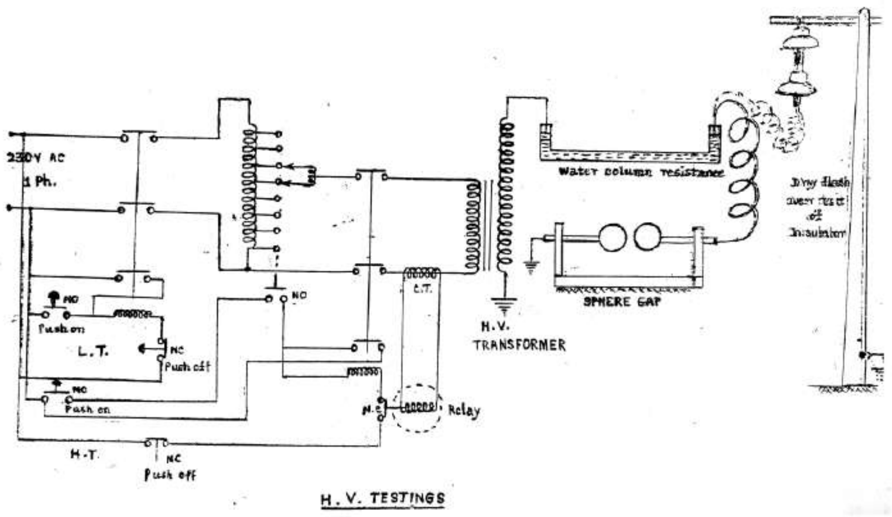


Figure 7.1: Experimental set-up for flashover test of insulators

test circuit should be stable enough to be practically unaffected by verifying leakage current. The steady state current delivered by the transformer when the test object is short-circuited at the test voltage is not less than 1A rms.
Air Density Factor (Kd):
For uniform field gap; m,n,w
For rod – rod gap and suspension insulators and rod plane gap refer to graph
Humidity correction factor (Kh):
K is determined from graph

7.4 Procedure

DRY FLASHOVER TEST / WET TEST (FOR INSULATORS)
Connect the insulator to the testing transformer. Increase the voltage at a steady rate till breakdown occurs. Record the voltage. Again increase the voltage at a steady rate up to a voltage slightly less than the flashover voltage. Wait for one minute. If the flashover occurs, this voltage is called as withstand voltage. If, the flashover occurs within one minute repeat the process at a slight lower voltage. Apply correction due to air density and humidity.

DRY TEST:

1. Connect the dry insulator and switch AC supply to transformer and push the ON bottom on the control panel
2. Slowly vary the input voltage from zero till the disruptive discharge occurs between the insulator and ground note down the flashover voltage of the insulator.
3. Repeat the same for other insulators.

Table 7.1: Tabulation for flashover test of insulators

SL. NO.	Std Flashover voltage (in kV RMS)	Measured flash over voltage (in kV RMS)	% error

WET TEST:
The methods involve spraying the test object with water but do not simulate natural rain condition. The test object is sprayed with water of prescribing resistively falling on it as droplets at an angle of 45 degree to the horizontal. The intensity and angle are measured with a dividing collecting vessels having opening of 100-750 cm.sqr. one horizontal, the vertical opening facing the spray. The collecting vessel should be placed near to the test object but avoiding drops from it. During measurement period, it should be moved slowly up and down to average out the effect of non-uniformity of the spray distribution. Preventing time of test object is 10 minutes. The collection time of spray droplets is one minute.
The disruptive discharge of external insulators depends on the prevailing atmospheric condition. Usually the flashover for a given path in air is increase with both an increases in air density and humidity. No humidity correction should be applied for wet test.
Wetting is done by spraying water for 10 minutes and collect the water as out line above. Perform the procedure in step (1), (2) and (3) to note down the flashover voltage of the insulator under wet condition.

Note: For every discharge voltages and flashover voltages apply correction factor given at the end of the theory.

7.5 Observation

Tabulate the reading for each of the insulators as described Table 7.1.

7.6 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications. Some questions are described below.

1. What is dry and wet creepage length of an insulator?
2. Will greasing help to increase the flashover voltage during wet condition? If yes, how?

Experiment 8

Impulse Generator

8.1 Aim of the Experiment

1. Study of impulse generator and generating standard impulse wave shape.
2. To Calibrate the Sphere gap using High Voltage Lightning Impulse as per IS

8.2 Apparatus Required

1. 100Kv Test transformer
2. 2 Nos. Silicon Rectifier (PIV-140kV), 20mA with 100k Ohm built in protective resistor.
3. 2 Nos. 140kV, 280 Mega-ohm, 0.5mA Measuring Resistor.
4. 140kV Grounding switch
5. Electrode 1 No.
6. Discharge rod
7. Support insulator 5 nos.
8. Connecting Rods 1 no.
9. Connecting Cup 6 nos.
10. Floor pedestal 6 nos.
11. Space bar 1 no.
12. 140kV, 10000pF Capacitor 1 no
13. Dia of Sphere = 10 cm.
14. 140kV, 12000pF Capacitor 1 no
15. 140kV, 10Mega ohm Charging resistor
16. Coaxial cable and surge oscillioscope

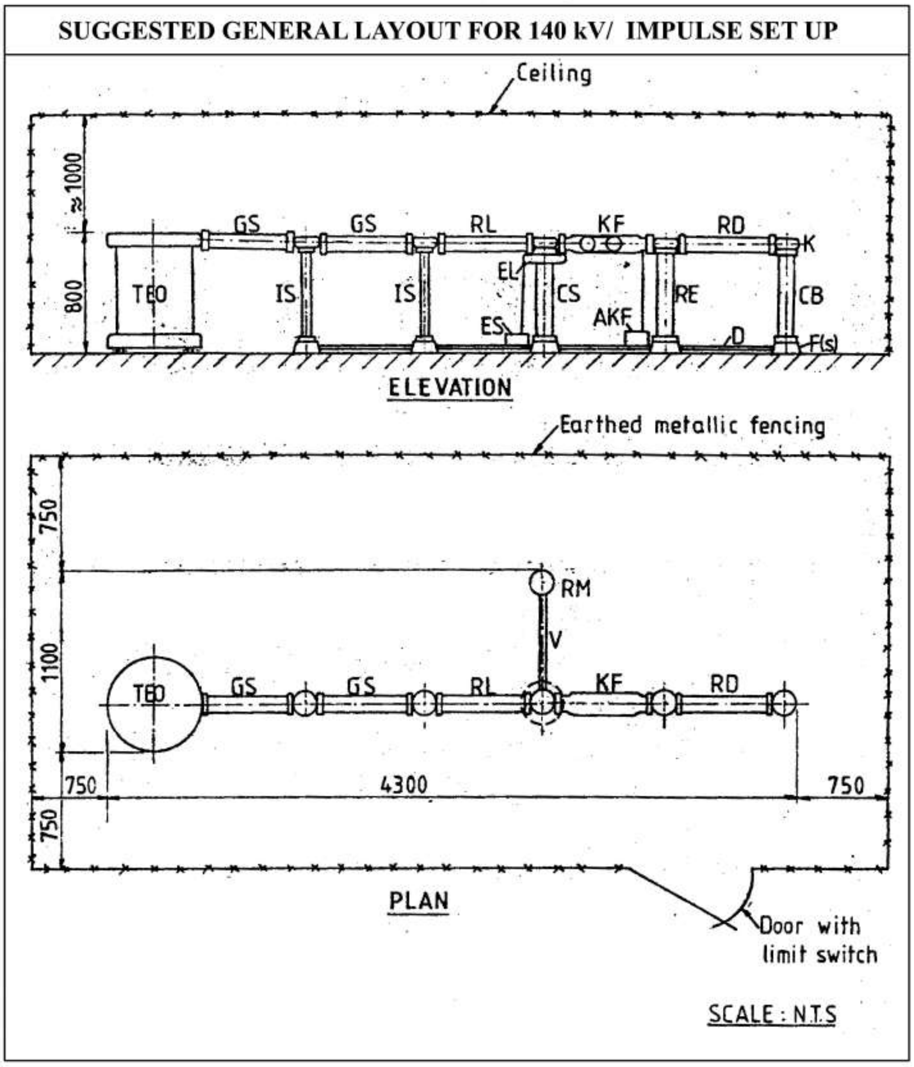


Figure 8.1: Schematic of Impulse Generator Setup

The laboratory has a single stage LI Voltage setup capable of producing 140kV at no load. Manufactured by WS Test Systems Bangalore, the unit has the following specification.

- Rated voltage (Charging voltage) 140kV, Maximum stored Energy = 490 Joule
- Voltage efficiency = 92
- The output can be controlled by varying the AC input at CONTROL DESK.

The schematic connection diagram is shown in Fig. 8.1.

Table 8.1: Generation of Impulse Voltage using 140 kV, 0.49 kJ Impulse Generator

SL. NO.	Distance b/w sphere	input voltage	DGM	DSPM

8.3 Theoretical Background

Sphere gaps are normally used for measurement of voltage as the spark over voltage of these gaps at uniform field have a known tolerance value under constant atmospheric conditions. There are also few more advantages of using sphere gaps for voltage measurements. The sphere gap was kept at a particular gap spacing. The spark over voltage at that spacing is noted and compared with IS 1876 of 1962.

It is essential to ensure that the electrical equipment is capable of withstanding the over voltages that are met within service. Overhead line insulators are tested by applying standard impulse voltages. The 50% flash over voltage is determined. Usually the probability of failure is determined for 40% and 60% failure values or 20% and 80% failure values, since it is difficult to adjust the test voltage for exact 50% flashover values.

The insulator surface should not be damaged by these tests, but slight marking on its surface or chipping off of the cement is allowed.

8.4 Procedure

As per the manufacturer's diagram connect all these devices. Apply voltage to the sphere gap 10 times and find the %age of flashover. Increase the voltage and note the % flashover. Plot a curve and determine 50% flashover voltage. Measure the wave from in Oscilloscope. Measure the atmospheric conditions and apply the correction factor. Using IS 1876 of 1962 find the % error in flashover voltage. Make observations in Table 8.1 (DGM: DC Voltmeter; DSPM: Impulse Voltmeter). The dc sample outputs are provided in Fig. 8.4, Fig. **??**,and Fig. 8.5.

8.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications. Discuss answers to the following questions.

1. What are the methods of measuring Impulse Voltages?
2. What are tests on line insulators?
3. Explain the importance of wet flashover test.

Figure 8.2: Experimental set-up for DC Impulse Generator

Figure 8.3: Sample Waveform for DC Impulse Generator

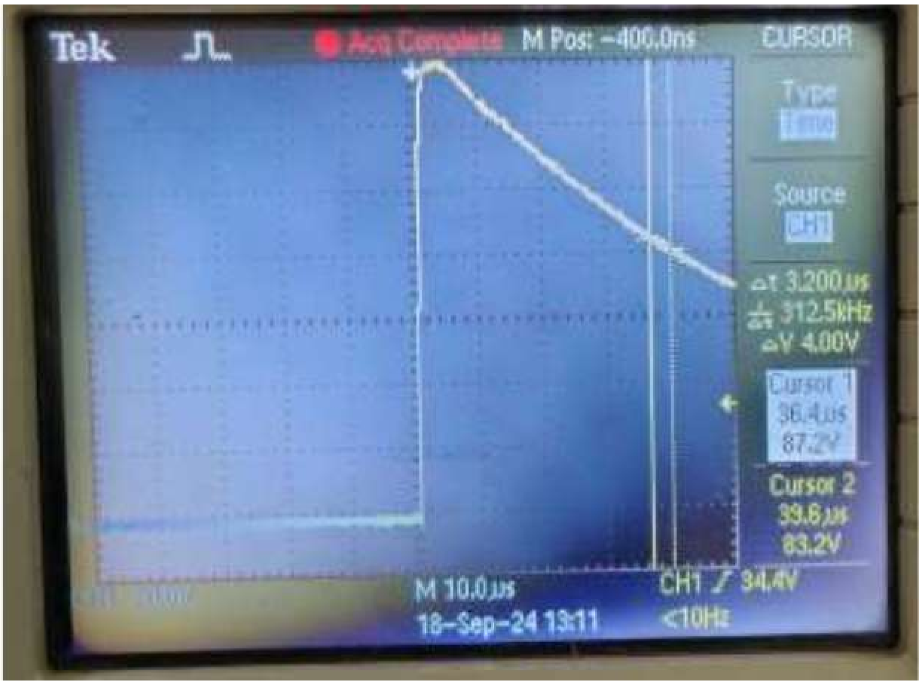


Figure 8.4: Sample Waveform for DC Impulse Generator (Part-2)

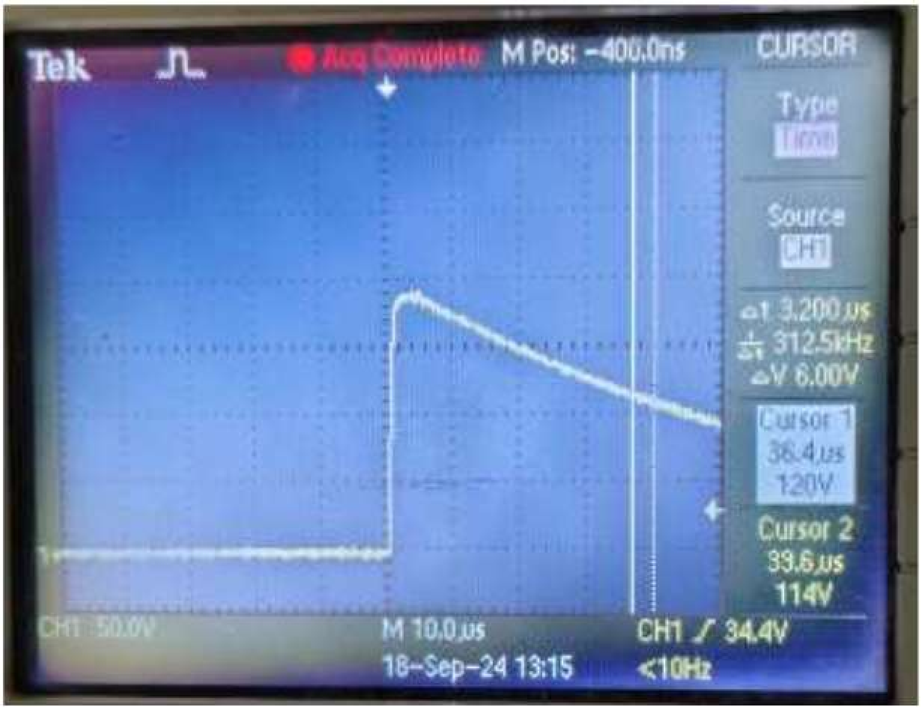


Figure 8.5: Sample Waveform for DC Impulse Generator (Part-3)

Experiment 9

Testing of insulation oil and Schering Bridge

9.1 Aim of the Experiment

1. Testing of insulating oil.
2. Measurement of loss tangent and dissipation factor using high voltage Schering bridge.

9.2 Apparatus Required

1. Transformer oil testing kit
2. High voltage schering bridge

9.3 Theoretical Background

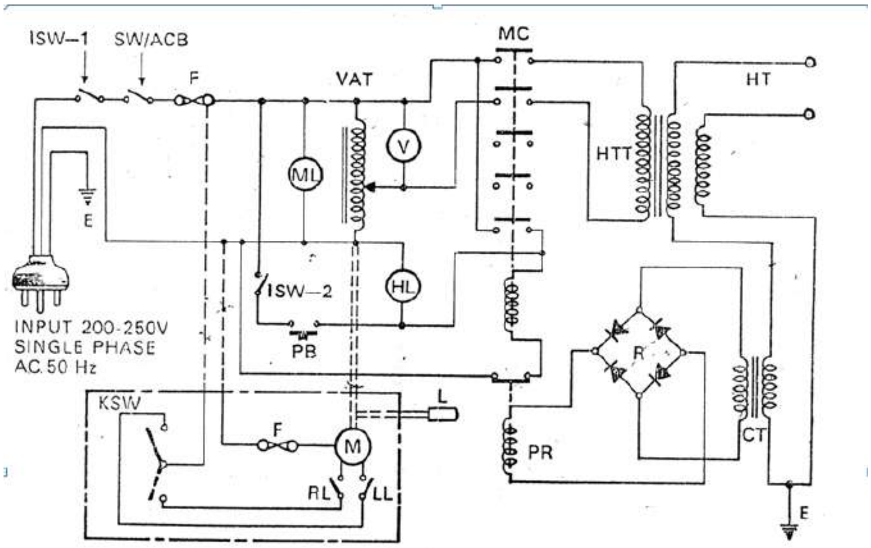
9.3.1 Transformer oil

9.3.2 Capacitance Measurements

9.4 Procedure

The equipment transformer 'Oil Test Set' is to be used for this test. Take minimum two samples of transformer oil and measure the breakdown strength (voltage) and one minute withstand voltage and tabulate the result.

1. Clean the vessel with the oil sample to be tested and fill up the vessel with this sample and fill the vessel in the oil testing kit.
2. Switch on the power supply to the kit and push the HT ON bottom.
3. Increase slowly the voltage between the sphere gap by rotating the knob, maintain uniform rate of increment 2 KV per second.



ISW - 1 - Cover Interlocking Switch.
ISW - 2 - Interlocking switch on variac.
SW/ACB - Switch/Air Circuit Breaker
F - Fuse
MC - Main Contactor
VAT - Variable Auto - Transformer.
HTT - H.T. Transformer
HT - H.T. Terminal
V - Voltmeter
ML - Lamp - Main Supply 'ON'
HL - Lamp. HT Supply 'ON'

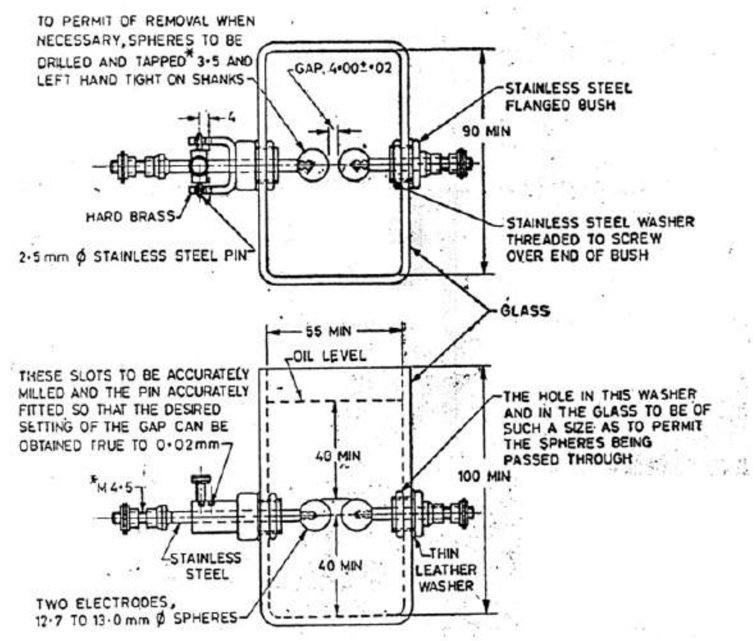
R -Rectifier
PB - Push Button
PR - Ptorective Relay
CT - Current Transformer
E - Earth Connection
L - Lever for coupling / Decoupling
RL - Raise Limit Switch
LL - Lower Limit Switch
KSW- Key Switch
M - Motor

Figure 9.1: Circuit diagram for oil testing kit

4. Note down the voltage at which the spark is flashed.
5. Repeat steps (3) and (4) for six times, give an interval of two minutes between two tests.
6. If the flash over does not occur after reaching 60 KV, note down the withstand time.

9.5 Discussion and Conclusion

Write what conclusions you have drawn from the experiments performed. Discuss the experiments and their relevance and practical applications.



*See IS : 1362-1962 Dimensions for Screw Threads for General Purposes (Diameter Range 0·25 to 39·0 mm) (*Revised*).

NOTE — When used, the test cell is to be stood in a thick porcelain dish or otherwise insulated from earth. All corners and edges to be well rounded off.

All dimensions in millimetres.

Figure 9.2: Test Cell with Electrode for determination of electric strength