Analytical approaches in optimization of design of Electrical system of INRP Project at Tarapur

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Abstract

Integrated Nuclear Recycle Plant (INRP) will be the first integrated nuclear fuel recycle facility where spent fuel storage, reprocessing, waste management plants & waste storage will be integrated into a single entity by locating all the civil structures in a single campus. Electrical power system of the plant comprises of various normal, emergency & un-interruptible power supplies in line with the existing nuclear recycle plants & the safety guide lines for such radio chemical facility. The power supply systems are significantly large and spread over length & breadth of the plant area. A large number of transformers and associated switch gear & cabling systems are envisaged for development of the power system network. In order to arrive at an optimum design solution, a number of technically feasible options for 6.6 kV and 415V power distribution network were analysed and compared techno economically.

This paper covers the analytical approaches adopted in design of such electrical systems of INRP Project at Tarapur. It involves Load Flow Study and Short Circuit Analysis using ETAP software as well as manual calculation of Steady State and Transient Voltage Dip. Load-flow study was performed to determine the steady-state operation of an electric power system. The voltage drop on each feeder, the voltage level at each bus, and the power flow in all branches and feeder circuits were calculated. It was determined if system voltages remain within specified limits under various contingency conditions, and whether equipment such as transformers and cables are protected against overload. Load-flow study was used to identify the need for additional active Power, capacitive, or inductive VAR support, or the placement of capacitors and/or reactors to maintain system voltages within specified limits. Prospective losses in each branch and total system power losses were also calculated. The short circuit study models the current that flows in the power system under abnormal conditions of all types of three phase short circuit faults and determines the prospective fault current in an electrical power system at various buses. The short circuit study was performed for both the typical and worst case scenarios.

RAMI analysis will be carried out for power distribution system for checking reliability, availability, maintainability and inspectability aspects of the system. The RAMI approach consists of four main steps: (1) performing function analysis; (2) analyzing initial failure modes, effects and criticality; (3) initiating risk mitigation actions to ensure compatibility with RAMI objectives; (4) integrating as RAMI requirements.

Keywords

ETAP, Load Flow, Short Circuit Analysis, Steady State, Transient Voltage, RAMI Analysis.
Introduction

INRP will be the first integrated nuclear fuel recycle facility where spent fuel storage, reprocessing, waste management plants & waste storage will be integrated into a single entity by locating all the civil structures in a single campus with suitable connectivity between them.

Several common blocks like Utility blocks, Block 106, Block 103, Exhaust Air Blocks (108A/B/C/D), Supply fan blocks, Electrical block (132), DG blocks (119 A/B) & Block 115, stores, Main Control Room (Block 101) etc. will cater to the needs of both reprocessing as well as waste management process & storage systems. O & M (Operation & Maintenance) personnel and administrative machinery will also serve to both the above mentioned systems.

The plant is designed to process spent fuel received from PHWRs (Pressurized Heavy Water Reactors) with an objective to recover Plutonium (Pu) and Uranium (U) meeting the required product specifications. The plant’s design capacity is 600 tonnes of Heavy Metal (HM) per annum. The plant is under construction on a plot near to TAPS 3 & 4, Tarapur, having width of 658 m at one side & 454 m at other side and length of 558 m for this project.

The plant is functionally divided into various blocks. Electrical system for project INRP comprises of Class IV, Class III, Class II and Class I power supply systems for the various utility and process loads of the facility. Class IV and Class III power supplies for various blocks are provided from Electrical Block (132) and DG Blocks (119A/B).

Class IV Mains power supply for INRP project, Tarapur will be received through two (2) independent 33 kV underground feeders from nearby source i.e. 33 kV indoor substation to be located within TAPS 1 and 2 Switchyard, to Electrical Block. Mains Power at 33 kV level will be stepped down to 6.6 kV level in Electrical block by installing 2 nos. 20/ 25 MVA outdoor oil-cooled transformers. Power at 6.6 kV level will be distributed to MV load centres i.e. Compressed air Plant, Chiller Plant etc. and also to DG block (119A), as well as to other load distribution centres viz., Substations at Supply Fan Block 1 (107A) & 2 (107B) etc. 6.6 kV feeders in DG block are proposed to be multiplied & extended to other two load distribution centres viz. Exhaust Air Block-4 (108D) & UOF Block (122). 6.6/0.433 KV, 2.5 MVA indoor dry type transformers are planned in blocks 132, 107A, 107B, 119A, 108D & 122 for catering to the entire class-IV load requirements of various blocks of INRP. Localised Class-II and Class-I power supply systems are proposed to be located in each of the blocks 132, 121A/B, 101, 102A/B, 105, 106, 110, 111, 113, 114, 119A, 122, 147.

Simultaneous maximum demands for class IV, class III, class II distribution systems are as follows:

- Class IV Maximum demand: 16 MVA.
- Class III Maximum demand: 5 MVA.
- Class II Maximum demand: 500 kVA.

The power supply systems are significantly large and spread over length & breadth of the plant area. A large number of transformers and associated switch gear & cabling systems are envisaged for development of the power system network. In order to arrive at an optimum design solution, a number of technically feasible options for 6.6 kV and 415V power distribution network were analysed and compared techno economically.

Short circuit analysis, Load flow study and transient voltage analysis have been carried out. RAMI analysis is in progress.

Objectives

These studies have been carried out to find out the best location and optimum capacity for the transformers, switchgears & cable feeders, to ensure:

- High reliability, safety, availability and maintainability of power supply.
- Steady state and transient voltage drops within limits as per Indian Electricity Rules.
- Optimum rating and capacity utilization of equipments viz. transformers, switchgears, cables etc.
• Minimal distribution losses.
• Reduced cable & cable tray lengths and cable sizes resulting in substantial savings & ease of cable laying.
• Optimum capital and running cost.

**Power distribution network options analyzed:**

To achieve the above objectives and to arrive at the optimum solution, a number of technically feasible options for 6.6 kV and 415V power distribution have been compared technically. Following comparative studies were carried out for:

• Two technically feasible options for 6.6 kV distribution.
• Eight technically feasible options for 415V distribution.
  – Comparison of Steady state voltage drops.
  – Comparison of Transient voltage dips.
  – Comparison of ohmic losses.
  – Comparison of cable sizes.
  – Cost analysis for Cables & cable trays.

The schemes for 6.6 kV and 415V power distribution were selected after comparison of the above parameters and arriving at an optimum solution, as detailed below.

**Case I: Comparisons of the two options for 6.6 kV power distribution:**

<table>
<thead>
<tr>
<th>Option-2</th>
<th>Option-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable and cable tray lengths were more in Option 1 of 6.6 kV Power Distribution Scheme. Also, laying of cables over service rack would have become very cumbersome.</td>
<td></td>
</tr>
<tr>
<td>Difference in cost estimates for Option 1 and Option 2 (for 6.6 kV power distribution) = 2.01Cr</td>
<td></td>
</tr>
<tr>
<td>Considering the above, it was found that Option 2 is better for 6.6 kV Power distribution from technical as well as commercial point of view.</td>
<td></td>
</tr>
</tbody>
</table>

**Case II: Comparison of the eight options for 415V power distribution:**

16 nos. of 6.6 kV/433V, 2.5 MVA transformers located at three load centres viz. Electrical block, DG block, UOF block in Option 1.

16 nos. of 6.6 kV/433V, 2.5 MVA transformers located at five load centres viz. Electrical block, DG block, Admin block, Training Centre block, UOF block in Option 2.

18 nos. of 6.6 kV/433V, 2.5 MVA transformers located at four load centres viz. Electrical block, DG block, SA fan-1 block, SA fan-2 block in Option 3.

16 nos. of 6.6 kV/433V, 2.5 MVA transformers located at four load centres viz. Electrical block, DG block, Admin block, UOF block in Option 4.

18 nos. of 6.6 kV/433V, 2.5 MVA transformers located at four load centres viz. Electrical block, DG block, Training Centre, UOF block in Option 5.

18 nos. of 6.6 kV/433V, 2.5 MVA transformers located at three load centres viz. Electrical block, DG block, UOF block in Option 6.
18 nos. of 6.6 kV/433V, 2.5 MVA transformers located at three load centres viz. Electrical block, DG block, SA fan-2 block in Option 7.

16 nos. of 6.6 kV/433V, 2.5 MVA transformers located at six load centres viz. Electrical block, DG block, SA fan-1 block, SA fan-2 block, Block 122, EA fan-4 block in Option 8. (DG Block is having 6 nos. transformers, out of which 4nos. are dedicated for Class-III System). The layout of selected option 8 of LV distribution scheme is shown as annexure 1. The photograph of newly constructed Electrical Block is shown in Fig. 1

**Load Flow Study**

Load flow studies are one of the most important aspects of power system planning and operation. The load flow gives us the sinusoidal steady state of the entire system viz. voltages, real and reactive power generated and absorbed and line losses. Since the load is a static quantity and it is the power that flows through transmission lines, the purists prefer to call this Power Flow studies rather than load flow studies. We shall however stick to the original nomenclature of load flow.

Through the load flow studies, we can obtain the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a specified limit. Once the bus voltage magnitudes and their angles are computed using the load flow, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed. Furthermore, from the line flow, we can also determine the over and under load conditions.

The steady state power and reactive power supplied by a bus in a power network are expressed in terms of nonlinear algebraic equations. We have therefore adopted iterative methods for solving these equations.

**Methods:**

**Newton–Raphson solution method:** This method begins with initial guesses of all unknown variables (voltage magnitude and angles at load buses and voltage angles at generator buses). Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations. The result is a linear system of equations that can be expressed as:

$$
\begin{bmatrix}
\Delta \theta \\
\Delta |V|
\end{bmatrix} = -J^{-1}
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
$$

where $\Delta P$ and $\Delta Q$ are called the mismatch equations:

$$
\Delta P_i = -P_i + \sum_{j=1}^{N} |V_j| |V_i| (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})
$$

$$
\Delta Q_i = -Q_i + \sum_{j=1}^{N} |V_j| |V_i| (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})
$$

Fig. 1: Photograph of Electrical Block (132)
and J is a matrix of partial derivatives known as a Jacobian:

\[
J = \begin{bmatrix}
\frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\
\frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|}
\end{bmatrix}
\]

The linearized system of equations is solved to determine the next guess \((m + 1)\) of voltage magnitude and angles based on:

\[
\theta^{m+1} = \theta^m + \Delta \theta \\
|V|^{m+1} = |V|^m + \Delta |V|
\]

The process continues until a stopping condition is met. A common stopping condition is to terminate if the norm of the mismatch equations is below a specified tolerance.

A rough outline of solution of the power-flow problem is to:-

1. Make an initial guess of all unknown voltage magnitudes and angles. It is common to use a “flat start” in which all voltage angles are set to zero and all voltage magnitudes are set to 1.0 p.u.
2. Solve the power balance equations using the most recent voltage angle and magnitude values.
3. Linearize the system around the most recent voltage angle and magnitude values.
4. Solve for the change in voltage angle and magnitude.
5. Update the voltage magnitude and angles.
6. Check the stopping conditions, if met then terminate, else go to step 2.

Other Methods:

**Gauss–Seidel method:** This is the earliest devised method. It shows slower rates of convergence compared to other iterative methods, but it uses very little memory and does not need to solve a matrix system.

**Fast-decoupled load-flow method:** This method is a variation on Newton-Raphson that exploits the approximate decoupling of active and reactive flows in well-behaved power networks, and additionally fixes the value of the Jacobian during the iteration in order to avoid costly matrix decompositions. It is also referred to as “fixed-slope, decoupled NR”. Within the algorithm, the Jacobian matrix gets inverted only once, and there are three assumptions. Firstly, the conductance between the buses is zero. Secondly, the magnitude of the bus voltage is one per unit. Thirdly, the sine of phases between buses is zero. Fast decoupled load flow can return the answer within seconds whereas the Newton Raphson method takes much longer. This is useful for real-time management of power grids.

**Holomorphic embedding load flow method:** A recently developed method based on advanced techniques of complex analysis. It is direct and guarantees the calculation of the correct (operative) branch, out of the multiple solutions present in the power flow equations.

**Load flow study for INRP:**

Load flow study has been carried out for planning operation of Class-IV power systems of Integrated Nuclear Recycle Plant (INRP) at Tarapur. Master One Line Diagram of INRP is attached as Annexure-2.

Technical comparison of 415V power distribution schemes is shown below. Transient voltage dip calculation for option 8 is also attached as annexure-3.

The study is performed for the worst case scenario when the highest rating motor at 415V bus is started.

Steady state voltage drops for various load centres for selected option 8 of LV distribution is shown as Fig. 2.

**Fig. 2:** Voltage drops during Steady state condition (Option 8)
### Technical comparison of 415V power distribution schemes:

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Item</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
<th>Option 5</th>
<th>Option 6</th>
<th>Option 7</th>
<th>Option 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Voltage drop</td>
<td>9.6% max.</td>
<td>6% max.</td>
<td>5.3% max.</td>
<td>8.1% max.</td>
<td>7.9% max.</td>
<td>9.4% max.</td>
<td>8.1% max.</td>
<td>2.99% max.</td>
</tr>
<tr>
<td>2</td>
<td>Ohmic losses</td>
<td>840 kW</td>
<td>350 kW</td>
<td>260 kW</td>
<td>570 kW</td>
<td>540 kW</td>
<td>720 kW</td>
<td>500kW</td>
<td>200kW</td>
</tr>
<tr>
<td>3</td>
<td>Cable length</td>
<td>109 km</td>
<td>47 km</td>
<td>39 km</td>
<td>75 km</td>
<td>71.5 km</td>
<td>94 km</td>
<td>65km</td>
<td>23km</td>
</tr>
<tr>
<td>4</td>
<td>Cable tray length</td>
<td>27 km</td>
<td>19 km</td>
<td>15.6 km</td>
<td>26 km</td>
<td>21.5 km</td>
<td>23.8 km</td>
<td>20.3km</td>
<td>9km</td>
</tr>
<tr>
<td>5</td>
<td>Ease of laying of cables</td>
<td>Cumber some</td>
<td>Easy</td>
<td>Easier</td>
<td>Cumber some</td>
<td>Cumber some</td>
<td>Cumber some</td>
<td>Easy</td>
<td>Easiest</td>
</tr>
<tr>
<td></td>
<td>over service rack</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Remarks</td>
<td>Cable density &amp; no. of</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
<td>Cable density &amp; no.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>eqpts very high leading to congestion</td>
<td>eqpts low.</td>
<td>eqpts very high leading to congestion</td>
<td>eqpts very high leading to congestion</td>
<td>eqpts very high leading to congestion</td>
<td>eqpts very high leading to congestion</td>
<td>eqpts low.</td>
<td></td>
</tr>
</tbody>
</table>

Considering the above, it is found that **Option 8** is better for 415V Power distribution from technical as well as commercial point of view.

### Short Circuit Analysis

A balanced 3-phase fault implies that all three phases of the power system are simultaneously short-circuited to each other through a direct or “bolted” connection. The other types of unbalanced short-circuit faults are important in selecting the time-current characteristics and settings of phase-overcurrent and ground-fault protective devices to provide selective coordination. This coordination assures service continuity and minimizes damage to switchgear and load equipment. However, unbalanced fault calculations are more difficult to perform for industrial and commercial power systems and require knowledge of the method of symmetrical components.

### Electrical Transient Analyser Program (ETAP)

ETAP is the most comprehensive solution for the design, simulation, and analysis of generation, transmission, distribution, and industrial power systems. ETAP organizes the work on a project basis. Each project that we create provides all the necessary tools and support for modelling and analysing an electrical power system. A project consists of an electrical system that requires a unique set of electrical components and interconnections. In ETAP, each project provides a set of users, user access controls, and a separate database in which its elements and connectivity data are stored.

### Short Circuit Analysis on ETAP

In order to determine the currents resulting from an asymmetrical fault, the values of per unit (p.u.) zero, positive and negative sequence impedances of transformers, generators, cables etc. are required.

### Calculation Methods

**Initial Symmetrical Short Circuit Current Calculation**

Initial symmetrical short-circuit current ($I_k''$) is calculated using the following formula:

$$I_k'' = \frac{cU_n}{\sqrt{3}Z_k}$$

where $Z_k$ is the equivalent impedance at the fault location, $c$ is the voltage factor and $U_n$ is the nominal system voltage. Voltage factor $c$ is the ratio of equivalent voltage to nominal voltage and is used to adjust the value of the equivalent voltage source for minimum and maximum current calculations.
Peak Short Circuit Current Calculation

Peak short-circuit current ($i_p$) is calculated using the following formula:

$$i_p = \sqrt{2} k I_k''$$

where $k$ is a function of the system R/X ratio at the fault location.

Symmetrical Short Circuit Breaking Current Calculation

For a far-from-generator fault, the symmetrical short circuit breaking current ($I_b$) is equal to the initial symmetrical short circuit current.

$$I_b = I_k''$$

For a near-to-generator fault, $I_b$ is obtained by combining contributions from each individual machine. $I_b$ for different types of machines is calculated using the following formula:

$$I_b = \frac{\mu I_k''}{\mu q I_k''}$$

for synchronous machines

$$I_b = \frac{\mu q I_k''}{\mu q I_k''}$$

for asynchronous machines

where $\mu$ and $q$ are factors that account for AC decay. They are functions of the minimum time delay and the ratio of the machine initial short circuit current to its rated current, as well as real power per pair of poles of asynchronous machines.

IEC Standards allow you to include or exclude AC decay effect from asynchronous machines in the calculation.

Steady-State Short circuit current Calculation

Steady-state short circuit current $I_k$ is a combination of contributions from synchronous generators and power grid. $I_k$ for each synchronous generator is calculated using the following formula:

$$I_{k_{\text{max}}} = \lambda_{\text{max}} I_{rG}$$

$$I_{k_{\text{max}}} = \lambda_{\text{min}} I_{rG}$$

where $\lambda$ is a function of a generator excitation voltage, ratio between its initial symmetrical short circuit current and rated current, other generator parameters, and $I_{rG}$ is the generator rated current.

The steady-state short circuit current calculated is dependent on the option selected for Short circuit current in the study case. If the Max and User-Defined c Factor is selected, the maximum steady-state short circuit current is reported. If the Min option is selected, the minimum steady-state short circuit current is reported.

This maximum steady-state short circuit current is used to determine minimum device ratings. The minimum steady-state short circuit value is used for relay coordination purposes in preventing the occurrence of nuisance trips and loading deviations.

Inputs

- Main One Line Diagram.
- Fault level at 33 kV bus is considered as 1500 MVA and the 33 kV bus has been considered in swing mode.

Basis/Methodology

- The Power System has been Modelled Using ETAP PowerStation Software, ver. 11.0.0.
- ETAP program calculations are in compliance with latest edition of IEC standards.
- Nodes are generated by ETAP software while connecting two impedances, e.g. between transformer impedance and cable impedance.
- The nomenclatures of the buses have been decided based on the block to which they are feeding.

Short Circuit Analysis for INRP

Short circuit analysis has been carried out to confirm that, during symmetrical and asymmetrical fault, the fault current should not exceed the anticipated maximum fault level. Short circuit analysis has been carried out at 33kV, 6.6kV and 415V buses. All these buses are connected by utility 33 kV connections.
through transformers to the switchgear. The short circuit level at faulted buses are found, which help in selecting the circuit breaker. ETAP Short Circuit Case study results are attached as Annexure-4.

Conclusion

The selected options for MV and LV distribution (Option 2 for MV distribution and option 8 for LV distribution) have resulted in significant reduction of cabling with cable racks (86 km reduction in cabling), substantial savings of about 20 Crores on account of cabling & cable racks (on comparison with option 1 for MV and LV distribution), and also in energy conservation. Further on account of reduction in cable power losses, energy savings of the order of Rs. 5 Crores is achieved per year. All transformer installations in blocks 107A/B, 108D and 122 will be unmanned and monitored remotely through Electrical SCADA and CCTV. SCADA and CCTV controls are proposed to be provided in blocks 132 and 119A, which will be manned substations. View stations are also provided in Main control room and Utility control room.

Short circuit analysis has been carried out at 33kV, 6.6kV and 415V buses. The short circuit level at faulted buses are found, which help in selecting the circuit breaker. Fault at 415V Class III EPCC-A1 bus has highest fault level with DG breaker closed and tie line breaker closed. L-L-G fault has the highest contribution level in all of the cases considered in comparison to all other asymmetrical faults. It is ensured that short circuit fault current duties are in compliance with the latest editions of the ANSI/IEEE Standards (C37 series) and IEC Standards (IEC 60909 and others). RAMI analysis will be carried out for power distribution system for checking reliability, availability, maintainability and inspectability aspects of the system.

Acknowledgment

The authors sincerely thank Shri S. Basu, Director, BARC & Chairman NRB for his continuous support and encouragement in all the activities pertaining to the design of electrical systems for nuclear fuel recycle facilities. The authors thank Shri Shashank Srivastava for his help in carrying out short circuit analysis using ETAP. The authors also thank Ms. Ambika Raja, SA/E, INRPRD and Shri Jai Prakash, TO/C, INRPRD for their help in writing the paper. The authors also thank their colleagues of INRPRD for providing all necessary help in extending whole hearted co-operation in design of the systems and in writing this paper.

References

1. Design of Electrical System for Large Projects by N. Balasubramanian.
3. IEEE 485 & IS 2026.
4. ETAP manual, version 11.0.0.
Annexure-2 : Master One Line Diagram of INRP
Annexure-3: Transient Voltage Drop Calculation for Option 8 of LV distribution

For NPCC-A in Supply air fan Block-107A:

1. Input Data

1.1 Rated voltage = 415V
   Fault MVA = 31.35MVA (Fault MVA at 415V level is calculated by considering a fault level of 1500MVA at 33 kV level at the source end i.e. TAPS 1&2 Switchyard).

1.2 Rating of highest motor (i.e. Supply air fan) connected to NPMCC in Supply Air Fan Room-1(107-A) = 110 kW
   Motor Full load current = 189A

1.3 Total running load on NPCC-A with highest motor running = 2.117 MVA

1.4 Total running load on NPCC-A without highest motor = 1.9795 MVA.

1.5 Cable from NPCC-A in Supply Air Fan (107-A) to proposed NMCC-A in Supply Air Fan Room-1(107-A)
   Size = 3C x 400 sq. mm 1.1 kV Al XLPE cable.
   Length of cable = 9 mtr.
   No. of runs = 6
   Resistance of Cable = 0.100 ohm/km (at 90°C)
   Reactance of Cable = 0.0704 ohm/km
   Impedance of Cable = 0.12229 ohm/km
   Total impedance of cable = 0.000183 ohm

1.6 Cable from proposed NMCC-A to Supply air fan motor
   Size of cable = 1x3x120 sq. mm. 1.1kV Al XLPE cable.
   Length of cable = 45 mtr.
   No. of runs = 1
   Resistance of cable = 0.324 ohm/km (at 90°C)
   Reactance of cable = 0.0712 ohm/km
   Impedance of cable = 0.3317 ohm/km
   Total impedance of cable = 0.01493 ohm

1.7 For bus duct from Transformer to NPCC in Supply Air Fan (107-A)
   Length of bus duct = 7 mtr.
   Resistance = 0.01171 ohm/km (at 95°C)
   Reactance = 0.00549 ohm/km
   Impedance = 0.01293 ohm/km
   Total Impedance of Bus duct = 0.00009051 ohm

2. Assumption

2.1 Base MVA = 100
2.2 Base kV = 0.415
2.3 Starting current of motor = 2.5 Ifl (considering VFD starting of motor)
2.4 Starting p.f. of motor = 0.2 lag
2.5 Outgoing cable impedance is neglected for all the feeders except S.A Fan.
2.6 Allowable voltage dip during starting of motor = 15% at motor terminals.
2.7 Voltage across motor terminals is assumed as 1 p.u. before starting.
3. Calculation of impedances at base MVA

**Source**

\[
Z_{\text{source}} = \frac{\text{Base MVA}}{\text{Fault MVA}} = \frac{100}{31.35} = 3.19 \text{ p.u.}
\]

**Cable**

*Incoming cable*

\[
Z_{\text{cable1}} = \frac{Z_{\text{actual}} \times \text{Base MVA}}{(\text{Base kV}) \times (\text{Base kV})} = \frac{0.000183 \times 100}{0.415 \times 0.415} = 0.106 \text{ p.u.}
\]

*Outgoing cable to SA fan*

\[
Z_{\text{cable2}} = \frac{Z_{\text{actual}} \times \text{Base MVA}}{(\text{Base kV}) \times (\text{Base kV})} = \frac{0.01493 \times 100}{0.415 \times 0.415} = 8.669 \text{ p.u.}
\]

**Bus Duct**

\[
Z_{\text{Bus Duct}} = \frac{Z_{\text{actual}} \times \text{Base MVA}}{(\text{Base kV}) \times (\text{Base kV})} = \frac{0.00009051 \times 100}{(0.415) \times (0.415)} = 0.0526 \text{ p.u.}
\]

**Base Load**

\[
Z_{\text{base load}} = \frac{\text{Base MVA}}{\text{MVA (base load)}} = \frac{100}{1.9795} = 50.52 \text{ p.u.}
\]

**Motor**

\[
\text{Motor Starting MVA} = \sqrt{3} \times I_0 \times 0.415 = \sqrt{3} \times 2.5 \times 189 \times 0.415/1000 = 0.3396
\]

\[
Z_{\text{motor}} = \frac{100}{0.3396} = 294.46 \text{ p.u.}
\]

**Calculation of Voltage Dip**

3.2.1 Equivalent circuit before motor starting is as indicated in Fig. 3

![Fig. 3](image)
The voltage at motor terminal before starting of motor is assumed as 1 p.u.

Equivalent impedance of circuit = \( Z \) (source) + \( Z \) (busduct) + \( Z \) (base load)

\[ = 3.19 + 0.0526 + 50.52 = 53.7626 \]

Current \( I_1 \) flowing in network = \( \frac{E_g}{\text{Equivalent impedance}} \) = \( \frac{E_g}{53.7626} \) = 0.018600 \( E_g \)

Voltage across motor terminals before starting = \( I_1 \times Z \) (base load)

1 p.u. = 0.018600 \( E_g \) x 50.52

1 p.u. = 0.93967\( E_g \)

\( E_g = 1.064 \) p.u.

Equivalent circuit during motor starting is as indicated in Fig. 4

![Fig. 4](image)

Equivalent impedance = \( |Z \) (source) + \( Z \) (busduct) + \( Z \) (base load) || (\( Z \) (cable1) + \( Z \) (cable2) + \( Z \) (motor))\)

\[ = 3.19 + 0.0526 + (50.52 || (0.106 + 8.669 + 294.46)) = 46.55 \text{ pu} \]

Total current drawn from supply = \( \frac{E_g}{\text{Equivalent impedance}} \) = \( \frac{1.064}{46.55} \) = 0.0229 pu

Current through motor branch = \( \frac{\text{Total current from supply} \times Z \) (base load)}{\text{Z (cable1) + Z (cable2) + Z (motor) + Z (base load)}} \)

\[ = \frac{0.0229 \times 50.52}{0.106 + 8.669 + 294.46 + 50.52} = 0.00327 \text{ p.u.} \]

Voltage across motor during starting in p.u. = \( \frac{\text{Current through motor branch} \times Z \) (motor)}{1 - 0.9629} \times 100 \)

\[ = \frac{0.00327 \times 294.46}{0.9629} \times 100 = 3.7 \% \]

The transient voltage dip is within limits (15%).
Annexure 4: ETAP Study Cases 1 to 4

I. Study Case 1:
Fault at Group A 33kV bus with tie breaker open.

Short-Circuit Summary Report

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<tbody>
<tr>
<td>ID</td>
<td>kV</td>
<td>( I_k'' )</td>
<td>( i_p )</td>
<td>( I_k )</td>
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All fault currents are in rms kA. Current \( i_p \) is calculated using Method C. (from ETAP software)

* LLG fault current is the larger of the two faulted line currents.

Where, \( I_k'' \) - Initial symmetrical current (kA, rms)
\( i_p \) - Peak Current (kA)
\( I_b \) - Breaking current (kA, rms, symm)
\( I_k \) - Steady state current (kA, rms)
II. **Study Case 2:**
Fault at 6.6 kV bus of Group A with tie breaker open.

**Short-Circuit Summary Report**

3-Phase, LG, LL, LLG Fault Currents

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All fault currents are in rms kA. Current $I_p$ is calculated using Method C. (from ETAP software)

* LLG fault current is the larger of the two faulted line currents.
III. Study Case 3:
Fault at 415V EPCC-A1 bus with DG breaker closed and tie line CB closed.

Short-Circuit Summary Report

3-Phase, LG, LL, LLG Fault Currents

<table>
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<tr>
<td></td>
<td></td>
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<td>I_p</td>
<td>I_k</td>
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<td>61.783</td>
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All fault currents are in rms kA. Current $I_p$ is calculated using Method C. (from ETAP software)

* LLG fault current is the larger of the two faulted line currents.
### Study Case 4:
Fault at 415V EPCC-A1 bus with DG breaker closed and tie line CB open.

#### Short-Circuit Summary Report

3-Phase, LG, LL, LLG Fault Currents

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<td>Line-to-Line</td>
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<td>Iₐ*</td>
<td>i_p</td>
<td>I_k</td>
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All fault currents are in rms kA. Current $I_p$ is calculated using Method C. (from ETAP software)

* LLG fault current is the larger of the two faulted line currents.