Voltage Sag Analysis

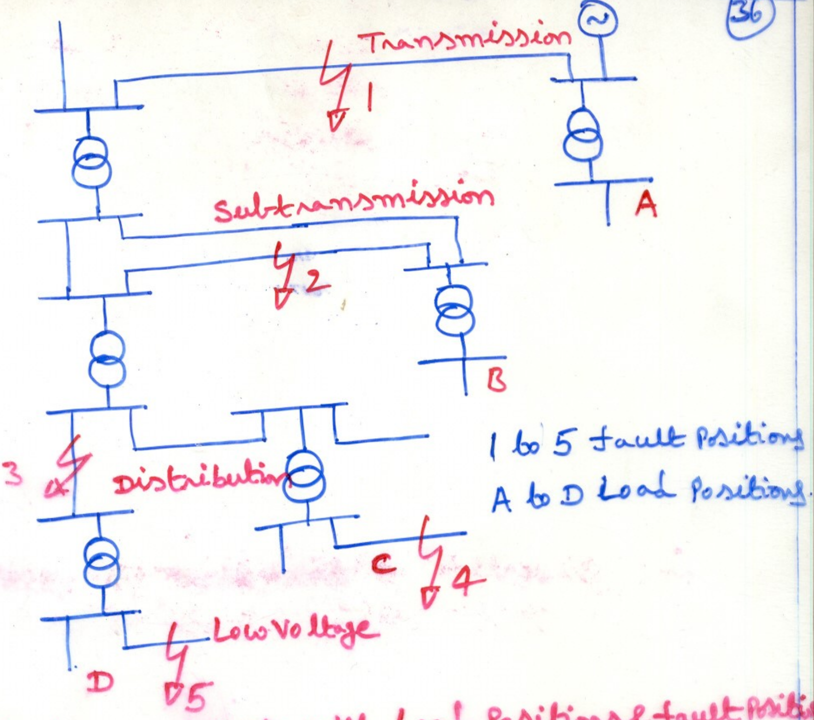
- Voltage sags are short duration reductions in rms Voltage caused by short circuits, overloads and starting of large Motors.
- Some equipment may trip when rms Voltage drops below 90% for longer than one or two cycles.
- If this is in case of Process Control equipment of a Paper mill or textile, the damage due to Voltage sag is enoromous.
- Voltage sag is not damaging to industry as a interruption. But if far more Voltage sags than interruptions the total damage due to sags is still larger.
- Interruptions originate in the local distribution network. But voltage sags at equipment due to short circuit faults 100 of Km's away in the transmission network.
- A Voltage sag is much more of a global Problem than an interruption. Reducing no. of interruptions typically requires improvements on one feeder, Reducing the no. of Voltage sags requires improvements on several feeders and often even at transmission lines far away.

what are the causes of Voltage Sags?

- The voltage sags are typically caused by fault conditions. Motor starting also result in under voltage (But typically longer in duration than 60 cycles).
- The large majority of faults on a utility system are single line to ground faults. 3-ϕ faults are severe, but much less.
- Weather conditions such as lightning, wind and ice, contamination of insulators, animal contact, accidents involving construction or transportation activites also cause faults.
- The faults are temporary, means that they will not reinitiate after they have been cleared and line is reclosed.
- Since faults are inevitable, critical equipment sensitive to voltage sags is adequately Protected.
- Power systems have non-zero impedance, so every increase in current causes a corresponding reduction in Voltage.
- Reductions in Voltage are small, remains within normal tolerences, But when there is a large variation in current, when system impedance is high, the Voltage can drop significantly.

What are the sources of Voltage Sags?

- The source of Voltage Sag is due to
  - (i) Large increase in current.
  - (ii) Increase in System Impedance.
- Most voltage sags are caused by increases in current.
- P S as a tree, Load connected to one of the twig. A voltage sag on trunk of the tree or on a branch leading out to twig, will cause voltage sag at load. But a short circuit at a distant Part of the tree can cause a sag at load.
- most voltage sags originate at the customer site.
  - (i) starting of large load, motor or resistive heater
  - (ii) Electric motors draw 150% to 500% operating current as they come up to speed.
  - (iii) Resistive heaters draw 150% rated current until they warm up.
  - (iv) Loose or defective wiring.
- occassionally a voltage sag originate on the utilitity grid.
  - (i) faults on distant circuit, causing voltage sag at load. Removed by reclosers or self resetting CB's
  - (ii) Voltage regulator failures are far less common. utilities have automated to voltage adjustment.



Distribution network with Load Positions & fault Positi

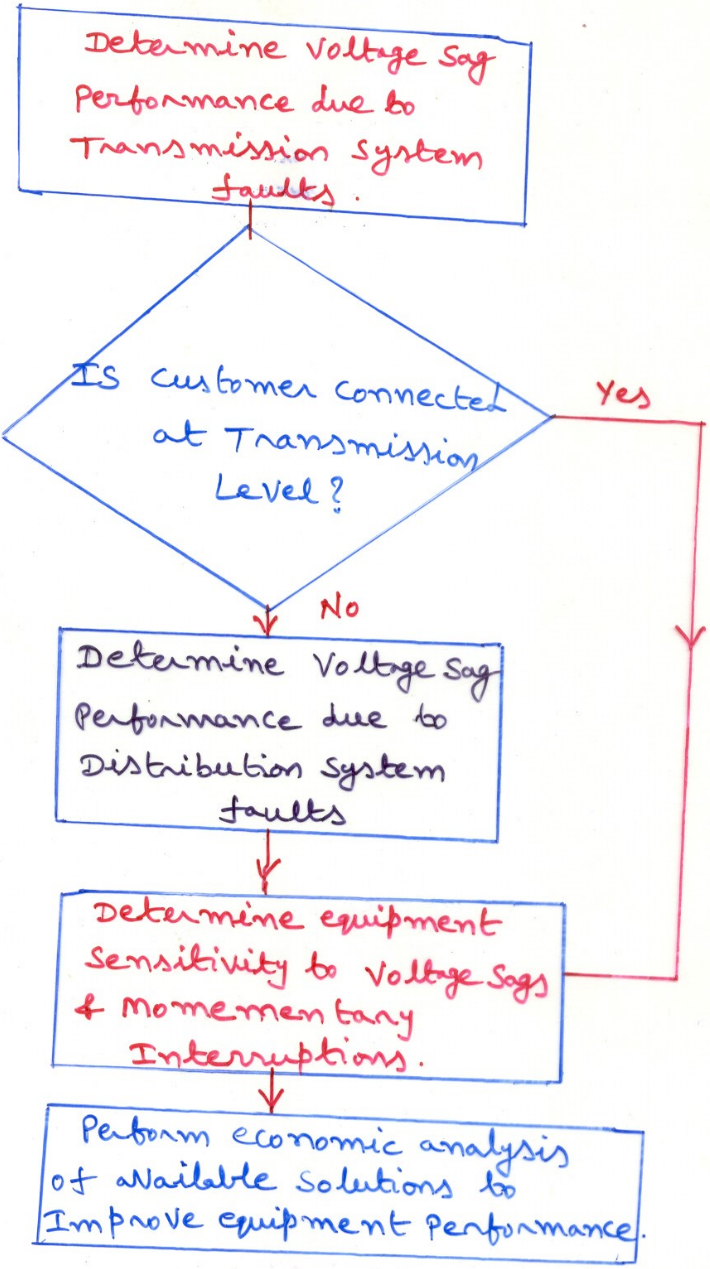
- A fault at 1 cause serious sag for both substations Transfered to all customers fed from these substations. No generation at low voltage Levels nothing to keep up the voltage, hence A, B, C, D Loads will effect. Sag experienced by A somewhat less deep, generators connected to substation will keep up the voltage.
- A fault at 2 will not cause much voltage drop for customer A. since 2 between Transmission & Sub-transmission are large hence limit the voltage drop at high voltage side of the transformer Sag mitigated by generators feeding at local transmission substation. However cause a deep sag at B, C, D

- A fault at 3 cause a very deep sag for D followed by a short or long interruption, when the protection clears the fault. C will experiences deep sag. B only experience shallow sag due to fault at 3. A not notice anything from this fault.
- A fault at 4 will cause a deep sag for customer C and shallow one for customer D.
- A fault at 5 will cause a deep sag for D and shallow sag for C. A & B will not be influenced at all by faults 4 and 5.

Sensitivity of equipment to Voltage Sags:-

- Process industry equipment with voltage sags cause the whole plant shut down. Examples: petrochemicals, textiles, semiconductor, Papermills Pharmacetical industries.
- motors, heating equipment, $3-\phi$ loads connected directly to the LV bus.
- Adjustable speed drive and Power electronic devices connected directly to LV Bus.
- Lighting often utilizes $1-\phi$ connections from phase to neutral.
- control devices such as computers, contactors, and programmable logic controllers are often supplied through a $1-\phi$ control transformer

Voltage Sag Analysis Flow chart :-



Voltage sag evaluation Procedure :

Methodology for Computation of Voltage Sag magnitude :-

Magnitude of Voltage Sag can be obtained in a No. of Ways.

(i) Rms Voltage (ii) Fundamental voltage component.

(iii) Peak voltage over each cycle or half-cycle.

- As long as voltage is sinusoidal, it does not matter, whether rms voltage, fundamental voltage, or Peak voltage is used to obtain the sag magnitude.

(i) Rms Voltage :- Voltage sags initially recorded as sampled Points in time. The rms voltage will have to be calculated from the sampled time-domain Voltages. This is done by following equation.

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \vartheta_i^2}$$

where N is the No. of samples per cycle.

ϑ_i sampled voltages in time domain.

(ii) Fundamental Voltage Component :- The fundamental voltage component as function of time may be calculated as

$$V = \frac{2}{T} \int_{t-T}^{t} \vartheta(t)\, e^{j\omega_0 t}\, d\tau$$

where $\omega_0 = \frac{2\pi}{T}$ and T one cycle of fundamental frequency.

Voltage Sag Duration :-

- The Voltage drop during a sag is due to a short circuit in the system. The moment the s/c fault is cleared by the Protection, the Voltage can return to its original value.
- Hence the duration of Sag is mainly determined by the fault clearing-time, but it may be longer than than the fault-clearing time.
- Faults in Transmission system are cleared faster than in distribution systems. Hence fault clearing time is small in transmission system. Thus fast Protection and fast acting circuit breakers are essential.
- Transmission and subtransmission operate as a grid, hence requiring Distance Protection or Differential Protection.(Both are fast.).
- Distribution operate as a Load, hence requiring over current Protection. This required time-grading which increases the fault-clearing time.

fault-clearing time of various Protective Devices :-

Current limiting fuses : Less than one cycle

Expulsion fuses : 10 to 1000 ms

Distance relay with fast Breaker : 50-100 ms

Distance relay in zone 1 : 100 - 200 ms

Distance relay in zone 2 : 200-500 ms

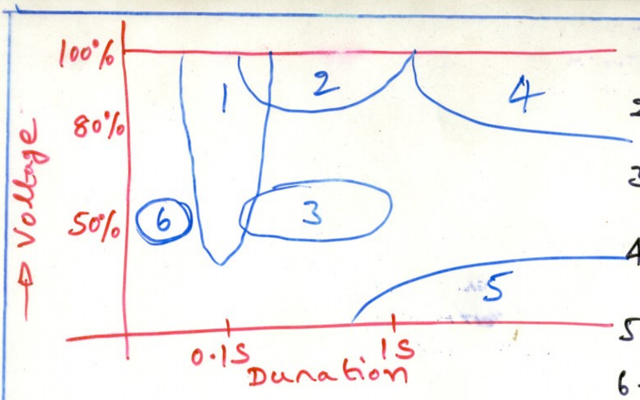
Differential relay : 100-300 ms

overcurrent relay : 200 - 2000 ms

Voltage Level	Best case	Typical case	Worse case.
750 kV	33 ms	50 ms	83 ms
400 kV	50 ms	67 ms	100 ms
220 kV	50 ms	83 ms	133 ms
132 kV	83 ms	83 ms	167 ms
66 kV	50 ms	83 ms	167 ms
11 kV	100 ms	2 Sec	3 Sec.

Magnitude - Duration Plots :-

- Knowing the magnitude and duration of a voltage sag, it can be presented by a Point in a magnitude - duration Plane. T
- This way of sag characterization used to describe both equipment and system Performance.



1. Transmission faults
2. Remote Distribution faults
3. Local distribution faults
4. Starting of Large motors
5. Short interruptions
6. Fuses.

Magnitude - Duration Plots

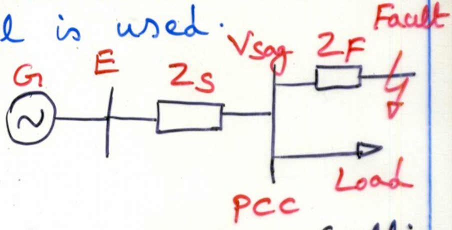
Calculations of Voltage Sag Magnitude in PS:-

1. Radial system
   - Without Transformers
   - with Transformers
2. Non-Radial system
   - Local Generators
   - Subtransmission Loops
   - Branches from Loops
   - Parallel operation across Voltage Levels.
3. Meshed system.

Radial system :-

(i) Without Transofmers :-

- To Quantify sag magnitude in Radial systems, the voltage divider model is used.



- Z_S – Source Impedance at the Point of common coupling

  Z_F – Fault impedance between common coupling and fault.

- The Point of common coupling is place, from which both fault and Load are fed.

  (or) PCC is the Place, where the Load current branches off from the fault current.

- In the Voltage divider model, the Load current before as well as during the fault is neglected. No voltage drop between PCC and Load.

- The Voltage at PCC and thus the Voltage at the equipment terminals,

$$V_{sag} = \left[\frac{Z_F}{Z_S + Z_F}\right] E.$$

- If Pre-event Voltage is exactly 1 Pu, thus E = 1

$$V_{sag} = \left[\frac{Z_F}{Z_S + Z_F}\right]$$

- Sag becomes deeper for faults electrically closer to the customer (Z_F becomes smaller) and for systems with a smaller fault level ((Z_S becomes larger)

The fault impedance is further influenced by (i) Distance between the fault and PCC

(ii) Conductor cross section

(iii) Faults behind transformers

(iv) Fault levels.

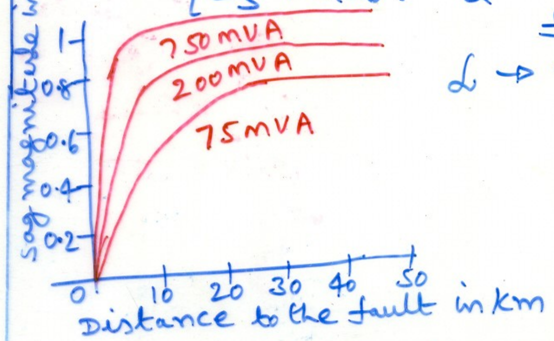
(a) Distance between the fault and PCC:

$$V_{sag} = \left[\frac{zL}{Z_s + zL}\right]$$

where $Z_F = z \times L$

z → impedance of the feeder per unit length.

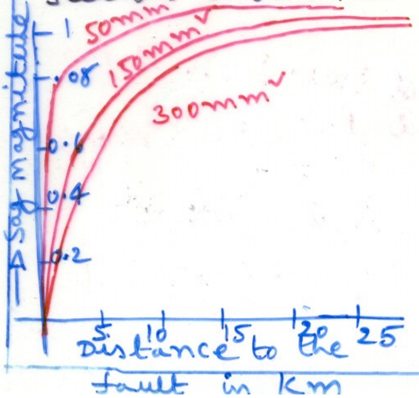
L → Distance between PCC and fault.



Sag magnitude increases (sag becomes Less severe) for increasing distance to the fault and for increasing the fault level.

(ii) Conductor cross section:

Overhead lines of different cross sections have different impedance. Hence the cross section influence the sag magnitude. as



Smaller the cross section higher the impedance of feeder, lower the voltage drop.

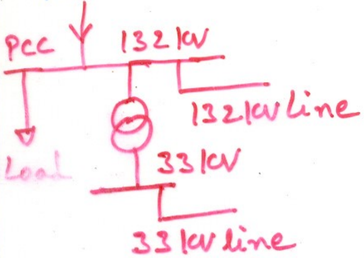
Overhead lines, influence rather small, X dominates Z.

Underground cables, the influence is much bigger. R more influence Z.

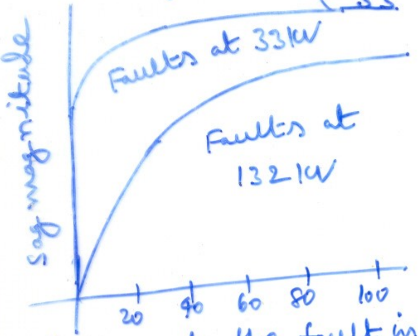
(iii) Faults behind Transformers :-

The impedance between the fault and the PCC not only consists of lines or cables but also of power transformers.

- Transformers have a large impedance, which limit the fault level on low voltage side. The presence of transformer between fault and P.C.C leads to relatively shallow sags.



- consider fault levels are 3000 MVA at 132 kV and 900 MVA at 33 kV.
- In impedance terms $Z_S = 5.81\Omega$, $Z_T = 13.55\Omega$ both refered to 132 kV voltage level.
- $Z_S = 5.81\Omega$; $Z_F = Z_T + z \times L$
- The feeder impedance must also refered to primary $z = \left(\frac{132}{33}\right)^2 \times 0.3$ [$z = 0.3\Omega/\text{km}$ on 33 kV side]



- Sags due to 33 kV are less severe than sags due to 132 kV faults. Due to Z_T the curve start at a higher level, also rises much faster.
- Feeder impedance seen from the 132 kV level is 16 times as high as 33 kV level.

(iv) Fault Levels :-

Sags due to fault levels are damped, they propagate upwards in the system.

critical distance:- $V_{sag} = \frac{z\mathcal{L}}{Z_S + z\mathcal{L}}$

Voltage sag magnitude as a function of distance to the fault.

- Distance at which a fault will lead to a sag of certain magnitude. If we assume equal X/R ratio of source and feeder.

$$\mathcal{L}_{crit} = \frac{Z_S}{z} \times \left(\frac{V}{1-V}\right)$$

- $\mathcal{L}_{crit}$. refer to the distance as the critical distance for a voltage V.
- $\mathcal{L}_{crit}$ is such that each fault within the critical distance will cause the equipment to trip.
- If the No. of faults ∝ to line length within the critical distance, then No. of sags below V is proportional to $(V/1-V)$.

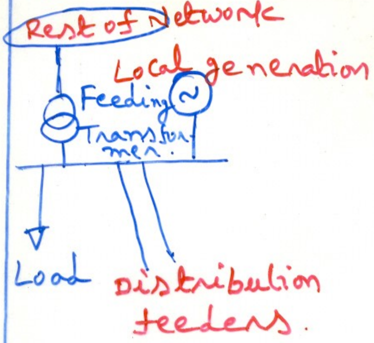
Sag Magnitude in Non-Radial Systems:-

- Radial systems are common in Low-Voltage and medium voltage networks.
- At higher Voltage levels Non-radial systems are common. Some typical cases are considered here, includes

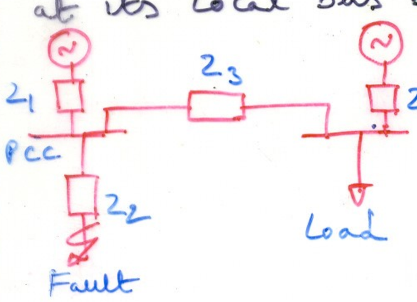
(i) Local generators (ii) Sub-transmission loops.

(iii) Branches from loops (iv) Parallel operation across Voltage Levels.

(a) Local generators :-



- The connection of local generator mitigates voltage sag of the indicated load in two different ways.
- For a weak system, the generator increases the fault level at the distribution bus, which mitigates voltage sag due to faults on the distribution feeder.
- For a strong system, the fault level cannot be increased much, without exceeding the max. allowable short circuit current of the switchgear.
- The installation of local generation requires a larger impedance of the feeding Transformer.
- A local generator also mitigates sags due to faults in the rest of the system. During a fault generator keeps up the voltage level at its local bus by feeding into fault.



Z_1 Source impedance at Pcc

Z_2 Impedance between fault and Pcc

Z_3 The impedance between generator and Pcc

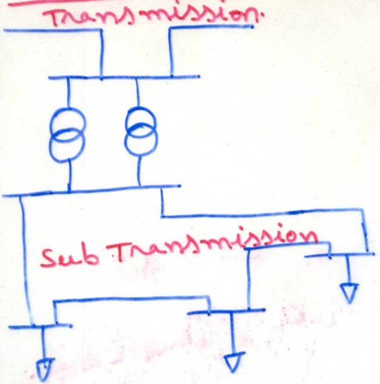
Z_4 Impedance of the local generator during fault.

- By adding a generator close to the Load second flow of fault current is introduced. Hence concept of PCC no longer holds. (which assumes single flow of fault current).
- PCC is introduced before the addition of Local generator. without Local generator the voltage at the equipment terminals would be equal to the Voltage at the PCC.
- when a Local generator present, the voltage at the equipment terminals during the sag equals the Voltage on the generator bus. This voltage is related to the voltage at PCC.

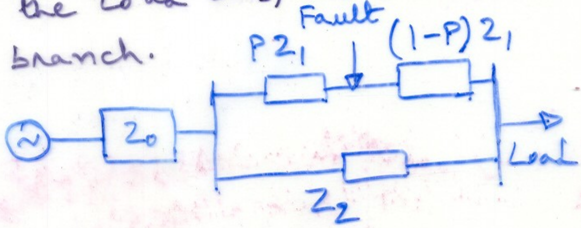
$$(1 - V_{sag}) = \frac{Z_4}{(Z_3 + Z_4)} (1 - V_{PCC})$$

- The Voltage drop at the generator bus is $[Z_4/(Z_3+Z_4)]$ times the voltage drop at the PCC.
- Voltage drop becomes smaller for lager impedance to the PCC (weaker connection), and for smaller generation impedance.
- The fault contribution of the rest of the system at the generator bus is often mainly determined by the impedance of feeding transformer. Reduction voltage drop is appox. equal to generator contribution to the fault Level.
- Generator delivers 50% of the fault current, a sag down to 40% PCC reduced to a sag down to 70% at the equipment terminals.

(b) Subtransmission Loops :-



- The network consists of several loops at sub-transmission network.
- Transmission may be connected to sub-transmission system through two or three transformers.
- From the buses at the Low-Voltage side of these transformers no. of Sub-stations are fed via loop.
- A loop also consists of two branches in Parallel.
- To calculate sag magnitude, we need to identify the Load bus, the faulted branch, and non-faulted branch.



Z_0 Source Impedance at the bus from which loop is fed.

Z_1 Impedance of faulted branch of the loop.

Z_2 impedance of the Non-faulted branch.

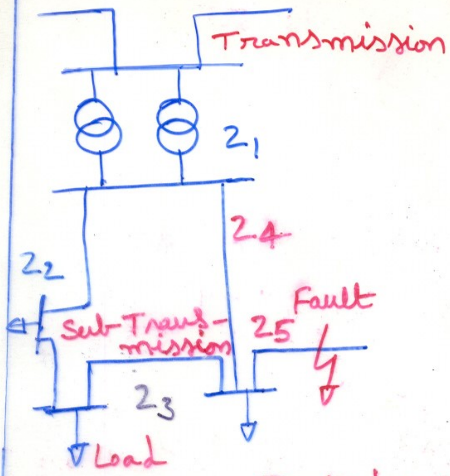
p is the Position of the fault on faulted branch.
($P=0$ fault at the bus from which Load is fed.
$P=1$ fault at the Load bus).

- The Voltage at the Load bus

$$V_{sag} = \frac{P(1-P)Z_1^2}{Z_0(Z_1+Z_2)+PZ_1Z_2+P(1-P)Z_1^2}$$

- Voltage is zero for $P=0$ (fault at the main sub-transmission bus) and for $P=1$ (fault at the Load bus) has max. Somewhere in between.
- concept also used to calculate Voltage Sag due to faults on Parallel feeders.

(c) Branches from the Loops:-



- Load fed from a Loop, and a fault away from that loop will also cause sag.
- The feeder to the fault does not necessiarly be a single feeder, but can represent effective impedance of another loop.

- Z_1 source Impedance of main sub-transmission

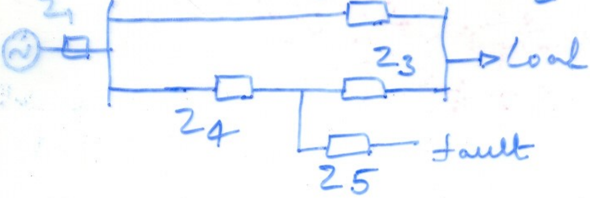
Z_2 Impedance between subtransmission bus and bus from which Load is fed.

Z_3 Impedance between bus from which Load is fed and the bus from which fault is fed.

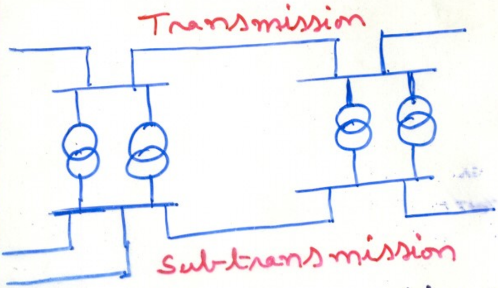
Z_4 & Z_5 between the bus from which fault is fed and the main sub-transmission and the fault.

- The voltage at the Load bus is found

$$V_{sag} = \frac{Z_5 Z_2 + Z_5 Z_3 + Z_5 Z_4 + Z_4 Z_3}{Z_1 Z_2 + Z_1 Z_3 + Z_1 Z_4 + Z_5 Z_2 + Z_5 Z_3 + Z_5 Z_4 + Z_4 Z_2 + Z_4 Z_3}$$



(d) Parallel operation across voltage Levels:-



- ~~The~~ sub-transmission is not fed from the transmission at one point but at a no. of points.

- This type of configuration can be treated like a loop that extends over two voltage levels.

- For a fault within the loop, we can treat this case as a sub-transmission loop and can be evaluated in the same way of the above.

$$V_{sag} = \frac{p(1-p)Z_1^2}{Z_0(Z_1+Z_2) + pZ_1Z_2 + p(1-p)Z_1^2}$$

- If the fault is away from the loop, then the case canbetreatedas a branches from the loop and can be evaluated in the same way ~~of~~ the above.

$$V_{sag} = \frac{Z_5Z_2 + Z_5Z_3 + Z_5Z_4 + Z_4Z_3}{Z_1Z_2 + Z_1Z_3 + Z_1Z_4 + Z_1Z_4 + Z_5Z_2 + Z_5Z_3 + Z_5Z_4 + Z_4Z_2 + Z_4Z_3}$$

- The equations are remains the same independent of the voltage level at which the fault takes place. The only thing that changes are the impedance values.

③ meshed systems :-

- system becomes more complicated, closed expressions for the voltage during sag get very complicated and unfeasible to handle.
- For meshed systems, matrix calculations proven to be very efficient for computer-based analysis.
- The calculation of voltages during a fault is based on two principles

(i) Thevenin's superposition theorem

(ii) Node impedance matrix.

- According to thevenin's superposition theorem voltages and currents during sag are sum of two contributions, V & I's before the event, and V & I's due to change in voltage at the fault position.

Voltages and currents before the fault are due to all generators.

V & I's due to fault originate at a voltage souce at the fault position. All other voltage sources are considered short circuited during the calculation of fault currents.

- Node impedance matrix Z relates node voltages and Node currents. $V = Z.I$.

Consider a system with N nodes plus a reference node. The voltages before the fault are denoted as $V_K^{(0)}$. Short circuit at node f.

- According to Thevenin's superposition theorem voltage during the fault at any node K

$$V_K = V_K^{(0)} + \Delta V_K$$

ΔV_K change in voltage at node K due to fault.

whis is due to a voltage source $V_f^{(0)}$ at fault.

- To calculate ΔV_K all other voltage sources are short circuited, so that node f only node with a non-zero node current.

$$\Delta V_K = Z_{Kf} I_f$$

- At the fault position $(K = f)$ $\Delta V_f = -V_f^{(0)}$

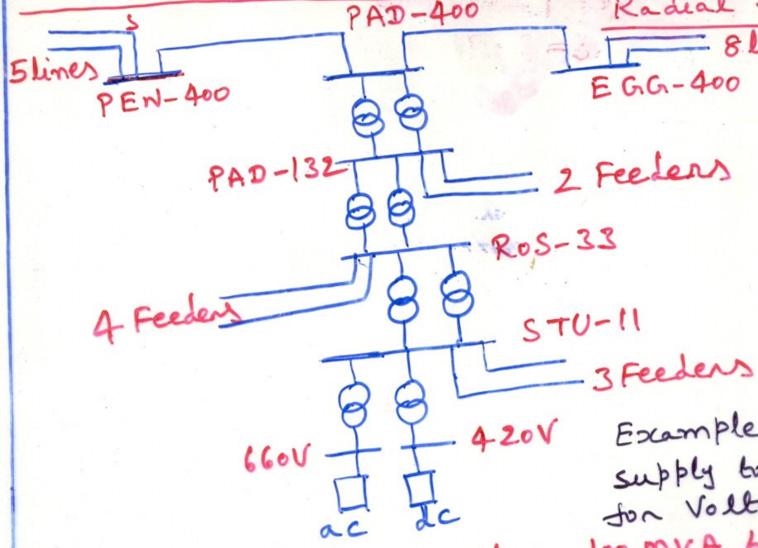
$$\therefore I_f = -\frac{V_f^{(0)}}{Z_{ff}}$$

- $$V_K = V_K^{(0)} - \frac{Z_{Kf}}{Z_{ff}} V_f^{(0)}$$

- Pre fault voltages are normally close to unity hence $V_K = 1 - \frac{Z_{Kf}}{Z_{ff}}$

- The moment node impedance matrix is known, calculating sag magnitude becomes very easy.

Example (Sag magnitude calculations of a Radial System):-



Example of Power supply to be used for Voltage sag calculati

Source Impedance at a 100 MVA base:

11 kV	4.94 + j65.9% (+ ve & −ve sequence)
33 kV	1.23 + j18.3%
132 kV	0.09 + j2.86%
400 kV	
From Egg	0.084 + j1.061%
From PEN	0.132 + j1.04%

Feeder data at a 100 MVA base:

11 kV	9.7 + j26% / km	5 km
33 kV	1.435 + j3.102% / km	10 km
132 kV	0.0101 + j0.257% / km	2 km
400 kV	0.001 + j0.018% / km	> 1000 km

Calculate voltage sags at 11 kV side of the network. Draw (plot) sag magnitude versus distance for faults.

- The first step in sag analysis is to recognize the possible PCC's.

PCC's are STU-11, ROS-33, PAD-132, PAD-400

- The calculate sag magnitude, we need source impedance and feeder impedance.
- For faults at the 11 kV the absolute values of feeder impedance and source impedances are

$Z = |(9.7 + j\,26)| = \sqrt{9.7^2 + 26^2} = 27.75\%$

$Z_s = |(4.94 + j\,65.9)| = \sqrt{4.94 + 65.9} = 66.08\%$

- The critical distance to be calculated

$$\mathcal{L}_{critical} = \frac{Z_s}{Z} \times \frac{V}{(1-V)}$$

$Z = 27.75\%$; $Z_s = 66.08\%$

$V = 10\%$ $\mathcal{L}_{critical} = 0.264$ km

$V = 30\%$ $\mathcal{L}_{critical} = 1.02$ km

$V = 50\%$ $\mathcal{L}_{critical} = 2.38$ km

$V = 70\%$ $\mathcal{L}_{critical} = 5.55$ km

$V = 90\%$ $\mathcal{L}_{critical} = 21.43$ km

- The sag magnitude to be calculated.

$$V_{sag} = \frac{Z_F}{Z_s + Z_F} = \frac{\mathcal{L}Z}{Z_s + \mathcal{L}Z} = \frac{5 \times 0.2775}{0.6608 + 5 \times 0.2775} = 67.7\%$$

$\mathcal{L} = 0$ $V_{sag} = 0$

$\mathcal{L} = 1$ km $V_{sag} = 29.5\%$

$\mathcal{L} = 2$ km $V_{sag} = 45.6\%$

$\mathcal{L} = 3$ km $V_{sag} = 55.7\%$

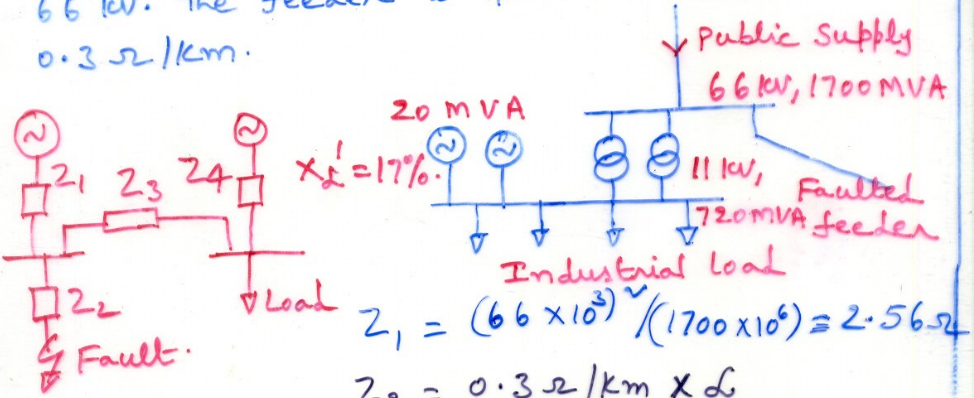
$\mathcal{L} = 4$ km $V_{sag} = 62.68\%$

$\mathcal{L} = 5$ km $V_{sag} = 67\%$

Calculation of Voltage sag magnitude in Non-Radial Systems :

(a) Local generators :-

Example :- The industrial system is fed from a 66 kV, 1700 MVA via two 66/11 kV transformers in Parallel. The fault Level at the 11 kV bus is 720 MVA, which includes the contribution of two 20 MVA on-site Generators with a transient reactance of 17%. The actual industrial Load is fed from the 11 kV bus. calculate the sag magnitude due to faults at 66 kV. The feeder impedance at 66 kV is 0.3 Ω/km.

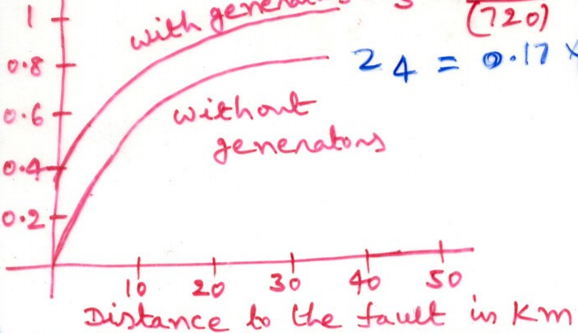


$Z_1 = (66 \times 10^3)^2 / (1700 \times 10^6) \simeq 2.56\,\Omega$

$Z_2 = 0.3\,\Omega/\text{km} \times \mathcal{L}$

$Z_3 = \frac{(11)^2}{(720)} \times \left(\frac{66}{11}\right)^2 = 6.05\,\Omega$

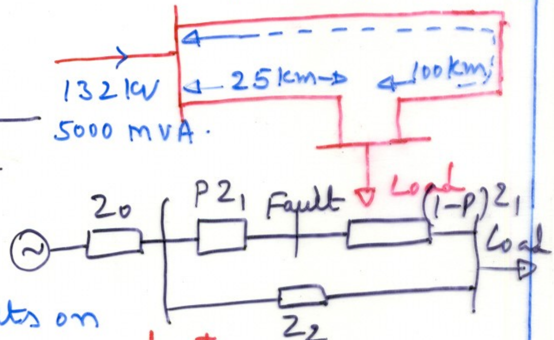
$Z_4 = 0.17 \times \left(\frac{66}{11}\right)^2 + \left(\frac{11^2}{20}\right) \times 2 = 18.22\,\Omega$



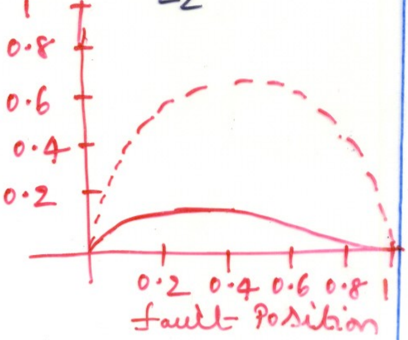
Calculation of Sag magnitude Subtransmission Loops :-

Example :- Consider the system shown in fig. a 125 km 132 kV loop connecting a No. of substations. This substation is located at 25 km from the main substation. The fault level at the point of supply is 5000 MVA and feeder impedance 0.3 Ω/km. Faults occur both in the 25 km part and in 100 km part of the loop. So that both may from the faulted branch. For a fault on the 25 km branch $Z_1 = 25z$ and $Z_2 = 100z$; z feeder impedance per km. Fault on the 100 km branch $Z_1 = 100z$; $Z_2 = 25z$.

$$V_{sag} = \frac{p(1-p)Z_1^2}{Z_0(Z_1+Z_2) + pZ_1Z_2 + p(1-p)Z_1^2}$$

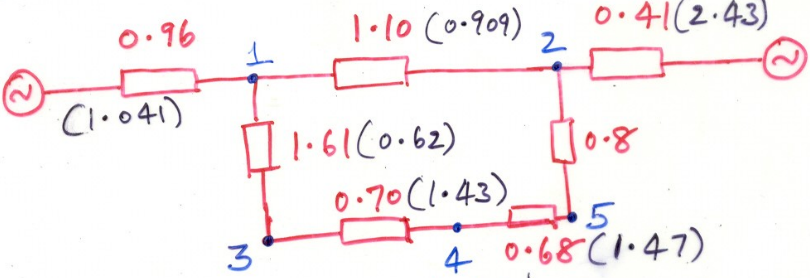


Top curve gives the sag magnitudes for faults on 100 km branch. The bottom curve holds for the 25 km branch.



Voltage calculations in meshed system :-

Example :- consider a 275/400 kV system with nodes 1 and 2 representing 400 kV substations. Nodes 3, 4 and 5 representing 275 kV substations. The branches between 1 and 3 and between 2 and 4 represents transformers. The impedance values indicated in figure in % at a 100 MVA base.



$$Y = \left[\begin{array}{ccc|cc} 2.57 & -0.909 & -0.62 & 0 & 0 \\ -0.909 & 4.59 & 0 & -1.25 & 0 \\ -0.62 & 0 & 2.049 & 0 & -1.43 \\ \hline 0 & -1.25 & 0 & 2.72 & -1.47 \\ 0 & 0 & -1.43 & -1.47 & 2.89 \end{array}\right]$$

$$Z = Y^{-1} = \begin{bmatrix} 0.5453 & 0.1771 & 0.3889 & 0.2548 & 0.32 \\ 0.1771 & 0.3344 & 0.2439 & 0.3012 & 0.2730 \\ 0.3889 & 0.2439 & 1.2534 & 0.6144 & 0.9292 \\ 0.2548 & 0.3012 & 0.6144 & 0.9225 & 0.7707 \\ 0.3209 & 0.2730 & 0.9292 & 0.7707 & 1.1137 \end{bmatrix}$$