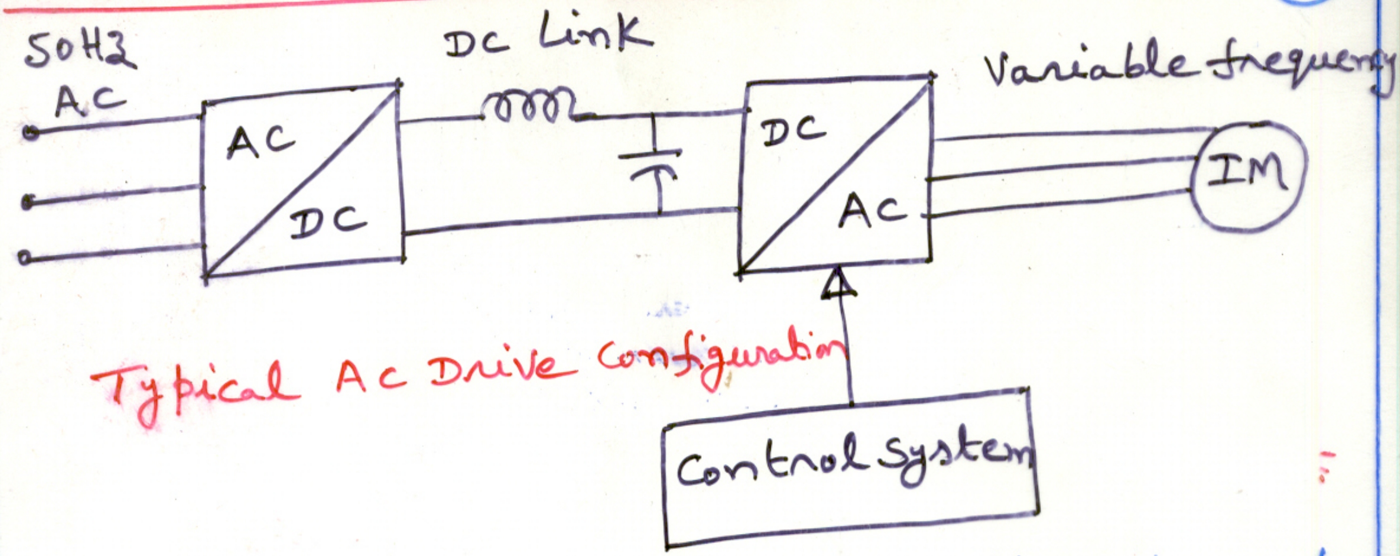
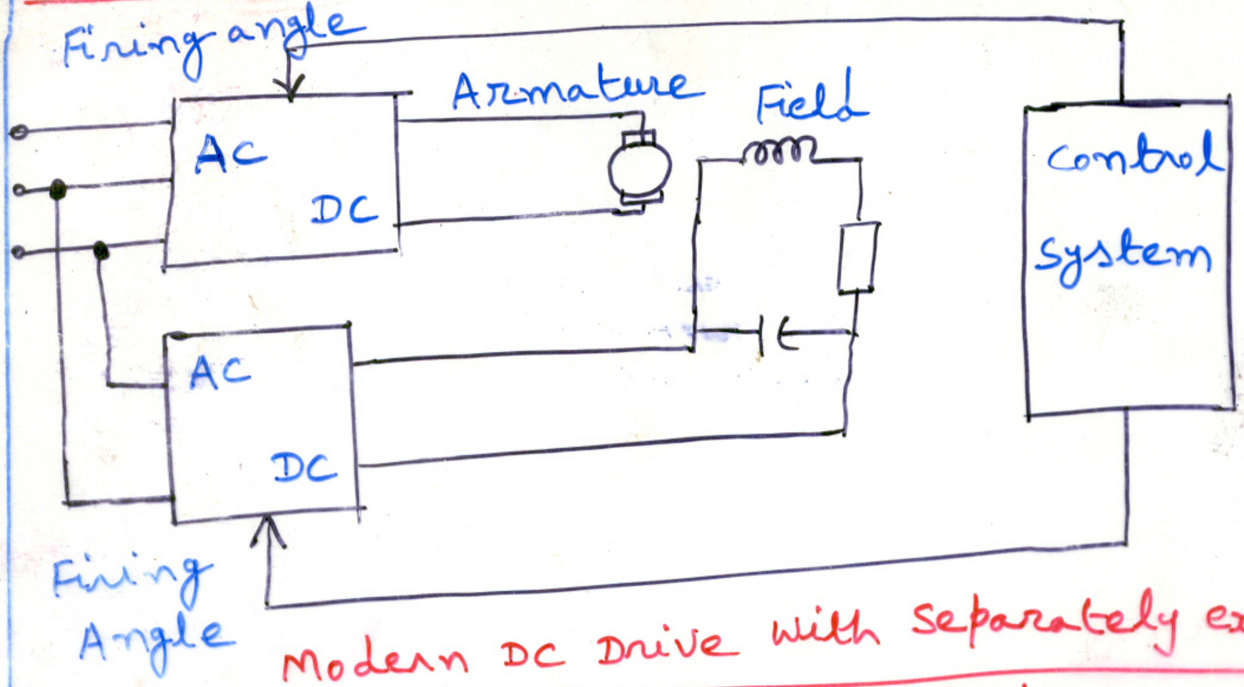
operation of Ac Drive :-



Typical Ac Drive configuration

- ASD's are either fed either through a 3-ϕ diode rectifier or through a 3-ϕ controlled rectifier.
- Diode rectifier found in ac motor Drives, controlled rectifier in dc drives and large ac drives.
- The configuration is shown in fig. The 3-ϕ a/c voltages are fed to a 3-ϕ diode rectifier. The o/p voltage of rectifier is smoothened by means of capacitor connected to the dc bus. The inductance aims at smoothening the dc link current and so reducing the harmonic distortion in the current taken from the supply.
- Dc voltage inverted to an ac voltage of variable frequency and magnitude by means of voltage source converter (VSC). The most commonly used method for this is Pulse-width modulation (PWM).

Operation of DC Drive:-



Modern DC Drive with separately excited armature and field winding.

- DC Drives traditionally much better suited for Adjustable speed operation than ac Drives.
- The speed of ac motors is first approximation, Proportional to the frequency of the voltage.
- The speed of dc motors is Proportional to the magnitude of voltage. voltage magnitude is much easier to vary than frequency.
- With the introduction of Power transistors have variable frequency inverters and thus ac adjustable speed drives becomes feasible.
- A typical configuration of a Dc Drive is presented in above fig.
- Armature winding, uses most of the Power is fed via a 3-ϕ controlled rectifier.
- Armature voltage is controlled through the firing angle of the thyristors. More delay in firing angle, lower the armature voltage.

- The torque produced by the armature current, which shows no ripple due to large inductance of the armature winding.
- The field winding takes only a small amount of power, thus a 1-ϕ rectifier is sufficient.
- field winding is powered from one of the phase to phase voltages of the supply. In case field-weakning is used to extend the speed range of dc motor, a controlled 1-ϕ rectifier is needed.
- To limit the field current, a resistance is placed in series with field winding. Resulting field circuit is resistive, so that voltage fluctuations result in current fluctuations and thus in torque fluctuations.
- A capacitor is used to limit the voltage ripple. Also to limit the torque fluctuations a capacitor is used like the one used to limit the voltage ripple in 1-ϕ rectifier.

TYPICAL Applications:-

The typical applications of ASD's are

(i) Fans and Pumps

(ii) crane Drives

(iii) Hot strip mill.

(i) Fans and Pumps :-

- Drives are used primarily for energy conservation. The flow rate is proportional to speed of the rotation ($Q \propto N$). The torque required at the motor shaft is proportional to the square of the speed of rotation ($T \propto N^2$). Thus the power would be proportional to the cube of the speed ($P \propto N^3$).
- speed decreases, the torque requirement reduces, motor can be used without deration. since rated torque has to produce only at rated speed.
- No electric braking is required and motor would operate only in forward motoring mode, or single quadrant operation.

(ii) crane Drives :-

- crane drive considered is Lifting drive or hoisting drive.
- crane is lifting the Load, it is pulling the weight against gravity. Motor rotating in forword direction and producing torque in the forword direction. ie $N > 0$; $T > 0$.
- crane is Lowering the Load, Motor has to produce torque in the direction opposite to that of rotation. otherwise the weight would tend to increase the speed of lowering due to free fall. Motor rotates in the reverse direction and produces torque in forword direction. $N < 0$; $T > 0$

This is an example of two quadrant operation.

(iii) Hot Strip Mill :- Each stand has two rollers one being driven by a motor and associated Variable speed drive. The Parameters of VS Drives are different.

- Parameter changes are fed to the Drive system through the Data communication System of the Automation hardware of the Plant.
- the Motor accelerate fast to the full speed at controlled acceleration and runs at constant speed for about three seconds. Then the roller table motors decelarate fast and come to a stop in one second.
- After three seconds, the roller table runs in reverse direction, accelerating in one second, runs for three second at constant speed and then decelerates to stop in one second.

Sources of harmonics :-

- Power systems are designated to operate at frequencies of 50 Hz. But certain types of Loads Produce currents and Voltages with frequencies that are integer multiples of 50 Hz.
- These higher frequencies are a form of electrical Pollution Known as Power system harmonics.
- The main sources of harmonics are

(i) Saturable devices (ii) Power electronic Devices.

(i) Saturable devices:-

- Produce harmonics mainly due to iron saturation, (In the case of transformers), machines, fluorescent lamps (with magnetic ballasts).
- Economic reasons transformers and motors designed to operate slightly past the knee of the iron core saturation curve.
- Resulting magnetizing currents are peaked and rich in the third harmonic. unless blocked by a delta transformation, a synchronous machine will produce a third harmonic current of approximately 30% of the fundamental.
- Fluorescent lamps with magnetic ballasts are usually souces of harmonics. current distortion is mainly due to arc and to the ballast. Distortions are dominated by 3rd harmonic with a magnitude in the range of 15% to 30% of the fundamental.

(ii) Power Electronic Devices:-

- Most common sources of harmonics are power electronic loads such as ASD and switch mode power supplies.
- Advantage in efficiency and controllability PE Loads are proliferating and can be found at power levels (Low voltage appliances to HV converters)

- PE converters generate harmonics currents, which will be injected into Grid, causing distortion of utility waveform.
- PE Loads control the flow of Power by drawing currents only during certain intervals current drawn by the Load is not Sinusoidal and can interact with system impedance to give rise to voltage distortion or resonance.
- In addition to voltage distortion, harmonic current may also cause Additional heating, over voltage due to resonant condition, Errors in metering, Malfunction of Utility relays, Interferance with communications, Notches in the Power Utility Voltage waveform, Low Power factor.
- Large Scale use of PE Loads will result in significant Negative impact on the Utilities as well on the customers.

Harmonic sources from commercial Loads:-

- commercial facilities such as office complexes, department stores, hospitals, and Internet centres are dominated with high efficiency fluorescent Lighting with electronic ballasts, ASD's for heating, ventilation and AC Loads, elevator drives,

- Commercial loads are characterized by a large number of small harmonic producing loads.
- Depending on the diversity of the loads, these small harmonic currents may add in phase or cancel each other.

Harmonic sources from Industrial loads:-

- Modern industrial facilities characterized by wide spread applications of non linear loads. These loads will inject harmonics into the system causing harmonic distortion in the voltage.
- Harmonic problem is compounded and nonlinear loads have a relatively low power factor.
- Industrial facilities often utilize capacitor banks to improve the Pf to avoid penalty charges.
- The application of Pf correction capacitors can potentially magnify harmonic currents from the non-linear loads, givising rise to resonance condition.
- Highest voltage distortion usually at facility's low-voltage bus, where the capacitors are applied. Resonance conditions cause motor and transformer overheating, and misoperation of sensitive electronic equipment.

Mitigation of Harmonics:-

- There are several no. of devices to control harmonic distortion. when a problem occurs, the basic options for controlling harmonics are.

(i) Reducing harmonic currents produced by Load.

(ii) Add filters to either siphon the harmonic currents off the system, block the currents from entering the system or supply the harmonic currents locally.

(iii) Modify the frequency response of the system by filters, inductors, or capacitors.

- A simple mitigation action such as adding, resizing, or relocating a shunt capacitor Bank can effectively modify an unfavorable system frequency response.
- The following methods discusses the effectiveness of a simple inline reactor, choke and two general classes of harmonic filters (passive & Active filters) in mitigating harmonic distortion.

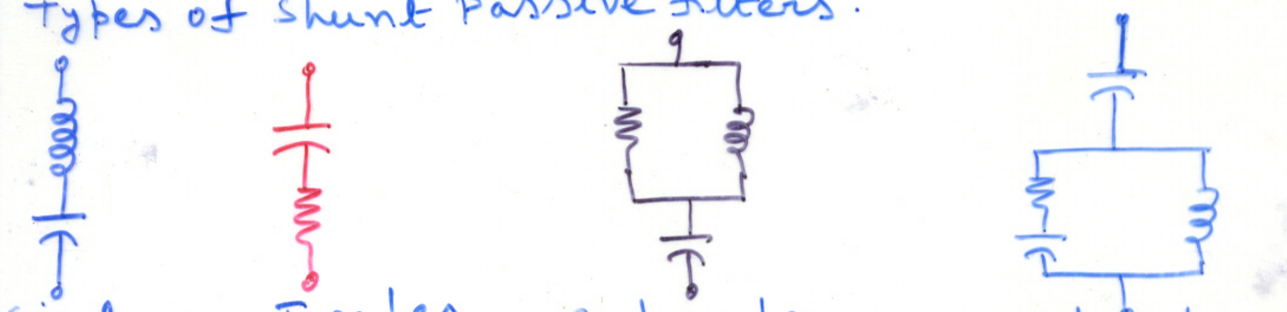
(a) In-line reactors or choke:

A simple, but often successful method to control harmonic distortion generated by ASD involves a relatively small reactor or choke. inserted at the line I/P side of the drive. This is more effective for PWM-type drives. The Inductance slows the rate at which the capacitor on dc bus can be charged and forces the drive to draw current over a longer time period. The net effect is the lower magnitude current with much less harmonic content, while still delivering the same energy.

(b) Zig Zag transformers: often applied in commercial facilities to control zero-sequence harmonic components. A zig-zag Transformer acts like a filter to the zero sequence current by offering a low-impedance path to neutral. Reduces the amount of current that flows in the neutral back toward the supply by providing a shorter path for the current. most important problems in commercial facilities are over loaded neutral conductors and transformer heating, both these problems can be solved using zig zag transformers.

(c) Passive filter: Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. commonly used and relatively inexpensive compared with other means for eliminating harmonic distortion.

Types of Shunt Passive filters.



Single-Tuned | I order High Pass | 2nd order High Pass | 3rd order High Pass

The most common type of Passive filter is notch filter. which is a series tuned to present a low impedance to a Particular harmonic current and is connected in shunt with the power system. Thus harmonic currents are diverted from their normal flow path on the line through the filter. These filters can also provide power factor correction in addition to harmonic suppression.

Series passive filter : which is connected in series with the Load. The L and C are connected in parallel and are tuned to provide a high impedance at a selected harmonic frequency. The High impedance blocks the flow of harmonic currents at the tuned frequency. The use of series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. A series filter must be designed to carry a full rated Load current. and must have overcurrent Protection series filters much less commonly applied than shunt

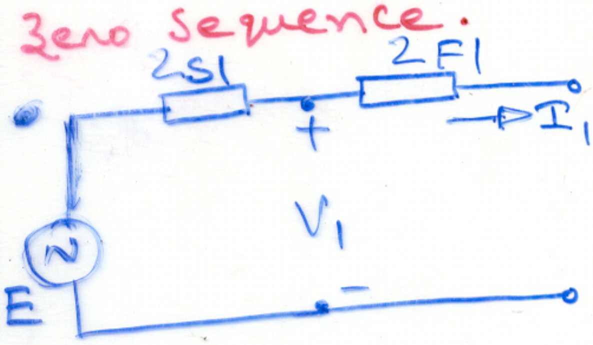
(d) Active filter: Relatively new devices for elimination of harmonics. Based on sophistigated PE and are much more expensive than passive filters. The distinct advantage that they do not resonate with the system. Work Independently of the system impedance characteristics. Address more than one harmonic at a time. Basic idea is to replace the portion of sine wave that is missing in the current in a Non linear load.

Characterization of Voltage Sags:

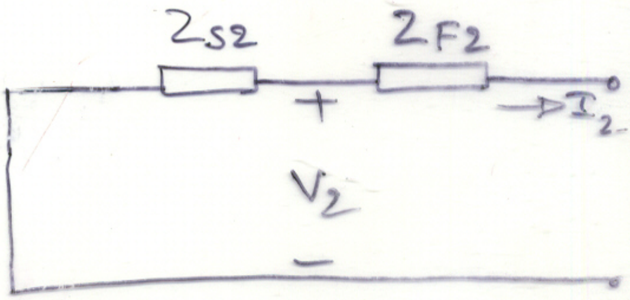
- The voltage sags can be characterized by the type of fault occur on 3-ϕ power system network. (a) 1-ϕ fault (b) Two-phase fault (c) Two-phase to ground fault.

- The analysis of sag magnitude i.e voltage divider model for 1-ϕ circuit can be extended to three-phase circuit. with the help of symmetrical component theory.

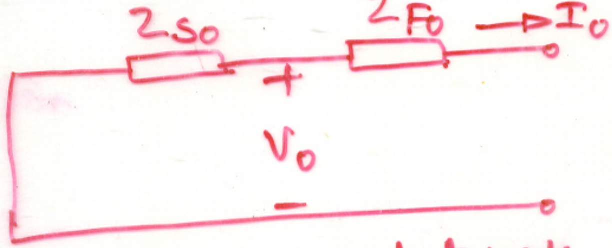
- For non-symmetrical faults, the model of voltage divider has to be split into three components. namely +ve sequence, −ve sequence, zero sequence.



+ve sequence Network



−ve sequence network



Zero Sequence Network

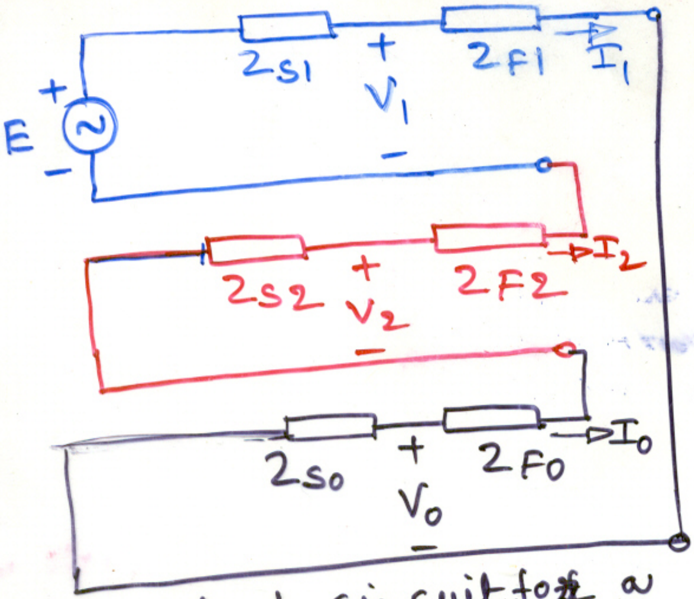
- V_0, V_1, V_2 represent zero, +ve, −ve voltages at PCC

Z_{S1}, Z_{S2}, Z_{S0} are source impedances

Z_{F1}, Z_{F2}, Z_{F0} are feeder impedances.

I_1, I_2, I_0 are three component of fault currents

(a) Single-phase fault :



Equivalent circuit for a 1-ϕ fault.

For 1-ϕ fault three networks should be connected in series. Assume $E = 1$ pu.

The expressions for the component voltages at the pcc are.

$$V_1 = \frac{Z_{F1} + Z_{S2} + Z_{F2} + Z_{S0} + Z_{F0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

$$V_2 = \frac{Z_{S2}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

$$V_0 = \frac{Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

$V_a = V_1 + V_2 + V_0$; $V_b = a^2 V_1 + a V_2 + V_0$; $V_c = a V_1 + a^2 V_2 + V_0$

For faulted phase V_a

$$V_a = \frac{(Z_{F1} + Z_{F2} + Z_{F0})}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

Compare with voltage divider model of 1-ϕ circuit.

$$Z_F = Z_{F1} + Z_{F2} + Z_{F0}$$

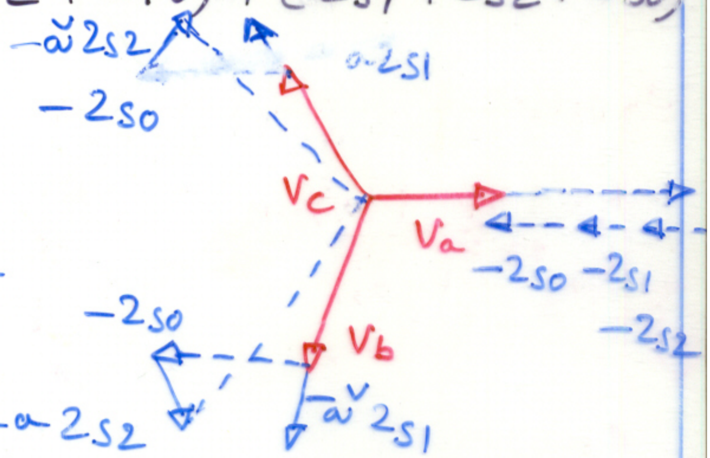
$$Z_S = Z_{S1} + Z_{S2} + Z_{S0}$$

Voltages in the non faulted phases

$$V_a = 1 - \frac{(Z_{S1} + Z_{S2} + Z_{S0})}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

$$V_b = a^2 - \frac{a^2 Z_{S1} + a Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$

$$V_c = a - \frac{a Z_{S1} + a^2 Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}$$



- Non-faulted phase voltage drop consists of

(i) voltage drop proportional to the +ve source Z, along the direction of pre fault voltage

(ii) Voltage drop proportional to −ve source Z, along the direction of pre fault voltage in other non faulted phase.

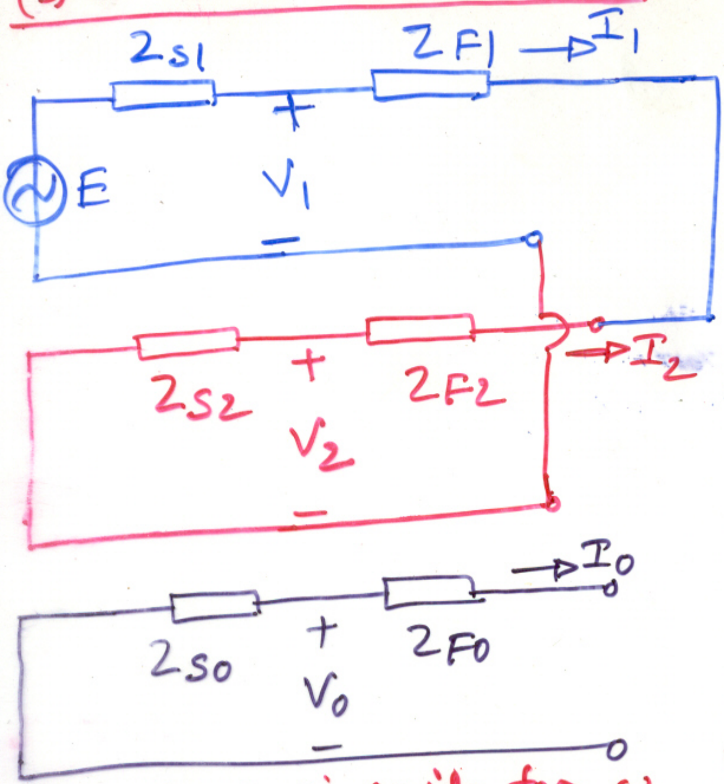
(iii) Voltage drop proportional to zero source Z, along the direction of pre-fault voltage in the faulted phase.

- voltage between two non-faulted phases is

$$V_b - V_c = (a^2 - a)\left[1 - \frac{(Z_{S1} - Z_{S2})}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})}\right]$$

changes are due to difference between +ve sequence and −ve sequence source Impedances. Z_{S1} and Z_{S2} are normally about to equal, voltage between non-faulted phases is normally not influenced by type of fault.

(b) Phase - phase fault :-



Equivalent circuit for a phase- phase fault.

For a phase- phase fault the + ve and − ve sequence networks are connected in parallel. The zero sequence current and voltages are zero for a phase- phase fault.

The sequence voltages at the PCC are

$$V_1 = E - \frac{E\, Z_{S1}}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$

$$V_2 = \frac{Z_{S2}}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$

$$V_0 = 0$$

The phase voltages are

$$V_a = 1 - \frac{(Z_{S1} - Z_{S2})}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$

$$V_b = a^2 - \frac{(a^2 Z_{S1} - a Z_{S2})}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$

$$V_c = a - \frac{(a Z_{S1} - a^2 Z_{S2})}{(Z_{S1}+Z_{S2})+(Z_{F1}+Z_{F2})}$$

- Voltage drop in Non- faulted phase depends on the difference between + ve and − ve sequence source impedances. Normally equal, voltage in the non- faulted phase will not be influenced by the phase- phase fault.

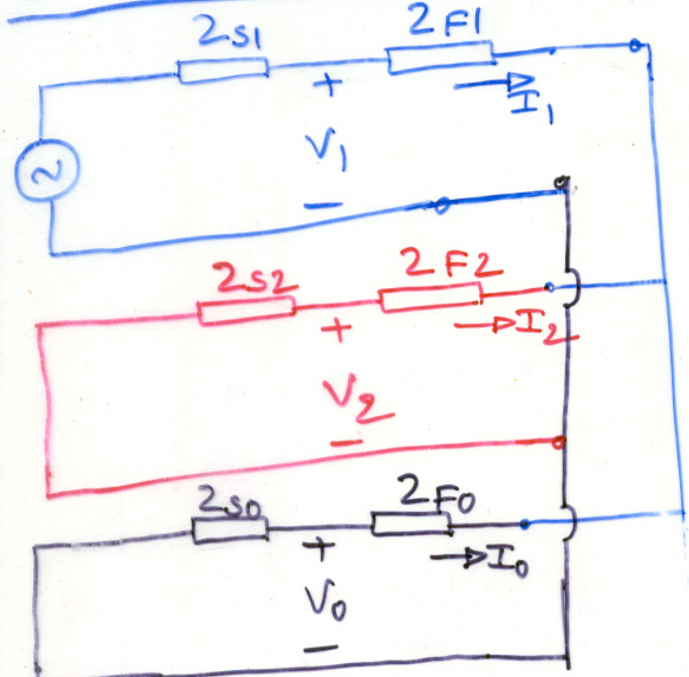
$$V_a = 1 \;;\quad V_b = a^2 - \frac{(a^2 - a)\, Z_{S1}}{(2Z_{S1} + 2Z_{F1})}$$

$$V_c = a + \frac{(a^2 - a)\, Z_{S1}}{(2Z_{S1} + 2Z_{F1})}$$

- The voltage in the faulted phases is equal to $Z_{S1}/(2Z_{S1}+2Z_{F1})$ but opposite direction. The direction of voltage drop along the pre fault phase-phase voltage between the faulted phases $(V_b - V_c)$.
- The voltage between the faulted phases

$$V_b - V_c = \frac{(Z_{F1} + Z_{F2})\,(a^2 - a)}{(Z_{S1} + Z_{S2}) + (Z_{F1} + Z_{F2})}$$

(c) Two phase to ground fault :



Equivalent circuit for a two-phase-ground fault.

For a two-phase to ground fault, the three sequence networks are connected in parallel.

The sequence voltages at the PCC for a fault between b and c and ground are given by

$$V_1 = 1 - \frac{Z_{S1}(Z_{S0} + Z_{F0} + Z_{S2} + Z_{F2})}{D}$$

$$V_2 = \frac{Z_{S2}(Z_{S0} + Z_{F0})}{D}$$

$$V_0 = \frac{Z_{S0}(Z_{S2} + Z_{F2})}{D}$$

$$D = (Z_{S0} + Z_{F0})(Z_{S1} + Z_{F1} + Z_{S2} + Z_{F2}) + (Z_{S1} + Z_{F1})(Z_{S2} + Z_{F2})$$

The phase to ground voltages in the three phases

$$V_a = 1 + \frac{(Z_{S2} - Z_{S1})(Z_{S0} + Z_{F0})}{D} + \frac{(Z_{S0} - Z_{S1})(Z_{S2} + Z_{F2})}{D}$$

$$V_b = a^2 + \frac{(a Z_{S2} - a^2 Z_{S1}) Z_0}{D} + \frac{(Z_{S0} - a^2 Z_{S1}) Z_2}{D}$$

$$V_c = a + \frac{(a^2 Z_{S2} - a Z_{S1}) Z_0}{D} + \frac{(Z_{S0} - a Z_{S1}) Z_2}{D}$$

- The difference between +ve and -ve sequence source Impedance, difference between the +ve and zero sequence source impedance effects a change in voltage in non-faulted phase (V_a).
- Both effects the non-faulted phase voltage drops, when +ve sequence impedance increases.
- -ve and +ve sequence impedance are normally equal, hence second term may be neglected. The third term, which depends on the difference between zero and +ve sequence source Impedance, could cause a serious change in voltage.
- But voltages in the faulted phases, realizing that Z_{S1} is close to Z_{S2}. Hence the second term voltage drop in the direction of other faulted phase. $(a - a^2)$ is the pre-fault voltage between the faulted phases. For $Z_{S0} = Z_{S1}$ the third term is a voltage drop towards the non-faulted phase pre-fault voltage.

Seven types of Three-Phase Unbalanced Sags:

- For each type of fault, expressions have been derived for voltages at the PCC.
- But this voltage is not equal to the voltage at the equipment terminals. Normally Equipment is connected at a Lower voltage level than the Level at which the fault occurs.
- The voltages at the equipment terminals, not only depend on the voltages at the PCC but also on the winding connection of the transformers between PCC and the equipment terminals.
- Voltages at the equipment terminals further dependent on Load connection. [3-ϕ Load normally connected in delta, but star is also used. 1-ϕ Load normally connected in star].
- Normally we consider the voltage sag as experienced at the terminals of end-user equipment. but not the voltage measured by monitoring equipment.
- Classification of 3-ϕ Unbalanced voltage sags, based on the following assumptions.

(i) +ve and −ve sequence impedances are identical.

(ii) Zero sequence component of the voltage does not propagate down to the equipment terminals.

(iii) Load currents, before, during, and after the fault can be neglected.

Single phase fault: The Phase Voltages due to 1-ϕ to ground fault are under assumptions

$$V_a = V \; ; \quad V_b = -\frac{1}{2} - \frac{1}{2} j\sqrt{3} \; ; \quad V_c = -\frac{1}{2} + \frac{1}{2} j\sqrt{3}$$

- If the Load is connected in star, thease are the voltages at the equipment terminals.
- If the Load is connected in delta the equipment terminal voltages are Phase-Phase voltages.

$$V_a' = j\frac{V_b - V_c}{\sqrt{3}} \; ; \quad V_b' = j\left(\frac{V_c - V_a}{\sqrt{3}}\right) \; ; \quad V_c' = j\frac{(V_a - V_b)}{\sqrt{3}}$$

- This transformation is important part of classification. The factor $\sqrt{3}$ is aimed at changing the base of pu values, so that the normal operating voltage remains at 100%.
- The 90° rotation by using a factor j aims at keeping the axis of symmetry of the sag along the real axis.
- The three-phase unbalanced voltage sag experienced by a delta connected Load due to a 1-ϕ fault, will have the ~~voltage~~ magnitudes as.

$$V_a = 1 \; ; \quad V_b = -\frac{1}{2} - \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3} \; ; \quad V_c = -\frac{1}{2} + \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3}$$

- Two voltages show a drop in magnitude and change in phase angle. The third voltage is not influenced at all. Delta connected equipment experienced a sag in two phases due to a 1-ϕ fault.

Phase to phase faults

The expressions for phase to neutral voltages during a phase to phase fault are,

$V_a = 1$; $V_b = -\frac{1}{2} - \frac{1}{2} V j\sqrt{3}$; $V_c = -\frac{1}{2} + \frac{1}{2} V j\sqrt{3}$

- After taking transformation to calculate voltages experienced by phase to phase connected load, resulting in

$V_a = V$; $V_b = -\frac{1}{2} V - \frac{1}{2} j\sqrt{3}$; $V_c = -\frac{1}{2} V + \frac{1}{2} j\sqrt{3}$

- Due to a phase to phase fault a star connected Load experiences a drop in two phases. A Delta connected Load experiences drop in three phases.

Transformer winding connections:

(a) Transformers that do not change anything to the voltages. For this type of transformers the secondary side voltages are equal to the primary side voltages. 

(b) Transformers that remove the zero-sequence voltage. The voltages on the secondary side are equal to the voltages on primary side minus the zero-sequence component. Y Y Δ Δ DZ

(c) Transformers that swap line and phase voltages. Secondary side voltage equals the difference between two primary side voltages.
Δ Y (DY) Y Δ (Yd) star-zigzag (YZ)

Tranfer of Voltage Sags across Transformers:

The Three types of transformers can be applied to the Sags due to $1-\phi$ and phase-phase faults.

- $1-\phi$ fault, star connected Load, No transformer. We will refer to this sag as X_1. Transformer of type1 gives the same result.
- $1-\phi$ fault, Delta connected Load, No transformer. This sag refered to as sag X_2.
- $1-\phi$ fault, star connected Load, transformer type2

Transformer type 2 removes zero sequence component of the voltage. The zero sequence component of the phase voltage due to $1-\phi$ fault is equal to $\frac{1}{3}(V-1)$.

$$V_a = \frac{1}{3} + \frac{2}{3}V \; ; \; V_b = -\frac{1}{6} - \frac{1}{3}V - \frac{1}{2}j\sqrt{3}$$

$$V_c = -\frac{1}{6} - \frac{1}{3}V + \frac{1}{2}j\sqrt{3}$$

This is a new type of sag, identical to the delta connected Load during a phase-phase fault. refered to as X_3

- $1-\phi$ fault, Delta connected Load, transformer type 2.

Phase to phase voltages experienced by a delta connected Load do not contain any zero sequence component, Type 2 does not have any influence on the sag voltages, Thus the sag of type X_2.

- 1-ϕ fault, star connected Load, transformer type 3.

The Transformer type 3 changes phase voltages into line voltages. Thus star connected load on secondary experiences same sag as delta-connected load on Primary. Hence sag X_2.

- 1-ϕ fault, Delta connected Load, transformer type 3.

There are two transformations, from Y to Δ Load and from Primary to secondary side of the transformer. Thus the sag experienced by this delta-connected Load is same as by star connected Load behind a transformer of type 2., Thus sag type X_3.

- phase-phase fault, Y connected Load, No transformer

This case will by sag type X_4.

- Phase-phase fault, Δ connected Load, No transformer

This case will refered to sag type X_5.

- Phase-phase fault, Y connected Load, transformer type 2.

phase to phase faults do not result in any zero sequence voltage, transformer type 2 does not have any effect. The sag thus remains of type X_4.

- Phase to phase fault, Δ connected Load, transformer type 2.

  The sag of type X5.

- phase to phase fault, Y connected Load, transformer type 3.

  star connected Load on secondary side of transformer type 2 experiences the same sag as delta connected Load on Primary side. Hence sag type X5

- phase to phase fault, Δ connected Load, transformer type 3.

  transformer gives two identical transformations. Again only removes the zero sequence But one component, and thus no influence on sags due to phase to phase faults. results again X4.

Basic Types of sags:

1-ϕ faults Leads to three types of sags, namely sag X_1, sag X_2 and sag X_3. Phase to phase faults Leads to sag X4 and sag X5. Sag X_1 and sag X_2 Leads to similar sags. Hence

X_1 & X_2 $V_a = 1$; $V_b = -\frac{1}{2} - \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3}$; $V_c = -\frac{1}{2} + \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3}$

X4 $V_a = 1$; $V_b = -\frac{1}{2} - \frac{1}{2} V j\sqrt{3}$; $V_c = -\frac{1}{2} + \frac{1}{2} V j\sqrt{3}$

X3 $V_a = \frac{1}{3} + \frac{2}{3}V$; $V_b = -\frac{1}{6} - \frac{1}{3}V - \frac{1}{2} j\sqrt{3}$; $V_c = -\frac{1}{6} - \frac{1}{3}V + \frac{1}{2} j\sqrt{3}$

X5 $V_a = V$; $V_b = -\frac{1}{2}V - \frac{1}{2} j\sqrt{3}$; $V_c = -\frac{1}{2}V + \frac{1}{2} j\sqrt{3}$

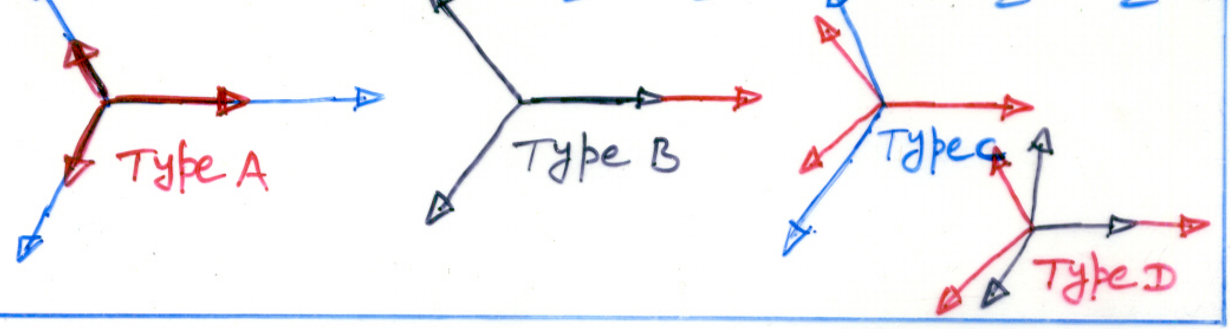
Type of fault	Type of Load	Typ of trans-former	Type of Sag
1-ϕ	Y	Type 1	X_1
1-ϕ	Δ	Type 1	X_2
1-ϕ	Y	Type 2	X_3
1-ϕ	Δ	Type 2	X_2
1-ϕ	Y	Type 3	X_2
1-ϕ	Δ	Type 3	X_3
2-ϕ	Y	Type 1	X_4
2-ϕ	Δ	Type 1	X_5
2-ϕ	Y	Type 2	X_4
2-ϕ	Δ	Type 2	X_5
2-ϕ	Y	Type 3	X_5
2-ϕ	Δ	Type 3	X_4

Type A : $V_a = V$; $V_b = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}V$; $V_c = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}V$

Type B : $V_a = V$; $V_b = -\frac{1}{2} - \frac{1}{2}j\sqrt{3}$; $V_c = -\frac{1}{2} - \frac{1}{2}j\sqrt{3}$

Type C ; $V_a = 1$; $V_b = -\frac{1}{2} - \frac{1}{2}Vj\sqrt{3}$; $V_c = -\frac{1}{2} + \frac{1}{2}Vj\sqrt{3}$

Type D : $V_a = V$; $V_b = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}$; $V_c = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}$



Two Phase to ground faults :-

The phase to ground voltages at the PCC due to a two phase to ground fault are

$V_a = 1$; $V_b = -\frac{1}{2}V - \frac{1}{2}Vj\sqrt{3}$; $V_c = -\frac{1}{2}V + \frac{1}{2}Vj\sqrt{3}$

After a Dy transformer or any other transformer of type 3, the voltages are

$V_a = V$; $V_b = -\frac{1}{3}j\sqrt{3} - \frac{1}{2}V - \frac{1}{6}Vj\sqrt{3}$; $V_c = \frac{1}{3}j\sqrt{3} - \frac{1}{2}V + \frac{1}{6}Vj\sqrt{3}$

[Type F]

After two transformers of type 3 or after one transformer of type 2, we get

$V_a = \frac{2}{3} + \frac{1}{3}V$; $V_b = -\frac{1}{3} - \frac{1}{6}V - \frac{1}{2}Vj\sqrt{3}$; $V_c = -\frac{1}{3} - \frac{1}{6}V + \frac{1}{2}Vj\sqrt{3}$

[Type G]

These three sags are different from four types found earlier. Two phase to ground faults lead to three more types of sags, resulting in a total of seven.

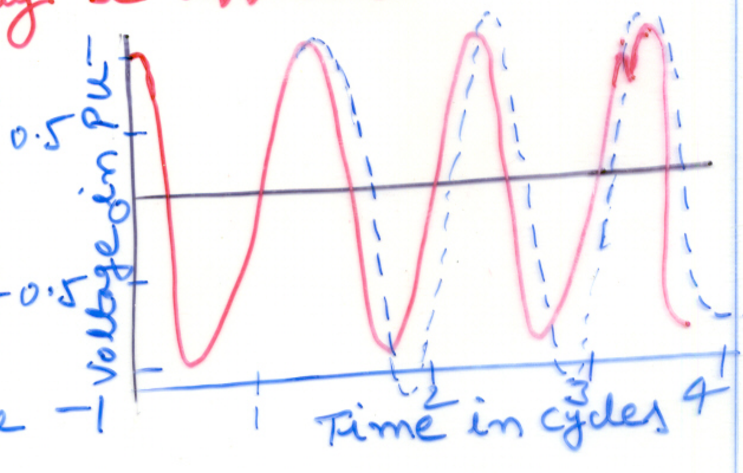
- 3-ϕ unbalanced sags of type B and type E can not occur at the terminals of equipment.
- At equipment terminals the following five types of 3-ϕ unbalanced sags can occur

Type A – Due to 3-ϕ faults ; Type C & D – Due to 1-ϕ and phase-phase faults

Type F & G – Due to two phase to ground fault.

Phase- Angle Jumps:

- A short circuit in a Power system not only causes a drop in Voltage magnitude but also a change in the Phase angle of the Voltage.
- The Latter as the Phase angle Jump associated with the Voltage sag.
- The phase angle Jump manifests itself as a shift in zero crossing of the instantaneous Voltage.
- Phase angle Jumps are not of concern for most equipment, but Power electronics converters using phase angle information for their firing instants may be affected.
- To obtain phase angle Jump of a measured Sag, the phase angle of the Voltage during the sag must be compared with phase angle of the Voltage before sag.



- The phase angle of Voltage can be obtained from the Voltage zero crossing or from the phase of fundamental component of the Voltage. The complex fundamental can be obtained by doing a Fourier transform on the signal.
- To understand the origin of 3-ϕ Jumps associated with Voltage Sags, the 1-ϕ Voltage divider model can be used, with difference that Z_s and Z_F are complex quantities.

- Neglect load current and assume $E = 1$.

The Voltage at PCC $V_{sag} = \frac{\bar{Z}_F}{\bar{Z}_S + \bar{Z}_F}$

Let $Z_S = R_S + jX_S$; $Z_F = R_F + jX_F$

- The argument of V_{sag}, thus the phase angle Jump in the Voltage.

$\Delta\phi = \arg(\bar{V}_{sag}) = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right)$

- If $\frac{X_S}{R_S} = \frac{X_F}{R_F}$ is zero and there is no phase angle Jump. The phase angle Jump will present if (X/R) ratio of the source and the feeder are different.

- A stronger source makes the sag Less severe, less drop in magnitude as well as smaller phase angle Jump. The phase angle Jump for zero distance to the fault is independent of the source strength.

characterization of Voltage Sags experienced by 3-ϕ ASD Systems.

AC Drive: Balanced Sags

- Trip of AC drive due to a Low Voltage at the dc bus. Mainly due to controller or PWM inverter not operating Properly, when the voltage gets too low.
- DC Bus Voltage is normally from the three ac Voltages through a diode rectifier. when voltage at ac drive drops, rectifier will stop conducting and the PWM inverter will be Powered from the capacitor Connected to the dc bus.
- capacitor has only limited energy content and will not be able to Supply the Load much longer than few cycles.
- Improved voltage tolerance of ASD can be achived by lowering the Setting of under voltage Protection of the dc bus.
- Protection should trip before any malfunction occur and before components are damaged.
- The dc bus under voltage should also protect against over current, when the ac drive recovers.
- Drive is equipped with fuses in series with diodes against large overcurrents. These should not be used to Protect against the overcurrent after a Sag.

(i) Decay of the dc bus Voltage

- Dc bus Voltage for an ASD during a Sag in three Phases behaves the Same as the dc bus Voltage of Personal computer.
- consider a drive with a motor Load P, a nominal bus Voltage V_0 and capacitance c connected to the dc bus, then the initial decay of the dc bus Voltage during the Sag.

$$V(t) = \sqrt{V_0^2 - \frac{2P}{c} t}$$

- Assuming that dc Voltage at Sag initiation equal to nominal Voltage and at a constant Load.

(ii) Voltage tolerence:

- ASD will trip either due to an active intervention by the Undervoltage Protection or by a maloperation of the inverter.
- In both cases the trip will occur, when a dc Voltage reaches a certain Value V_{min}. For Sags below V(t) can be used to calculate the time it takes for dc bus Voltage to reach the value V_{min}.

$$t = \frac{c}{2P}\left(V_0^2 - V_{min}^2\right)$$

(iii) capacitor size

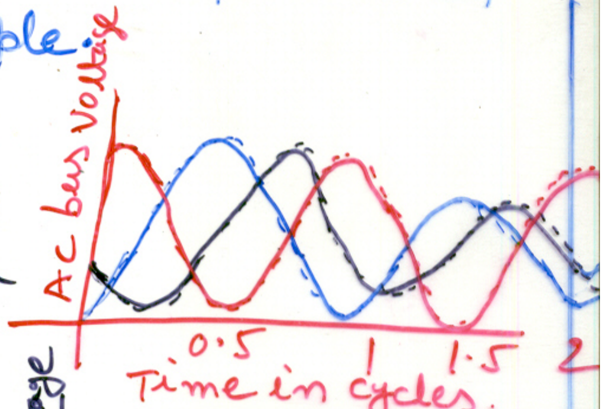
$$c = \frac{2Pt}{(V_0^2 - V_{min}^2)}$$

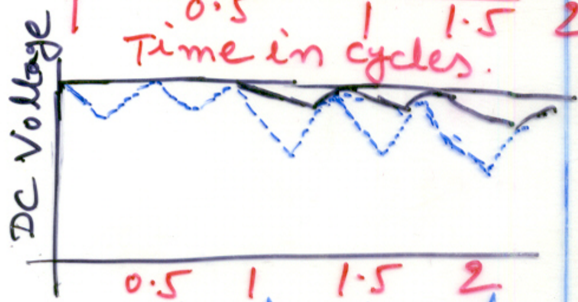
The immunity can be improved by adding more capacitance to the dc bus.

Three phase Unbalanced Sags:

- Normal operation dc bus Voltage is Smoothend by the capacitance. Larger the capacitance, smaller the voltage ripple.

(i) Sags of Type C:



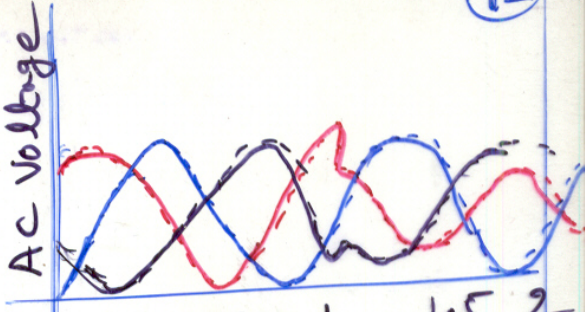


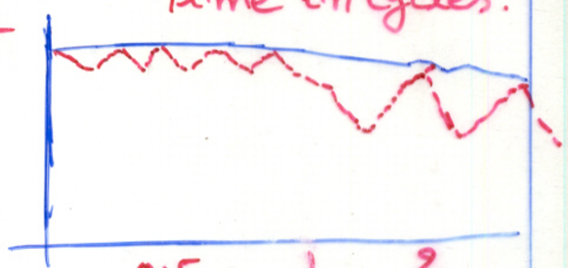
- The graphs shows the voltages at the drive terminals for a sag of type c.
- In two phases, the sine wave move toward each other. third phase does not drop in voltage.
- A sag with a characteristic magnitude of 50% and zero characteristic phase angle jump is shown. The voltage magnitude at the drive terminals 66.1% (In two phases) and 100% in third phase
- Effect of three- phase unbalanced sag on the dc bus voltage shown in the lower graph. For the large capacitance, dc voltage hardly deviates from it's normal operating value. The drive will never trip during a sag type of c.
- one phase remains at its Pre event value, the 3-ϕ rectifier simply operates as a 1-ϕ rectifier during the voltage sag.

(ii) Sags of Type D:

The voltage sags on ac side and dc side of the rectifier are shown.

For Sag of type D all three Phases drop in Voltage. The magnitudes of Voltages at drive terminals 50%, 90.14%, 90.14%. with characteristic magnitude of 50% and no Phase angle Jump.





- The drop in Voltage for two phases is moderate. one phase Voltagedrops significantly, other two Phases drop less in Voltage magnitude.
- The effect of Sag on dc bus Voltage shown. DC bus Voltage reaches a Value slightly below the Peak Value of the Voltage in the two Phases with the moderate drop. The Sag on the dc Voltage and thus on the motor speed and torque is much less than for a balanced Sag.

(iii) Phase angle jumps:

- Assumed that the phase angle jump is zero. Hence two of the phase voltages have the same Peak Value. The highest Phases for a sag of type D, the lowest phases for a Sag of type C. one of the these two Voltages gets lower, and the other higher. when there is no capacitance connected to the dc bus the minimum dc bus Voltage is determined by the lowest ac side Voltage. The effect of Phase angle Jump is that minimum dc Voltage gets lower.

Adjustable speed DC Drive:

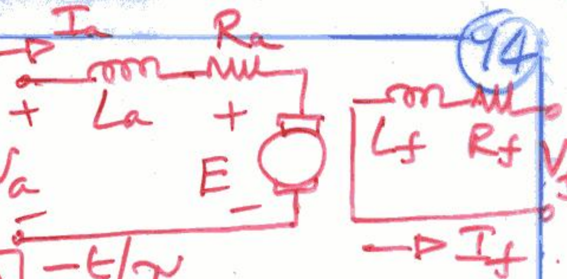
(a) Balanced sags: which leads to a complicated tranient in the dc motor, with a new steady state at the same speed as the original one.

- since $\omega_m = R_f V_a / (K V_f)$, hence motor speed is proportional to the ratio of Armature voltage and field voltage. The balanced sag makes the armature and field voltage drop the same amount, the speed should remain the same.
- Because of voltage sag, the voltage on ac side of the field winding rectifier will drop. Lead to decay in field current. The speed of decay is determined by the amount of energy stored in the inductance and in the capacitance. $I_f(t) = I_{fo}(1 - e^{-t/\tau})$

The field current will not decay to zero. For a voltage drop of 20%, the field current will also drop 20%.

- Voltage sag leads to direct drop in armature voltage. Leads to decay in armature current. This decay slightly different with decay in field current. I_a driven by difference between the armature voltage drop and induced back emf. This difference is normally few percent, change in I_a is very large. I_a quickly becomes zero.

$$V_a = L_a \frac{dI_a}{dt} + R_a I_a + E$$



Solution leads to

$$I_a = \left(\frac{V_a - E}{R_a}\right) + \left[I_0 - \left(\frac{V_0 - E}{R_a}\right)\right] e^{-t/\tau}$$

$V_0 \rightarrow$ armature Voltage during Sag. and $\tau = \frac{L_a}{R_a}$

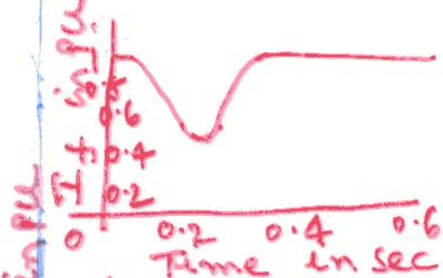
- Drop in armature and in field current Leads to a drop in torque, causes a drop in speed. The drop in speed and drop in field current cause a reduction in back emf.
- more speed drops, more back emf drops, more the I_a increases, more torque increases. DC motor has a built in speed control mechanism via back emf.
- The torque becomes higher than the load torque and Load reaccelerates.
- The Load stabilizes at the original speed and torque, but for a lower field current and higher armature current. The drop in field current equals the drop in Voltage the I_a increases, I_f drops, the torque remains constant

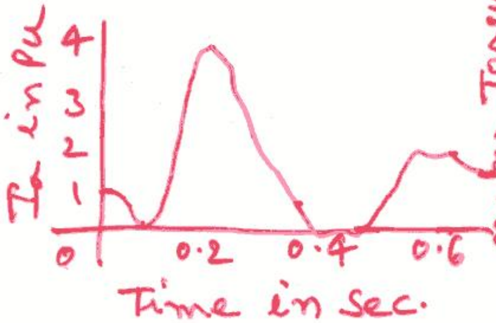
(b) Unbalanced Sags:

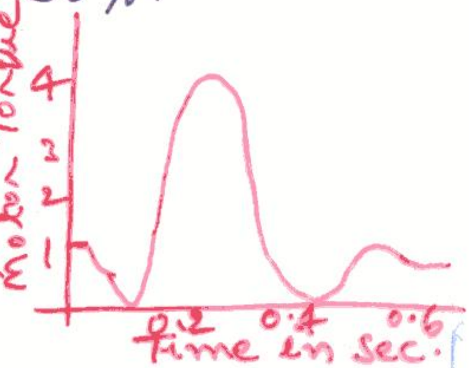
- Effect of unbalanced sag on dc drive is that V_a and V_f do not drop the same amount. V_a obtained from a 3-ϕ rectifier. V_f from a 1-ϕ rectifier.

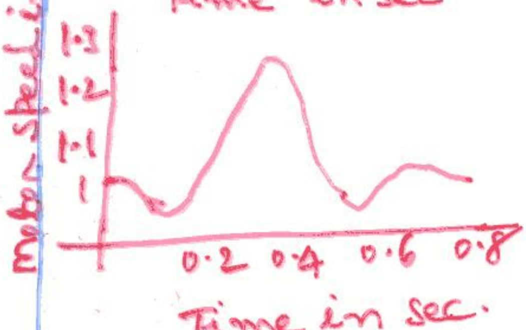
- During an Unbalanced sag, 1-ϕ rectifier is likely to give a different output Voltage than the 3-ϕ rectifier.
- If V_f more than V_a, the E will less than V_a, Leading to an increase I_a. New steady state speed is higher than pre-event speed.

- A sag of type D with large Voltage drop in phase from which the field winding is powered. Thus the field Voltage drops to 50%.

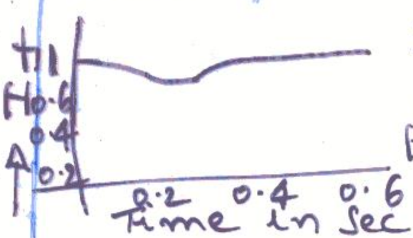


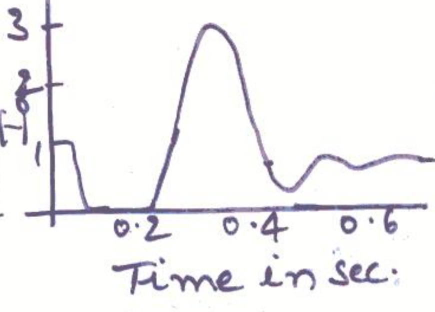


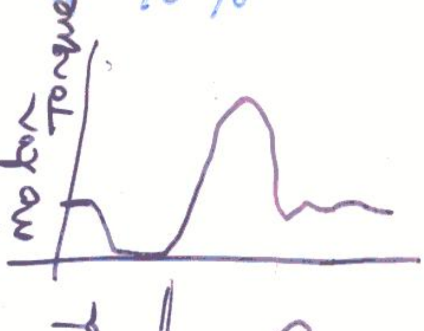




- A sag of type D with a small voltage drop in phase from which field winding is powered. making the field Voltage drop 90%.





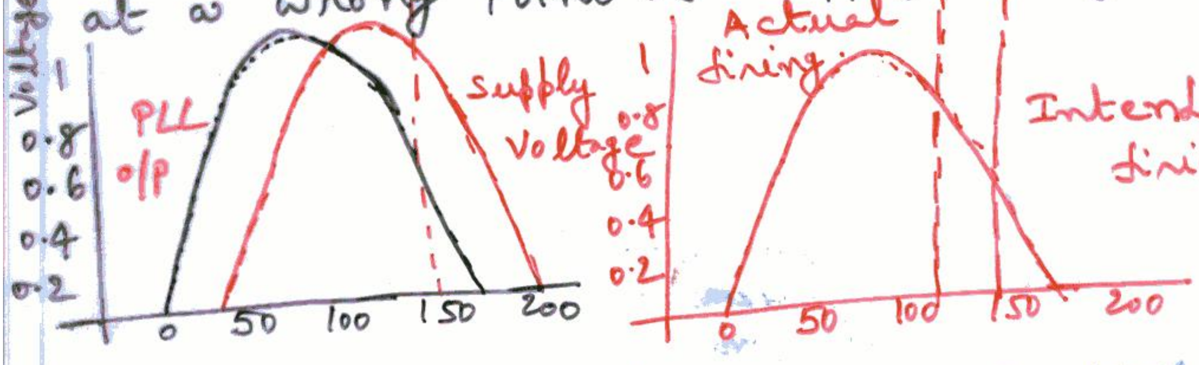


- A Sag of type C with the field winding powered from the phase without voltage drop. The field voltage drop remains 100%. The results are similar to previous sags.

Sag	Type	V_f	I_f min	I_f max	I_a min	I_a max	Torque min	Torque max	speed min	speed max
I	D	50%	59%	100%	0	460%	0	367%	93%	124%
II	D	90%	98%	100%	0	264%	0	256%	85%	107%
III	C	100%	100%	100%	0	229%	0	229%	85%	114%

(c) Phase angle Jumps:

- Phase angle jumps affect the angle at which the thyristors are fired. The firing instant normally determined from PLL output.
- The effect of phase angle jump is that actual voltage is shifted compared to the reference voltage. Because of this thyristors are fired at a wrong point of supply voltage.



During sag voltage lags the pre sag voltage. then ~~the~~ zero crossing of actual supply voltage comes later than the zero crossing of PLL output. For balanced sags the phase angle jump is equal in three phases. shift in firingle angle is same for all three voltages.

Effect of momentary Voltage dips on Directly fed Induction motors:

- Majority of IM's are still directly fed. motor terminals are connected to the constant frequency, constant voltage supply.
- Directly fed IM's are insensitive to voltage sags, although problems could occur when too many motors are fed from the same bus.
- The drop in terminal voltage cause drop in torque. Due to this drop in torque the motor will down, untill it reaches a new operating point.
- If the terminal voltage drops too much, the load torque will be higher than the pull-out torque and will continue to slow down.
- IM typically operated with half it's pull-out torque. This torque is proportional to square of the voltage. A voltage drop of 70% will not lead to a new stable operating point.
- Deep sag lead to severe torque oscillations at sag commencement and voltage recovers. These could lead to damage the motor and to process interruptions. The recovery torque becomes more severe, internal flux out of phase with supply. Hence sag is associated with phase angle jump.
- At sag commencement the magnetic field will be driven out of airgap. The associated transient causes an additional drop in speed.

During this period the motor contributes to short circuit current and some what mitigates the sag.

- when the voltage recovers, the airgap flux has to built up again. and the motor takes a high inrush current. For first to build up airgap field., next to reaccelerate the motor. Inrush current cause a post-fault sag and lead to tripping of over voltage and overcurrent relays. This problem is more severe for a weak supply.
- For unbalanced sags the motor is subjected to +ve sequence and −ve sequence voltage at the terminals. −ve sequence voltage causes a torque ripple and large −ve sequence current.

Directly fed synchronous motor:

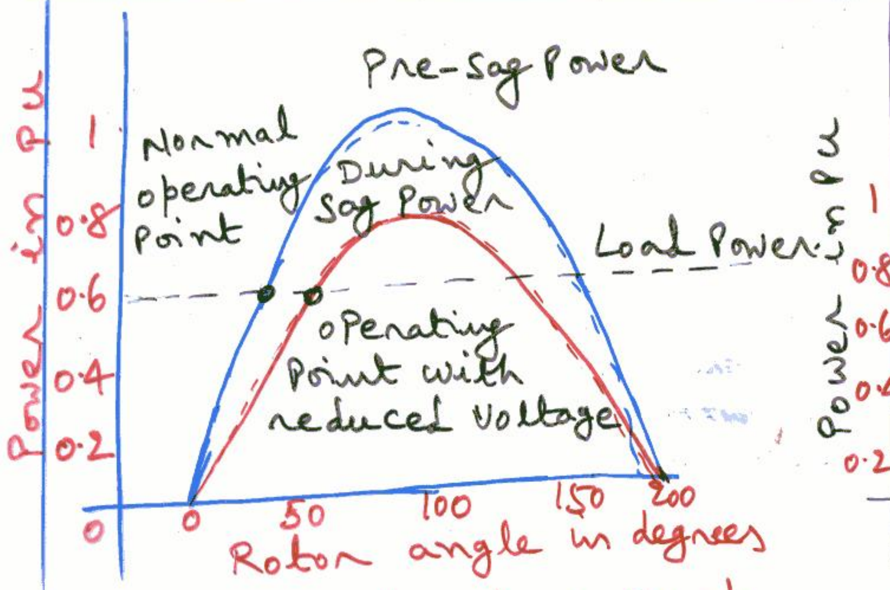
- Synchronous motor has similar problems with voltage sags as an I.M. overcurrent, torque oscillations, drop in speed, but this motor actually lose synchronism.
- Synchronous motor loses synchronism, it has to be stopped and load has to be removed before brought back to nominal speed.
- $P = \dfrac{V_{sup} E \sin\phi}{X}$

$V_{sup} \rightarrow$ supply voltage

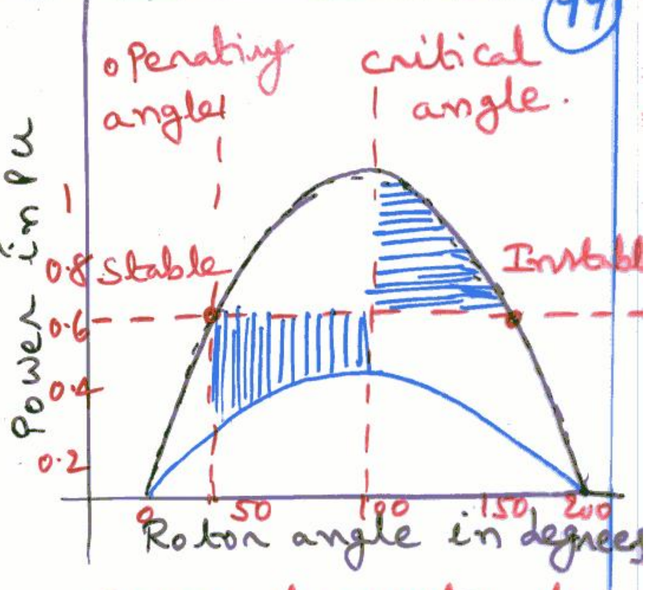
$E \rightarrow$ Back-Emf.

$\phi \rightarrow$ Angle between back Emf and supply voltage

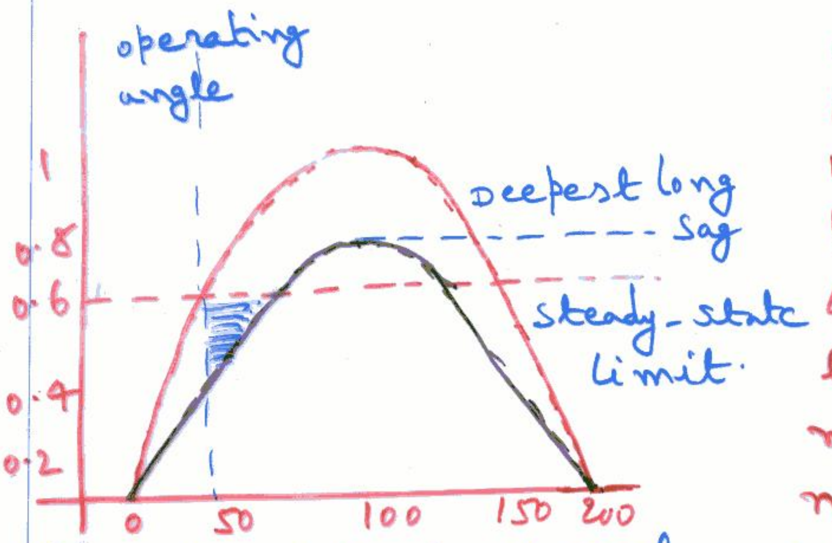
$X \rightarrow$ reactance between supply and m.t.h.



Power transfer to a synchronous motor as a function of rotor angle.



Power transfer to synchronous motor in normal situation for a deep Sag



Power transfer in Normal situation and deepest long duration Sag.

- For a given motor Load the operating will be such that the Power taken by the Load equals the Power transported to the motor. This Point as normal operating Point.
- During a Sag, the Power transported to the motor becomes smaller than the Power taken by the Load. As a result motor slows down, means ϕ increases. settle at new Point. operating Point with reduced voltage. Again the Power to the motor and Power taken by the Load are in balance.

- In case of deep sags no longer a stable operating point. rotor angle continue to increase until supply voltage recovers. If the angle increased too much the motor loses synchronism.
- Hence there are two operating points as stable and unstable. In the latter point both power flows are again equal, so motor operate at constant speed. The motor loses synchronism the moment it's rotor angle exceeds this unstable operating point.
- The power transfer during the sag, no stable operating point and the motor continue to slow down until the voltage recovers. The motor start to accelerate again but it still rotates slower than the airgap, its rotor angle will continue to increase. The maximum rotor angle is reached the moment the motor speed comes to nominal. As long as this angle is smaller than the unstable point, the motor does not lose synchronism.
- Highest possible rotor angle equals 90°. this occurs when the load equals the max. power transported to the motor. If motor load is half this max. value, a drop in voltage to 50% will bring the operating point back to the top. 50% drop is not deepest sag, motor can withstand for a long time. cause the motor to slow down, rotor angle reaches 90°, not stop till continue to increase until voltage recovers.

Power System Quantities under Non Sinusoidal conditions:

- Traditional Power system quantities such as rms, power (reactive, active, apparent), Pf and phase sequences are defined for the fundamental frequency contexct in a, Pure sinusoidal condition
- But in the Presence of harmonic distortion power system no longer operates in a sinusoidal condition.

(a) Active, reactive and apparent Power.

(i) Active Power is defined as the average rate of delivery of energy.

(ii) Reactive Power is the Portion of the apparent power that is out Phase, or an quadrature, with the active Power.

(iii) APParant Power is the Product of the rms voltage and current.

Apparant Power S applies to both sinusoidal and Non-sinusoidal conditions.

$$S = V_{rms} I_{rms} ; \quad V_{rms} = \frac{V_1}{\sqrt{2}} ; \quad I_{rms} = \frac{I_1}{\sqrt{2}}$$

- In a sinusoidal condition both wave forms contain only the fundamental component.
- The Sub-script '1' denotes quantities of fundamental frequency. But in a Non Sinusoidal condition a harmonically distorted waveform is made of sinusoids of harmonic frequencies with different amplitudes.

- The RMS values of waveforms computed as square root of the sum of rms squares of all individual components.

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left(\frac{1}{\sqrt{2}} V_h\right)^2} = \frac{1}{\sqrt{2}} \sqrt{V_1^2 + V_2^2 + \cdots + V_{h_{max}}^2}$$

$$I_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{\sqrt{2}}\right)^2} = \frac{1}{\sqrt{2}} \sqrt{I_1^2 + I_2^2 + \cdots + I_{h_{max}}^2}$$

where V_h and I_h are the amplitude of a waveform at the harmonic component h.

- The active power P refered as average power, real power, or true power. It represents useful power expended by loads to perform real work. i.e. to convert electrical energy to other forms of energy. The active power is the rate at which energy is expended, dissipated, or consumed by the Load and is measured in watts.

$$P = \frac{1}{T}\int_0^T v(t)\, i(t) \cdot dt = \text{Averaging the Product of instantaneous } v \,\&\, i$$

[it is valid for both sinusoidal & Non-sinusoidal]

$$P = \frac{V_1 I_1}{2} \cos\theta_1 = V_{1rms} I_{1rms} \cos\theta_1 = S \cos\theta_1 .$$

- Equ. Indicates average active power is a function only of the fundamental frequency quantities.
- In Non sinusoidal case P must include contributions from all harmonic components. Thus it is the sum of active power at each component

- Generally voltage distortion very low on Power systems (< 5%) hence the above is a good approximation.
- This approximation can not be applied when computing the apparent reactive Power. Because these two quantities are greatly influenced by the distortion.

- The reactive Power is a type of Power that does no real work and is associated with reactive elements - In sinusoidal case, the reactive Power is defined as

$$Q = S \sin\theta_1 = \frac{V_1 I_1}{2} \sin\theta_1 = V_{1rms} I_{1rms} \sin\theta_1$$

- In the Presence of harmonic distortion it is difficult to ~~define~~ Q. Because it is more important to determine P and S. P defines how much active Power consumed. S defines the capacity of the Power system required to deliver P. Q is not actually useful. But reactive Power component at fundamental frequency, may be used to size shunt capacitor.
- When harmonic distortion Present, the component S that remains after P is taken out is not conserved ie does not sum to zero at a bus. But Power quantities are Presumed to flow around the system in a conservative manner.

- This does not imply that P is conserved. because the conservation of energy and KCL must applicable to any wave form. The reactive components actually sum in quadrature. (square root of the sum of the squares).
- Hence Q be used to denote reactive components that are conserved and introduce a new quantity for the components that are not. call this quantity as D distortion Power or distortion volt amperes.
- In this context Q consists of sum of the traditional reactive values at each frequency. D represents all cross products of V and I at different frequencies. which yield average Power is zero.

$$S = \sqrt{P^2 + Q^2 + D^2}\ ; \quad Q = \sum_K V_K I_K \sin\theta_K$$

$$\therefore D = \sqrt{S^2 - P^2 - Q^2}$$

P and Q tribute the traditional sinusoidal components to S. while D represents the additional contribuation to apparent power by the harmonics.

Power factor (Displacement and True)

- power factor is a ratio of useful power to perform real work (Active power) to the power supplied by a utility (Apparent power) i.e $PF = P/S$
- In other words, PF ratio measures the percentage of power expended for its intended use. which ranges from zero to unity. A load with 0.9 lagging denotes that the load can effectively expend 90% of apparent power supplied and convert it to perform useful work
- In sinusoidal case there is only one phase angle between the V and I, hence the pf can be computed as the cosine of the phase angle refered as displacement power factor
- In Non-sinusoidal case the power factor cannot be defined as the cosine of the face angle. The power factor that takes into account the contribution from all active power, including both fundemental and harmonic frequencies, known as true power.
- The true power factor is simply the ratio of total active power for all frequencies to the apparent power delivered by the utility

  power Factor = (P at all frequencies / S)

- PQ monitoring instruments report both displacement and true power factors. many devices such as switch mode power supplies and PWM have a near unity displacement factor but true power factor may i.e 0.5 to 0.6.

Harmonic Phase difference:

- The theory of symmetrical components can be used to describe 3-ϕ system behaviour. which is transformed into three 1-ϕ systems that are much simpler to analyze.
- The method of symmetrical components can be employed for analysis of system response to harmonic currents, provided not to violate the fundamental assumptions of the method.
- This method allows any unbalanced set of phase currents to be transfered into three balanced sets. + sequence set contains three sinusoids displaced 120° from each other with ABC phase rotation (0, −120°, 120°).

− sequence set contains three sinusoids are also displaced by 120° with opposite phase rotation. (0, 120°, −120°)

zero sequence contains three sinusoids are in phase with each other (0°, 0°, 0°).

- In a perfect 3-ϕ system, the harmonic phase sequence determined by multiplying the harmonic h with the normal + sequence phase rotation.
- For the second harmonic $h = 2$, we get $2 \times (0, -120°, 120°)$ which is −ve sequence. $h = 3$, we get $3 \times (0, -120°, 120°)$ which is zero sequence.
- The Distored wave form in PS contains only odd harmonic component. since the waveform is symmetrical.

$h = 1, 7, 13, \dots$ + sequence ; $h = 5, 11, 17 \dots$ −ve sequence

$h = 3, 9, 15, \dots$ zero sequence.

Measurement of Harmonics :-

- The most commonly used indices for measuring the harmonic content of a waveform are the Total harmonic distortion, (THD) and total Demand distortion (TDD).
- The other indices are Telephone Influence factor (TIF), V.T Product, Distortion Index (DIN), C-message weights[C], Flicker factor.

Total harmonic distortion (THD):

- THD is a measure of effective value of the harmonic components of a distored waveform. This index can be calculated for either V or I.

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} M_h^2}}{M_1}$$

where M_h = rms value of harmonic component h of the quantity M.

- The rms value of a distorted waveform is the square root of the sum of the squares. The THD is related to RMS value of waveform as

$$RMS = \sqrt{\sum_{h=1}^{h_{max}} M_h^2} = M_1\sqrt{1+THD^2}$$

- Properties of THD are

THD is zero for a sinusoidal waveform, As the distortion increses, THD becomes very large. THD level in distribution system is 5%. Quick measure of distortion can be calculated easily. only the disadvantage is detailed information of full spectrum is lost.

Total Demand distortion:

- Current distortion Levels can be characterized by a THD Value. But this can often mislead. A Small current may have a high THD, but not be a significant threat to the system.
- Many ASD's exhibit high THD Values for the input current, when they are operating at very light Loads. This not significant concern because the magnitude of harmonic current is low, even though its relative current distortion is high.
- This difficulty can avoid by referring THD to fundamental of the peak demand Load demand rather than the fundamental of the present sample. This is called Total demand distortion.

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L}$$

I_L is the Peak, or maximum demand Load current at the fundamental frequency measured at the Point of Common Coupling (PCC).

Total Inference factor:

- TIF is a Variation of THD, in which the root of the sum of Squares is weighted using weight factors, which reflect the effect of human ear.

$$TIF = \frac{\sqrt{\sum_{h=1}^{h_{max}} \omega_h^2 V_h^2}}{\sqrt{\sum_{h=1}^{h_{max}} V_h^2}}$$

TIF is used to assess the interference of Power distribution with audio communication circuits as mutual coupling is modelled in TIF and not in THD. TIF is usually applied to line currents.

V·T Product:

- THD Index does not give information about the amplitude of the voltage. V·T index is an alternative index which incorporates the information

$$VT = \sqrt{\sum_{h=1}^{h_{max}} w_h^2 V_h^2} = [TIF_V] V_{rms}$$

where w_h is the TIF weighted factor and V_h is the hth harmonic component of line to line voltage V. which gives the measure of audio circuit interference due to bus voltage.

IIly IT is a measure of line current.

$$IT = \sqrt{\sum_{h=1}^{h_{max}} w_h^2 I_h^2} = [TIF_I] I_{rms}$$

Distortion Index: THD determines DIN and vice-versa. DIN becomes unity for a Highly distorted wave, where as THD becomes infinite.

$$DIN = \frac{\sqrt{\sum_{h=2}^{h_{max}} V_h^2}}{\sqrt{\sum_{h=1}^{h_{max}} V_h^2}} \quad ; \quad DIN = \frac{THD}{\sqrt{1+THD^2}}$$

C-message weights [C]: This is similar to TIF excepts that weights C are used in place of w. The C message weighted index for current $i(t)$

$$C = \frac{\sqrt{\sum_{h=1}^{h_{max}} C_h^2 I_h^2}}{\sqrt{\sum_{h=1}^{h_{max}} I_h^2}} = \sqrt{\frac{\sum_{h=1}^{h_{max}} C_h^2 I_h^2}{I_{rms}^2}}$$

The TIF weights account for the mutual coupling between circuits increases linearly. while C-message weights are free from this consideration.

Flicker factor (F) :

Voltage flicker (Low frequency voltage fluctuations) are sinusoidal of frequency ω_r rad/sec, the nominal instantaneous bus voltage, $V_m \cos(\omega_r t)$ may be modulated by the signal $V_f \cos(\omega_r t)$. where V_f flicker amplitude. Flicker component bus voltage is

$$V_f(t) = V_f \cos(\omega_f t) \cdot V_m \cos(\omega_0 t)$$

Total bus voltage is

$$V(t) = V_m \cos(\omega_0 t) + V_f(t)$$

$$= \left[1 + V_f \cos(\omega_f t)\right] V_m \cos(\omega_0 t).$$

$$\text{Flicker factor } F = \left[\frac{V_f}{V_m}\right]$$

Bus voltage flicker is not a sinusoidal modulation effect.