EE6508 - Power Quality

Voltage Disturbances

presented by

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References

Texts:

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2. Kennedy B W, Power Quality Primer, First Edition, McGraw-Hill, 2000.

Reference:

3. Allan Greenwood, “Electrical Transients in Power Systems”, 2nd Edition, John Wiley & Sons Inc., 1991.

References

- Voltage variations

  - MHJ Bollen, Understanding Power Quality Problems – Voltage sags and interruptions, IEEE Press 2000.
  - European Standard EN-50160, Voltage characteristics of electricity supplied by public distribution systems, CENELEC, Brussels, Belgium, 1994
  - IEEE Std 493-1997, IEEE recommended practice for the design of reliable industrial and commercial power systems (Gold book), New York, 1997
  - IEEE Std 1159-1995, IEEE recommended practice for monitoring power quality, New York, 1995
  - IEC 61000-4-30, Testing and measurement techniques - Power Quality measurement methods, 2003
  - IEC 61000-4-11 / 61000-4-34, Voltage dip immunity for equipment that requires less than / more than 16 amps per phase.
  - IEEE Std 1346-1998, IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment, 1998.
  - SEMI F47: Specification for semiconductor processing equipment voltage sag immunity, Semiconductor Equipment and Materials International.

References

- Voltage fluctuations
  - IEC 61000-4-15, Flickermeter—Functional and design specifications.
  - IEEE 1453-2004, IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems.
  - IEC 61000-3-3, Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection.
  - IEC 61000-3-5, Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 16 A.
  - IEC 61000-3-7, Assessment of emission limits for fluctuating loads in MV and HV power systems

Voltage Variations

- Deviation of RMS voltage magnitude characterized by
  - ✓ Change in the voltage magnitude
    - ➢ Voltage dip/sag: decrease in magnitude
    - ➢ Voltage swell: increase in magnitude
    - ➢ Voltage interruption: drop to very low (close to zero) magnitude
  - ✓ Duration of the disturbance
  - ✓ Jump in voltage phase angle at beginning and end of disturbance

- Majority of problems lie with voltage sags/dips and interruptions
  - ✓ Insufficient voltage to maintain the continuous supply of energy to the loads, resulting in load tripping-off or malfunction
  - ✓ High current surges when voltage recovers after disturbance, causing equipment with low over-current withstand capability to trip

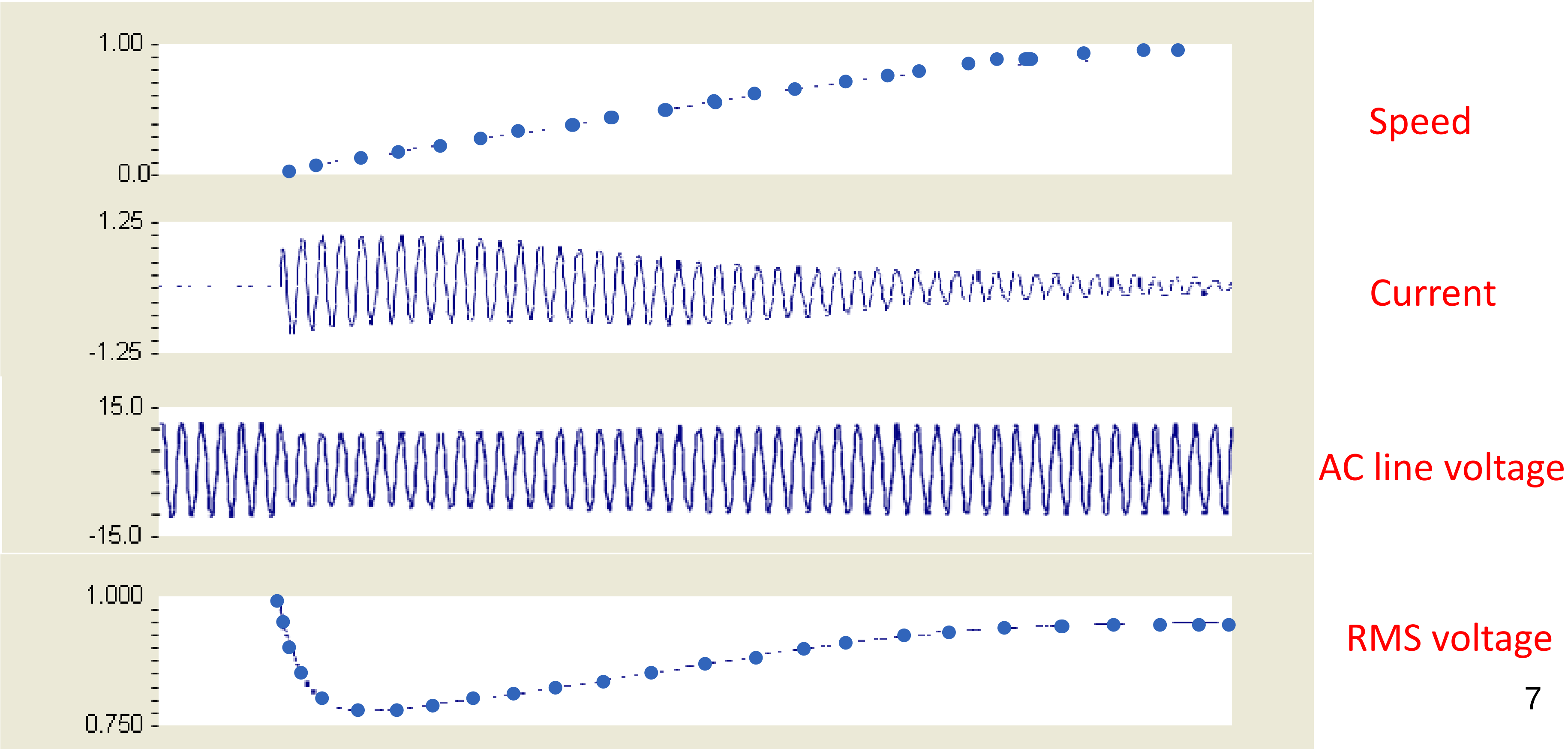
Definitions of Voltage Variations

- Short duration variations (< 1 min)
  - ✓ Duration (1 cycle of 50 Hz system is 20 ms)
    - ➢ Instantaneous (0.5-30 cycles),
    - ➢ Momentary (30 cycles – 3 s),
    - ➢ Temporary (3 s – 1 min)
  - ✓ RMS magnitude
    - ➢ Interruption (< 0.1 pu),
    - ➢ Sag/dip (0.1-0.9 pu),
    - ➢ Swell (1.1-1.8 pu)

- Long duration variations (> 1 min)
    - ➢ Sustained interruption (0.0 pu),
    - ➢ Undervoltages (0.8-0.9 pu typical),
    - ➢ Overvoltages (1.1-1.2 pu typical)

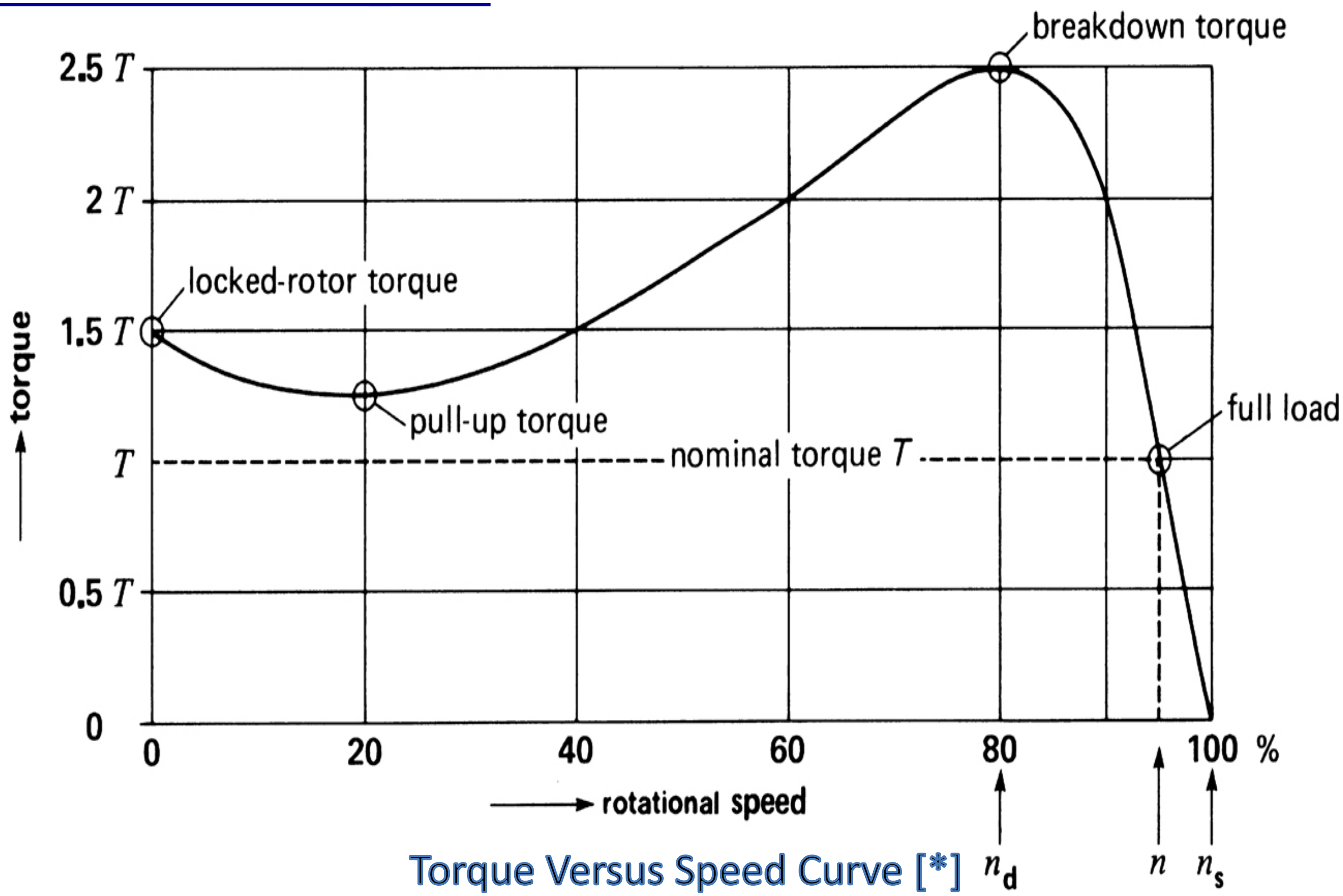
Sag Caused by Starting of Induction Motor

- Bollen – ss. 4.9 pp. 248-251; Ch. 9 of IEEE Std 399-1997
- During start-up of induction motor,
  - ✓ It takes a larger current than normal, typically 5-6 times larger
  - ✓ Current remains high until motors reaches its nominal speed, typically between several seconds to one minute



Useful Induction Motor Link

https://www.youtube.com/playlist?list=PLat6nFKIgrM702J6fhBX546-d0VA_6awb



Torque Versus Speed Curve [*]

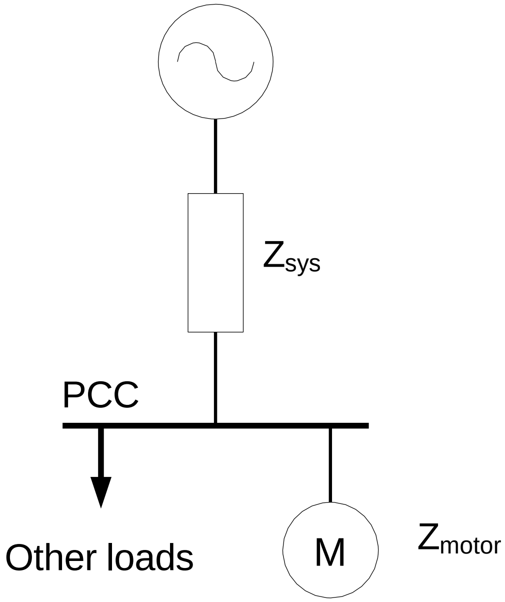
[*] http://electricalacademia.com/induction-motor/torque-speed-characteristics-induction-motor/

Sag Caused by Starting of Induction Motor

- Using voltage divider, standing voltage Vsag at the node of motor starting

$$V_{sag} = \frac{Z_{motor}}{Z_{motor} + Z_{sys}}$$

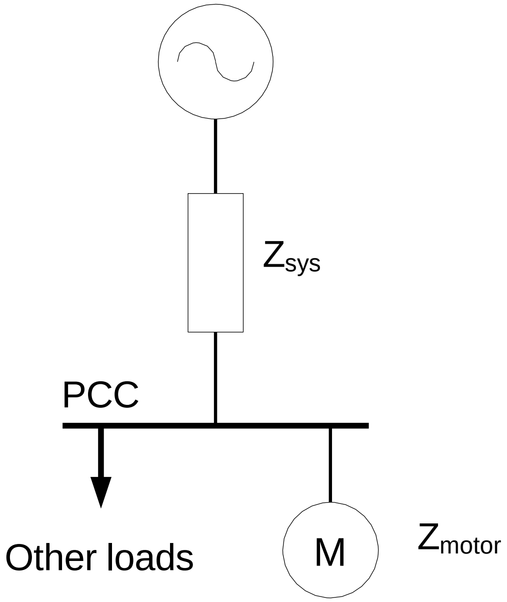
  - ✓ Assuming source voltage of 1.0 p.u.,
  - ✓ At starting, Z_{motor} is locked-rotor impedance



Sag Caused by Starting of Induction Motor

- When starting a motor from source with a short circuit capacity S_{source}.

$$Z_{sys} = \frac{V_n^2}{S_{source}} \; ; \; Z_{motor} = \frac{V_n^2}{\beta S_{motor}}$$



- ✓ V_n is rated voltage
- ✓ β is the ratio between the motor's starting current and the nominal current i.e. ratio of locked-rotor current at rated voltage to rated current
- ✓ S_{motor} is the motor rated apparent power

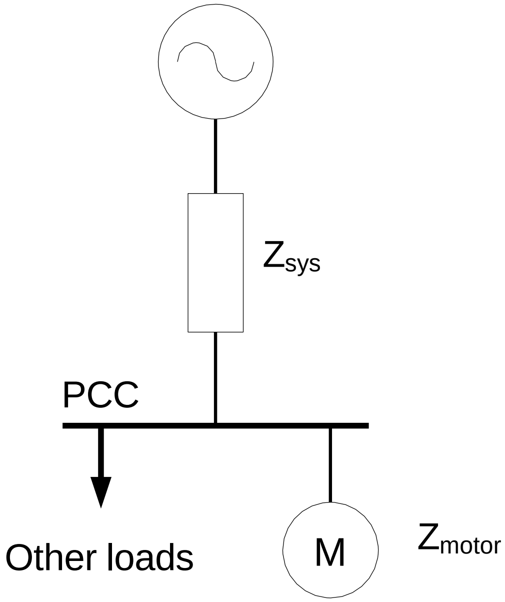
Sag Caused by Starting of Induction Motor

$$V_{sag} = \frac{Z_{motor}}{Z_{motor} + Z_{sys}}$$

$$V_{sag} = \frac{\frac{V_n^2}{\beta S_{motor}}}{\frac{V_n^2}{\beta S_{motor}} + \frac{V_n^2}{S_{source}}}$$

$$V_{sag} = \frac{\frac{1}{\beta S_{motor}}}{\frac{S_{source}+\beta S_{motor}}{\beta S_{motor} S_{source}}}$$

$$V_{sag} = \frac{S_{source}}{S_{source}+\beta S_{motor}}$$



- The corresponding per-unit change in voltage or voltage sag,

$$\Delta V = 1 - V_{sag} = 1 - \frac{S_{source}}{S_{source} + \beta S_{motor}} = \frac{\beta S_{motor}}{S_{source} + \beta S_{motor}}$$

$$\approx \frac{\beta S_{motor}}{S_{source}} \quad for \;\; S_{source} \gg \beta S_{motor}$$

Other Characteristics of Motor-Startup

- Duration of voltage sag depends on motor inertia
  - ✓ Motor torque is proportional to square of voltage
  - ✓ Reduced accelerating torque if voltage sag occurs
  - ✓ Prolong the motor run-up time
  - ✓ Lengthen the duration of voltage sag

- Effect on other motors
  - ✓ As voltage at motor terminal drops, other existing motors will slow down, causing an increase in the motors’ load currents
  - ✓ This will pull the voltage down even further, reduce the motor accelerating torque even more
  - ✓ Deeper voltage sag
  - ✓ Prolonging the voltage sag recovery
  - ✓ Long run-up time for the motor

Motor-Starting Methods

- Dugan ss. 3.6, pp. 78-81
- Full-voltage starting is simple, low-cost and allows rapid acceleration but voltage sag can be excessive
  - ✓ Current (and torque) is proportional to square of voltage
- Reduced starting voltage limits starting current, reducing voltage sag
  - ✓ Must ensure sufficient torque to build up the motor speed
- Autotransformer starter
  - ✓ Transformer tap of 80, 65 or 50% at starting to reduce starting current

Motor-Starting Methods

- Autotransformer with turn ratio α = N2 / N1

$$V_{start} = V_{sec} = \mathrm{N}_2 / \mathrm{N}_1 V_{pri} = \alpha V_{pri}$$

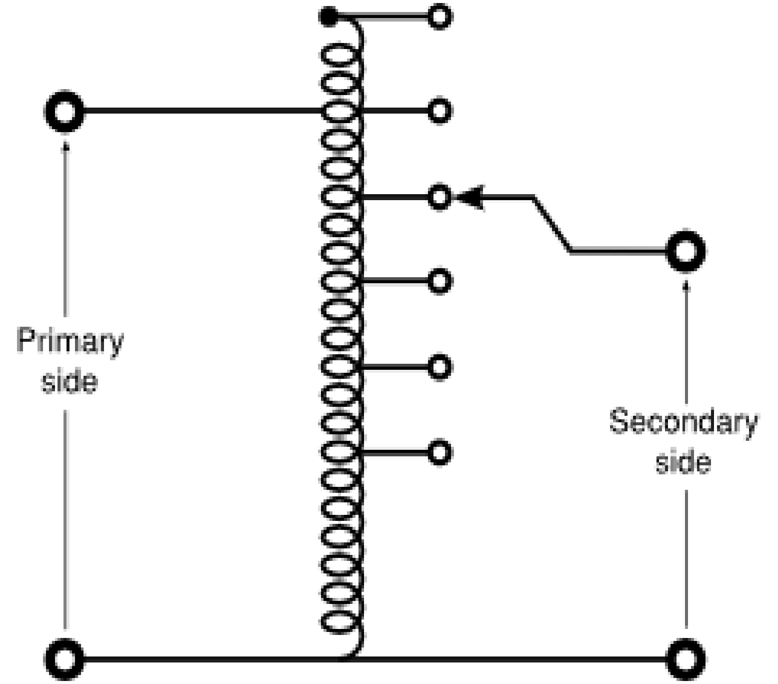
$$\Rightarrow I_{start-sec} = \frac{V_{sec}}{Z_{motor}} = \frac{\alpha V_{pri}}{Z_{motor}}$$

$$I_{start-sec} = \alpha I_{start-original}$$

$$I_{start-pri} = \alpha I_{start-sec}$$

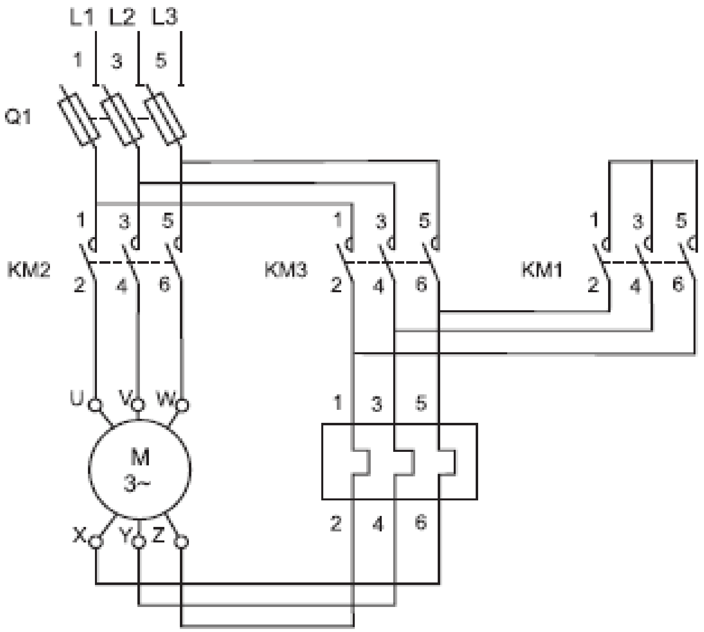
$$\therefore\ I_{start-pri} = \alpha^2 I_{start-original}$$

$$\Rightarrow \beta_{autotransformer} = \alpha^2 \times \beta_{original}$$



Motor-Starting Methods

- Delta-Wye starter
  - ✓ Stator windings are connected in wye at starting, reducing starting voltage to 57% of original level, and current (and torque) to 33% of original level
  - ✓ At starting, the order of switching is KM1, KM2 and KM3, with the last switch only closed after the motor has sped up to predefined value.



Motor-Starting Methods

- Without this starter, the motor will be turned on with winding connected in delta

$$I_{start-delta} = I_{line-delta} = \sqrt{3} I_{phase-delta} = \frac{\sqrt{3} V_{line-to-line}}{Z_{motor}}$$

- With delta-wye starter, the motor winding is connected in wye at starting

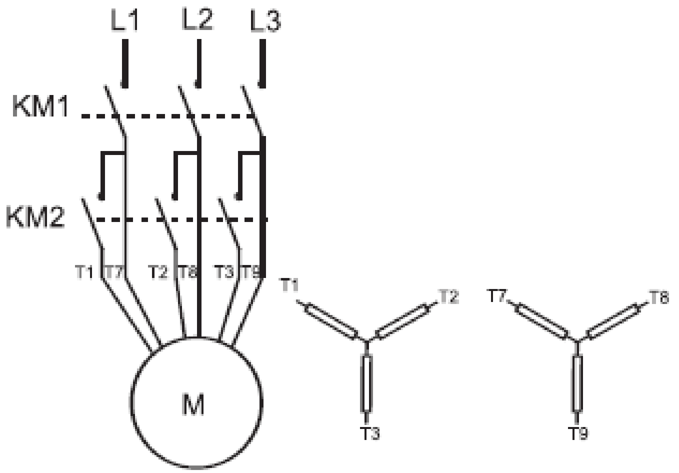
$$I_{start-wye} = I_{phase-wye} = \frac{V_{phase}}{Z_{motor}} = \frac{V_{line-to-line}/\sqrt{3}}{Z_{motor}}$$

$$I_{start-wye} = \frac{I_{start-delta}}{\sqrt{3}\sqrt{3}} = \frac{I_{start-delta}}{3}$$

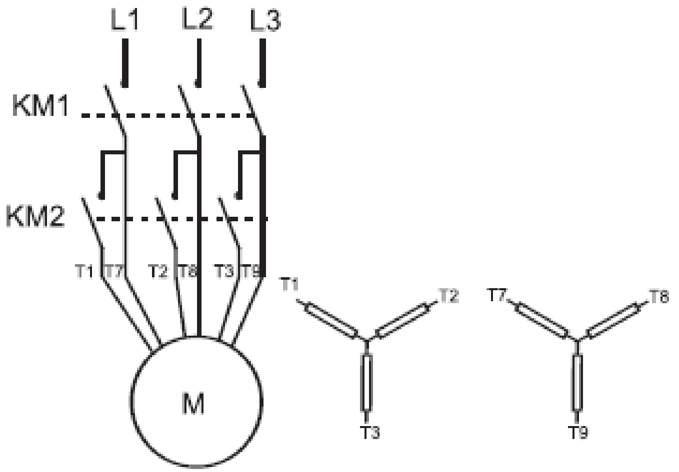
$$\therefore \frac{I_{start-wye}}{I_{start-delta}} = \frac{1}{3} \Rightarrow \beta_{start-wye} = \frac{\beta_{start-delta}}{3}$$

Motor-Starting Methods

- Part-Winding starter
  - ✓ Attractive for use with dual-rated motors (220/440 V or 230/460 V) (equivalent to two small motors with each half of motor ratings)
  - ✓ Stator has two windings that can be connected in parallel or series
  - ✓ Only one winding is connected at starting to limit starting current
  - ✓ Second winding is only connected after the motor has sped up and therefore, the inrush current would be small



Motor-Starting Methods



- Part-Winding starter

$$I_{start-full} = \frac{V_{phase}}{Z_{motor}};$$

$$I_{start-half} = \frac{V_{phase}}{2 \times Z_{motor}} = \frac{I_{start-full}}{2}$$

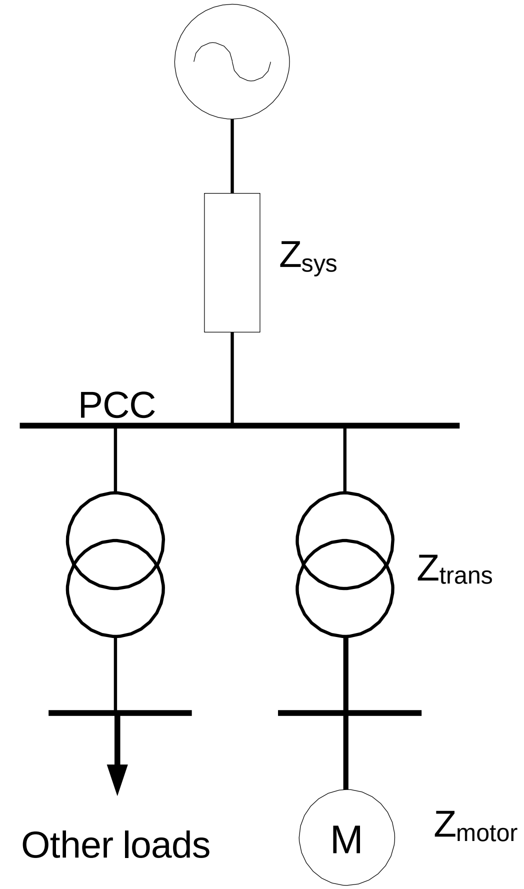
$$\therefore \frac{I_{start-half}}{I_{start-full}} = \frac{1}{2} \Rightarrow \beta_{start-half} = \frac{\beta_{start-full}}{2}$$

- Capacitor starting system
  - ✓ Compensate for the predominant inductive starting current

Motor-Starting Methods

- To reduce the voltage sag at PCC, the motor can be fed through a dedicated transformer, the voltage at PCC at motor starting is

$$V_{sag} = \frac{Z_{motor} + Z_{trans}}{Z_{motor} + Z_{sys} + Z_{trans}}$$



Where,

$$Z_{sys} = \frac{V_n^2}{S_{source}}, \qquad Z_{sys} = \frac{V_n^2}{S_{source}}$$

$$Z_{motor} = \frac{V_n^2}{\beta S_{motor}}, \text{and } Z_{trans} = \varepsilon \frac{V_n^2}{S_{trans}}$$

✓ Assuming transformer is of same power rating as induction motor and has an impedance ε p.u.

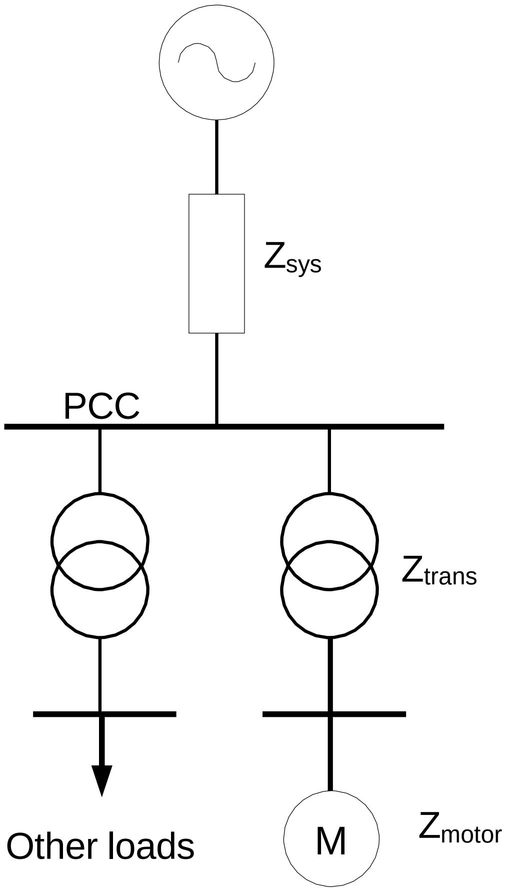
Motor-Starting Methods

- ✓ Less voltage sag at sensitive load point (PCC) is now electrically separated from the motor terminal by the transformer

$$V_{sag} = \frac{\frac{V_n^2}{\beta S_{motor}} + \varepsilon \frac{V_n^2}{S_{trans}}}{\frac{V_n^2}{\beta S_{motor}} + \varepsilon \frac{V_n^2}{S_{trans}} + \frac{V_n^2}{S_{source}}}$$

$$V_{sag} = \frac{\frac{1+\beta\varepsilon}{\beta S_{motor}}}{\frac{S_{source}+\beta\varepsilon S_{source}+\beta S_{motor}}{\beta S_{motor} S_{source}}}$$

$$V_{sag} = \frac{(1+\beta\varepsilon)S_{source}}{(1+\beta\varepsilon)S_{source}+\beta S_{motor}}$$



Other Motor-Starting Methods

- Resistance or reactance starter
  - ✓ Insert an impedance in series at starting to limit starting current
  - ✓ For a starting resistance of *R* or inductance of *L,*

$$\varepsilon = \frac{R}{Z_{base}} \ or \ \frac{2\pi f L}{Z_{base}}, \text{ where } Z_{base} = \frac{V_n^2}{S_{motor}}$$

Exercise

- Example – An 50-kW, 0.8 p.f., 90% efficiency induction motor is started from a 11kV supply with 1 MVA short circuit capacity. The motor starting current is six times the nominal or full-load current. Calculate the amount of voltage sag at starting.

- If the motor is fed through a dedicated 33/11kV transformer of the same power rating as the motor and with a leakage impedance of 10%. Assuming that the short circuit capacity at PCC remains unchanged,

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$$S_{motor} = \frac{50\text{ kW}}{0.8 \times 0.9} = 69.44\text{ kVA}$$

$$V_{sag} = \frac{1000}{1000 + 6 \times 69.44} = 0.706 = 70.6\ \% \quad \Rightarrow \quad \Delta V = 1 - V_{sag} = 29.4\%$$

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- If the motor is fed through a dedicated 33/11kV transformer of the same power rating as the motor and with a leakage impedance of 10%. Assuming that the short circuit capacity at PCC remains unchanged,

$$V_{sag} = \frac{(1 + 6 \times 0.1) \times 1000}{(1 + 6 \times 0.1) \times 1000 + 6 \times 69.44} = 0.793 = 79.3\,\%$$

$$\Rightarrow \quad \Delta V = 1 - V_{sag} = 20.7\%$$

Exercise

- If delta-star starter is used instead,

Exercise

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$$V_{sag} = \frac{1000}{1000 + (6 \diagup 3) \times 69.44} = 0.878 = 87.8\,\%$$

$$\Delta V = 1 - V_{sag} = 12.2\%$$

Minimum SCC to Maintain Voltage

- Employing specific motor-starting method alone may not be sufficient to solve the problem as the voltage may still remain low.

  ✓ What is needed is a stronger supply, also termed higher short circuit ratio (see page 31)

  ✓ To limit the voltage drop at the motor terminal to V_{min}, the source strength needs to be (assuming the desirable voltage is 1 pu, set $V_{sag} = V_{min}$ shown on page 9):

$$S_{source} = \beta S_{motor} \times \frac{V_{min}}{1 - V_{min}}$$

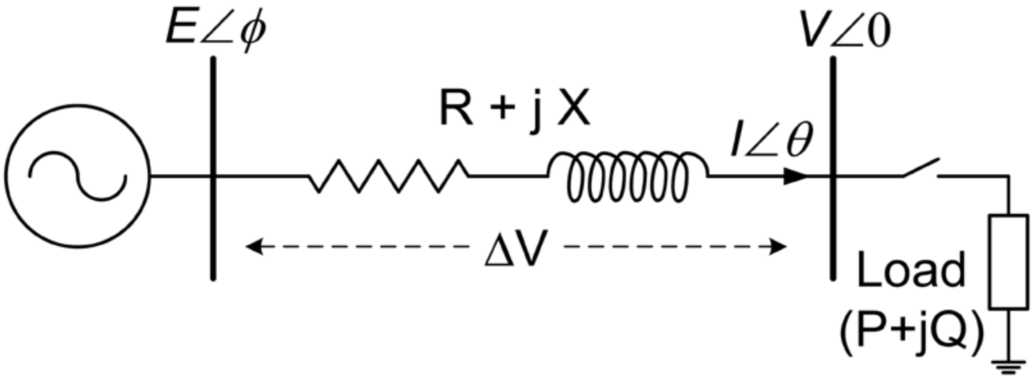
Minimum SCC to Maintain Voltage

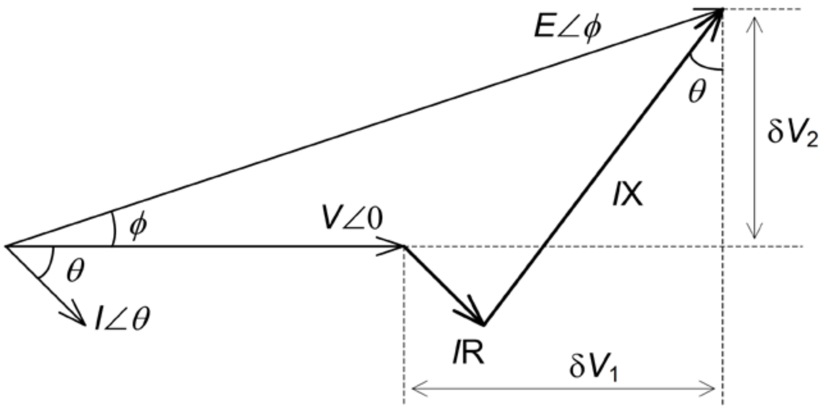
✓ With dedicated transformer or starting resistance/inductance (set Vsag = Vmin, page 20),

$$S_{source} = \frac{\beta S_{motor}}{1+\beta\varepsilon} \times \frac{V_{min}}{1-V_{min}}$$

- In the previous example, to keep voltage above a minimum of 90%, it is necessary to use a stronger source of SCC = 2.34 MVA, given β = 6, ε =0.1 pu and S_{motor} = 69.44 kVA.

System Voltage Response





- Before switch is closed, V=E
- When switch is closed, there is a sudden increase in the flow of power and current to the load
  - ✓ Drop in voltage magnitude and shift in voltage phase angle as load current flows through the system impedance

$$E^2 = (V + \delta V_1)^2 + \delta {V_2}^2$$

$$E^2 = (V + RIcos\theta + XIsin\theta)^2 + (XIcos\theta - RIsin\theta)^2$$

$$E^2 = (V + RIcos\theta + XIsin\theta)^2$$

$$E = V + RIcos\theta + XIsin\theta$$

Last expression is approximate: valid for small shift in voltage angle delta

System Voltage Response

$$E = V + RIcos\theta + XIsin\theta$$

$$E = V + \frac{RVIcos\theta}{V} + \frac{XVIsin\theta}{V}$$

$$E = V + \frac{RP}{V} + \frac{XQ}{V}$$

note: $\begin{Bmatrix} P = VIcos\theta \\ Q = VIsin\theta \end{Bmatrix}$

- Energizing the load results in a change in load terminal voltage ΔV of

$$\Delta V \approx E - V = \frac{RP}{V} + \frac{XQ}{V} = \frac{RP+XQ}{V} = \frac{XQ}{V} \text{ for } \mathrm{X} \gg \mathrm{R}$$

$$\frac{\Delta V}{V} \approx \frac{XQ}{V^2} = \frac{Q}{V^2/X} = \frac{Q}{S_{SCC}} \text{ as } S_{SCC} = \frac{V^2}{X}$$

✓ where Δ V / V is the percentage voltage variation at load terminal

✓ The amount of change in voltage magnitude can be estimated by comparing the load reactive demand against system short circuit capacity

System Voltage Response

- Voltage E is usually regulated at system nominal value,
  - ✓ The magnitude deviation ΔV can be taken as
    - ➢ Voltage dip when a new load with Q lagging power, such as large induction motor, is energized
    - ➢ Voltage swell when a new capacitor with Q leading power is turned on
    - ➢ Vice versa when the above devices are turned off / de-energized
    - ➢ Constant variation or fluctuation of the voltage magnitude when load with dynamic reactive demand is operating e.g. welding machine

Short Circuit Capacity (SCC)

- Describes voltage support strength of a power network
- Product of three-phase fault current and rated voltage

$$S_{SCC} = \sqrt{3} \times V \times I \text{ MVA}$$

  - *I* – three-phase short circuit fault current in kA
  - *V* – phase to phase system nominal voltage in kV

✓ Or expressed in terms of system impedance or reactance

$$I = \frac{V}{\sqrt{3} \times Z_{sys}} \Rightarrow S_{SCC} = \frac{V^2}{Z_{sys}} \text{ MVA}$$

✓ In per unit system,

  - *V* is taken as 1.0 p.u.
  - *I* is the fault current at the fault location

$$S_{SCC} = \frac{1}{Z_{sys}} \text{ or } \frac{1}{X_{sys}} \text{ p.u}$$

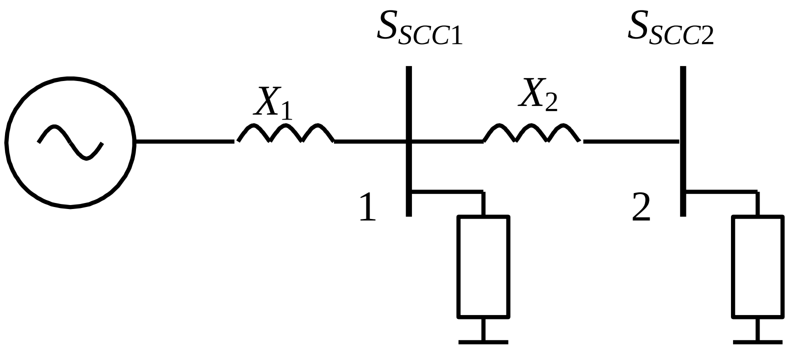
Note: Last expression assumes negligible system resistance.

SCC and Concept of Electrical Distance

- SCC measures the system voltage support strength
  - ✓ A high capacity means network is “strong” or “stiff”
    - ➢ System impedance / reactance is low
    - ➢ Load terminal is electrically close to the supply source
    - ➢ Source tends to be more capable of regulating the load terminal voltage (magnitude, frequency and shape)
  - ✓ A low capacity implies a “weak” network
    - ➢ Large system impedance means long electrical distance
    - ➢ Poor voltage regulation results

SCC and Concept of Electrical Distance

- Short circuit ratio and voltage regulation
  - ✓ Comparing size of load against supply strength, $\Delta V \cong \dfrac{\Delta Q}{S_{SCC}}$



$$S_{SCC1} = \frac{1}{X_1}$$

$$S_{SCC2} = \frac{1}{X_1 + X_2}$$

$$S_{SCC1} > S_{SCC2} \Rightarrow \Delta V_{1,\%} < \Delta V_{2,\%}$$

Compare voltage regulation for the same amount of reactive power switching

Switching of reactive compensation

- Power systems is predominantly inductive,
  - ✓ Reactive loading has a bigger effect on voltage magnitude than active power demand (See results on pages 30)
  - ✓ Voltage variation can be estimated by ratio of “Change in reactive power loading/short circuit capacity”

$$\Delta V \cong \frac{\Delta Q}{S_{SCC}}$$

- Capacitor switching
  - ✓ Voltage swell occurs at energization of capacitor
  - ✓ Voltage dip at de - energization of capacitor

Switching of reactive compensation

- Reactor switching
  - ✓ Voltage swell occurs at de - energization of reactor
  - ✓ Voltage dip at energization of reactor

$$\Delta V_{\%} \cong \frac{Q_{compensation}}{S_{SCC}}$$

$Q_{compensation}$ is the amount of reactive power switched in/out

Exercise

- A single-phase 200kW induction motor, rated with full load efficiency of 90% and power factor of 0.85 lagging, has a starting current, which is 6 times its full load value. The voltage dip at the motor terminals during motor starting is 30%.
- In order to enhance the security of supply to the motor, a second incoming source with a source impedance 4 times the source impedance of the original supply is connected.

a) Find the short circuit capacity at the motor terminals before and after the supply reinforcement

b) After the enforcement, determine the amount of voltage variations at the motor terminals when the motor is switched on and switched off

Exercise

Solution (a)

Before Reinforcement

Induction motor capacity, P=200kW (1ph)

Rated full-load efficiency,η =90%

Rated power factor = 0.85

Since S = VphxIph

Therefore Iph = S/(Vph)

Since motor starting current is 6 times of its full load value, therefore

Iph(starting) = 6 x Iph = (6x200x1000)/(0.85 x 0.90 x Vph)

Where S=P/(eff x pf)

Since ΔV=Q/SCC

Assuming starting current is purely reactive

(i.e. Sstarting = 0+jQstarting)

ΔV=Vph x Iph(starting)/SCC

Exercise

Given $\Delta V = 30\%$

SCC= Vph x 6 x 200 x 1000/(0.85 x 0.90 x Vph x 0.3) = 5228.758kVA (1 Ph)

After Reinforcement

X_{old} = 1/ SCC_{old} = 1/5228.75=0.1913μΩ

X_{new}= [4 x $(X_{old})^2$]/(5x X_{old})=4 x X_{old}/5

SCC_{new}=1/ X_{new}=7 /(6 x X_{old})= 5 /(4 x 0.1913 x 10^{-6})=6534.24kVA (1 Ph)

Exercise

b) When the motor is switched on,

$\Delta V = Q/SCC = [V_{ph} \times 6 \times 200 \times 1000/(0.85 \times 0.9 \times V_{ph} \times 6534.24 \times 1000)] \times 100$

$\Delta V = 24\%$ (DIP)

When motor is switched off,

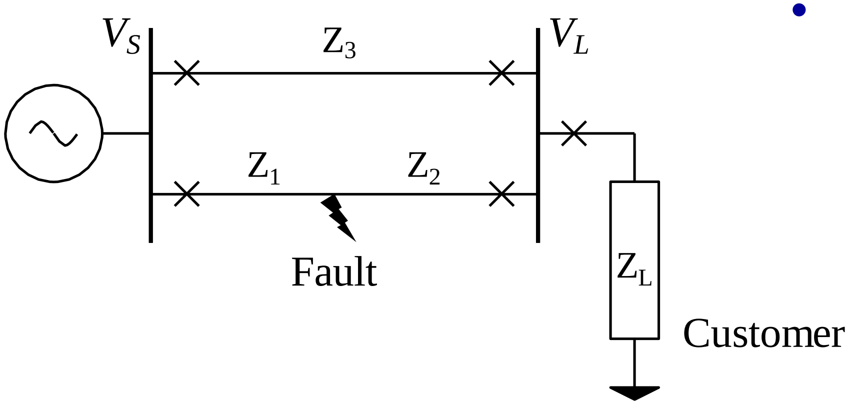
The motor reactive power changes from rated Q to 0, during this time

$Q_{rated} = 200 \times 1000 \times \sin(\cos^{-1}(0.85)) / (0.9 \times 0.85) \approx 137.721\text{kVAr}$

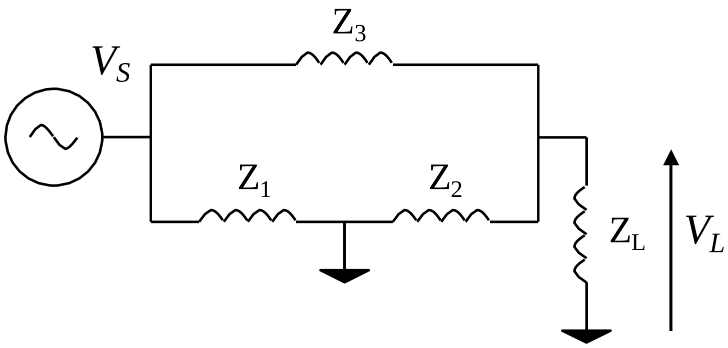
$\Delta V = Q/SCC = 137.721 \times 1000 \times 100 / (6534.24 \times 1000) \approx 2.1\%$ (Swell)

Voltage sags caused by system faults

System connection



Equivalent circuit during fault



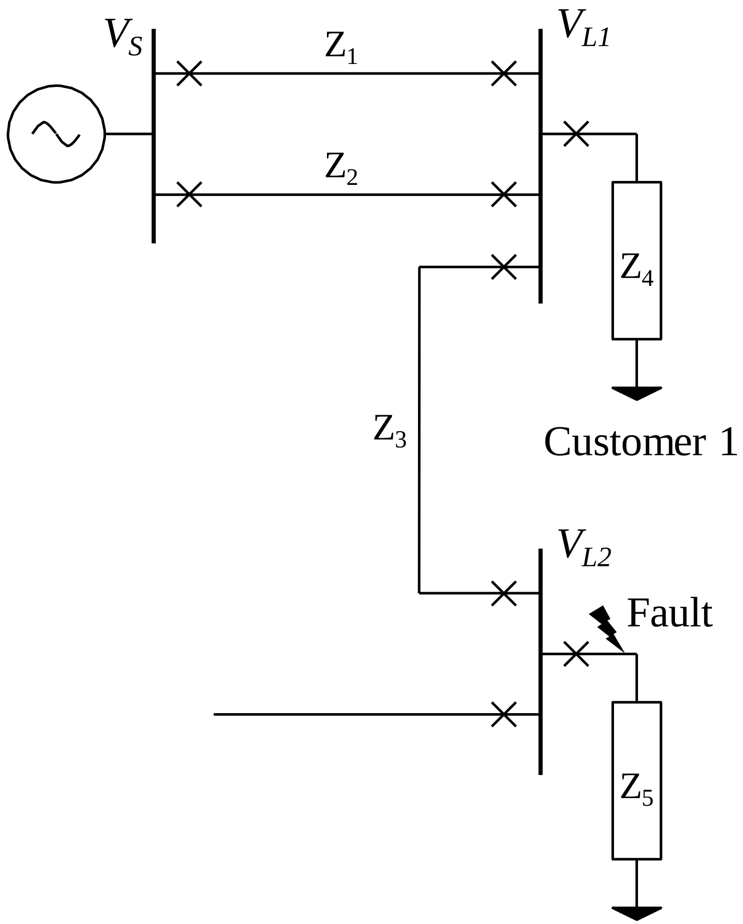
- Fault occurs on the transmission or distribution system such as a cable fault

- In general, Z_1, Z_2 and Z_3 << Z_L

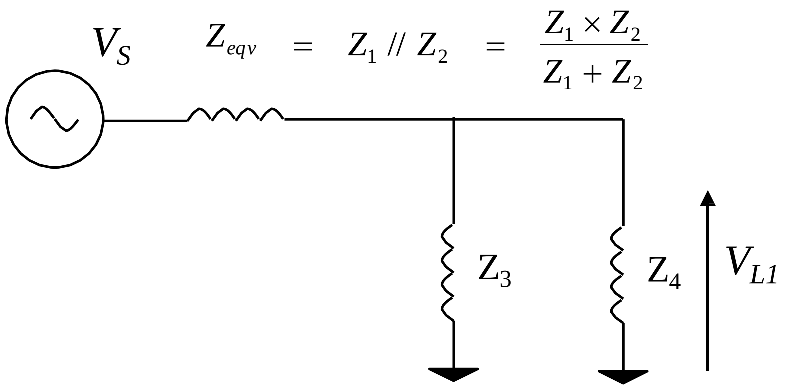
$$V_L = V_S \times \frac{Z_2}{Z_3 + Z_2}$$

Voltage sags caused by customer faults

System connection



Equivalent circuit during fault

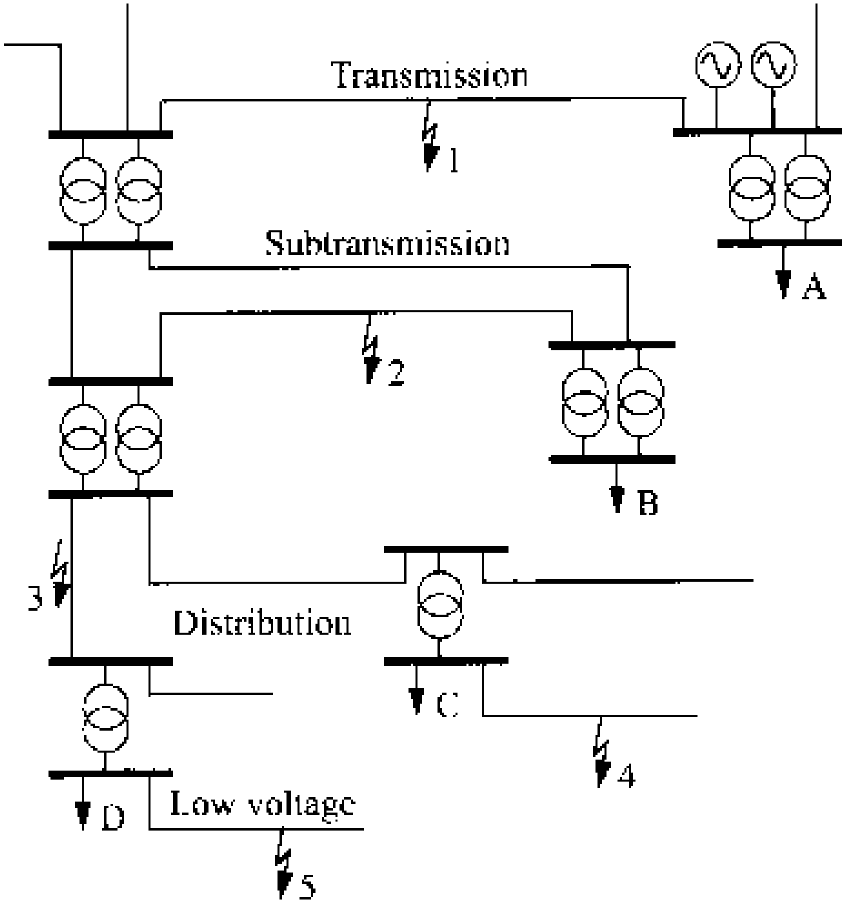


- Fault occurs within the premise of another customer
- In general, Z_{eqv} and $Z_3 << Z_4$

$$V_{L1} = V_S \times \frac{Z_3}{Z_{eqv} + Z_3}$$

Characteristics of fault-induced voltage sags

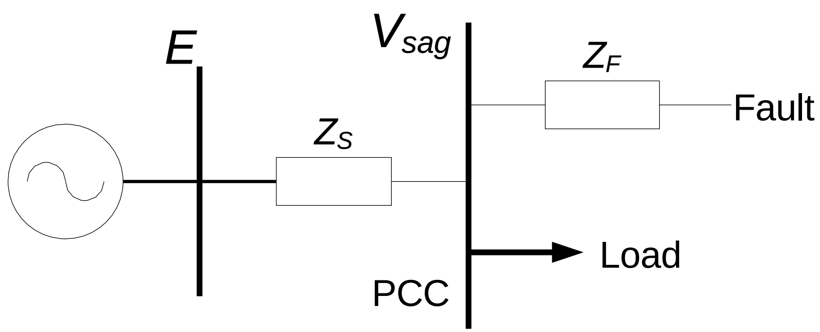
- Characteristics of voltage sags / interruptions depend very much on the location of fault and sensitive point
  - Fault positions 1 to 5 and sensitive points A to D
- Fault position 1
  - Serious sag for both substations
  - Deep sag transferred down to all
- Fault position 2
  - Minor dip at A, severe dips at others
- Fault position 3
  - Very deep sag at D, deep sag at C
  - Recloser may cause multiple sags to occur at C for permanent fault
- Fault position 4
  - Deep sag for C, shallow sag for D
- Fault position 5
  - Deep sag for D, shallow sag for C
  - A and B minimally affected by fault at 4 or 5



Voltage sags caused by system faults

- Dugan ss. 3.2.3-3.2.4; Bollen ss. 4.2.2-4.2.5
- Interruptions, dips and swells
  - Dip occurs at the faulted phase
  - Swell may occur at healthy phases, depending on neutral grounding conditions
  - Momentary interruptions when line/busbar/… is isolated to clear fault
- For a radial system, simple voltage divider rule can be used to determine the sag magnitude at PCC (point of common coupling)

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} = \frac{z \cdot L}{Z_S + z \cdot L}$$



  - System voltage *E* is taken as 1 p.u.
  - *z* is the impedance of feeder per unit length
  - *L* is the distance between the fault and PCC
- Expressed V_{sag} in terms of fault levels,

$$S_{FLT} = \frac{V_n^2}{Z_S + Z_F} \quad ; \quad S_{PCC} = \frac{V_n^2}{Z_S} \quad \Rightarrow \quad V_{sag} = 1 - \frac{S_{FLT}}{S_{PCC}}$$

  - S_{FLT} and S_{PCC} are fault levels at the fault point and PCC respectively
  - V_n is the nominal voltage level at fault point and PCC
- Extensive impacts if system is highly meshed or interconnected
  - Short electrical distance between fault point and sensitive point (small Z_F)

Local generators

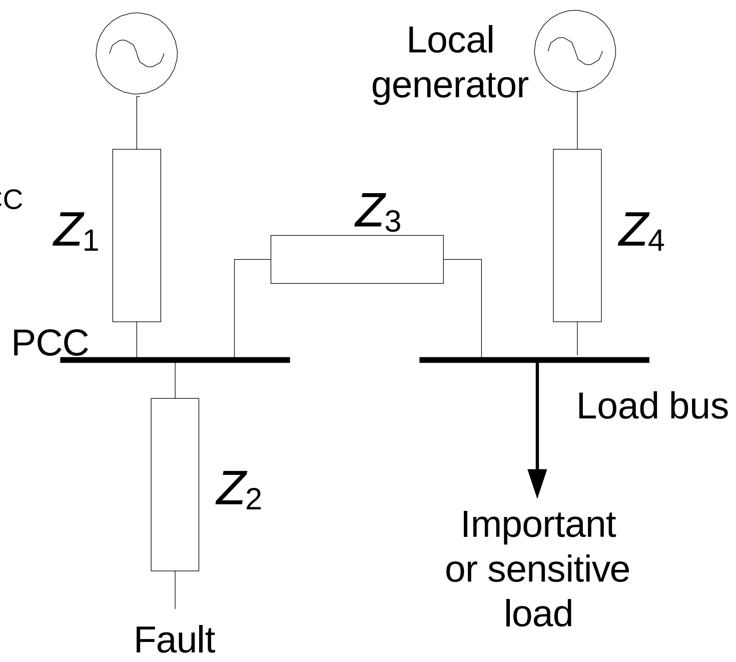
- Local generator to distribution network mitigates voltage sags
  - Increase fault level at distribution bus (works well for weak system)
  - Keep up voltage at local bus by feeding into system faults
    - Without local generator, voltage sag at load terminals is same as that at PCC
    - With local generator in, the load terminal becomes local generator bus with the following relationship,

$$\left(1 - V_{sag}\right) = \frac{Z_4}{Z_3 + Z_4}\left(1 - V_{pcc}\right)$$

    - Last expression assumes pre-sag voltages of generators are identical at 1 p.u. V_{sag} and V_{PCC} are the voltages at the load and PCC buses respectively.
  - Lower generator voltage drop ($1-V_{sag}$)
    - Generator impedance Z_4 is small and/or
    - Link to PCC is weak (large Z_3)
    - When $Z_3 = Z_4$, $V_{sag} = 70\%$ when $V_{pcc}=40\%$

    - Short-circuit fault at PCC, load bus voltage

$$V_{sag,\min} = \frac{Z_3}{Z_3 + Z_4}$$



Local generator - example

- A system with impedance Z_1 has a short circuit capacity of 1 MVA, and Z_2 is a 200 kVA (10% X) transformer. (Refer to the power system of previous page, without local generation).
  - Compute the amount of voltage sag experienced by a sensitive load connected to the PCC when a short circuit fault occurs at the load end of Z_2

Using 200 kVA power base,

$$Z_1 = \frac{1}{1 \text{ MVA}/200 \text{ kVA}} = 0.2 \text{ p.u.}$$

$$V_{pcc} = 1 \times \frac{Z_2}{Z_1 + Z_2} = \frac{0.1}{0.2 + 0.1} = 0.33$$

$$\Delta V_{load} = \Delta V_{pcc} = 1 - 0.33 = 67\%$$

- To reduce voltage sag impact, a local generator is used to supply to the sensitive load.
  - Generator is rated at 50 kVA, 5% X and interconnecting transformer between generator and PCC is rated at 50 kVA, 10% X.
  - Compute the voltage sag at the sensitive load when the same fault occurs

$$Z_3 = 0.1 \times \frac{200}{50} = 0.4 \text{ p.u.} \quad ; \quad Z_4 = 0.05 \times \frac{200}{50} = 0.2 \text{ p.u.}$$

$$Z_{eq,pcc} = Z_1 // (Z_3 + Z_4) = 0.15 \text{ p.u.}$$

$$V_{pcc} = 1 \times \frac{Z_2}{Z_{eq,pcc} + Z_2} = \frac{0.1}{0.15 + 0.1} = 0.4 \text{ p.u.}$$

$$\Delta V_{load} = 1 - V_{load} = \frac{Z_4}{Z_3 + Z_4}(1 - V_{pcc}) = \frac{0.2}{0.4 + 0.2}(1 - 0.4) = 20\%$$

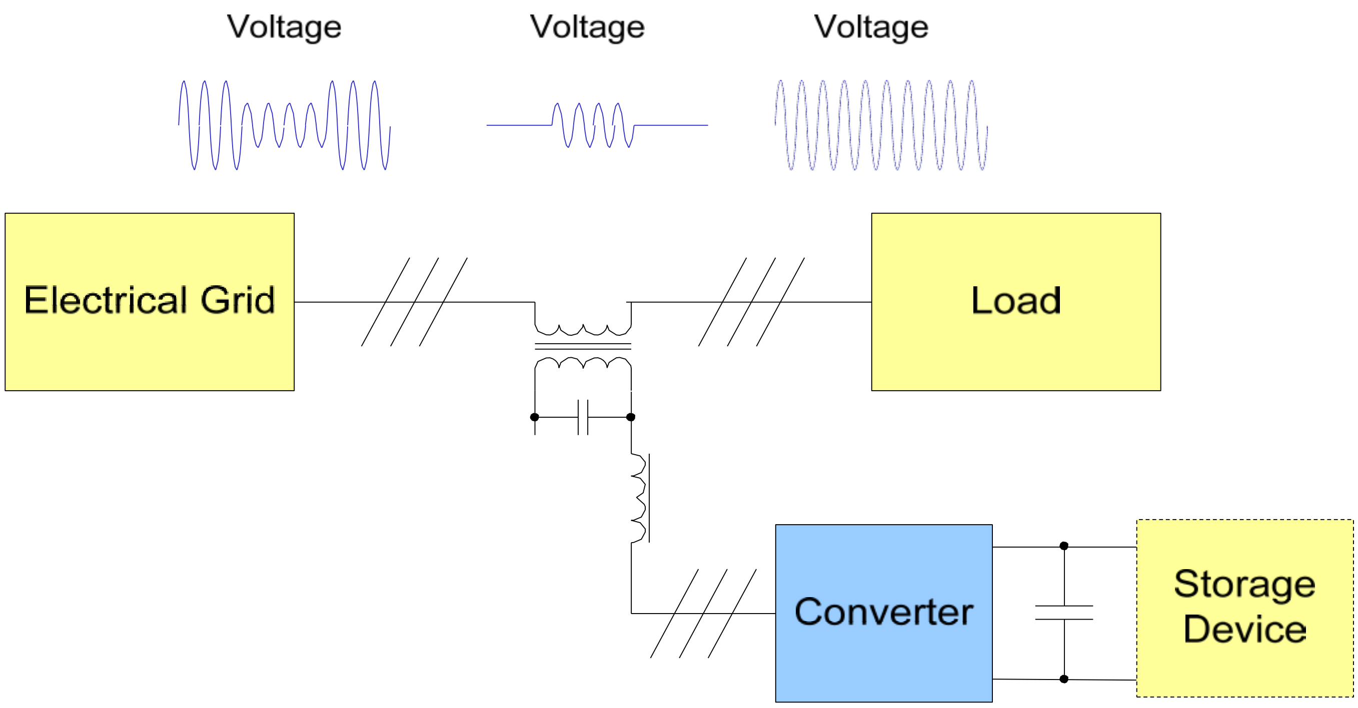
Slight improvement in V_{pcc} and much improvement in V_{load} levels

Methods to avoid or reduce voltage sags

- Reducing the number of faults along overhead lines
  - Replace overhead lines by underground cables: minimize faults caused by adverse weather or other external influences
  - Use covered or insulated wires to reduce fault rate
  - Strict policy of tree trimming to avoids faults due to contacts or felling branches.
  - Install shielded wires to reduce the risk of lightning strokes
  - Raise insulation level to reduce risk of short circuit faults
  - Increase maintenance and inspection
- Reducing the severity of voltage sag
  - Fault current limiter reduces the depth of sag
  - Faster fault clearing time to shorten sag duration
  - Faster backup protection
  - Installation of transformer
- Alter the power systems
  - Install generator near sensitive loads
  - Split busses or substations to limit the number of feeders in exposed area

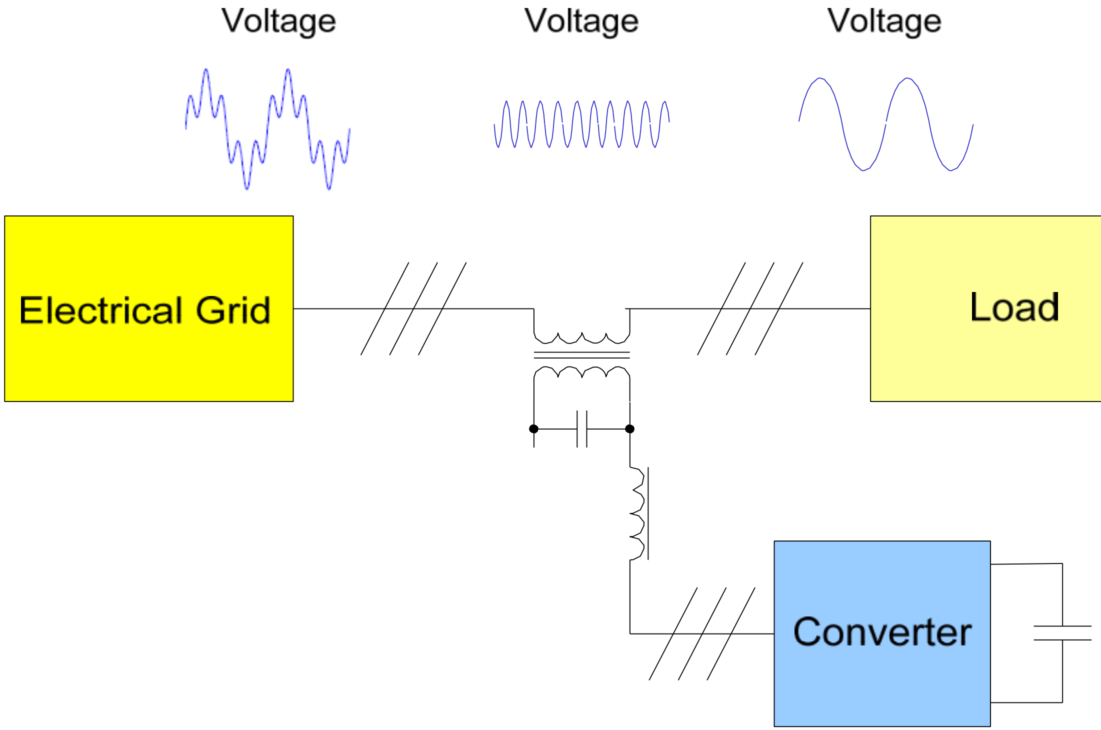
Power quality and other grid-connected devices

- Dynamic Voltage Restorer (DVR)



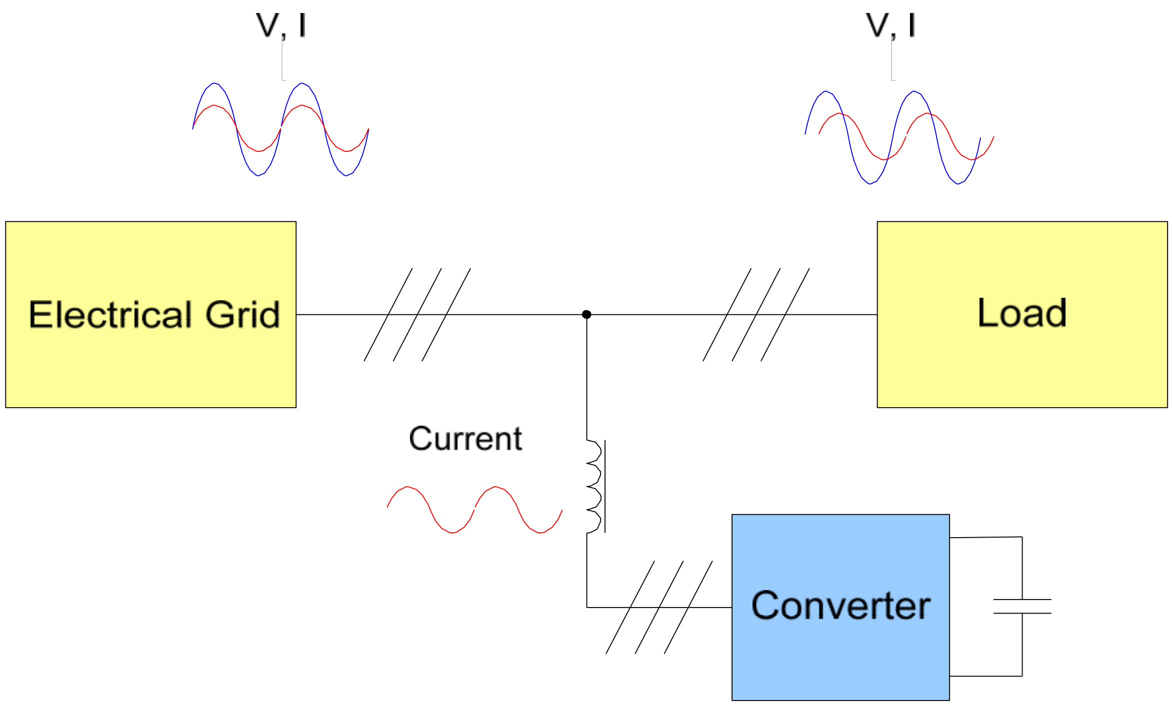
Power quality and other grid-connected devices

- Series Active Filter



Power quality and other grid-connected devices

- Static Compensator (STATCOM)



Power quality and other grid-connected devices

- Shunt Active Filter