EE 741

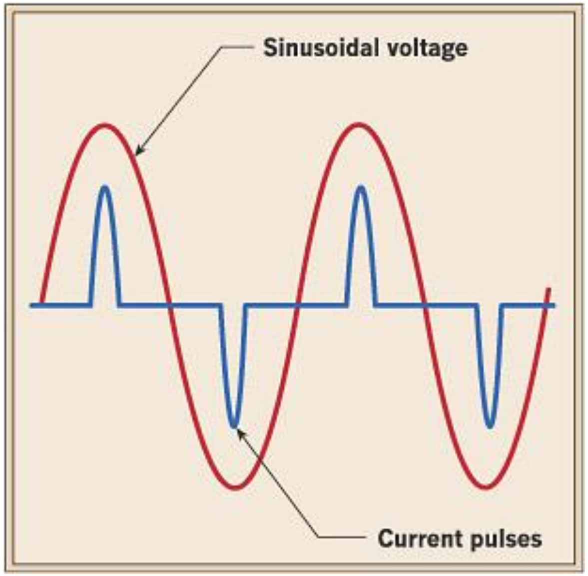
Power Quality & System Reliability

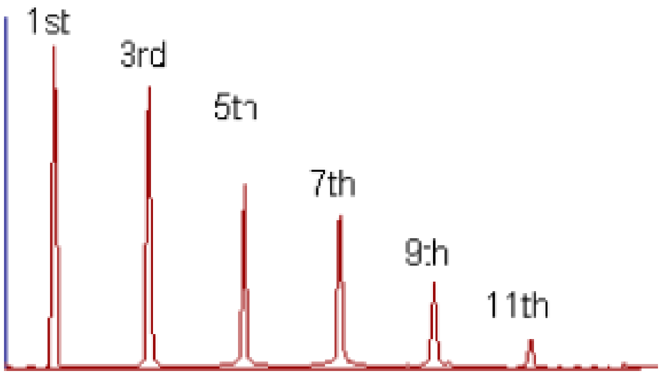
Definition

- **Power Quality** can be defined as the goodness of the electric power supply in terms of its voltage and current wave-shapes, its voltage regulation, continuity of power supply and its frequency.
- **Perfect Power** refers to an ideal case where the voltage and current waveforms are balanced and sinusoidal, with constant amplitude and constant frequency.
- **Power Quality Problem** refers to deviations of the above variables that result in failure or unsatisfactory operation of the customer's equipment.

Types of Disturbances: Harmonic Distortion

Computer (switched-mode power supply)





Harmonic Spectrums

$$u(t) = \sum_{i=1,3,5,....} u_i(t)$$

$$U_{rms} = \sqrt{\sum_{i=1.3.5,...} U_i^2}$$

$$TDD_u = \frac{\sqrt{\sum_{i=3,5,...} U_i^2}}{U_L}$$

$$THD_u = \frac{\sqrt{\sum_{i=3,5,...} U_i^2}}{U_1} = \sqrt{\left(\frac{U_{rms}}{U_1}\right)^2 - 1},$$

U_L = *peak demand current*

Impact of Harmonics

- **Source of Harmonics:** Mainly modern electronic loads
- **Impact of Harmonics:** capacitor overload by harmonic currents, additional losses (heat) in transformers, motors, cables, etc…, neutral conductor overloading, ….
- **Transformer Derating**:
  - K-Factor

$$K = \left(\sum_{i=1,3,\ldots} i^2 I_i^2\right) \Big/ \left(\sum_{i=1,3,\ldots} I_i^2\right)$$

  - Derating Factor

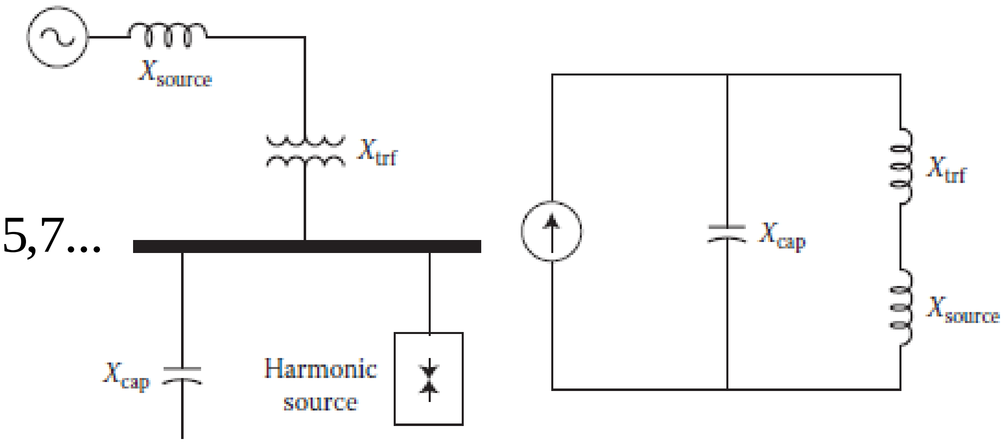
$$TD = \sqrt{(1+P_{ec}) \big/ (1+KP_{ec})}$$

P_{ec} = transformer eddy current loss

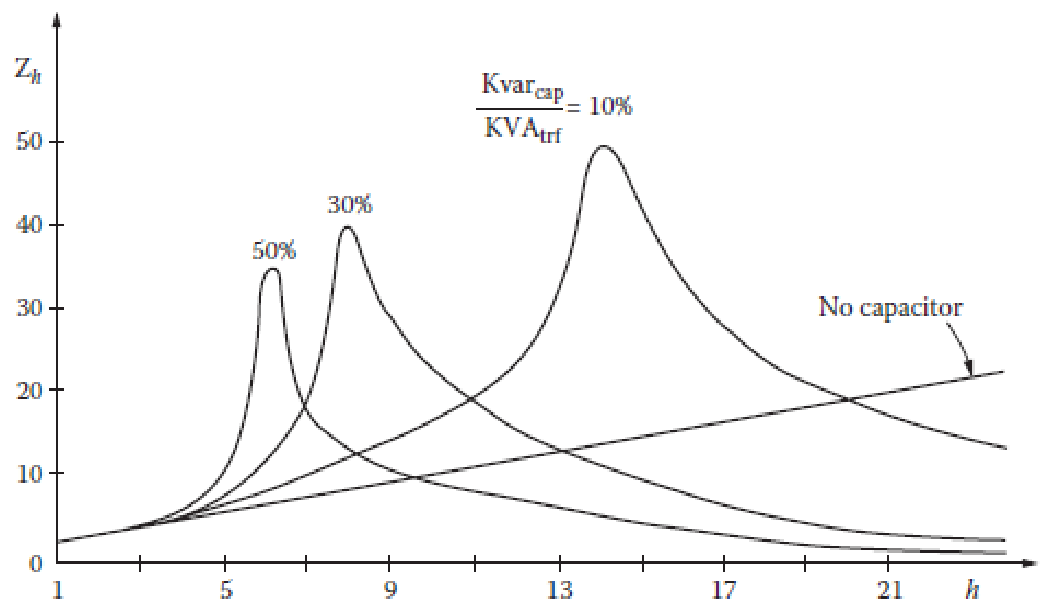
  - K-factor transformers: The K-factor rating is an index of the transformer's ability to withstand harmonic content while operating within the temperature limits of its insulating system (see UL1561).
- **Harmonic Amplification (resonance):** Parallel resonance of shunt capacitors with source impedance magnifies can cause excessive distortion in the voltage.

Harmonic Currents Cause Harmonic Voltages

$$V_h = I_h Z_h, \quad i = 3,5,7...$$



(a) (b)



Power Definitions in Non-Sinusoidal Cases

$$P = \sum_{i=1,3,5,\ldots} V_i I_i \cos(\theta_i - \varphi_i)$$

$$Q = \sum_{i=1,3,5,\ldots} V_i I_i \sin(\theta_i - \varphi_i)$$

$$S = V_{rms} I_{rms} = \sqrt{\left(\sum_{i=1,3,5,\ldots} V_i^2\right)\left(\sum_{i=1,3,5,\ldots} I_i^2\right)} = \sqrt{P^2 + Q^2 + D^2}$$

$$TPF = \frac{P}{S},$$

$$DPF = \frac{P_1}{S_1} = \cos(\theta_1 - \varphi_1)$$

Harmonic Distortion Limits (IEEE Std. 519)

Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages 120 - 69,000 volts						
Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order						
ISC/IL	**<11**	**11<17**	**17<23**	**23<35**	**35**	**TDD**
<20*	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

Bus Voltage at Point of Common Coupling	**Individual Voltage Distortion (%)**	**Total VoltageDistortion THD (%)**
Below 69 kV	3	5
69 kV to 137.9 kV	1.5	2.5
138 kV and above	1	1.5
Note: High Voltage systems can have up to 2.0% THD where the cause is a High Voltage DC terminal which will attenuate by the time it is tapped for a user.		

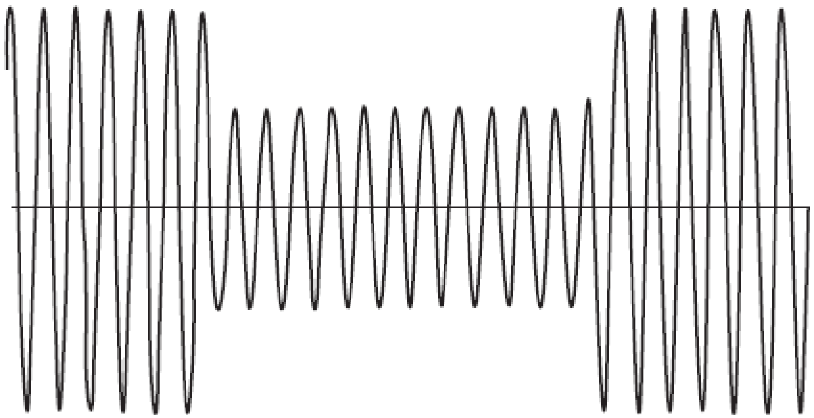
IEEE Standard 519-2014

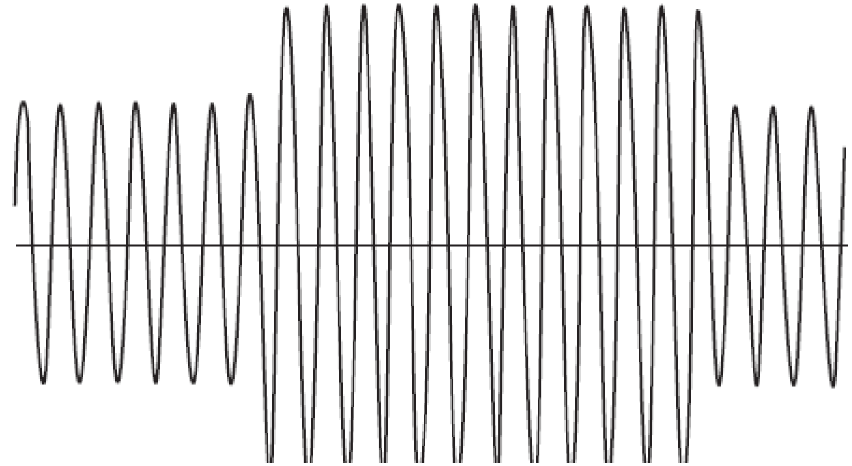
Compliances, Updates, Solutions and Case Studies

- See link below.

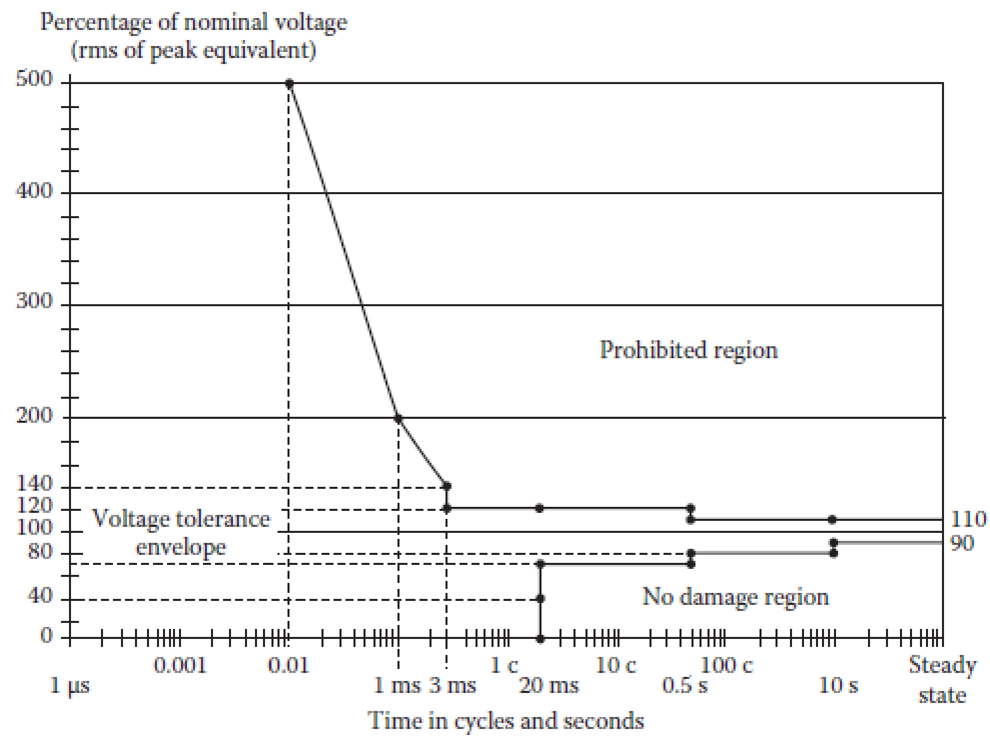
http://www.schneider-electric.com.tw/documents/Event/2016_electrical_engineering_seminar/IEEE_STD_519_1992vs2014.pdf

Types of Disturbances: Sags & Swells

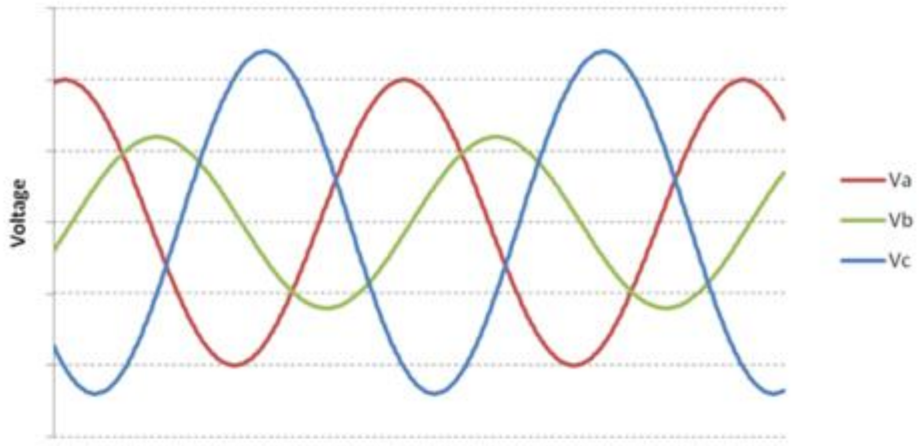




- Allowable magnitudes sags and swells – depends on duration: see (ITI Curve) to the right.



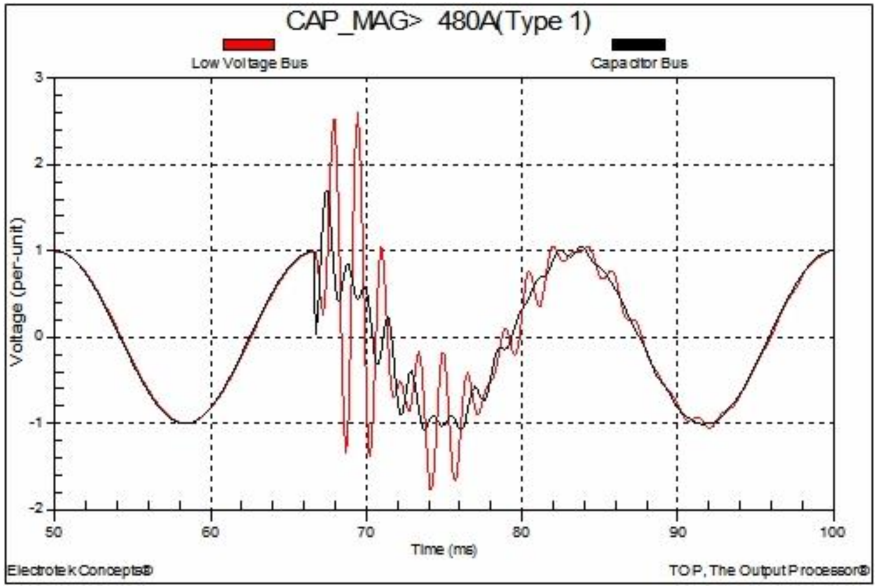
Types of Disturbances: Imbalance

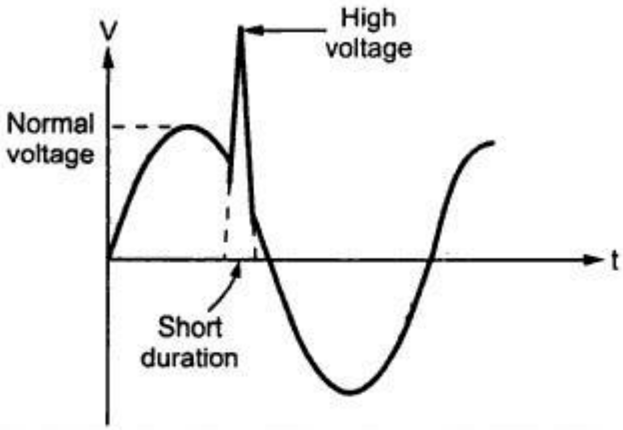


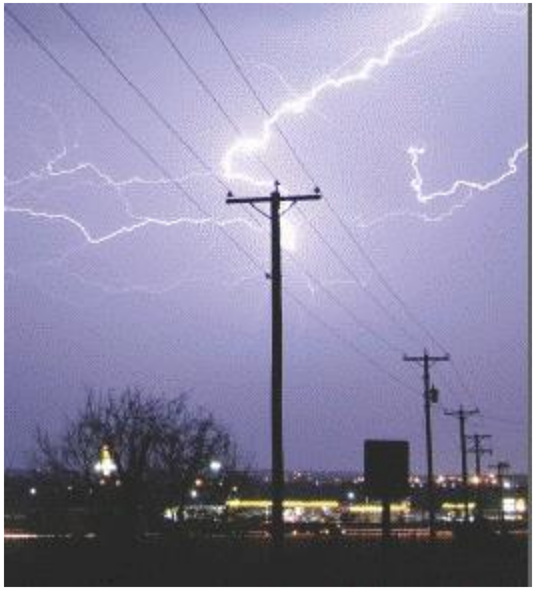
% voltage imbalance = Maximum deviation from the average ÷ average × 100

% Voltage Imbalance	% Motor Winding Temperature Increase
2%	8%
3%	18%
4%	32%
5%	50%
6%	72%
7%	98%
8%	128%

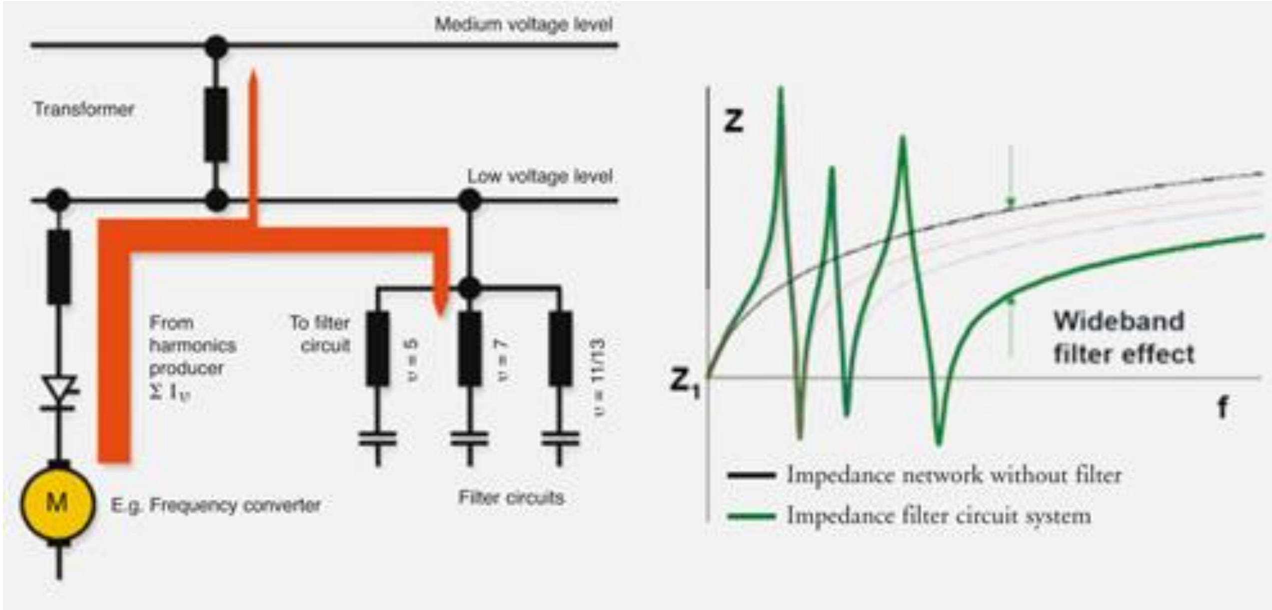
Other Disturbances: Momentary Transients

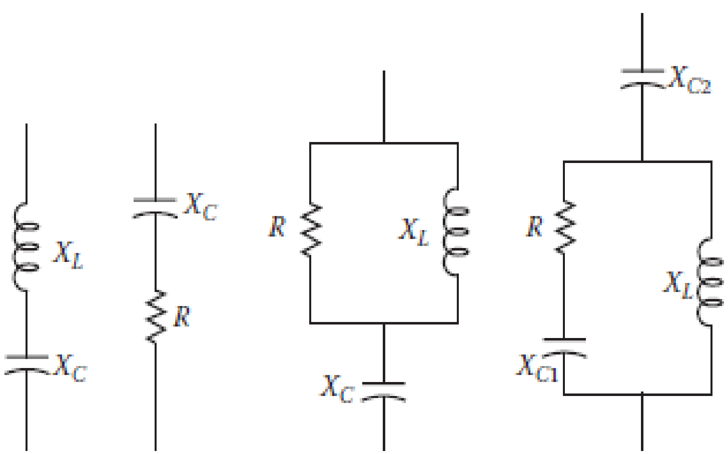




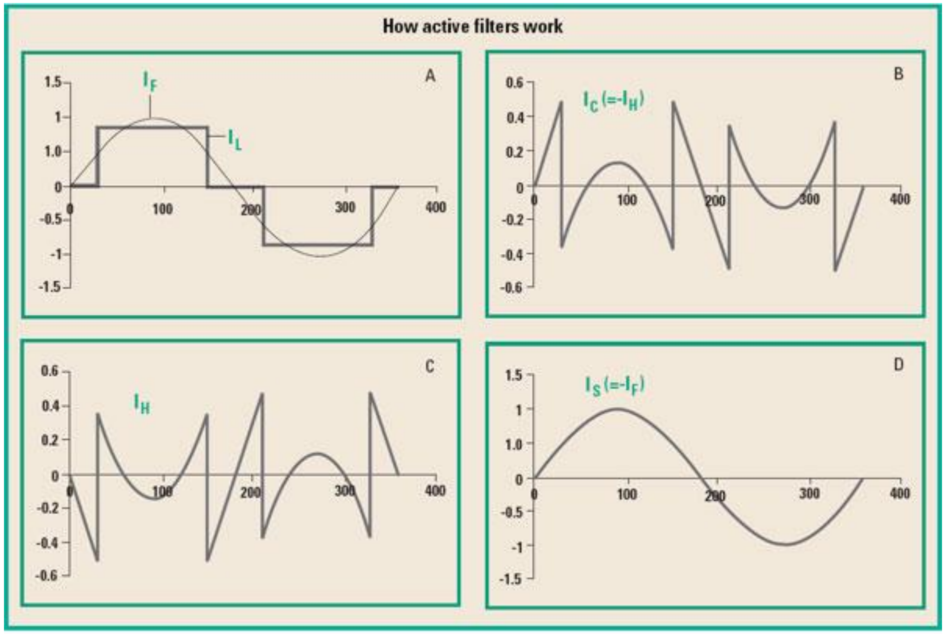


Harmonic Filtering (Passive)





Harmonic Filtering (Active)



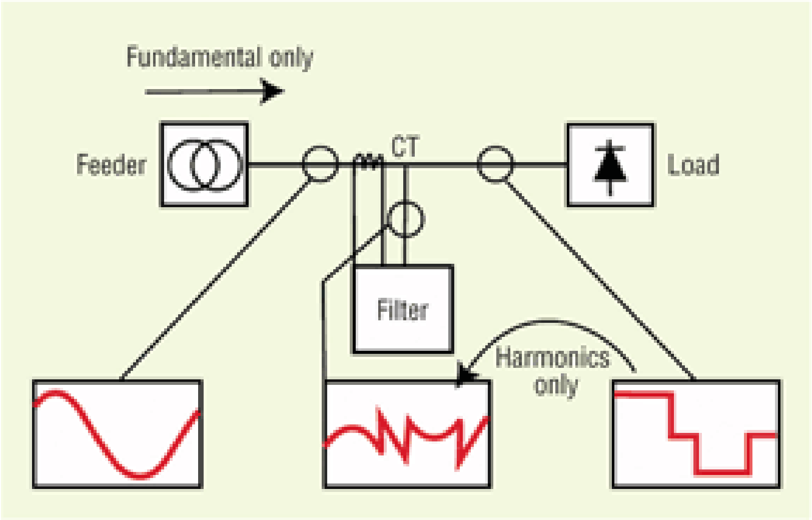
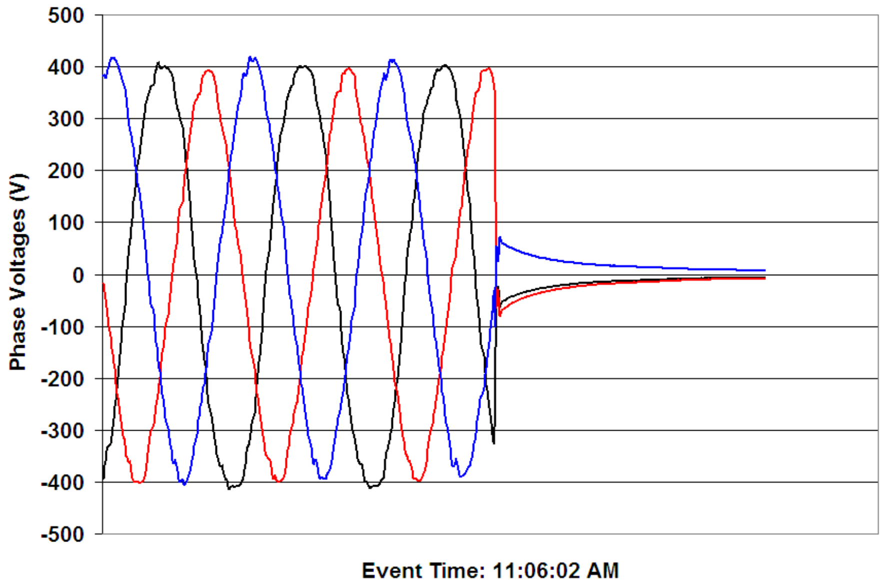


FIGURE 8. Active filter.

Worst Type of Disturbance: Power Outage



Causes of outages: Lightning, tree contact, animals, ice/snow, vandalism, construction activity, vehicle accident, wind, equipment failure, etc…

Sustained interruption: lasting more than 5 min
Momentary interruption: lasting less than 5 min

(Sustained) Distribution Reliability Indices

– SAIFI (System Average Interruption Frequency Index). This is the average frequency of sustained interruptions per customer.

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} = \frac{\sum N_i}{N_T}$$

– SAIDI (System Average Interruption Duration Index). Average time the customers are interrupted.

$$SAIDI = \frac{Total\ Duration\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} = \frac{\sum r_i N_i}{N_T}$$

Where r_i is the restoration time of i-th interruption

- ASAI (Average Service Availability Index)

$$ASAI = \frac{Customer\ Hours\ Service\ Availability}{Customer\ Hours\ Service\ Demand} = \frac{N_T \cdot 8760 - \sum r_i N_i}{N_T \cdot 8760}$$

(Sustained) Distribution Reliability Indices

- CAIDI (Customer Average Interruption Duration Index). Average time required to restore service to the average customer per interruption.

$$CAIDI = \frac{Total\ Duration\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customer\ Interruptions} = \frac{\sum r_i N_i}{\sum N_i} = \frac{SAIDI}{SAIFI}$$

- CAIFI (Customer Average Interruption Frequency Index)

$$CAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Interrupted} = \frac{\sum N_i}{CN}$$

Example

Table 1 Calculation of Customer-Hours				
Date	**Time**	**Customers**	**Duration**	**Customer -hours**
28th	9:53	10	90	15.00
28th	11:02	1,000	20	333.33
28th	13:15	2	175	5.83
28th	20:48	1	120	2.00
28th	22:35	1	38	0.63
		1,014	443	356.80

Let total number of customers served N_T = 50,000

SAIDI = 356.8*60/50000 = 0.43 min

CAIDI = 356.8*60/1014 = 21.1 min

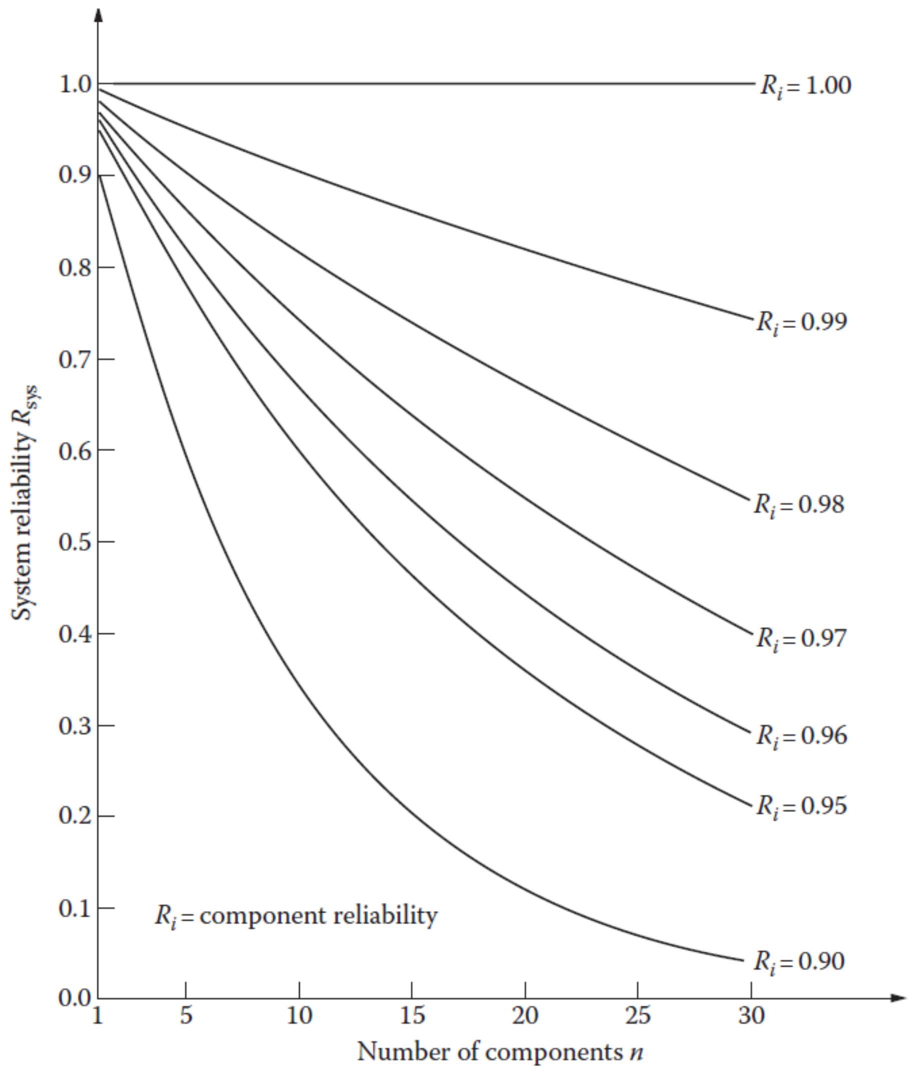
SAIFI = 1014/50000 = .02

CAIFI = 5/1014 = .005

ASAI = 99.97%

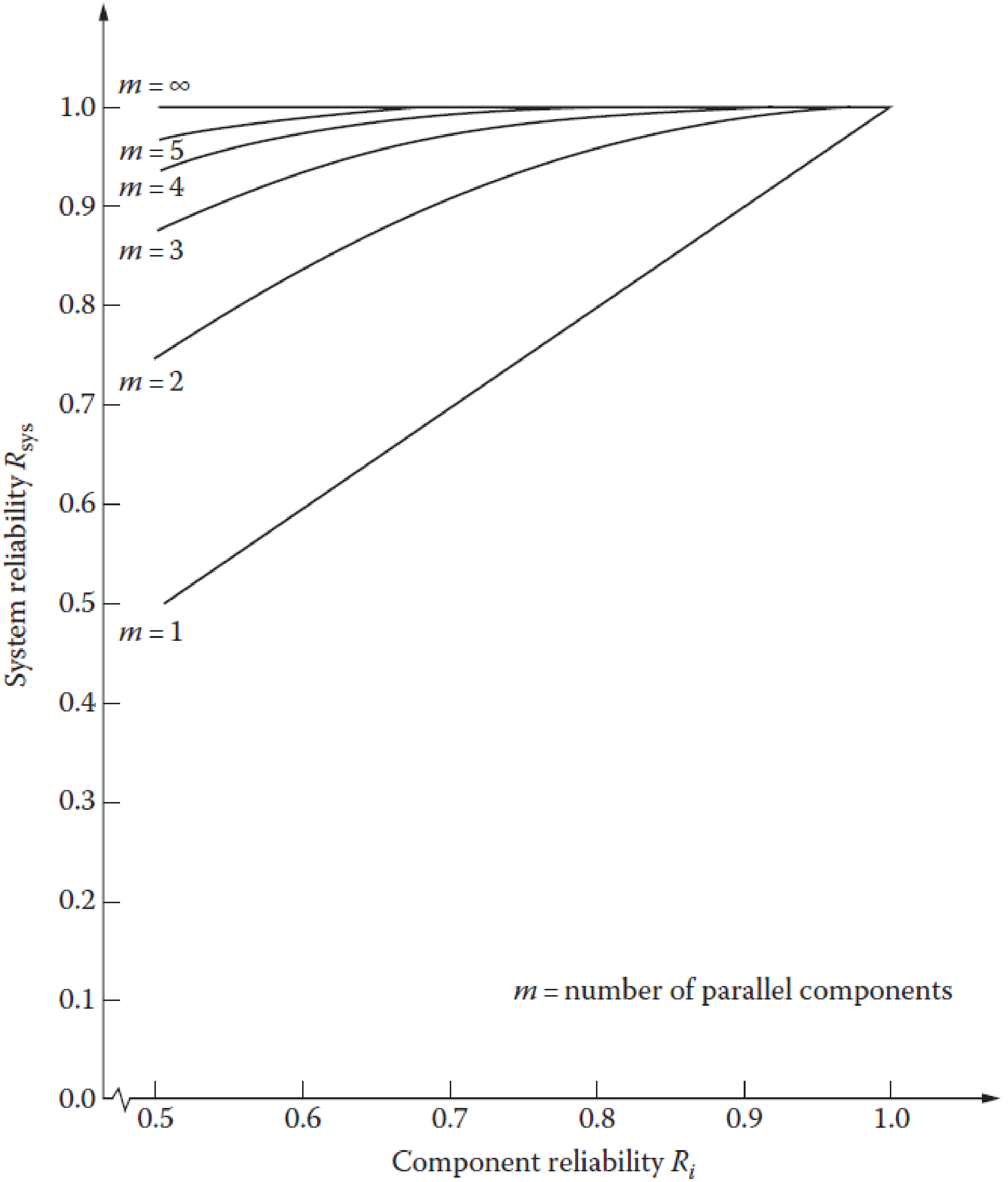
Series Unrepairable Components

$$R_{sys} = \prod_{i=1}^{n} R_i$$



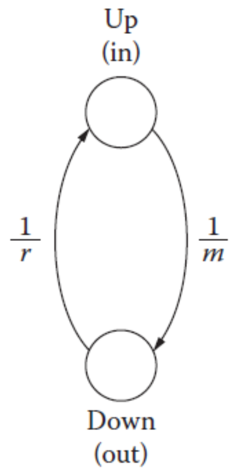
Unrepairable Parallel Components

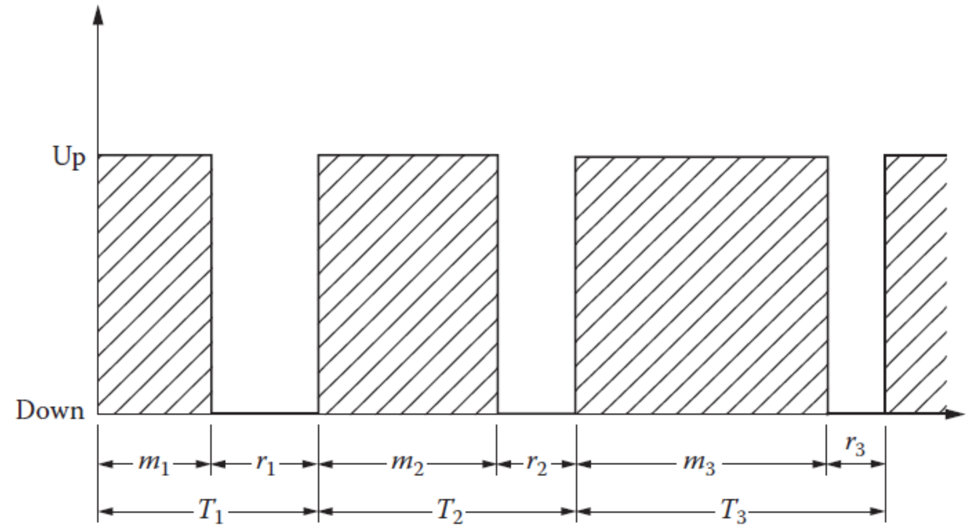
$$R_{sys} = 1 - \prod_{i=1}^{n} (1 - R_i)$$



Repairable Series Components

r: mean time to repair
1/r: repair rate = μ
m: mean time to failure
1/m: failure rate = λ





Failure rate : $$\lambda_{sys} = \sum_{i=1}^{n} \lambda_i$$

Mean time to repair: $$r_{sys} = \frac{1}{\lambda_{sys}} \sum_{i=1}^{n} \lambda_i r_i$$

Repairable Parallel Components

Failure rate: $\lambda_{sys} = \dfrac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2}$

Mean time to repair: $r_{sys} = \dfrac{r_1 r_2}{r_1 + r_2}$

Use binomial distribution for n > 2