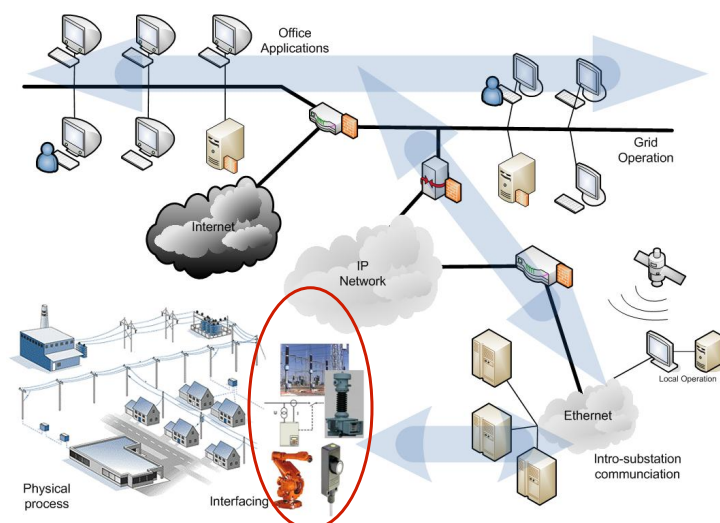# Lecture 3
Power System
Instrumentation

Course map

Outline of the Lecture

- Instrument Transformers
  - Voltage Transformer
  - Current Transformers

- Measurement Setups

- Instrumentation

The Current Transformer (CT)

Bushing type
Medium Voltage

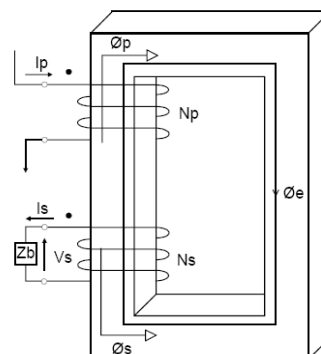High Voltage

Medium Voltage

CT – General Types

- Wound primary
  - Traditional transformer with secondary and primary windings

- Bar primary
  - The primary winding is a single bar, that passes through a core with the secondary winding.
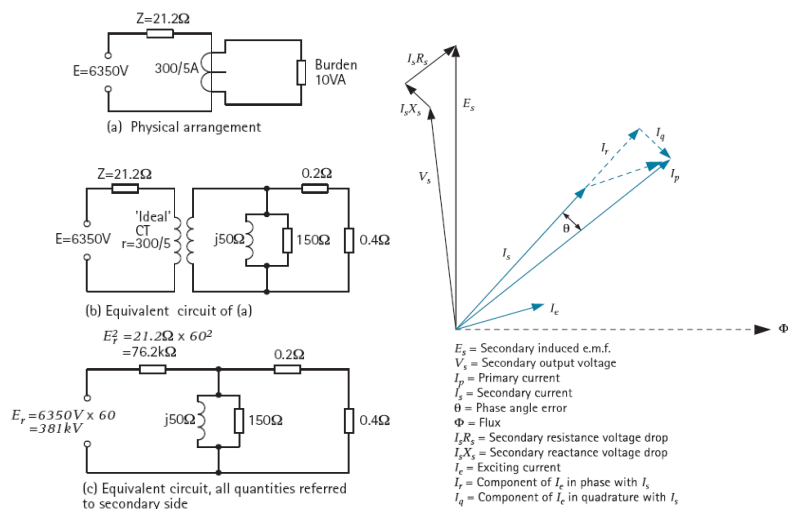
CT – Principle of Operation

- Traditional Electromagnetic transformer

- $Is = Ip*Np/Ns$

- Normally Bar type CTs are used

CT – Equivalent Model

Z=21.2Ω
E=6350V 300/5A Burden 10VA

(a) Physical arrangement

Z=21.2Ω 0.2Ω
E=6350V 'Ideal' CT r=300/5 j50Ω 150Ω 0.4Ω

(b) Equivalent circuit of (a)

$E_r^2 = 21.2Ω \times 60^2$
$= 76.2kΩ$ 0.2Ω

$E_r = 6350V \times 60$
$= 381kV$ j50Ω 150Ω 0.4Ω

(c) Equivalent circuit, all quantities referred to secondary side

$I_s R_s$ E_s $I_s X_s$ V_s I_q I_r I_p θ I_s I_e Φ

E_s = Secondary induced e.m.f.
V_s = Secondary output voltage
I_p = Primary current
I_s = Secondary current
θ = Phase angle error
Φ = Flux
$I_s R_s$ = Secondary resistance voltage drop
$I_s X_s$ = Secondary reactance voltage drop
I_e = Exciting current
I_r = Component of I_e in phase with I_s
I_q = Component of I_e in quadrature with I_s

CTs Accuracy

Accuracy class		+/- Percentage current (ratio) error				+/- Phase displacement (minutes)			
	% current	5	20	100	120	5	20	100	120
0.1		0.4	0.2	0.1	0.1	15	8	5	5
0.2		0.75	0.35	0.2	0.2	30	15	10	10
0.5		1.5	0.75	0.5	0.5	90	45	30	30
1		3	1.5	1.0	1.0	180	90	60	60

(a) Limits of error accuracy for error classes 0.1 – 1.0

Accuracy class		+/- current (ratio) error, %	
	% current	50	120
3		3	3
5		5	5

(b) Limits of error for error classes 3 and 5

Table 6.4: CT error classes

Voltage Transformers (VT)

Up to 5,5 meters
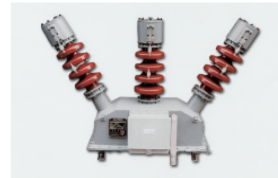
Medium Voltage
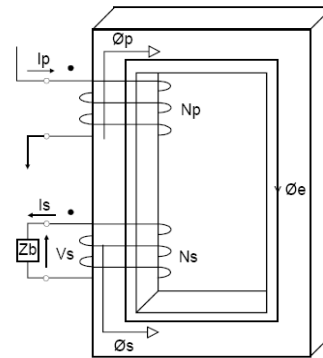< 36kV

High Voltage

VT – General Types

- Electromagnetic type
  - Commonly referred to as VT
  - Traditional Electromagnetic transformer
  - Used up to approx 130kV
    - Thereafter insulation problems arise

- Capacitor Type
  - Commonly referred to as CVT
  - Series coupled capacitors
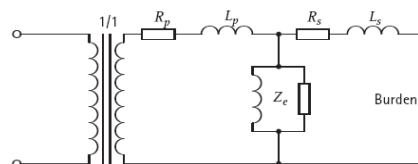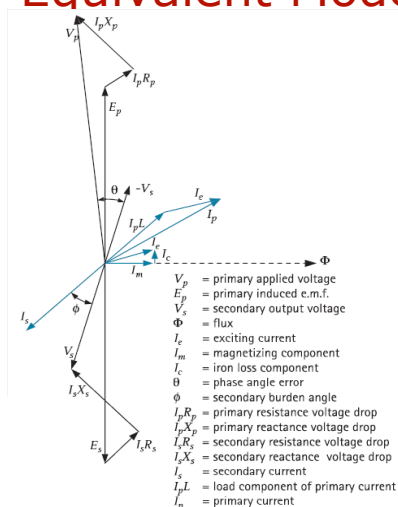 - Used up to EHV/UHV levels

VT – Principle of Operation

- Traditional Electromagnetic transformer

- Vs = Vp*Ns/Np

- Connected either
  - Phase – Earth
  - Phase – Phase

- Single-pole
  - Star coupled

Equivalent Model

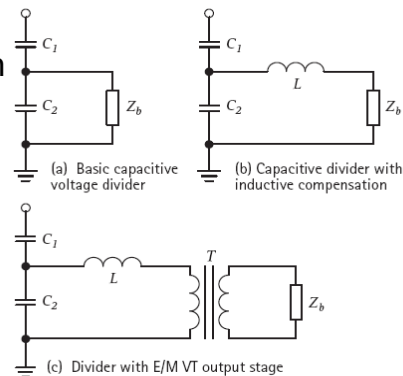V_p = primary applied voltage
E_p = primary induced e.m.f.
V_s = secondary output voltage
Φ = flux
I_e = exciting current
I_m = magnetizing component
I_c = iron loss component
θ = phase angle error
ϕ = secondary burden angle
$I_p R_p$ = primary resistance voltage drop
$I_p X_p$ = primary reactance voltage drop
$I_s R_s$ = secondary resistance voltage drop
$I_s X_s$ = secondary reactance voltage drop
I_s = secondary current
$I_p L$ = load component of primary current
I_p = primary current

CVT – Principle of Operation

- Basic potential divider

- Inductive compensation to cancel effect of capacitive source impedance

- To reduce the size of capacitors, a VT is added on output side.

(a) Basic capacitive voltage divider

(b) Capacitive divider with inductive compensation

(c) Divider with E/M VT output stage

VT – Design Factors

- Electromagnetic VT
  - Flux density in core well below saturation
  - Output design ranges 200-300 VA
  - Insulation larger volume than windings

- Capacitive VTs
  - More space conserving
  - May include a VT
  - Can be used for overloading High-Frequency signals on Power Line.

VT Connection

- VTs are single pole above 36 kV
- CVTs
  - Phase to Earth
- VTs
  - Phase to Phase, Phase to Earth
  - Star coupling

VT - Accuracy

- Accuracy classes for measurement & revenue metering
- Accuracy classes for protection

Accuracy class	0.8 – 1.2 x rated voltage 0.25 - 1.0 x rated burden at 0.8pf	
	voltage ratio error (%)	phase displacement (minutes)
0.1	+/- 0.1	+/- 5
0.2	+/- 0.2	+/- 10
0.5	+/- 0.5	+/- 20
1.0	+/- 1.0	+/- 40
3.0	+/- 3.0	not specified

Table 6.1: Measuring voltage transformer error limits

Accuracy class	0.25 - 1.0 x rated burden at 0.8pf 0.05 – V_f x rated primary voltage	
	voltage ratio error (%)	phase displacement (%)
3P	+/- 3.0	+/- 120
6P	+/- 6.0	+/- 240

Table 6.2: Additional limits for protection voltage transformers.

Summary - VTs/CTs

- VTs and CTs are the primary measurement method for medium and high voltage
- Important design characteristics are
  - Accuracy for revenue metering
  - Linearity for protection
  - Size = cost
- The output is further transformed using transducers.

Contents of the Lecture

- Instrument Transformers   *(NPAG Ch. 6)*
  - Voltage Transformer
  - Current Transformers

- **Measurement Setups**

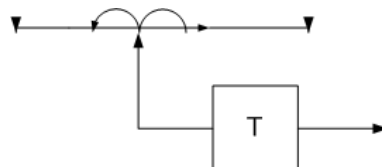- Transducers   *(NPAG Ch. 22)*

What do we need to measure?

- Voltage   V
- Current   I
- Frequency   f
- Phase angle   φ
- Power   Q,P
- Position   on/off
- …..

Current Measurement

- Connected to secondary side of CT
- Cannot sense direction
- Measurement types
  - Mean sensing
  - r.m.s. measurement

Current measurements

- Instantaneous current per phase
  - $i_A(t)$ $i_B(t)$ $i_C(t)$

Voltage Measurement

- Connected to secondary of VT/CVT
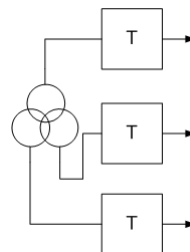
Phase Angle Measurement

- Implemented using zero-crossing detection
- Sensitive to harmonics
- Connected to phases and quantities (U or I) as needed for measurement
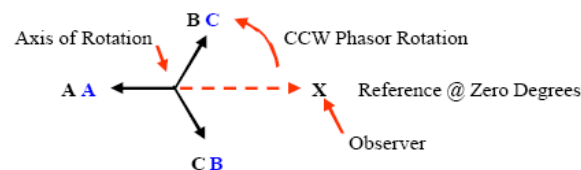
Frequency Measurement

- Important for system operation
- Analog – Digital conversion
  - Fourier Transform for *f* analysis
- Accuracy up to 0,01% available, +/- 5 mHz
- Connected to VT or CT secondary

Outline of the Lecture

- Instrument Transformers
  - Voltage Transformer
  - Current Transformers

- Measurement Setups.

- Instrumentation

Wiring & Communication
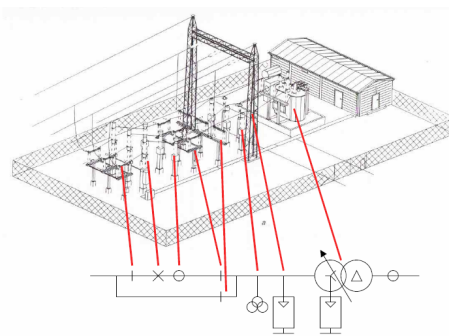
Source: Lakervi & Holmes

Transducer types

- Analog or Digital transducers

- Digital transducers (A/D conversion)
  - Benefits
    - Improved long-term stability
    - More accurate r.m.s measurement
    - Improved Communications
    - Programmable scaling
    - Reduced size
    - Wider range of functions
  - Output normally a RS-485 or 232 interface

Equivalent Model (analog)

- Output from a transducer normally a current source
- E.g. 4-20 mA as a function of input

A/D conversion

Analog Signal → Antialiasing Filtering for Analog Signals → Sampling → Quantization → Decimation → Digitized Signal
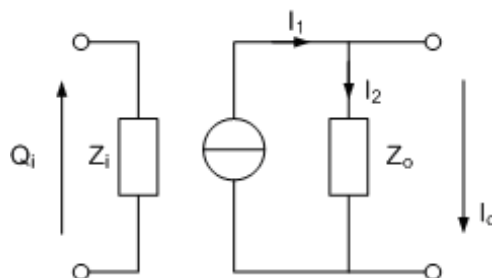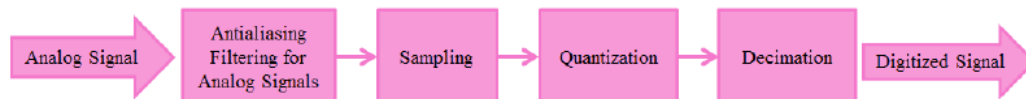
- Accuracy determined by
  – Bit resolution, Least Significant Bit
  – Non-linearity due to imperfections.
  – Sampling & Aliasing

Signal conditionings

signal conditioning subsystem

transducer → surge protective circuit → LP filter → analogue multiplexer
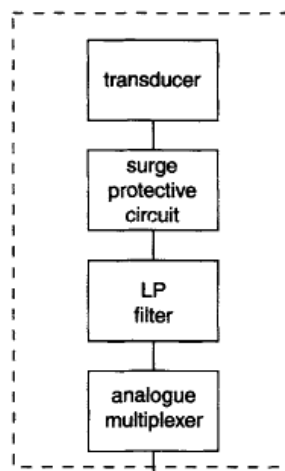
- To prepare analog signal for A/D conversion
- To protect circuits
- Enable multiplexing, depending on capability of digital channels

Analogue LP filter

output voltage / input voltage
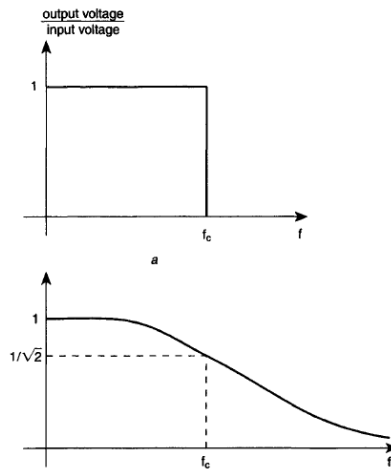
- To limit frequency content of measurement signal

- Multiplexing principle:

inputs 1 2 3 4 5 6 7 → serial output
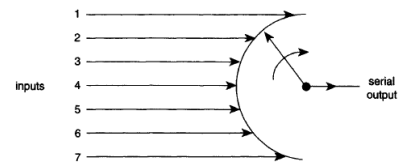
A/D Conversion

conversion subsystem

sample hold circuit

A/D converter

digital multiplexer
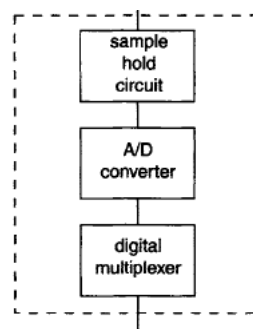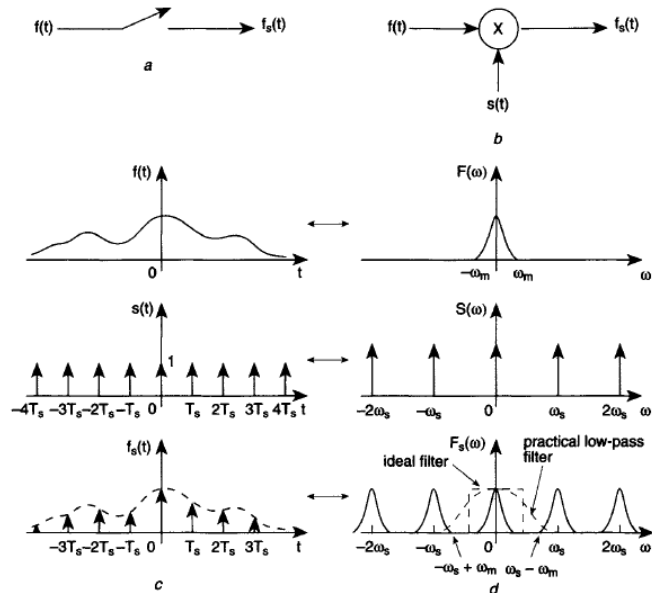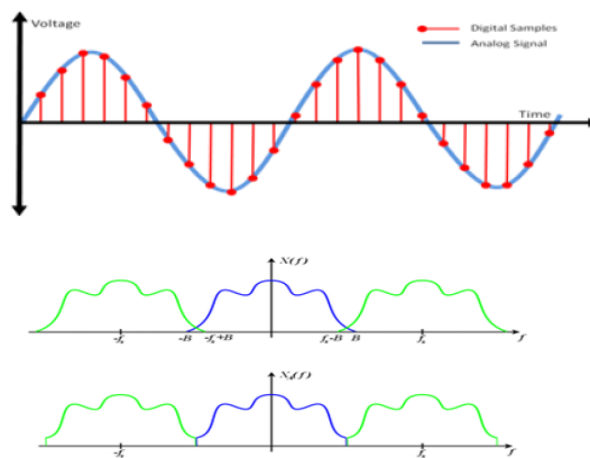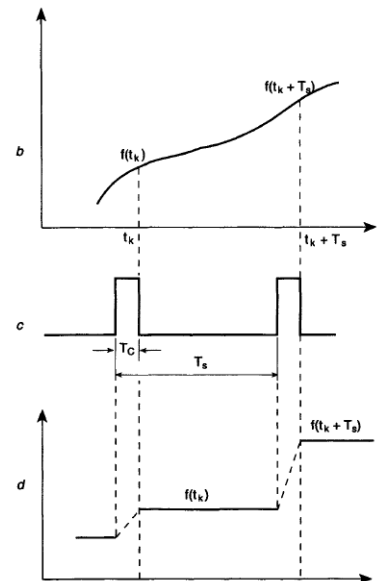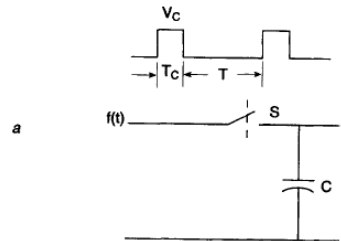
Sampling & Aliasing

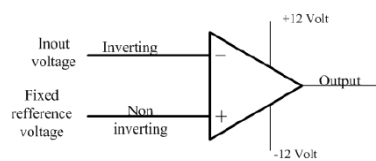# Sample & Hold

A/D - Quantization

- Base circuit is the comparator
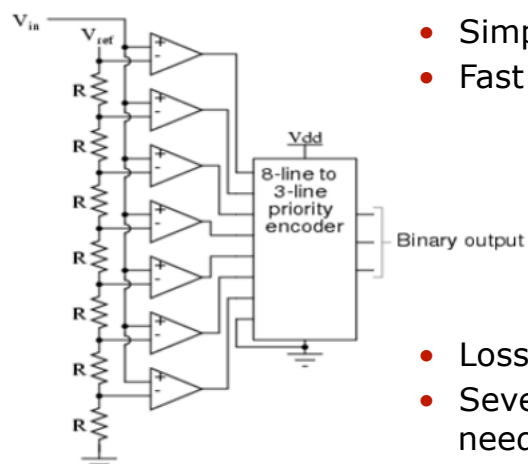- If Input > Vref output = V+
- If Input < Vref = Output = V-

Counter based A/D
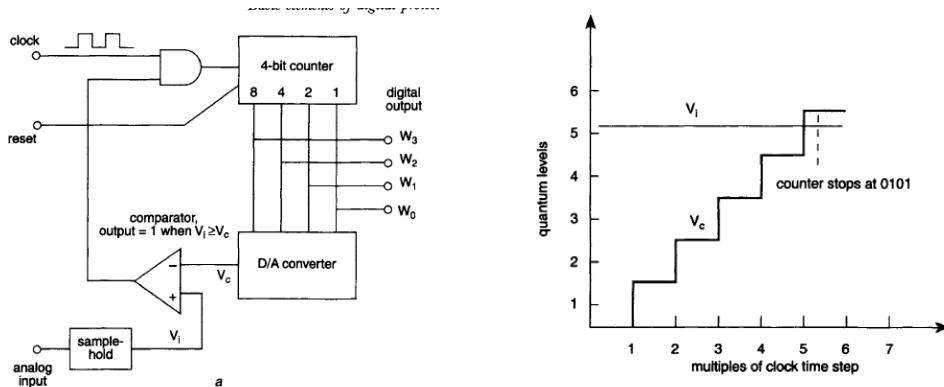
Flash ADC

- Simple concept
- Fast

- Losses increase
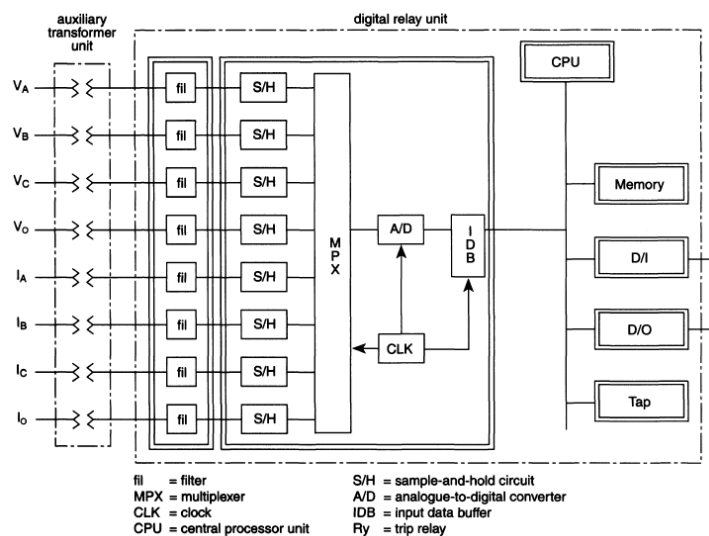- Several comparators needed
- Low resultion

Further AD-Converter types

- Integrator
  - Integrating signal applied to input of comparator and reference
- Sigma Delta
  - Oversampling of the input, and successive stages of comparation and summing.

- Accuracy still determined by
  - Bit resolution, Least Significant Bit
  - Non-linearity due to imperfections.
  - Sampling & Aliasing

Putting it all together


```
fil   = filter                    S/H = sample-and-hold circuit
MPX   = multiplexer               A/D = analogue-to-digital converter
CLK   = clock                     IDB = input data buffer
CPU   = central processor unit    Ry  = trip relay
```

Questions or comments?