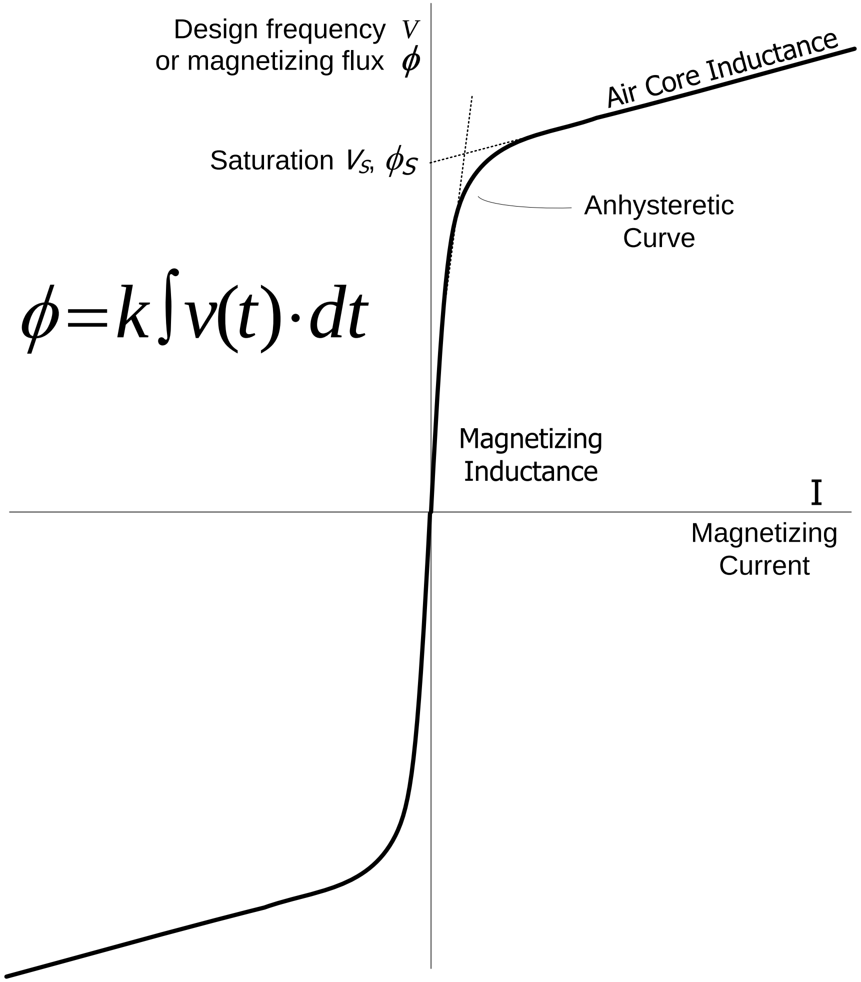
A Tutorial on Ferroresonance

Elmo Price
ABB Inc.

Introduction

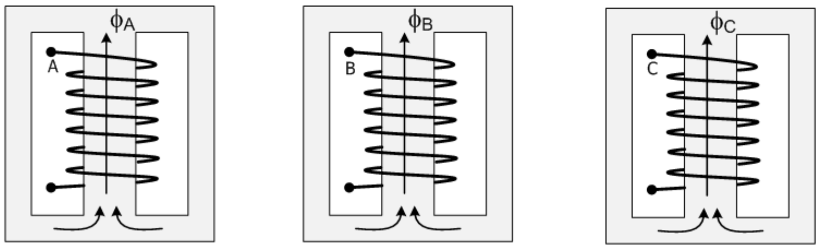
- Occurs in power system circuits containing series capacitance, a non-linear transformer magnetizing inductance and minimum transformer and load losses
- Initiated with transient disturbance such as opening a switch
- Results in overvoltages and/or high current spikes that may subject system apparatus to dielectric and thermal stresses resulting in apparatus failure
- Poses risk to operating personnel
- Protective relays that measure these quantities are subject to incorrect operations causing unwanted outages
- This presentation will present a simple tutorial with a graphical approach to explaining the ferroresonant operating states, circuit configurations and mitigation.
- It will provide the basic concepts necessary to understanding more advanced investigations into unique occurrences.

Transformer Characteristics

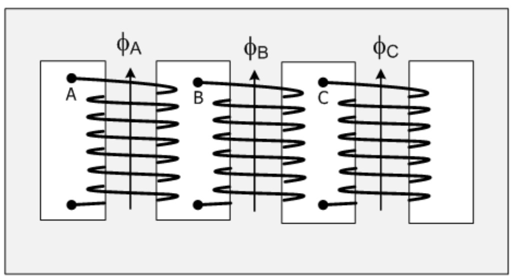


$$\phi = k\int v(t)\cdot dt$$

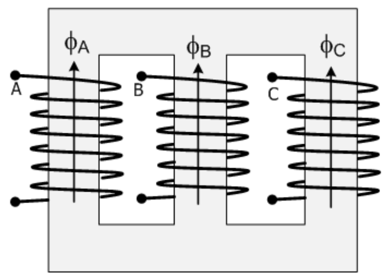
Transformer Core and Coil



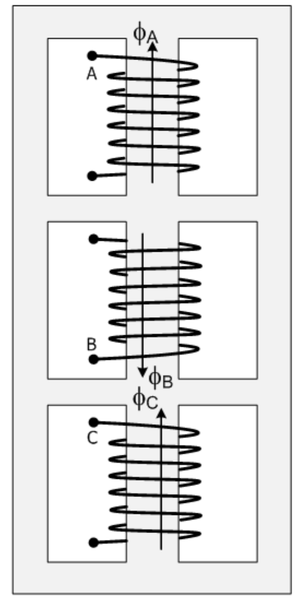
(a) Three single phase cores



(b) Three phase five legged core form



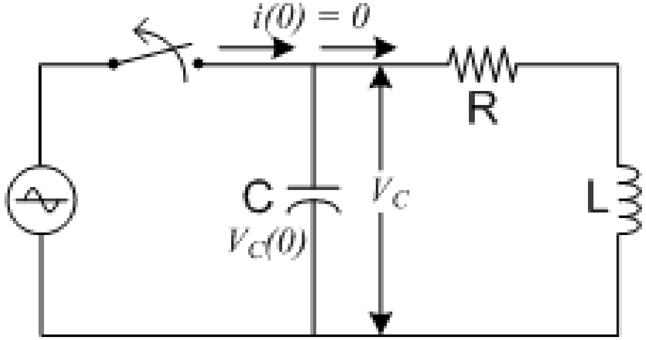
(c) Three phase three legged core form

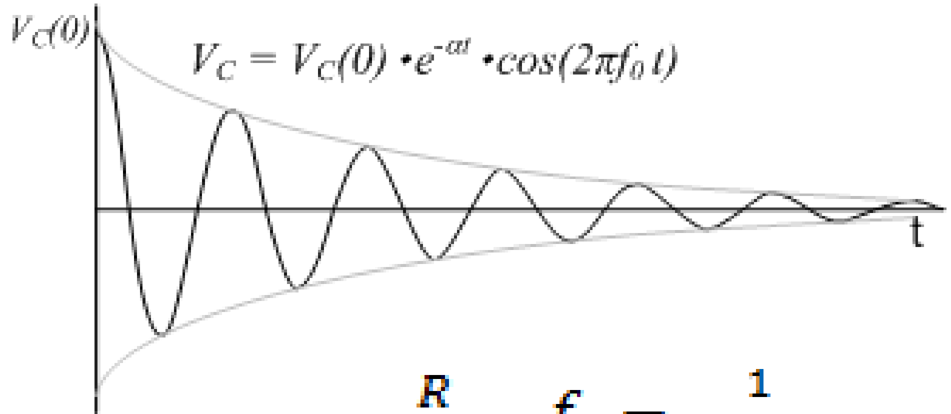


(d) Three phase shell form

- Magnetic coupling between phases
  - Core construction
  - Winding connections
  - Core bracing, joints, etc.
- Phase flux saturation
- Zero sequence flux saturation

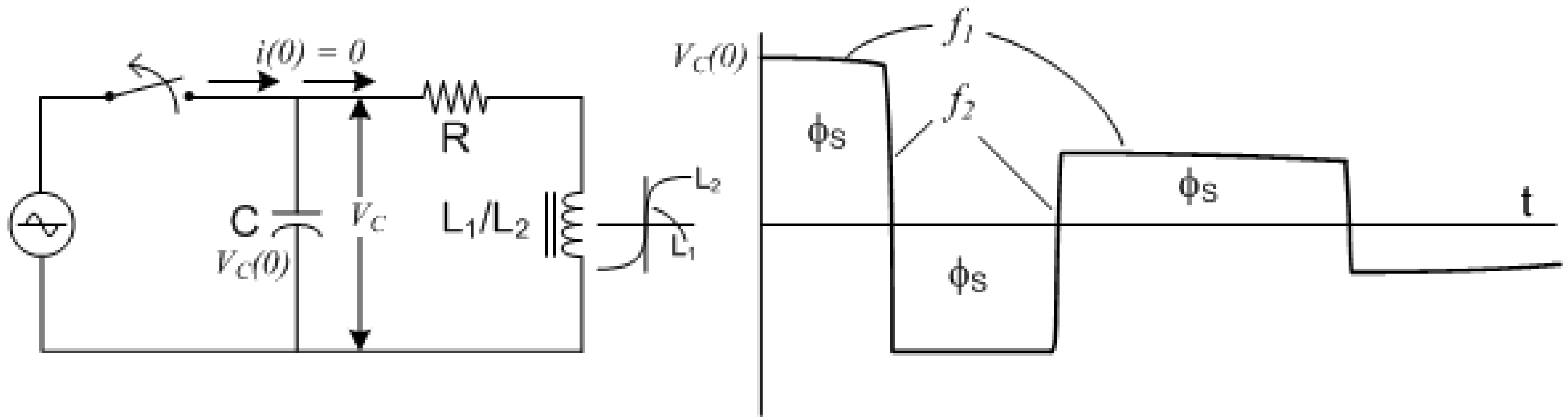
RLC Circuit and Transient Response





$$\alpha = \frac{R}{2L} \qquad f_0 = \frac{1}{2\pi\sqrt{LC}}$$

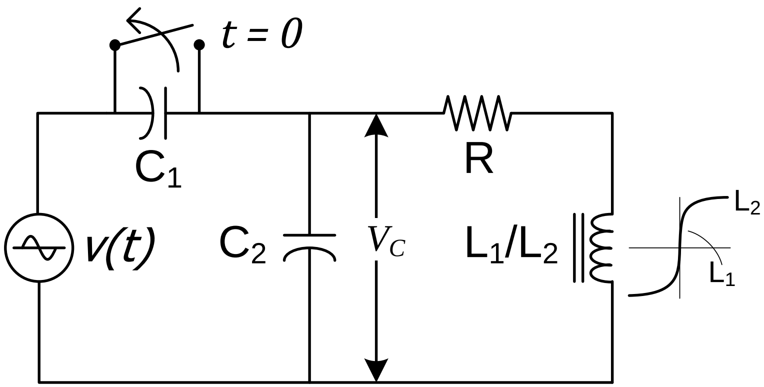
$RL_{1/2}C$ Circuit and Transient Response
($L_{1/2}$ is nonlinear transformer inductance)



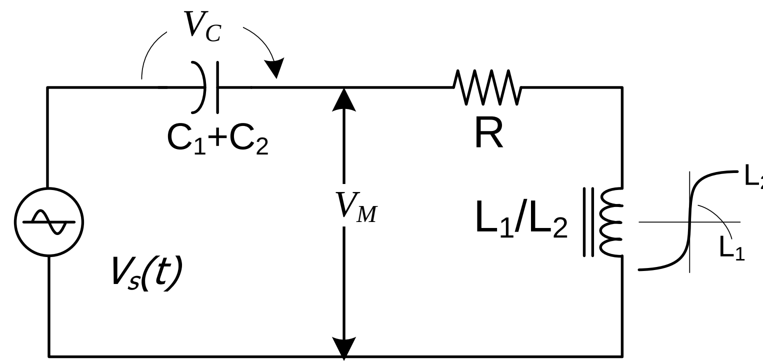
$$f_1 = \frac{1}{2\pi\sqrt{L_1 C}}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_2 C}}$$

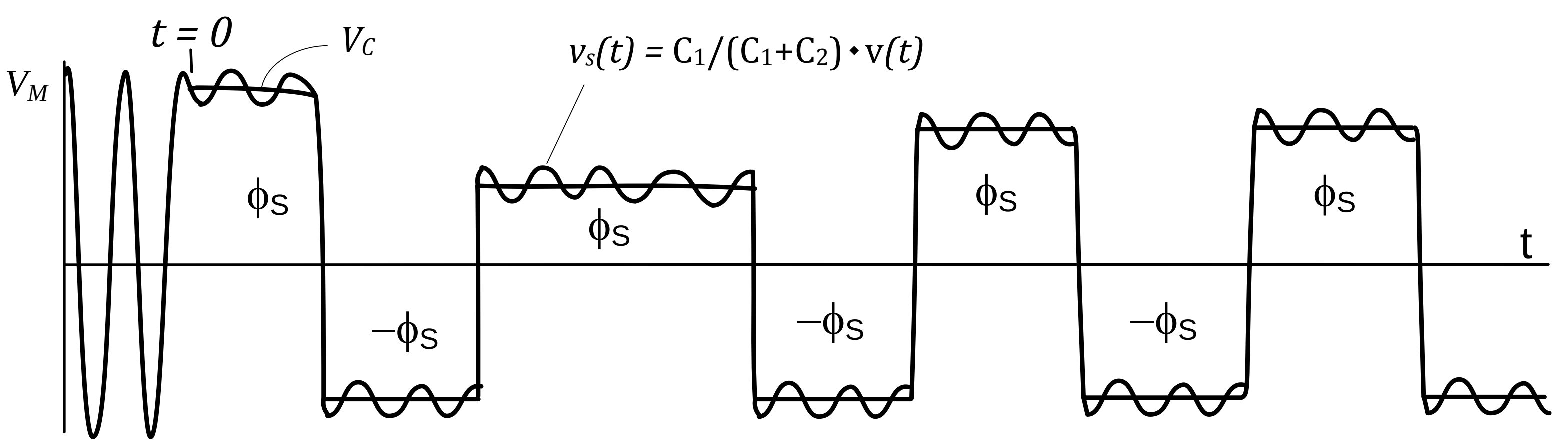
$RL_{1/2}C$ Circuit with Driving Voltage and Transient Response



(a) RLC circuit with saturating inductance and driving voltage

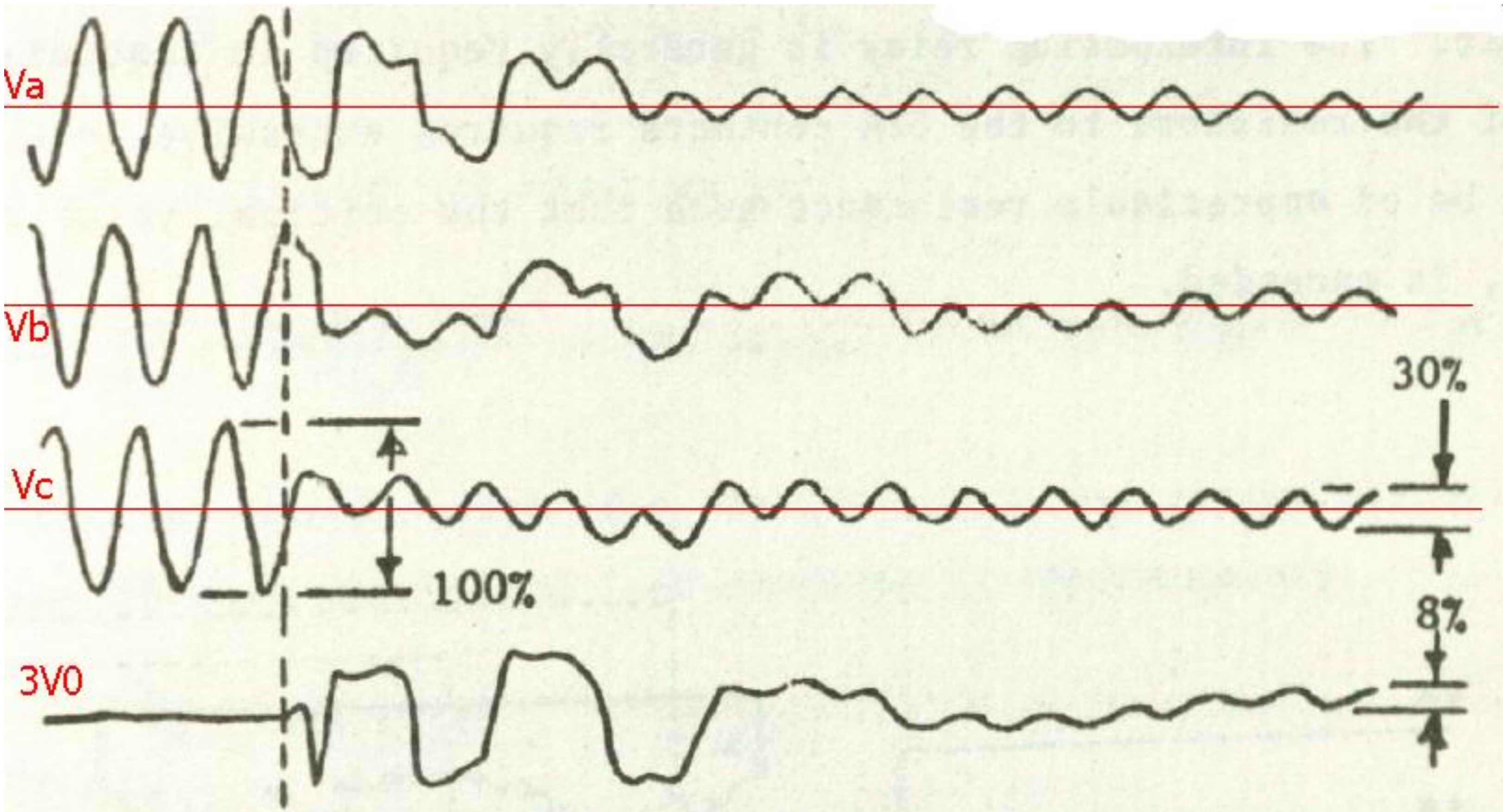


(b) Equivalent of figure (a)



(c) Transient response and ferroresonant operating state

345 kV Bus Clearing

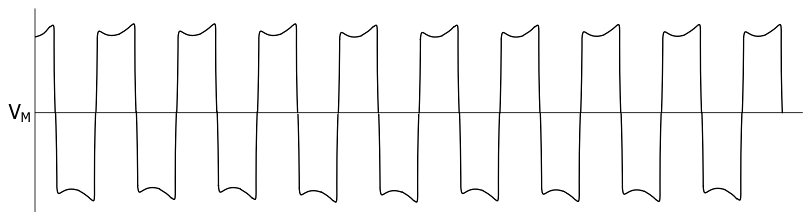


Energized through open breaker capacitance, circa 1976

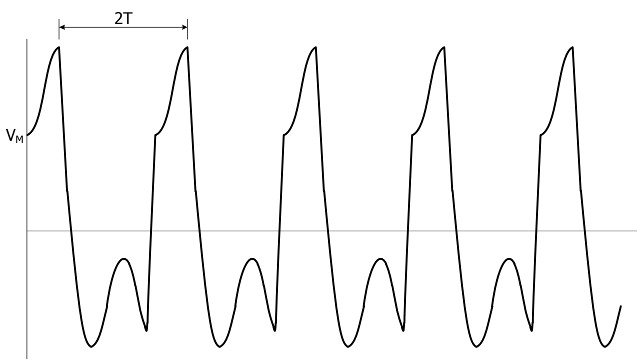
Ferroresonant Modes

- Transformer operation in the ferroresonant state is dependent on a number of factors
  - system voltage magnitude
  - the initial voltage on the capacitor
  - the initial state of the magnetic characteristics of the transformer
  - the total loss in the ferroresonant circuit
  - the point on wave of initial switching
- It is normally initiated after some type of switching event such as transformer energization, single-phase switching, fault clearing, breakers opening, or loss of system grounding
- Given the right conditions it can lock into any of the following ferroresonant modes
- The one common characteristic among these ferroresonant modes is that they all contain the fundamental frequency driving voltage component, which sustains it.

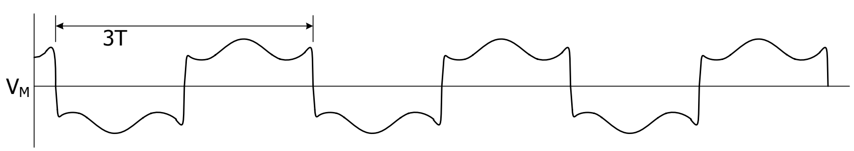
Ferroresonant Modes



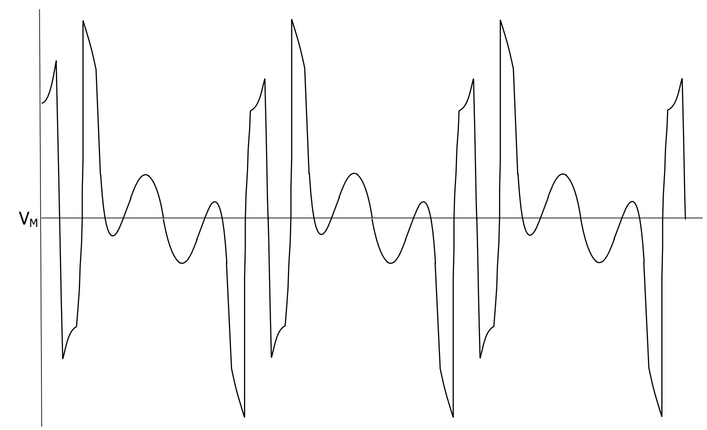
Fundamental – 60 Hz



Subharmonic – 30 Hz



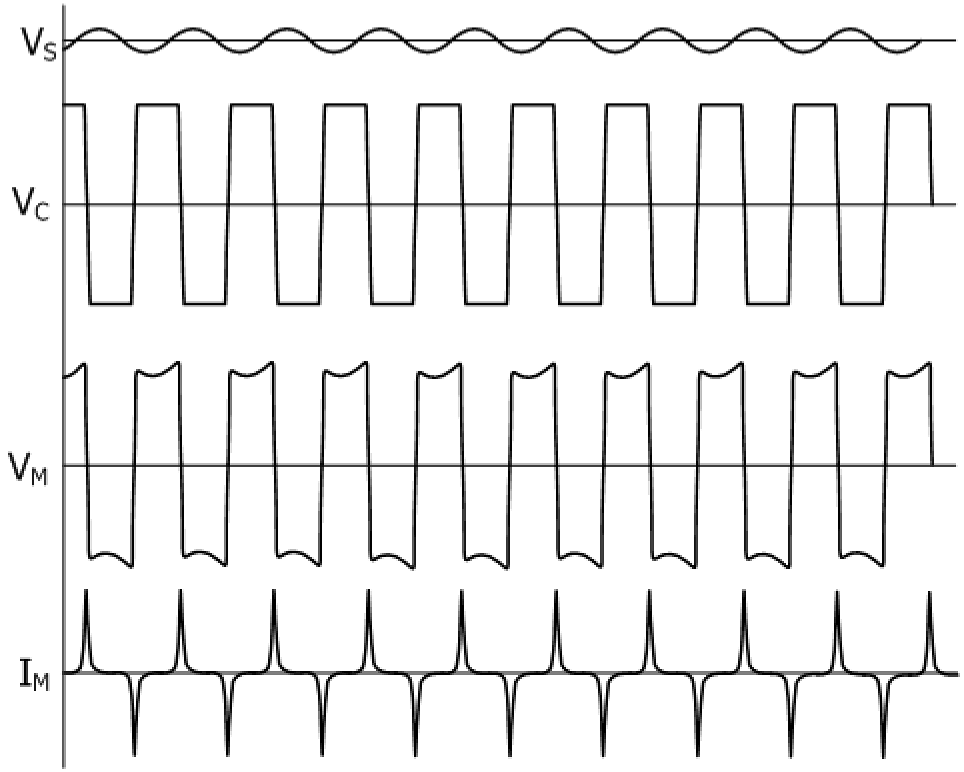
Subharmonic – 20 Hz



Quasi-periodic

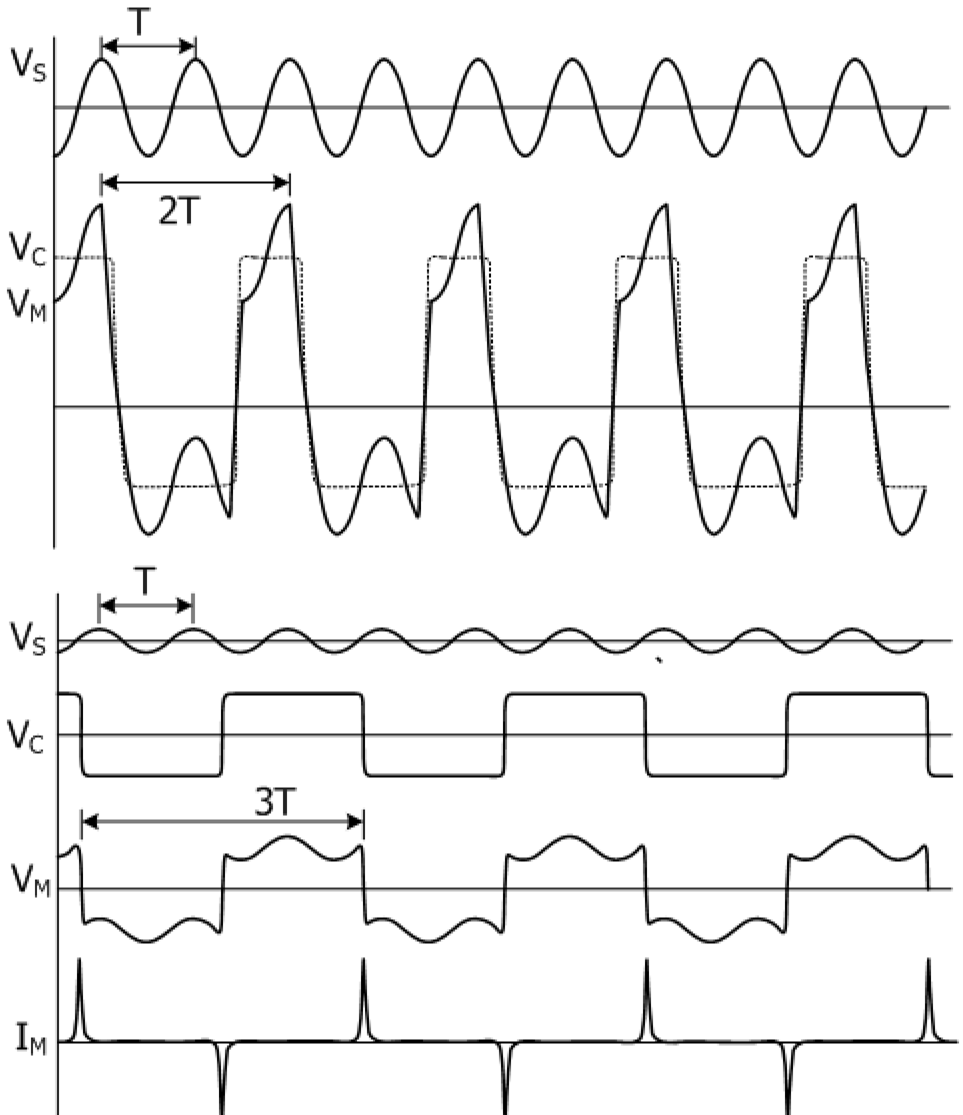
Chaotic
(hunts for, but cannot lock into pattern)

Fundamental Mode Ferroresonance



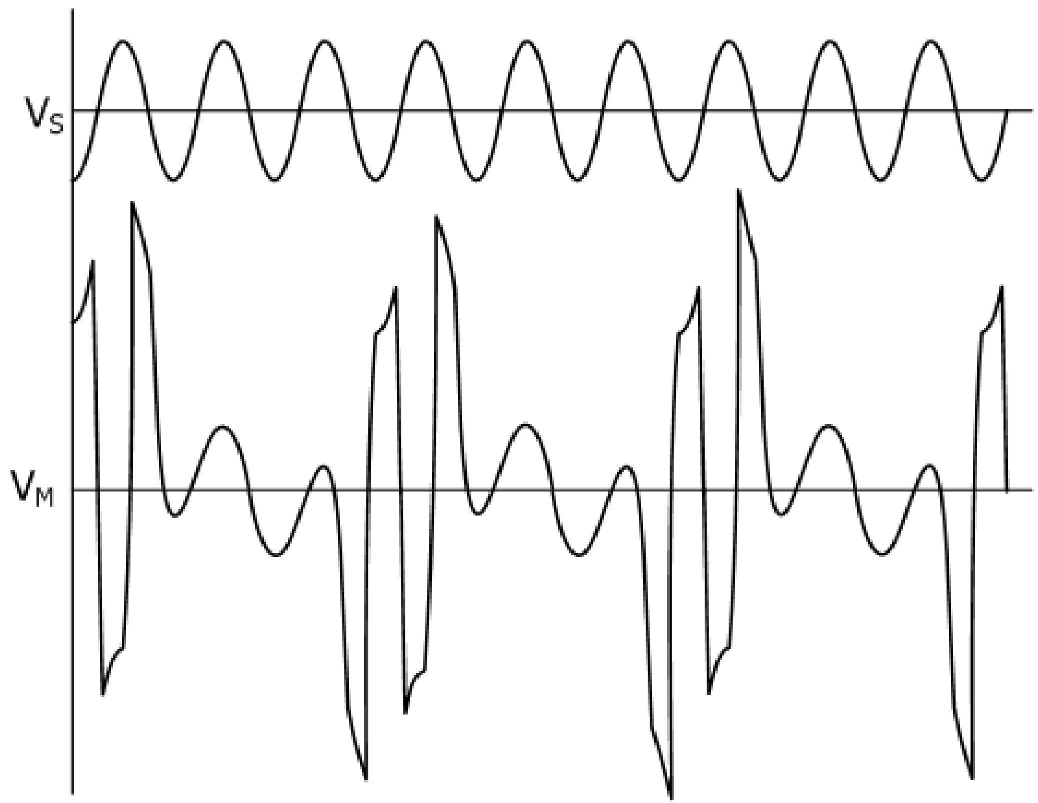
- V_M oscillations at V_S (system) frequency
- Higher than nominal voltage of transformer
- V_C and V_S components
- Phase reversal – opposite polarity to V_S
- Positive and negative half cycles are generally symmetrical – exceptions
- High current spikes

Sub-harmonic Mode Ferroresonance



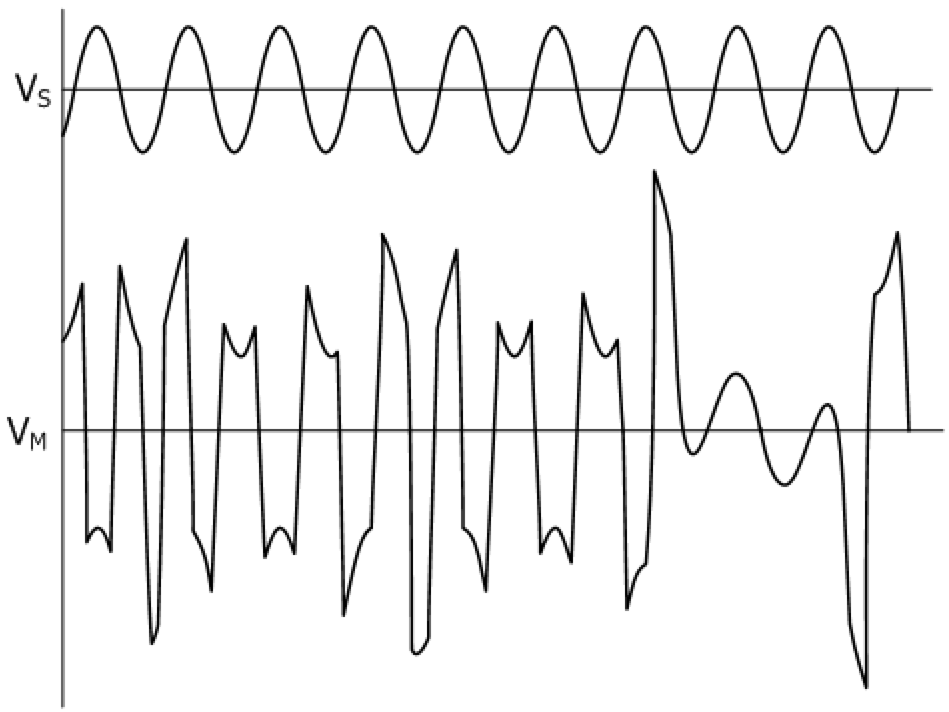
- V_M oscillation periods in integer multiples of fundamental period, $T_S = nT$, n = 2, 3, …
- 30 Hz (T=2) - Positive and negative half cycles are not always symmetrical, but patterns are repeated
- 20 Hz (T=3) - Oscillations generally symmetrical and magnitude is lower than nominal voltage of transformer
- V_C and V_S components
- High current spikes

Quasi-periodic Mode Ferroresonance



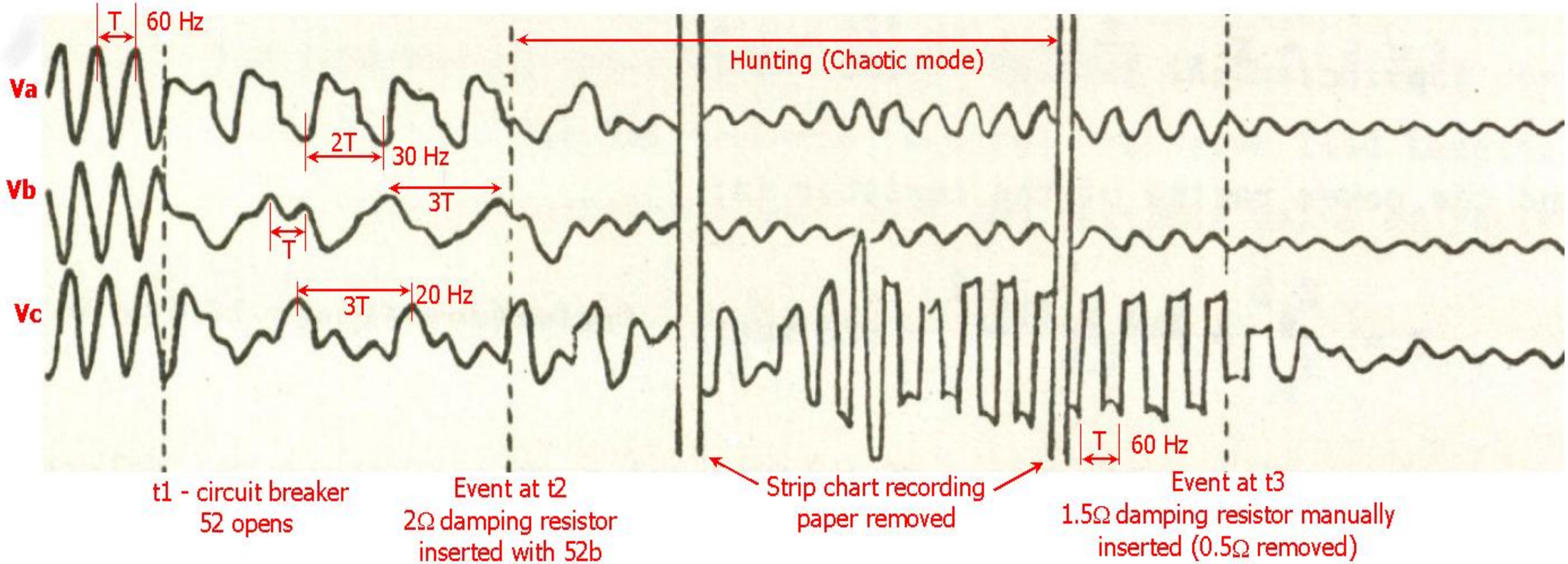
- V_M oscillation are irregular, but appear periodic
  - Patterns are very nearly repeated, T^+, T^-,T^+, etc., and with different magnitudes
- Peak voltage much greater than transformer nominal
- Greater degree of saturation
- More coupling with other phases
- V_C and V_S components
- High current spikes

Chaotic (Hunting) Mode Ferroresonance



- V_M oscillation are irregular with no repetition of patterns
- The system is hunting for a stable ferroresonant mode with a chaotic variation in voltage magnitudes and frequency
- Peak voltage much greater than transformer nominal
- Greater degree of saturation
- More coupling with other phases
- V_C and V_S components
- High current spikes

345 kV Substation Vt Ferroresonance

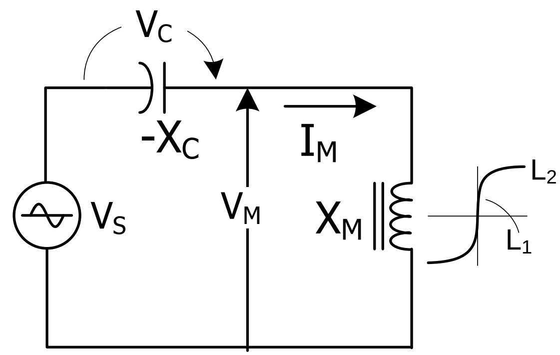


- Copy of strip chart record - Circa 1976

Transformer Operating States

Without series resistance

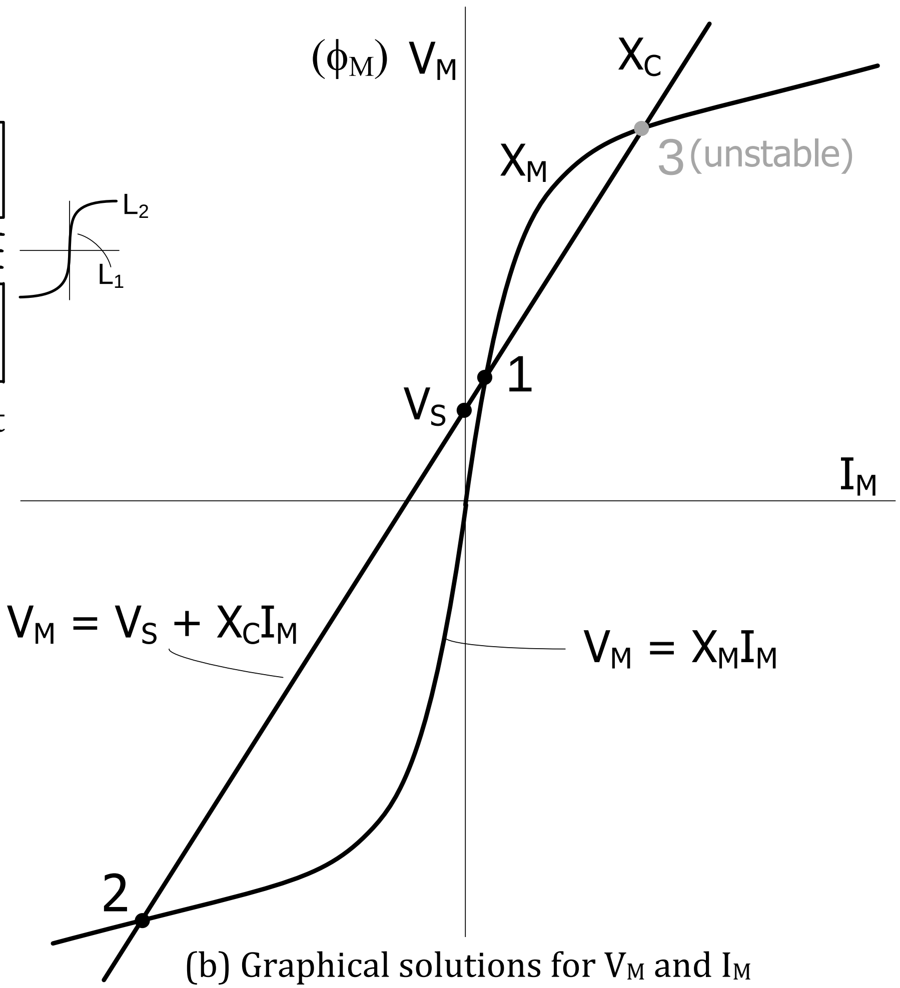
Without series resistance



(a) Equivalent circuit

Two operating states

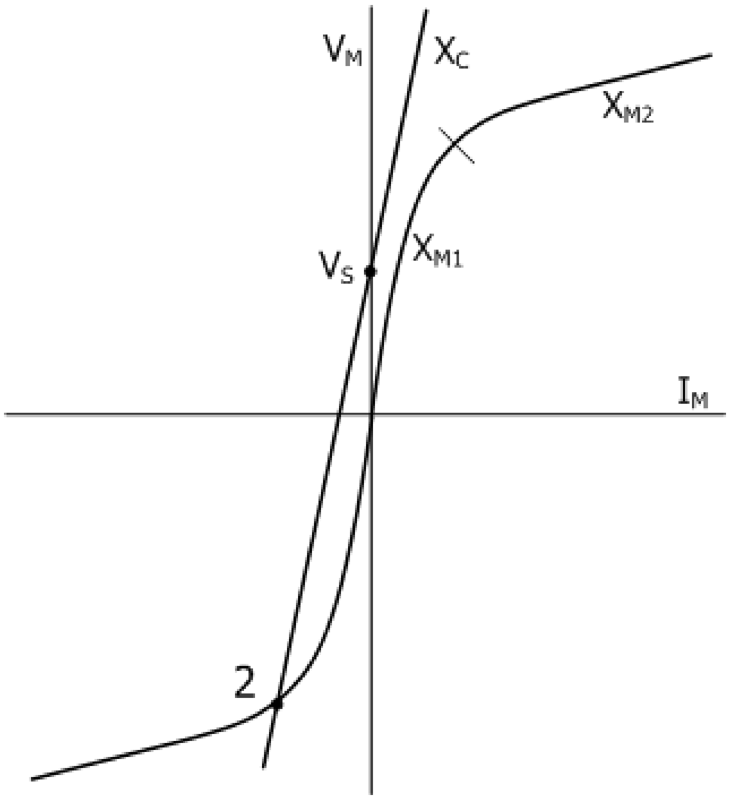
- Point 1 – normal
- Point 2 – ferroresonant with phase reversal from point 1
- Point 3 cannot occur



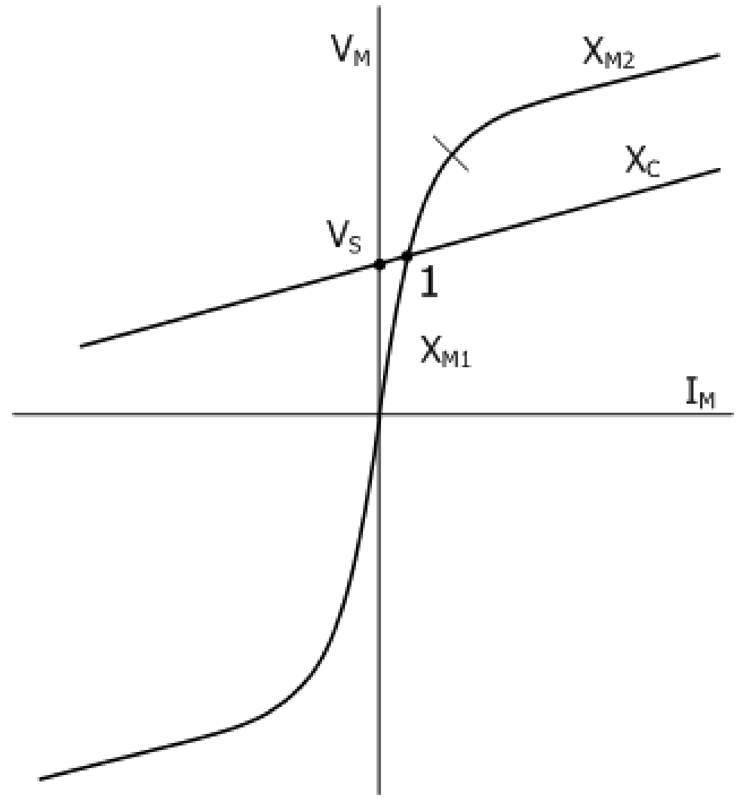
(b) Graphical solutions for V_M and I_M

Transformer Operating States

Without series resistance



(a) Ferroresonant (over excited) state - $|X_C| \geq X_{M1}$

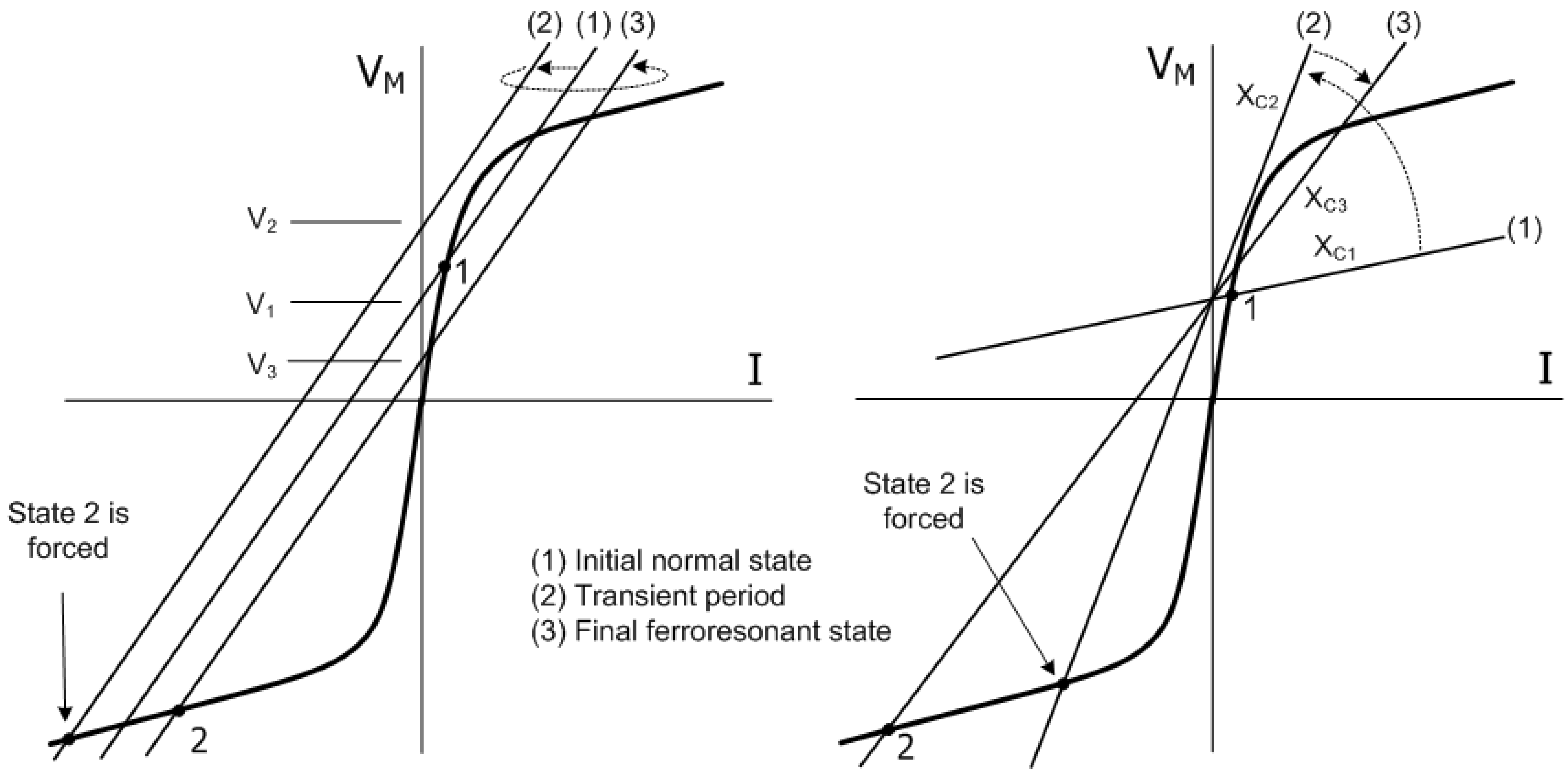


(b) Normal state – $|X_C| \leq X_{M2}$

Single point solutions

Transformer Operating States

Without series resistance



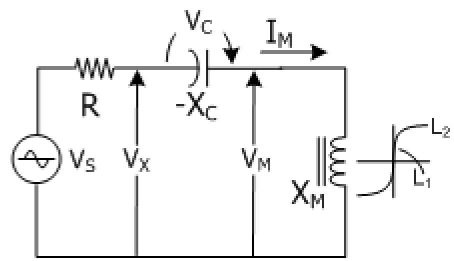
(a) Voltage transient – constant impedance

(b) Impedance transient – constant voltage

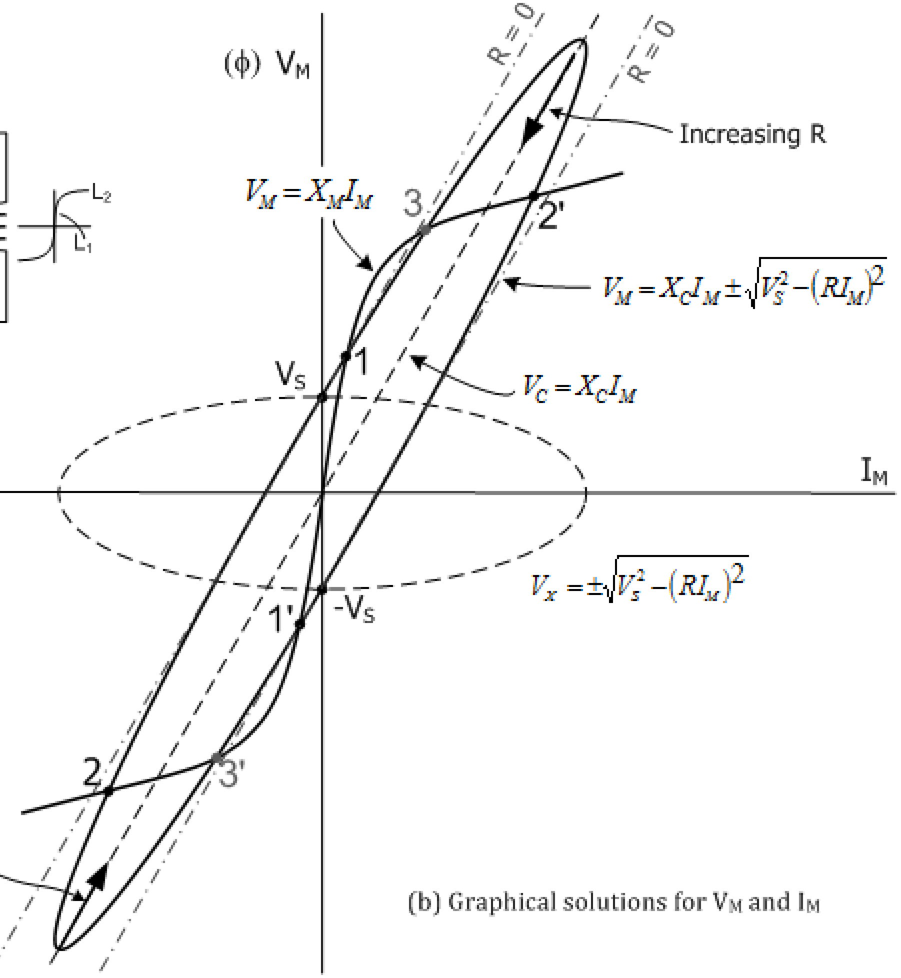
Transient change of operating state

Transformer Operating States

With series resistance



(a) Equivalent circuit



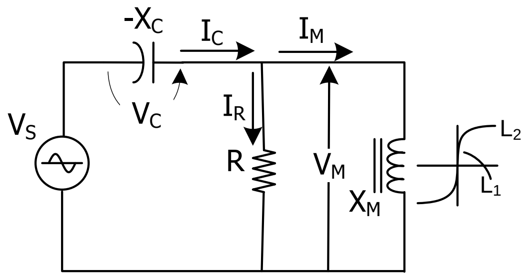
(b) Graphical solutions for V_M and I_M

Two operating states

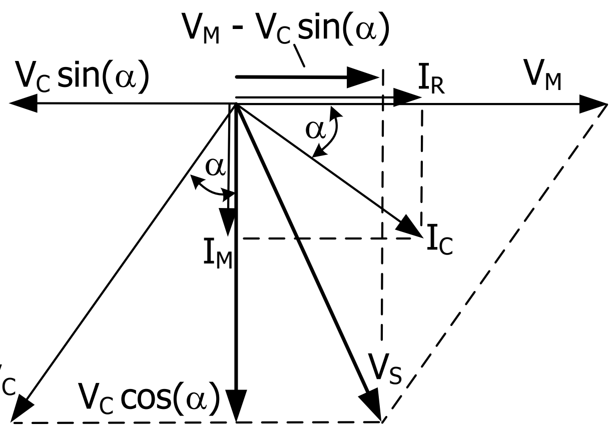
- Point 1/1′ – normal
- Point 2/2′ – ferroresonant with phase reversal from point 1
- Point 3/3′ cannot occur

Transformer Operating States

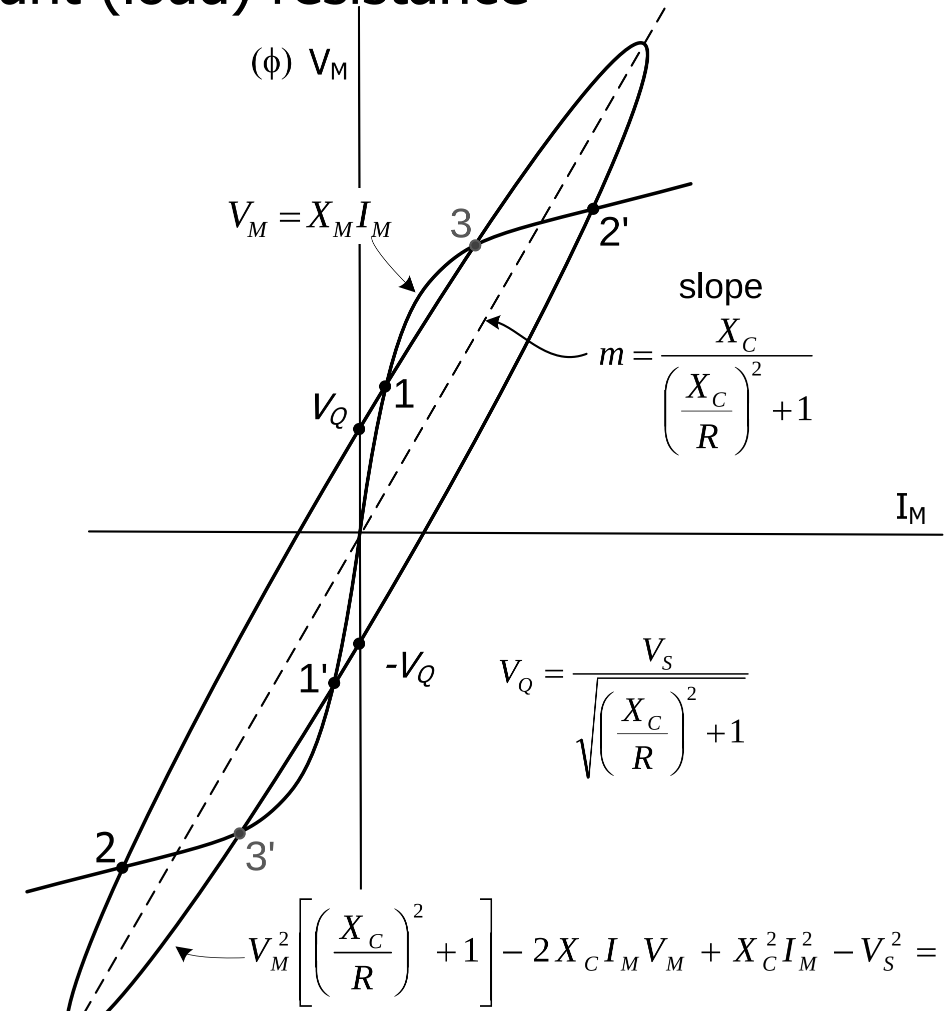
With shunt (load) resistance



(a) Equivalent circuit



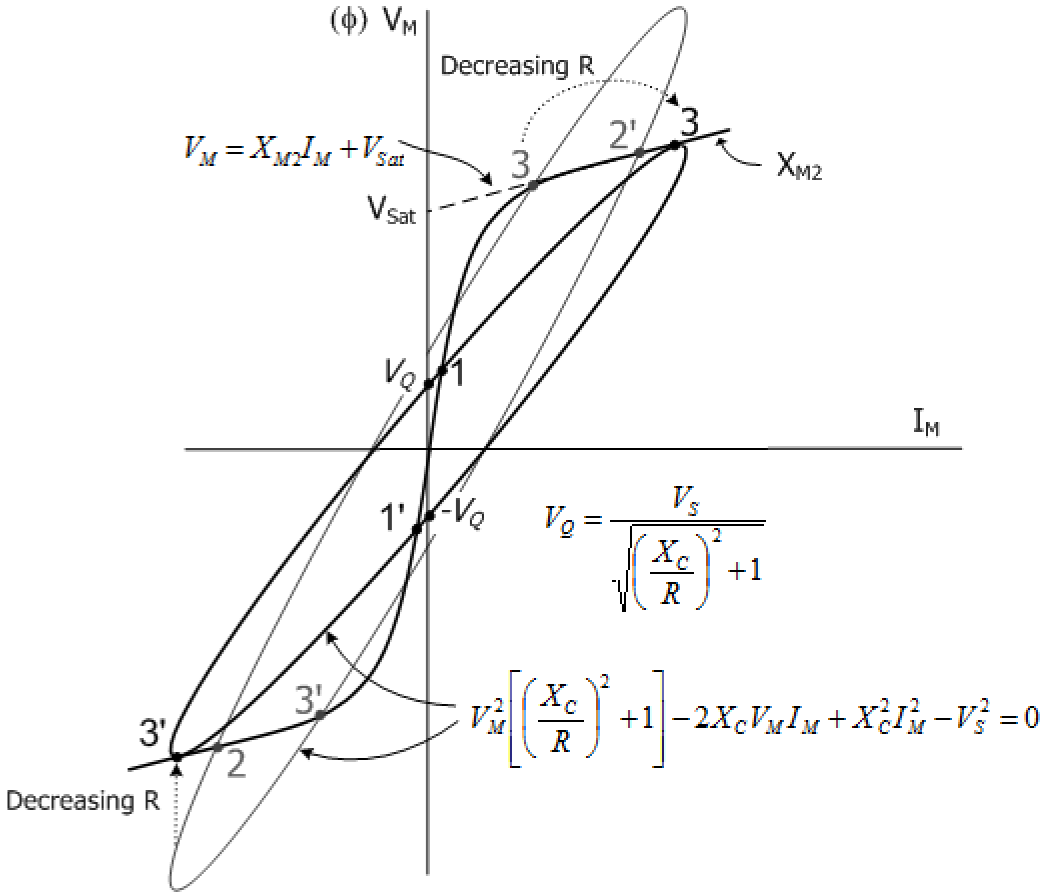
(b) Phasor diagramt



(c) Graphical solutions for V_M and I_M

Transformer Operating States

With shunt (load) resistance

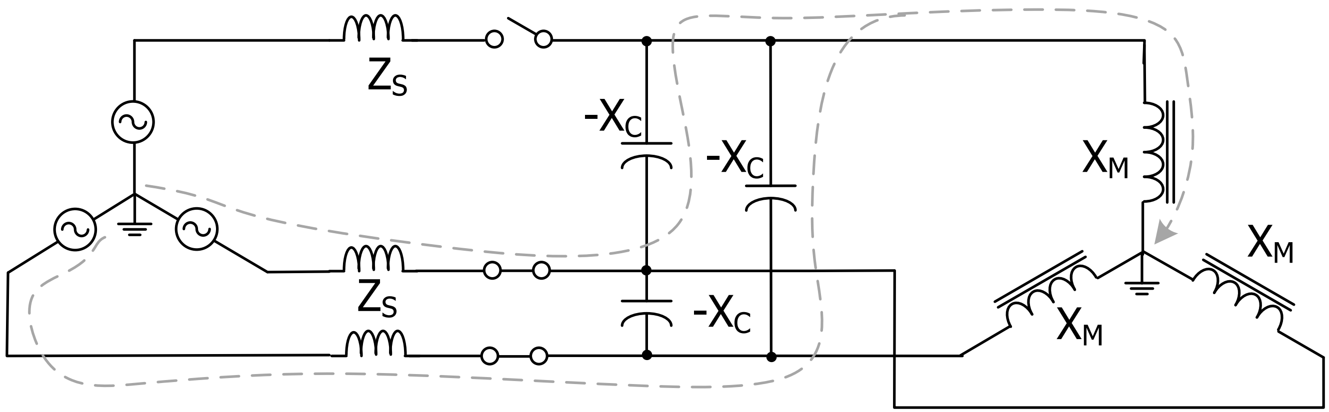


$$R_{Max} = \frac{X_C X_{M2}}{X_C - X_{M2}} \sqrt{\left(\frac{X_C V_{Sat}}{X_{M2} V_S}\right)^2 - 1}$$

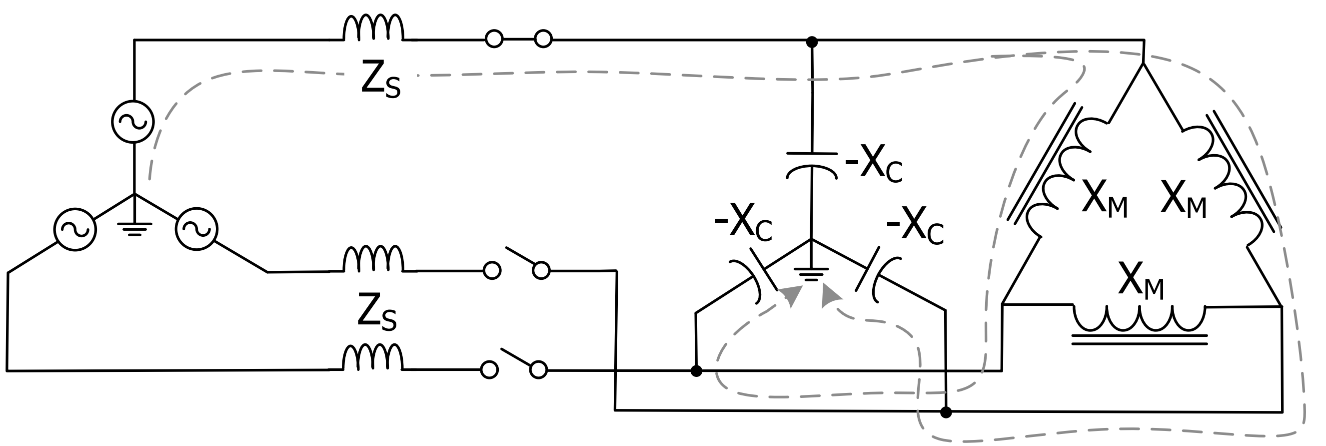
$X_C >> X_{M2}$

$$R_{Max} = \frac{X_C V_{Sat}}{V_S}$$

Ferroresonant Configurations

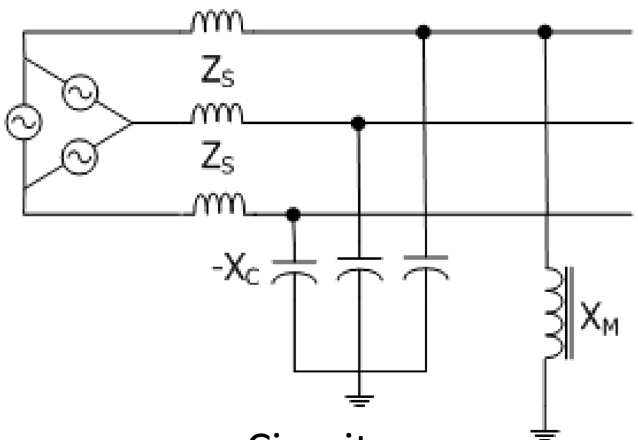


(a) Coupling through phase-to-phase capacitance with grounded transformer

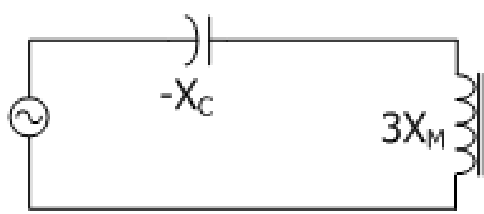


(b) Coupling through phase-to-ground capacitance with ungrounded transformer

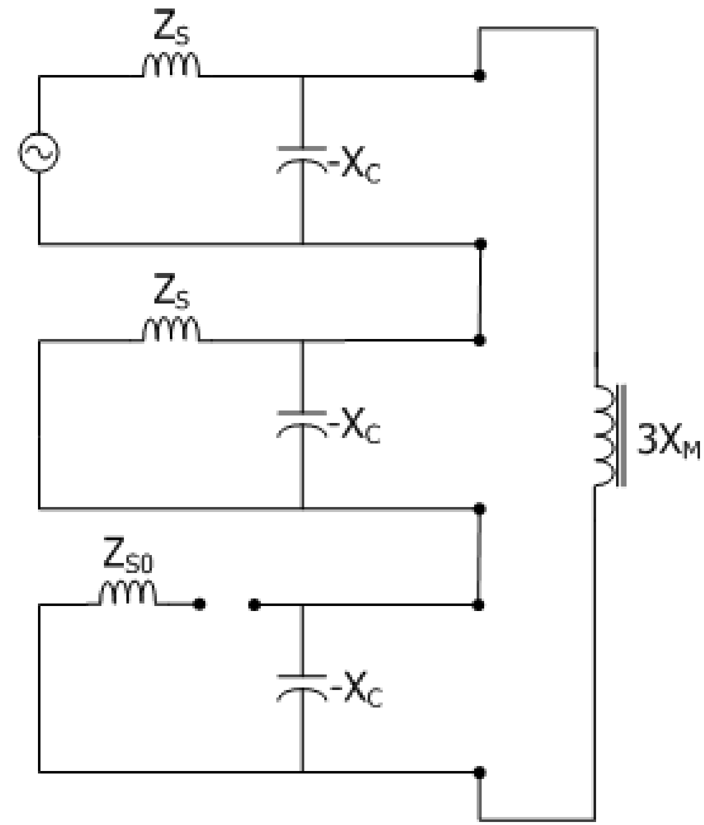
Ferroresonant Configurations



Circuit



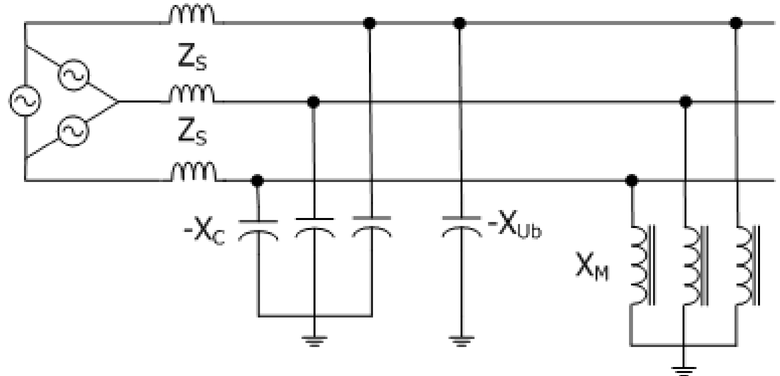
Equivalent circuit, $Z_S = 0$



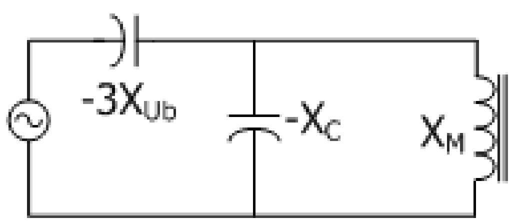
Sequence networks and connection

Grounded single phase transformer on ungrounded system

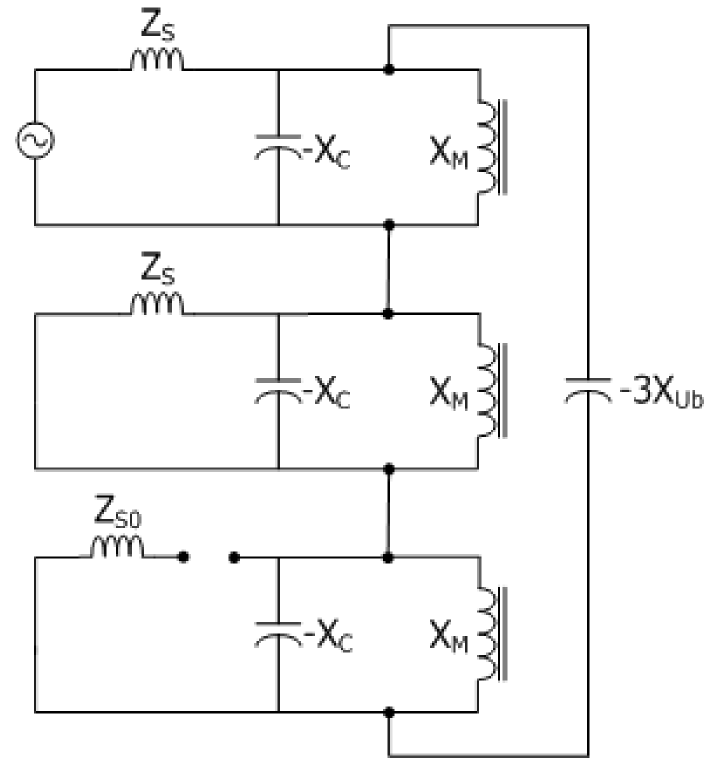
Ferroresonant Configurations



Circuit



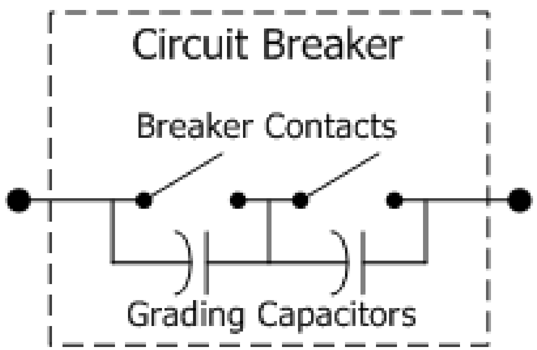
Equivalent circuit, $Z_S = 0$

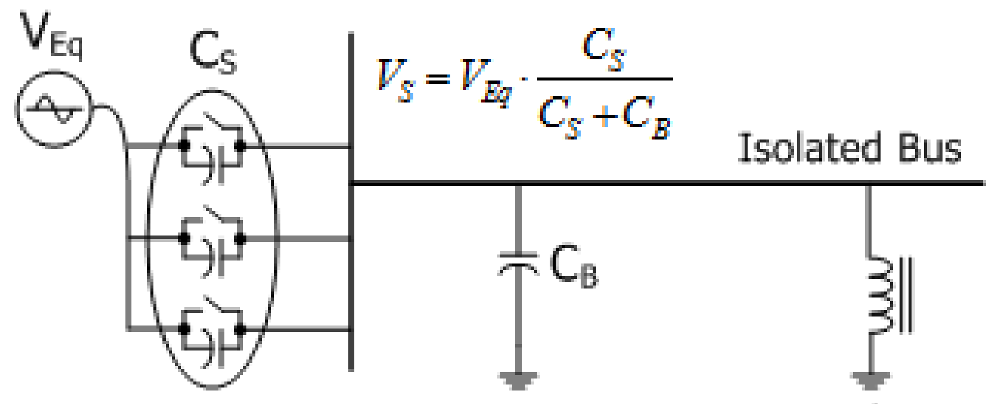


Sequence networks and connection

Grounded three phase transformer on ungrounded system with unbalanced phase-to-ground capacitance

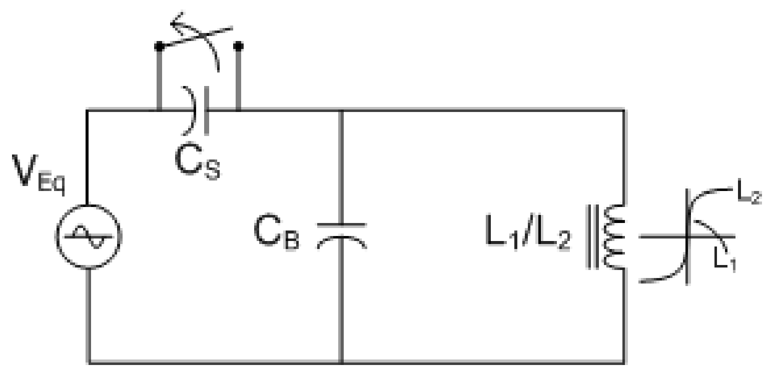
Ferroresonant Configurations





$$V_S = V_{Eq} \cdot \frac{C_S}{C_S + C_B}$$

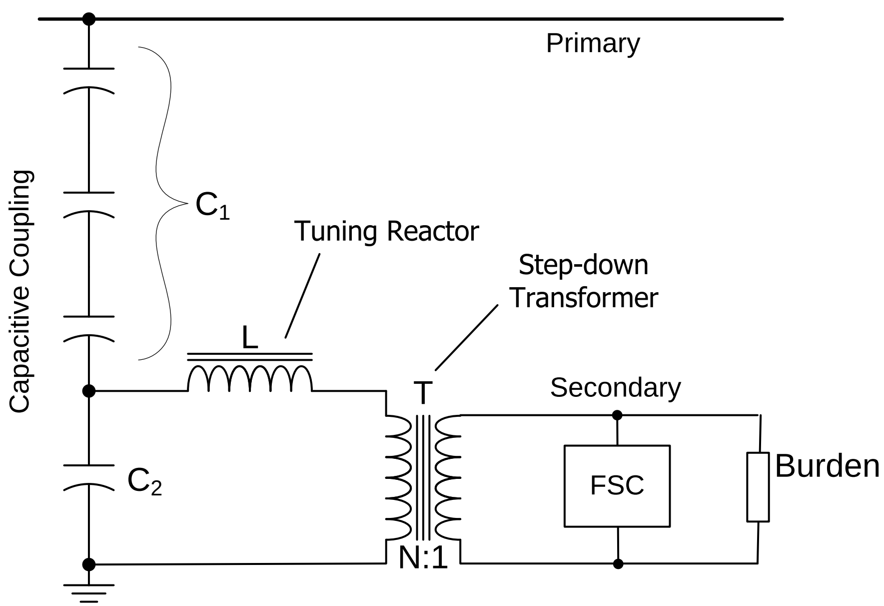
Transformer can be vt or power transformer



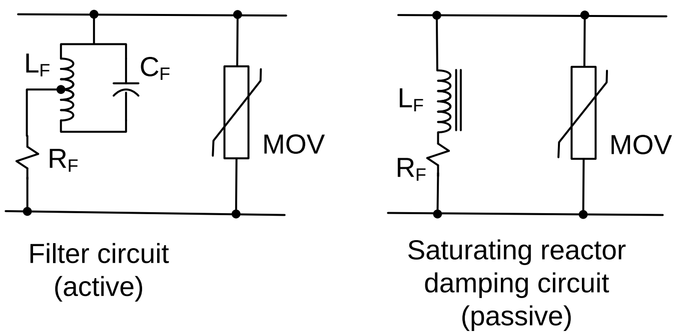
Equivalent circuit

Open breaker capacitance and transformers

Ferroresonant Configurations



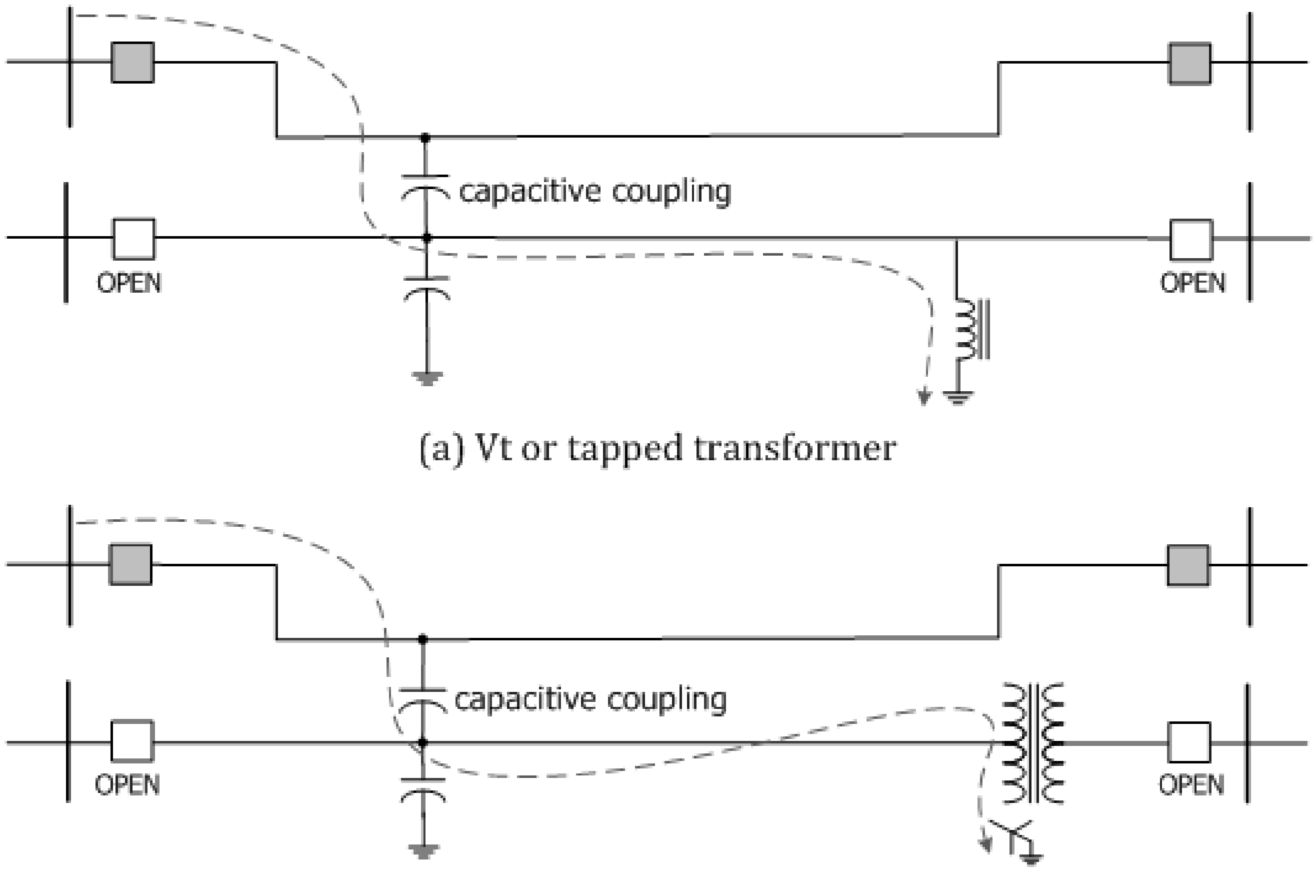
(a) CVT equivalent circuit



(b) Typical Ferroresonance suppression circuits with surge arrestor

Ccvt

Ferroresonant Configurations



(a) Vt or tapped transformer

(b) Transformer terminated line

Transformer connected to isolated line

Mitigation

- Mitigation of ferroresonance involves one or more of following:
  - Correcting voltage unbalance
  - Changing the transformer magnetic design
  - Inserting damping resistance
  - Detuning the circuit

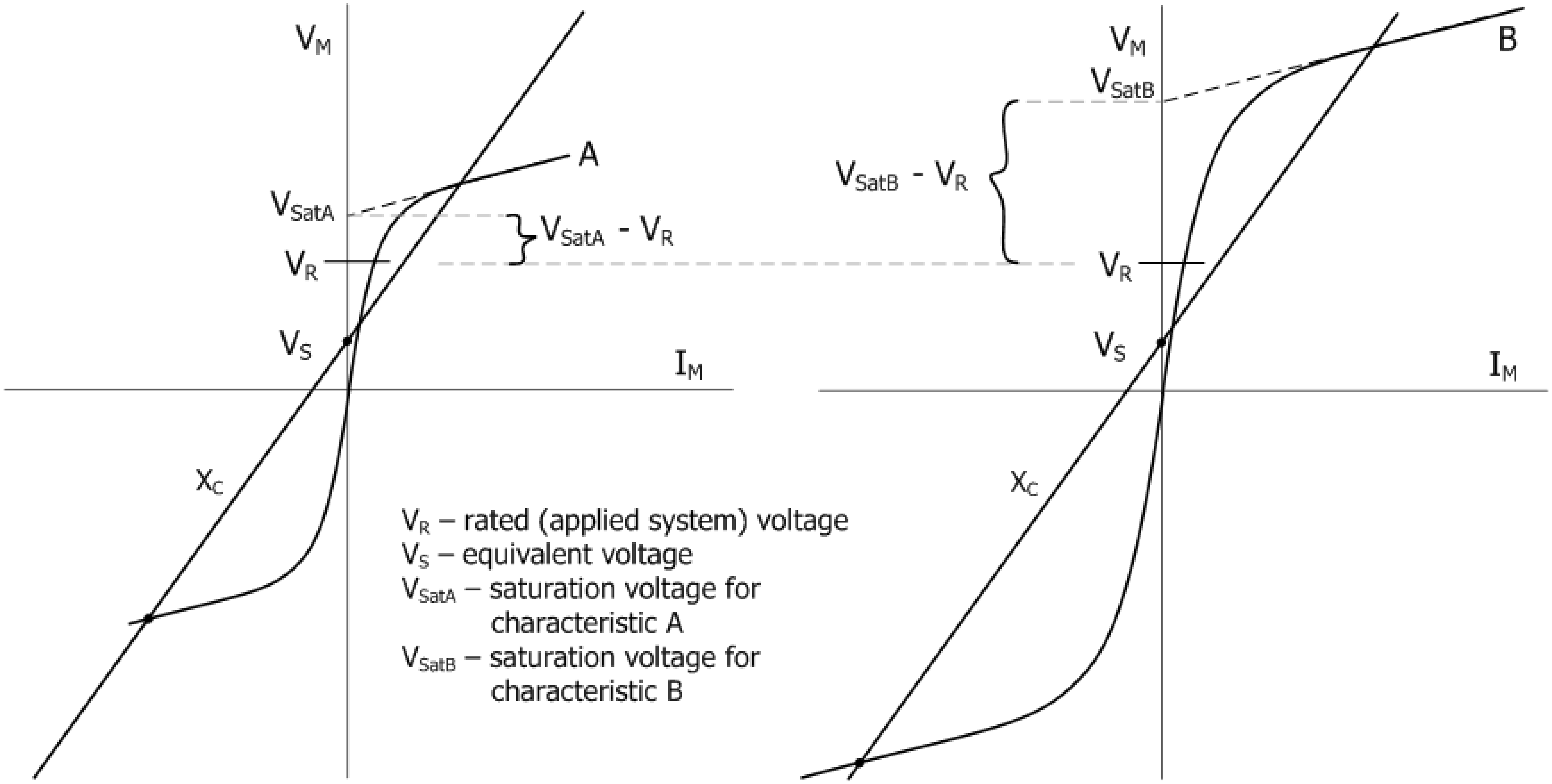
Mitigation

Correcting voltage unbalance

- Change operating procedures
  - E.g. - single phase switching of three phase distribution transformers may be changed to three phase operation
- Applying protective relays to sense and remove the unbalanced condition that drives ferroresonance
  - E.g. - a voltage relay that is used to sense excessive zero sequence voltage and trip a circuit breaker
- Opportunities to correct voltage unbalance should be investigated.
- There are many applications where steady state unbalanced voltages cannot be avoided and alternative solutions are required

Mitigation

Changing the transformer magnetic design

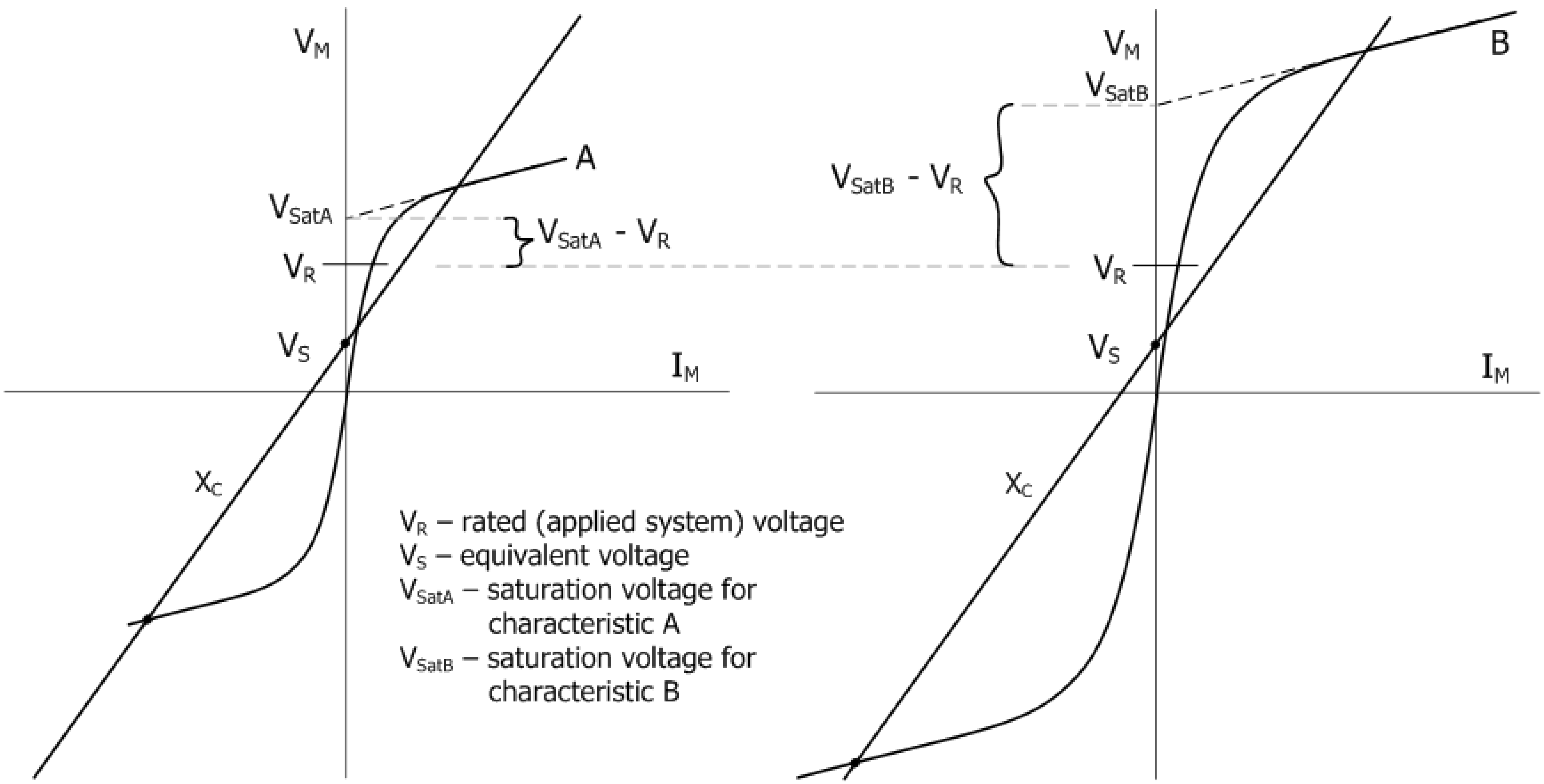


(a) Magnetizing characteristic A

(b) Magnetizing characteristic B

Mitigation

Changing the transformer magnetic design

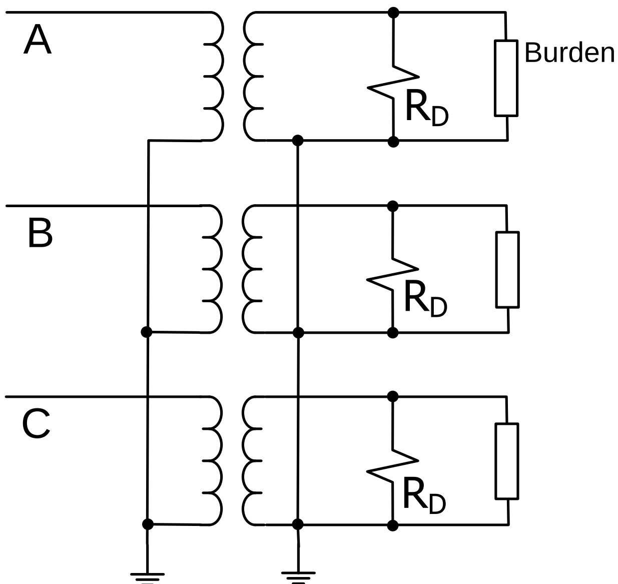


(a) Magnetizing characteristic A

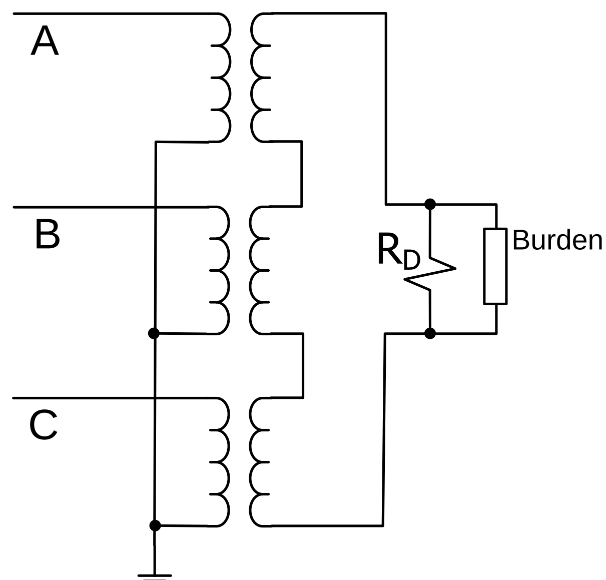
(b) Magnetizing characteristic B

Mitigation

Inserting damping resistance



(a) per phase damping with a wye grounded secondary



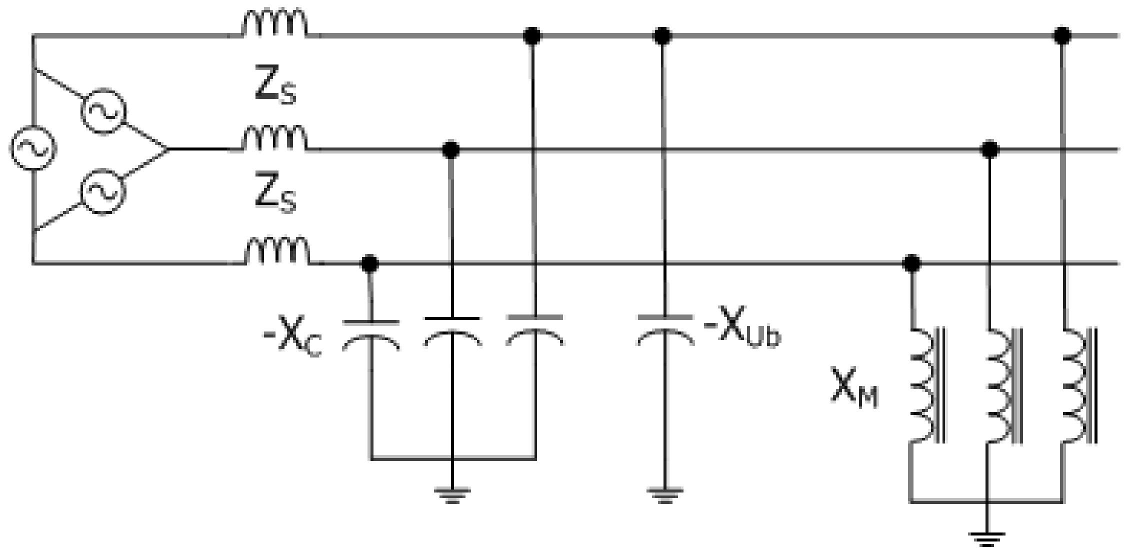
(b) zero sequence damping with a broken delta secondary

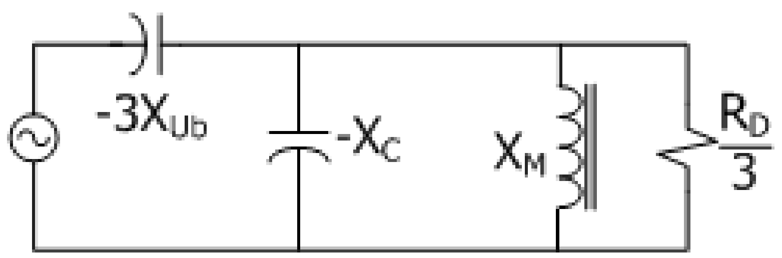
- Generally requires some form of “switching” R_D to address thermal requirements

- May require “switching” to address thermal requirements
- Affect of permanent connection on measurement accuracy of burden devices
- Correction of unbalance

Mitigation

With zero sequence damping resistance

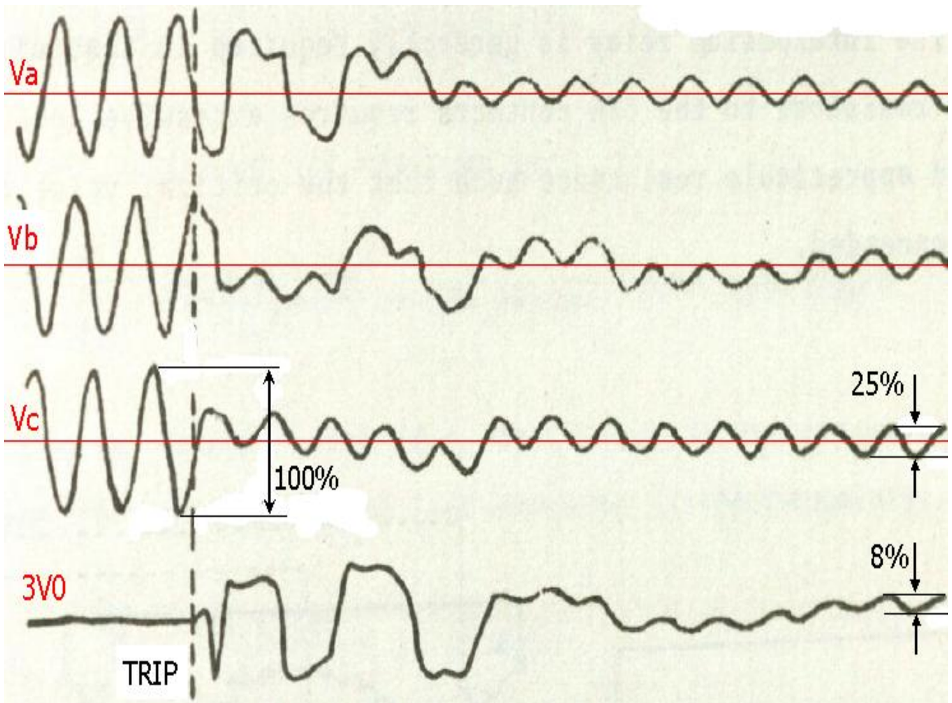




Equivalent Circuit with broken delta resistor R_D

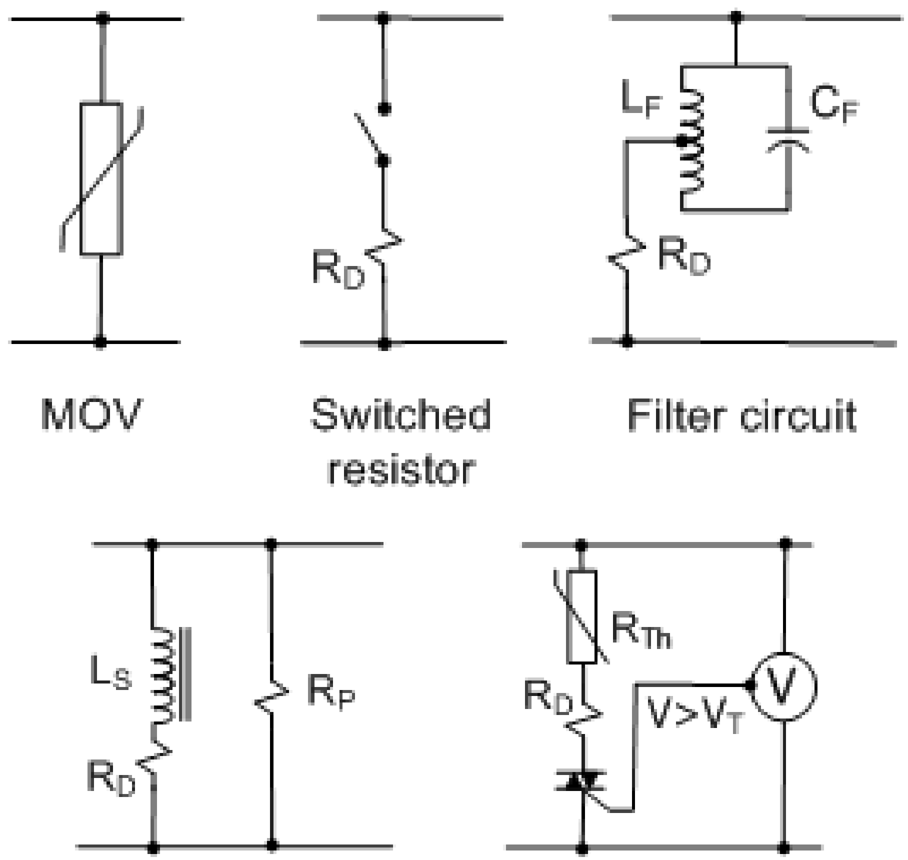
Mitigation

With zero sequence damping resistance



- Ferroresonance has often been mitigated with zero sequence damping
- Coupled phase voltage V_A, V_B, V_C is an indication of phase-to-ground capacitance
- $3V_0$ is an indication of the bus capacitance unbalance
- If $3V_0$ is relatively small zero sequence damping will probably not be sufficient and phase damping required
- About the only generalization that can be made is that the greater the unbalance (the higher $3V_0$) the more likely zero sequence damping will be successful

Ferroresonance Suppression Circuits



MOV

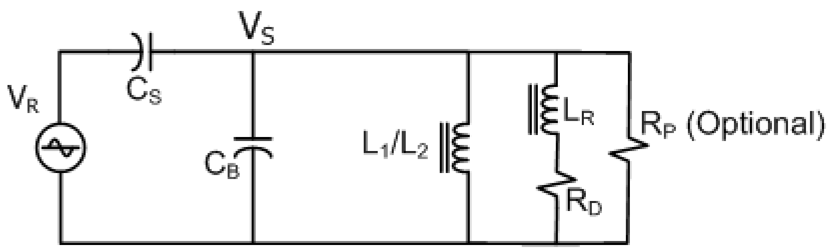
Switched resistor

Filter circuit

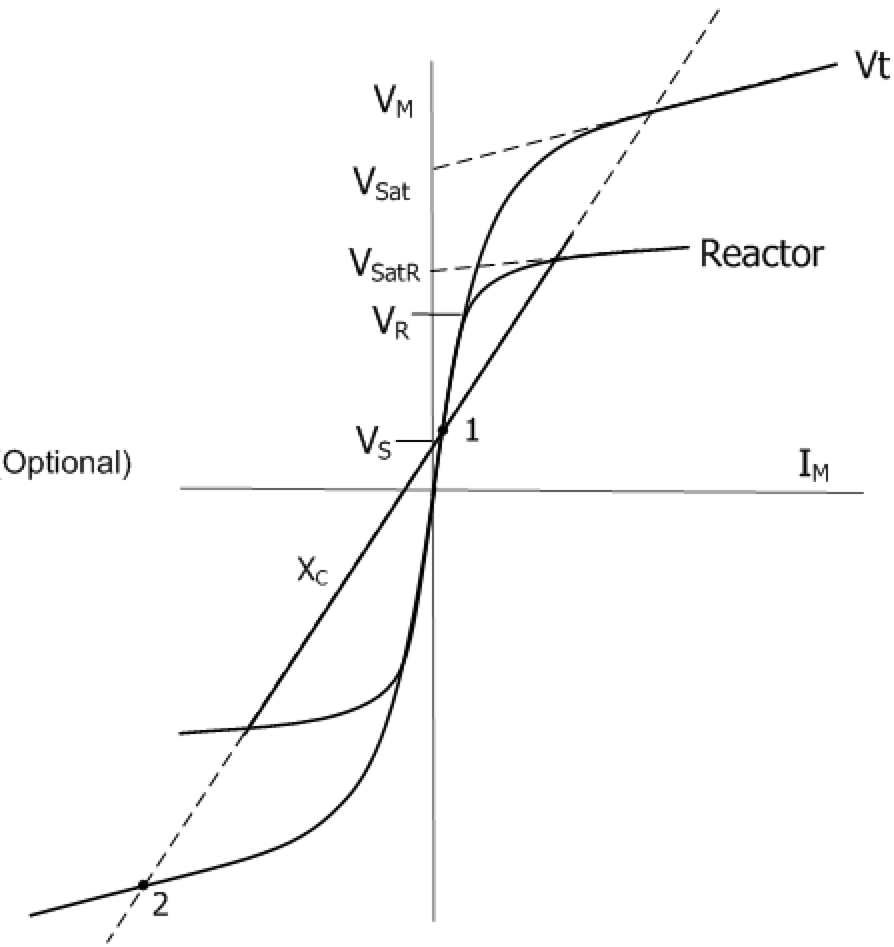
Saturating reactor damping circuit

PTC thermistor with triac switch

Saturating Reactor Damping Circuit

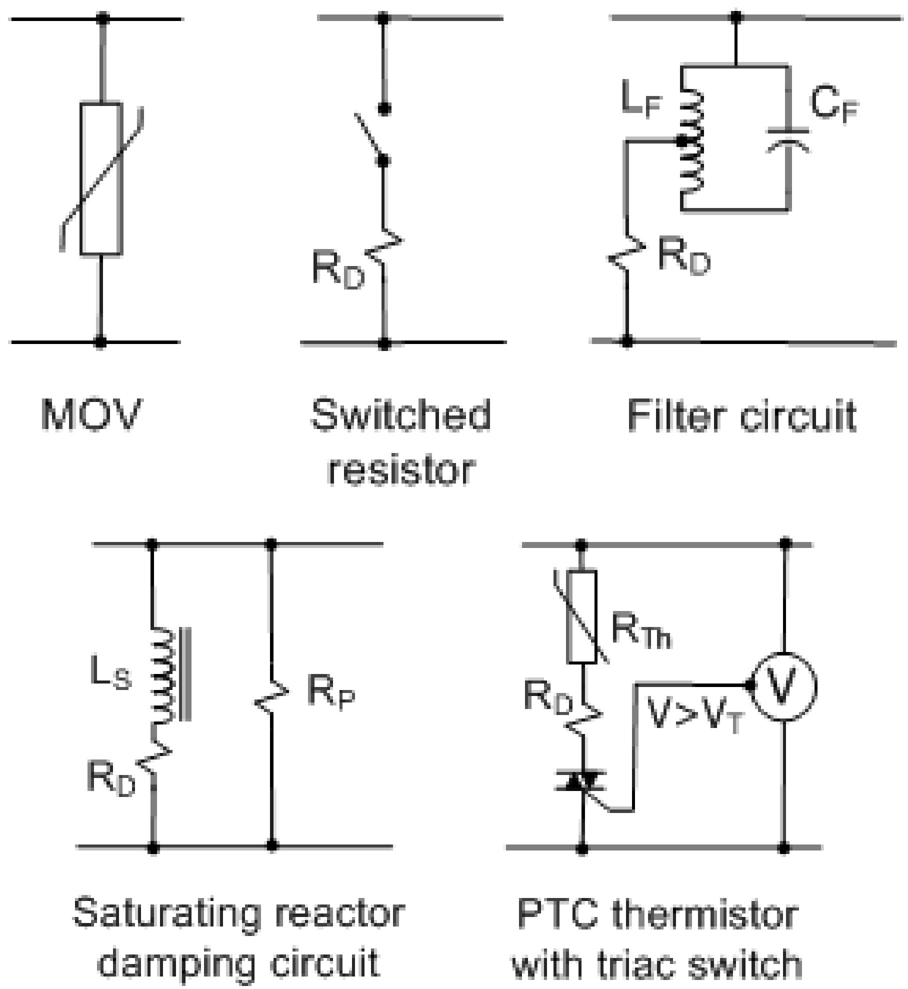


(a) Ferroresonant circuit



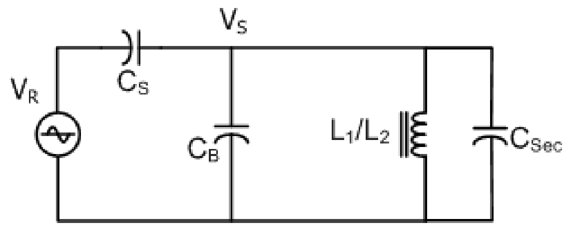
(b) Saturating reactor

Ferroresonance Suppression Circuits

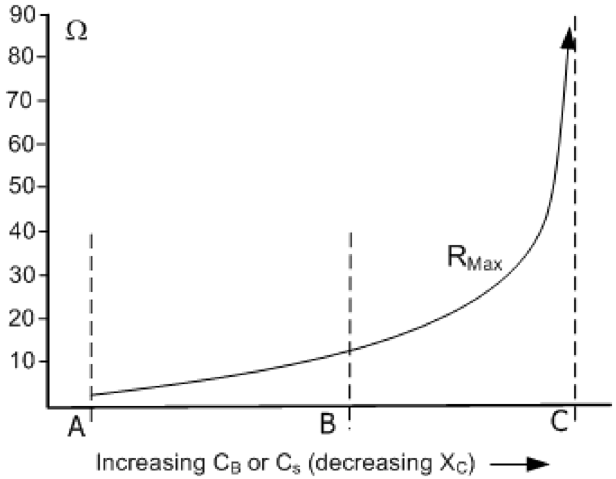


Mitigation

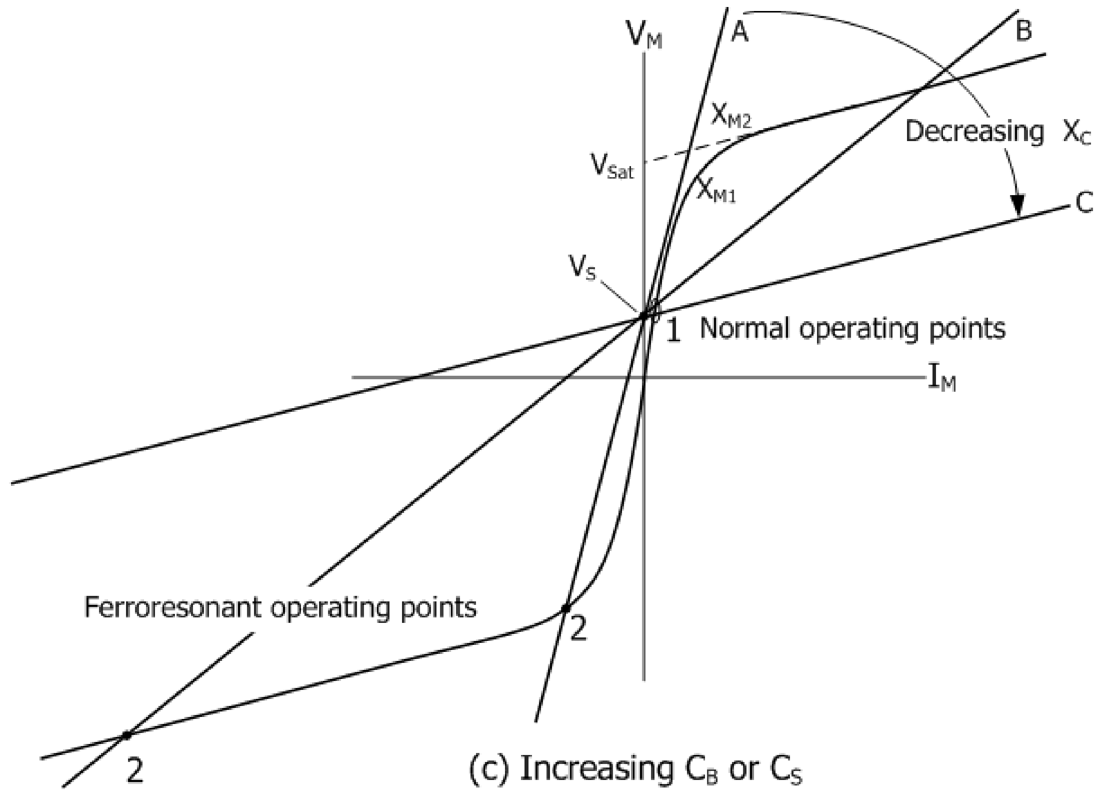
Detuning the ferroresonant circuit



(a) Ferroresonant circuit



(b) Maximum damping resistance



(c) Increasing C_B or C_S

Conclusions

- Ferroresonance is a widely studied phenomenon but it is still not well understood because of its complex behavior - “fuzzy-resonance”
- A simple graphical approach using fundamental frequency phasors has been presented to elevate the readers understanding
- Its occurrence and how it appears is extremely sensitive to the transformer characteristics, system parameters, transient voltages and initial conditions
- More efficient transformer core material has lead to its increased occurrence
- It has considerable effects on system apparatus and protection
- Power system engineers should strive to recognize potential ferroresonant configurations and design solutions to prevent its occurrence