POWER QUALITY

THE SYSTEM MUST BE DESIGNED AND OPERATED MINIMIZING POWER QUALITY PROBLEM.

THE END USER MUST EMPLOY PROPER WIRING SYSTEM, GROUNDING AND STATE OF ART ELECTRONICS DEVICES.

THE MANUFACTURER MUST DESIGN ELECTRONICS DEVICES THAT KEEP ELECTRICAL ENVIRONMENTAL DISTURBANCE TO MINIMUM.

MAIN PHENOMENA CAUSING ELECTROMAGNETIC AND POWER QUALITY DISTURBANCES

LOW FREQUENCY

HARMONICS, SIGNALLING VOLTAGE, FLUCTUATING VOLTAGE, VOLTAGE DIP, VOLTAGE IMBALANCE, POWER FREQUENCY VARIATION, DC COMPONENT IN AC

OPERATED MINIMIZING

WIRING SYSTEM, GROUNDING
CES.

TRONICS DEVICES THAT
TURBANCE TO MINIMUM.

MAGNETIC AND POWER

, FLUCTUATING VOLTAGE,
CE, POWER FREQUENCY
AC

RADIATED LOW FREQUENCY PHENOMENA

MAGNETIC FIELD, ELECTRIC FIELD.

CONDUCTED HIGH FREQUENCY PHEONEMA

INDUCED CONTINUOUS WAVE VOLTAGE / CURRENT

UNIDIRECTIONAL TRANSIENT

OSCILLATORY TRANSIENT.

RADIATED HIGH FREQUENCY PHENOMENA

MAGNETIC FIELD, ELECTRIC FIELD, ELECTROMAGNETIC FIELD

STEADY STATE WAVE, TRANSIENT.

MAGNITUDE OF EVENTS				
above 110%	VERY SHORT OVER VOLTAGE	SHORT OVER VOLTAGE	LONG OVER VOLTAGE	VERY LONG OVERVOLTAGE
110% – 100% – 90%		NORMAL OPERATING VOLTAGE		
below 90%	VERY SHORT UNDER VOLTAGG	SHORT UNDER VOLTAGE	LONG UNDER VOLTAGG	VERY LONG UNDER VOLTAGG
	1-3 cycle		1 → 3 MINUTES	1 → 3 HOUR

TRANSIENT

IMPULSIVE TRA

OSCILLATORY TRAN

SUSTAINED INT

INTERVENTION O

LOW VOLTAGE NE

UNDER VOLTAGE

UNDER U

OVER VOLT

RRENT

A

GNETIC FIELD

LONG OVER VOLTAGE	VERY LONG OVERVOLTAGE
RATING VOLTAGE	
R LONG UNDER VOLTAGE	VERY LONG UNDER VOLTAGE
→ 3 MINUTES	1 → 3 HOUR

TRANSIENT

IMPULSIVE TRANSIENT → SUDDEN FREQUENCY CHANGE IN THE STEADY CONDITION OF VOLTAGE, CURRENT (OR) BOTH

OSCILLATORY TRANSIENT → SUDDEN FREQUENCY CHANGE IN THE STEADY STATE CONDITION OF VOLTAGE, CURRENT OR BOTH THAT INCLUDE BOTH POSITIVE AND NEGATIVE POLARITY VALUES

SUSTAINED INTERRUPTION CAUSED BY FAULT OCCURANCE, INCORRECT INTERVENTION OF PROTECTIVE RELAY, SCHEDULED INTERRUPTION IN A LOW VOLTAGE NETWORK WITH NO REDUNDANCIES CAN CAUSE OVER / UNDER VOLTAGES

UNDER VOLTAGE → 0.8 → 0.9 PU

OVER VOLTAGE → 1.1 → 1.2 PU

P.U - PERUNIT

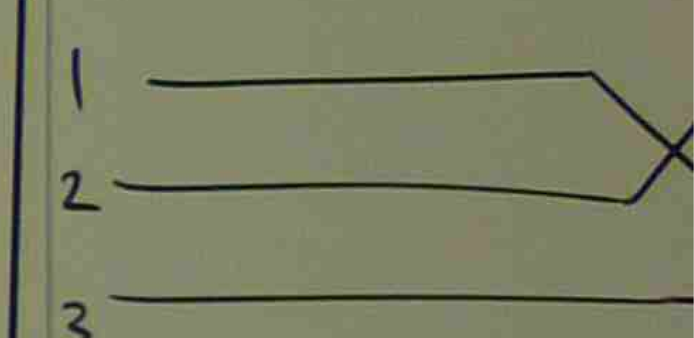
0.8 PU → 80% OF 150V

0.8 x 150 = 120V

VOLTAGE I

CAUSES

- IMBALANCE SI
- OVER HEAD T
- BLOWN OUT
- SEVERE VOLT
  SINGLE PH



WAVE FORM

DC OFFSET

PRESENCE
IN AC SYS

MAIN CAUSES

- EMPLOYME
  DISTURBAN

ANGE IN THE STEADY CONDITION OF
BOTH

HANGE IN THE STEADY STATE
CURRENT OR BOTH THAT
VE AND NEGATIVE POLARITY VALUES

T OCCURANCE, INCORRECT
ULED INTERRUPTION IN A
CLES CAN CAUSE OVER /

P.U - PERUNIT

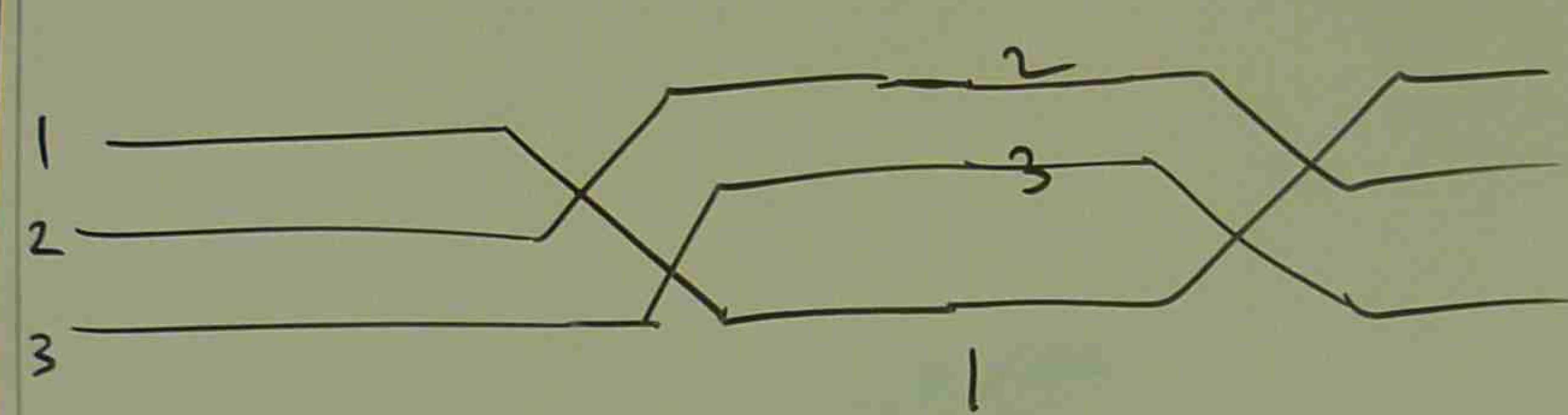
0.8 PU → 80%
OF 150V

0.8×150 = 120V

VOLTAGE IMBALANCE

CAUSES

- IMBALANCE SINGLE PHASE LOADING IN 3ϕ SYSTEM
- OVER HEAD TRANSMISSION LINES THAT ARE NOT TRANSPOSED.
- BLOWN OUT FUSES IN 1ϕ OR 3ϕ CAPACITOR BANKS.
- SEVERE VOLTAGE IMBALANCE (> 5%) RESULTED FROM SINGLE PHASING CONDITION.



WAVE FORM DISTORTION

DC OFFSET

PRESENCE OF DC CURRENT AND/OR VOLTAGE COMPONENT IN AC SYSTEM.

MAIN CAUSES

- EMPLOYMENT OF RECTIFIERS AND OTHER ELECTRONIC SWITCHING DISTURBANCES.

EFFECT

- $\frac{1}{2}$ CYCLE SATURAT
- GENERATION OF EVE
ODD HARMONIC
- ADDITIONAL HEATIN
DECREASE OF THE
- ELECTROLYTIC ER
AND OTHER CONNECT

HARMONIC

HARMONIC IS CAUSE
LOADS SUCH AS TR
LOAD WITH SWITCHING

NOTCHING

MOMENTARY S
COMMUTATING P
- REPRESENTED

NG IN 3φ SYSTEM

THAT ARE NOT TRANSPOSED.

R 3φ CAPACITOR BANKS.

> 5%) RESULTED FROM

AND/OR VOLTAGE COMPONENT

AND OTHER ELECTRONIC SWITCHING

EFFECT

- $\frac{1}{2}$ CYCLE SATURATION OF TRANSFORMER CORE
- GENERATION OF EVEN HARMONIC IN ADDITION TO ODD HARMONIC
- ADDITIONAL HEATING IN APPLIANCES LEADING TO DECREASE OF THE LIFE TIME OF TRANSFORMER.
- ELECTROLYTIC EROSION OF GROUNDING ELECTRODES AND OTHER CONNECTORS.

HARMONIC

HARMONIC IS CAUSED BY INDUSTRIAL NON LINEAR LOADS SUCH AS TRANSFORMER, INVERTER, RESIDENTIAL LOAD WITH SWITCHING MODE POWER SUPPLIES.

NOTCHING

MOMENTARY SHORT CIRCUIT BETWEEN TWO COMMUTATING PHASES REDUCING LING VOLTAGE.

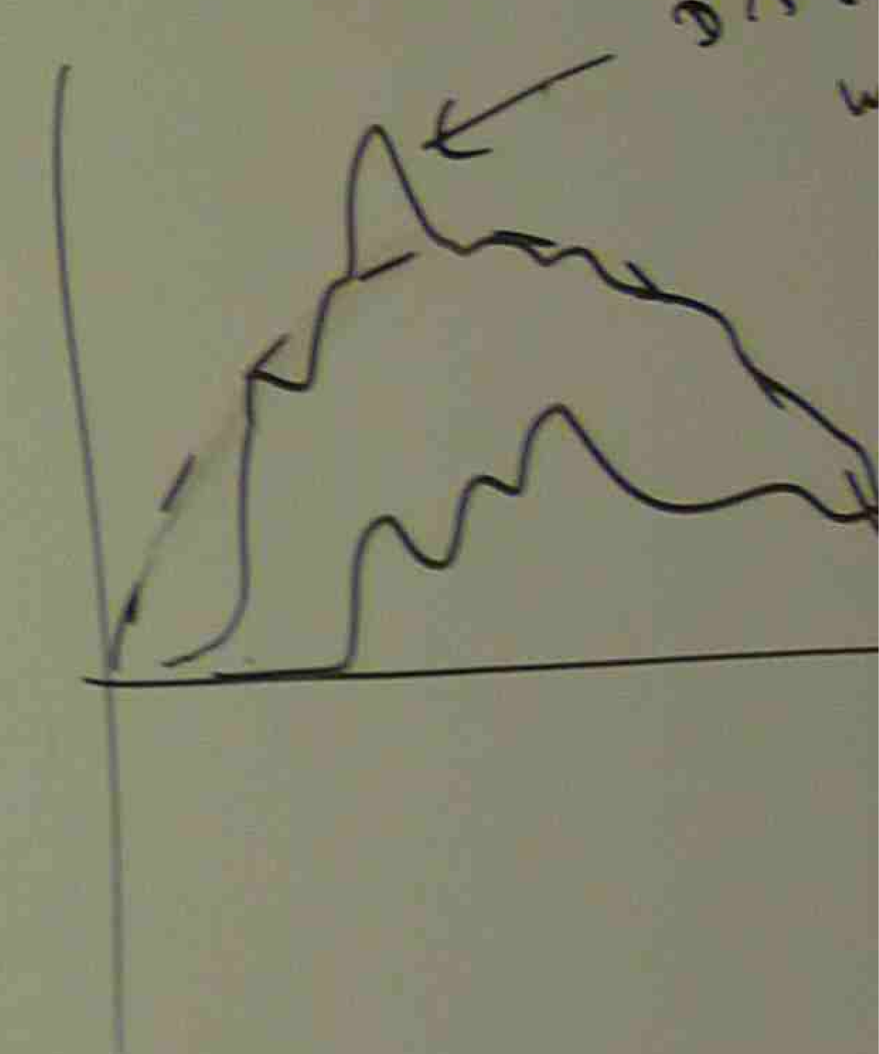
- REPRESENTED BY ELECTRIC NOISE, FLICKERING.

POWER FREQUENCY VARIATI

- CAUSED BY CHANGES IN R
ELECTROMAGNETIC GENER

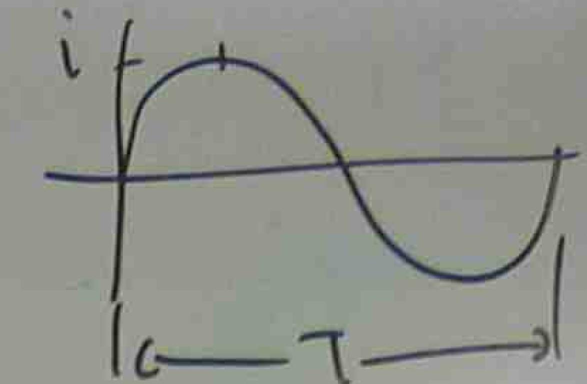
POWER QUALITY MEASUREME

IEC STANDARD



FILTER IS TO B

THE HARMONIC.

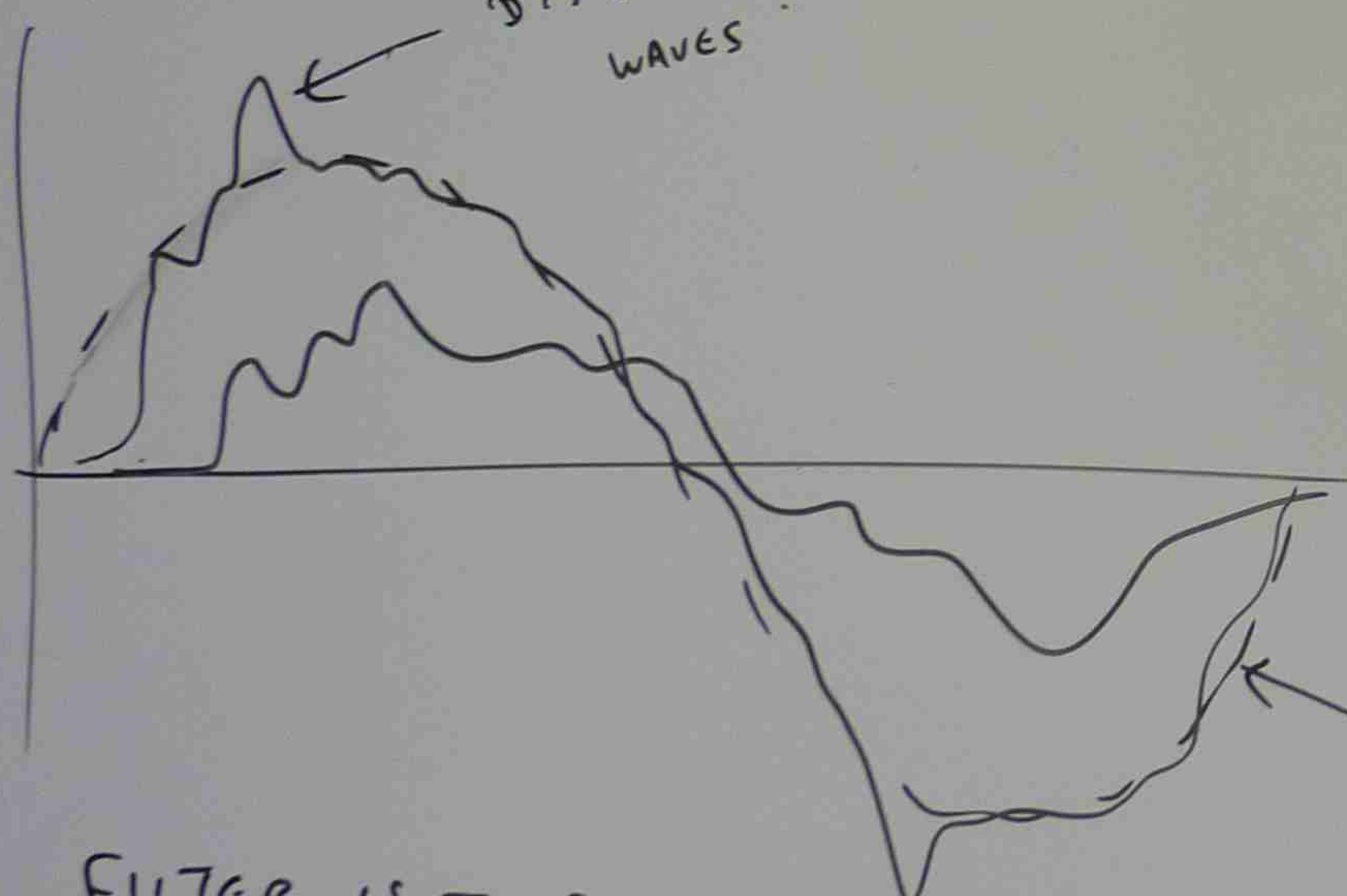


POWER FREQUENCY VARIATION

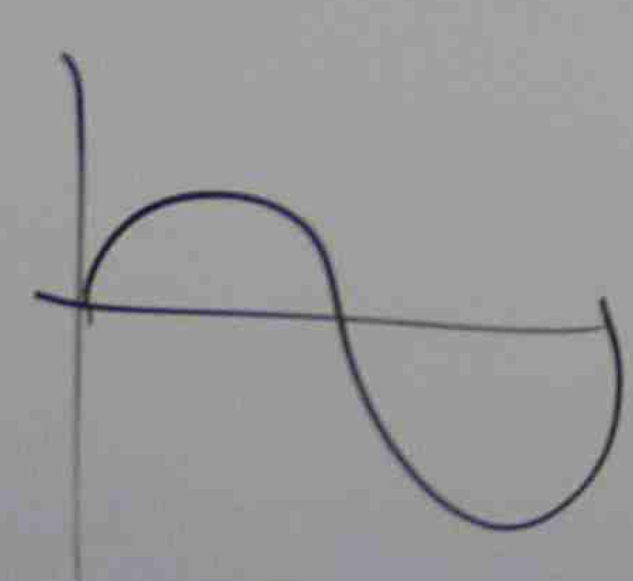
- CAUSED BY CHANGES IN ROTATIONAL SPEED OF ELECTROMAGNETIC GENERATORS.

POWER QUALITY MEASUREMENT → IEEE STANDARD 100

IEC STANDARD 61000



FILTER IS TO BE USED TO REDUCE THE HARMONIC.



$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2\,dt}$$

FF – form factor $= \dfrac{I_{rms}}{I_{AVERAGE}}$

FF = 1.1 for SING WAVE

RIPPLE FACTOR $= \sqrt{\text{form factor}^2 - 1}$

TOTAL DEMAND DISTORTION $= \dfrac{\sqrt{\sum_{2}^{L} (I^h)^2}}{\text{RATED CURRENT}}$

$I_1 = 3A$, $I_2 = 2A$, $I_3 = 5A$

$$I_{rms} = \sqrt{\frac{3^2 + 2^2 + 5^2}{3}}$$

$$I_{AVG} = \frac{3 + 2 + 5}{3}$$

EFFECTS OF POOR POWER QUALITY ON POWER SYSTEM DEVICES

- HARMONIC ADDED TO THE RMS AND PEAK VALUE OF THE WAVE FORM. THE EQUIPMENT CAN RECEIVE A DAMAGINGLY HIGH PEAK VOLTAGE

- ADVERSE EFFECT FROM HEATING, NOISE, REDUCED LIFE OF CAPACITORS, SURGE SUPPRESSORS, ROTATING MACHINES, CABLE, TRANSFORMERS
- OVER HEATING OF DISTRIBUTION TRANSFORMERS.
- FAILURE OF POWER SYSTEM EQUIPMENTS.
- MALFUNCTIONING OF PROTECTIVE DEVICES
- HARMONIC INSTABILITY

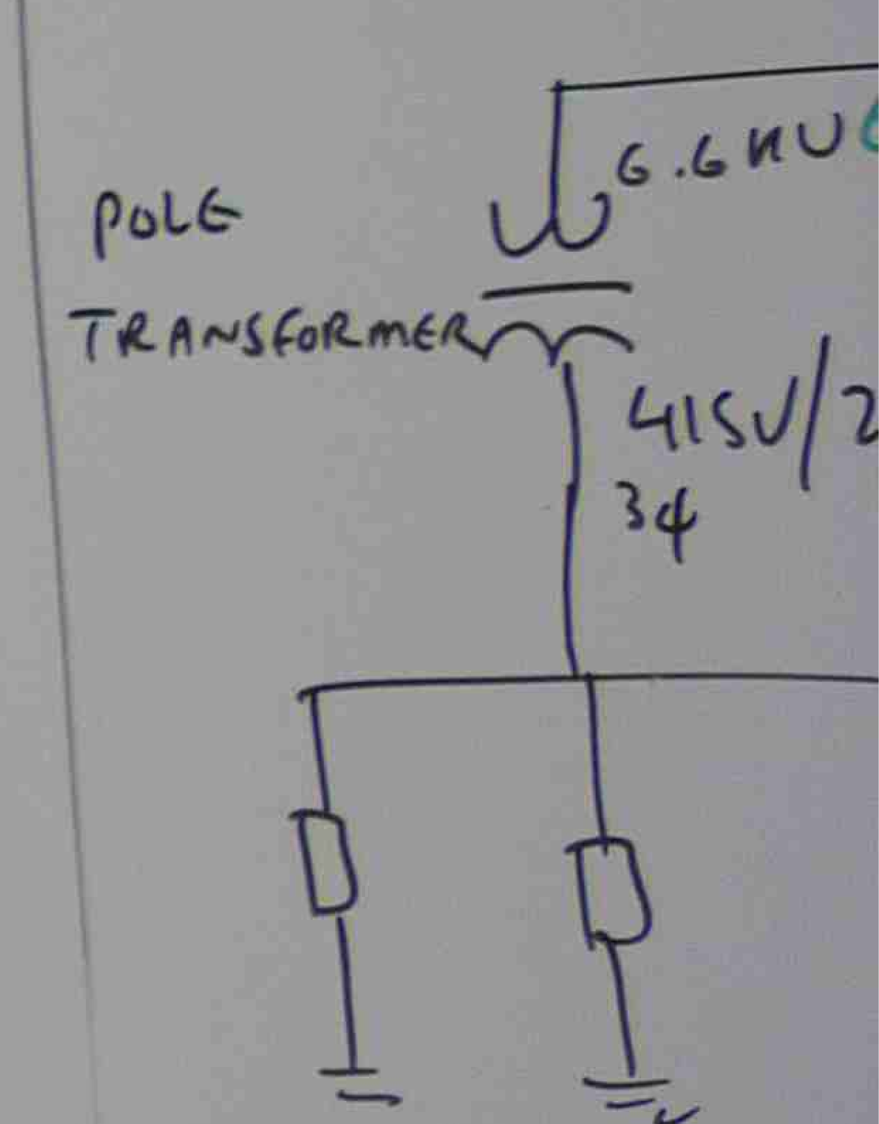
ITERATIVE

HARMONIC IEC 61000

HARMONIC MODELLING ⟶ TIME DOMAIN
HARMONIC DOMAIN SIMULATION
ITERATIVE SIMULATION

POWER QUALITY (M

- HARMONIC CA
- FILTERING (
- USE OF ISO
- DERATING P



YSTEM DEVICES

AK VALUE OF THE
E A DAMAGINGLY

REDUCED LIFE OF
NG MACHINES,

RANSFORMERS.
NTS,
VICES

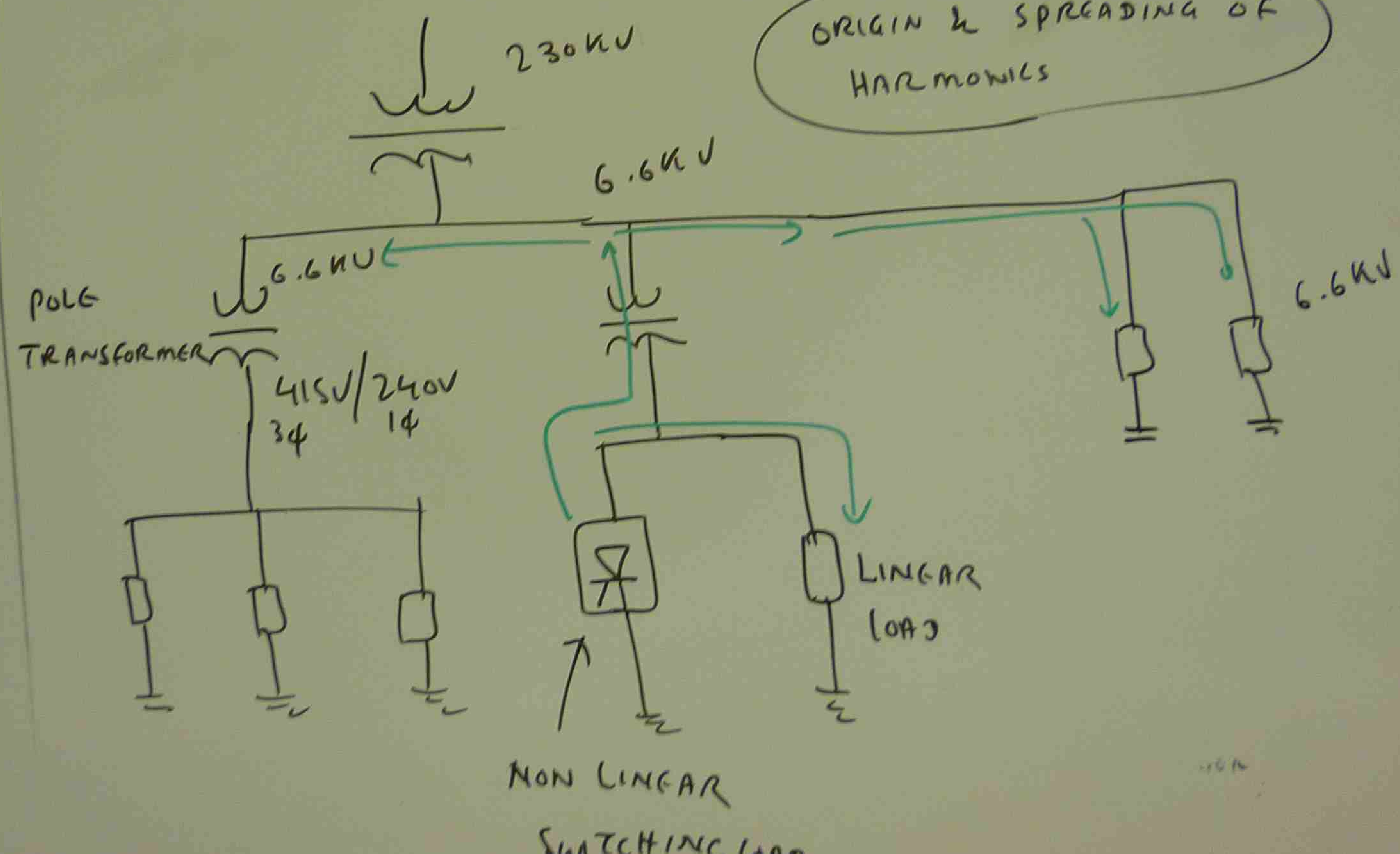
ITERATIVE

MAIN
AC DOMAIN SIMULATION
TIVE SIMULATION

POWER QUALITY IMPROVEMENT

- HARMONIC CANCELLATION
- FILTERING (ACTIVE / PASSIVE / HYBRID)
- USE OF ISOLATION TRANSFORMER
- DERATING POWER SYSTEM DEVICES.

ORIGIN & SPREADING OF HARMONICS



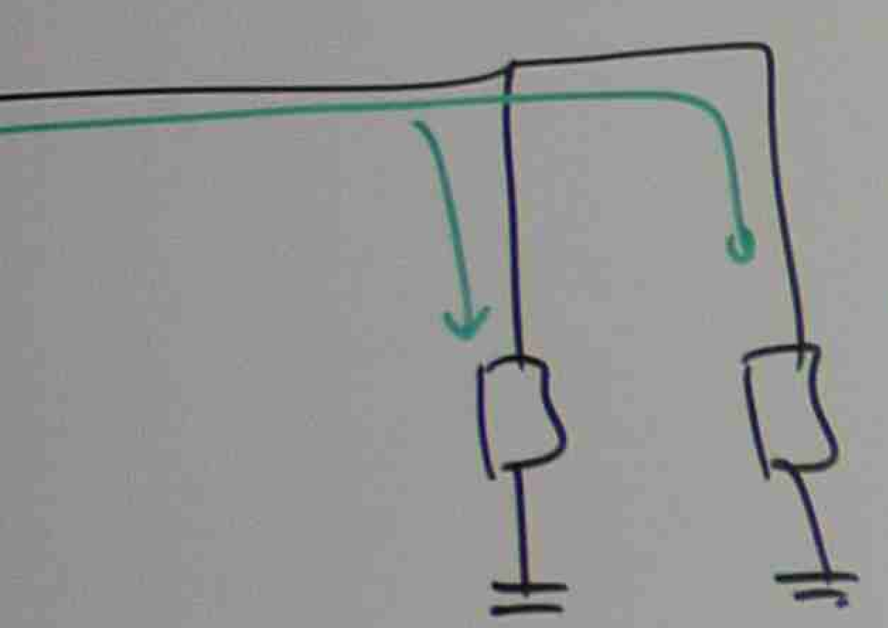
- CAPACITORS
- TRIPLEX
3ϕ SYSTE
- LEADING
INSTABILIT

POWER QU

- UNBALANCE
- TORQUES
LINE TO
- UNBALAN
- WINDING
- EXCESSIV
- EXCESSI
- MECHAN
- HEATIN
- DYNAM

D/

IN & SPREADING OF
RMONICS



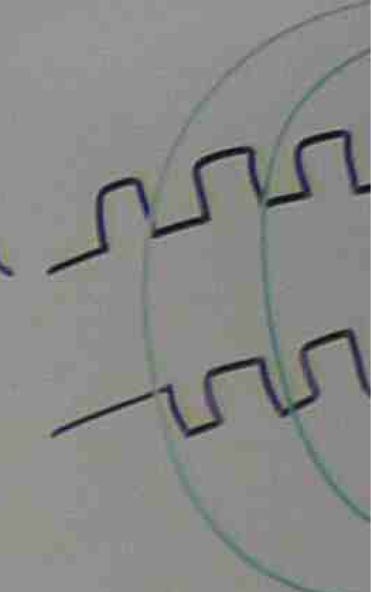
EAR
D

- CAPACITORS USED FOR P.F CORRECTION CAN CAUSE HARMONIC
- TRIPLEX (MULTIPLES OF 3) AND EVEN HARMONIC DO NOT EXIST IN 3ϕ SYSTEM
- LEADING POWER FACTOR LOADS CAN CAUSE OSCILLATIONS AND INSTABILITY IN POWER SYSTEM.

POWER QUALITY PROBLEMS OF SYNCHRONOUS MACHINES

- UNBALANCED LOADS.
- TORQUES DURING FAULTS SUCH AS SHORT CIRCUITS (BALANCED 3ϕ LINE TO LINE, LINE TO GROUND)
- UNBALANCED LINE VOLTAGES, RECLOSURES
- WINDING FORCES DURING ABNORMAL OPERATION & FAULTS.
- EXCESSIVE SATURATION OF IRON CORES
- EXCESSIVE VOLTAGE AND CURRENT HARMONICS
- MECHANICAL VIBRATION AND HUNTING
- HEATING / INSULATION STRESSES.
- DYNAMIC INSTABILITY.

ELECT



V =

T = K

CONST

EQUIVALENT CIR

...ronic

...o NOT EXIST IN

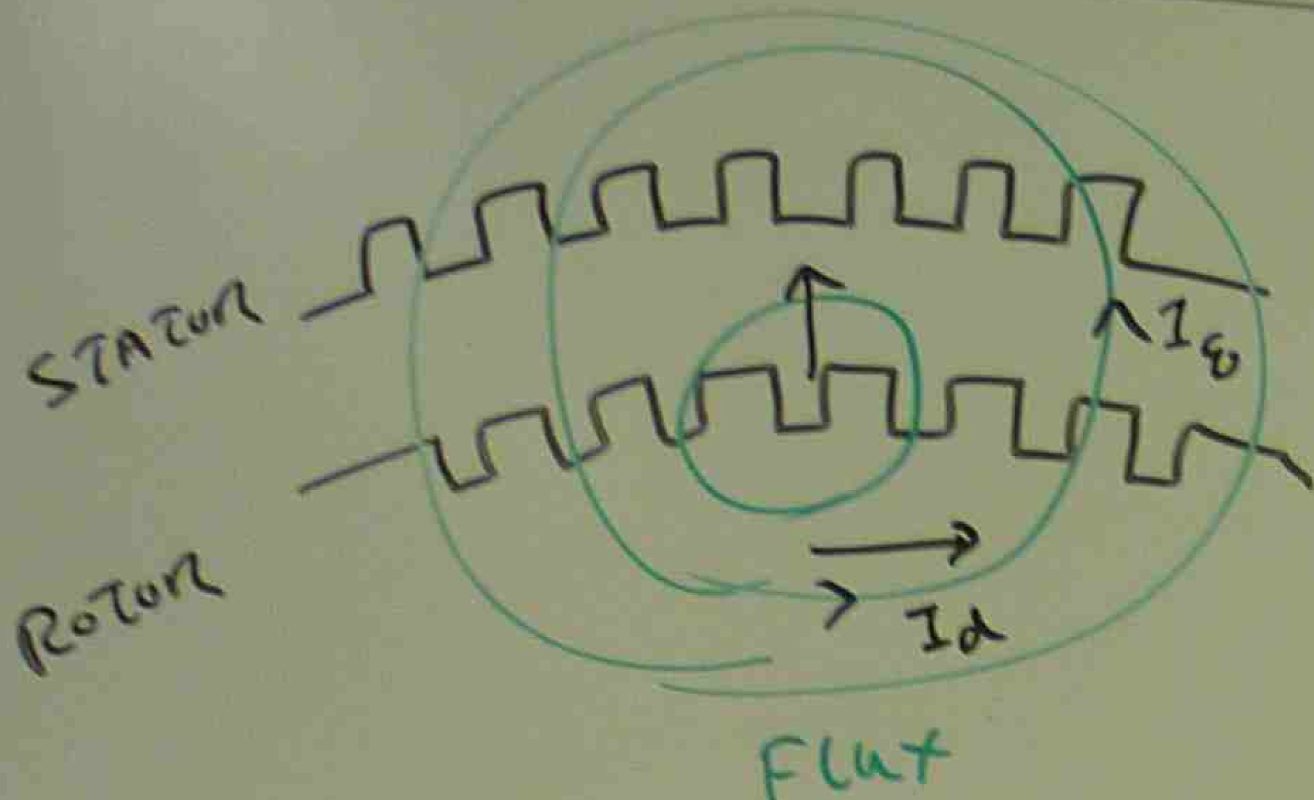
...US AND

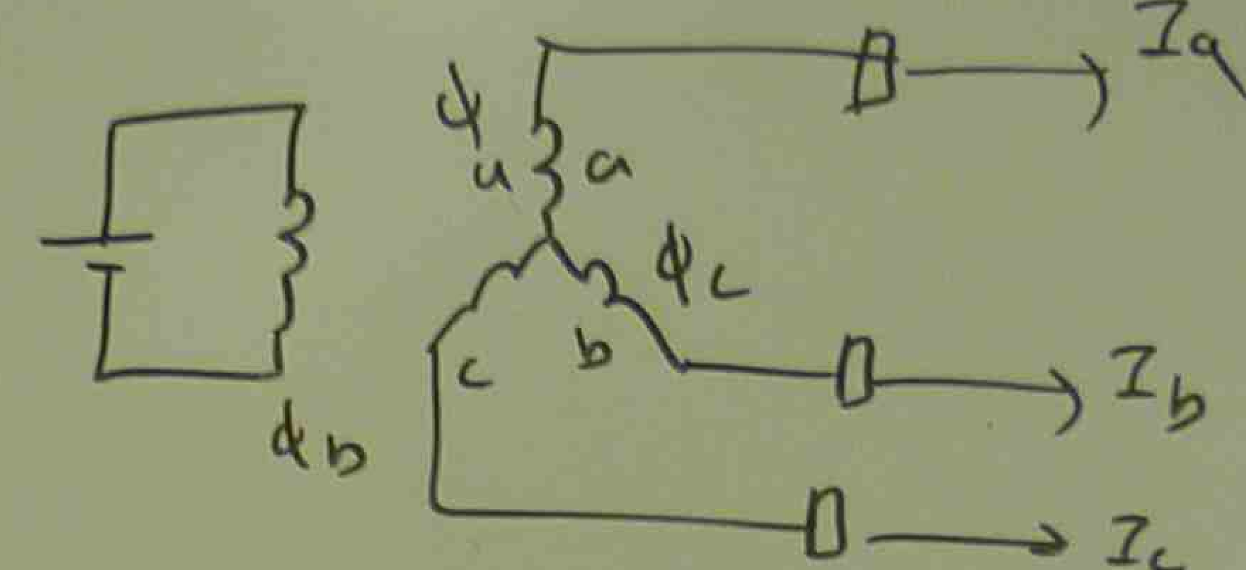
...ES

...LANCED 3φ

FAULTS.

ELECTRICAL EQUATION OF SYNCHRONOUS MACHINE





R_a = WINDING RESISTANCE

$$V = Ri + \frac{d\phi}{dt}$$

$$T = K \frac{2}{3\sqrt{3}} \left[\phi_a (i_b - i_c) + \phi_b (i_c - i_a) + \phi_c (i_a - i_b) \right]$$

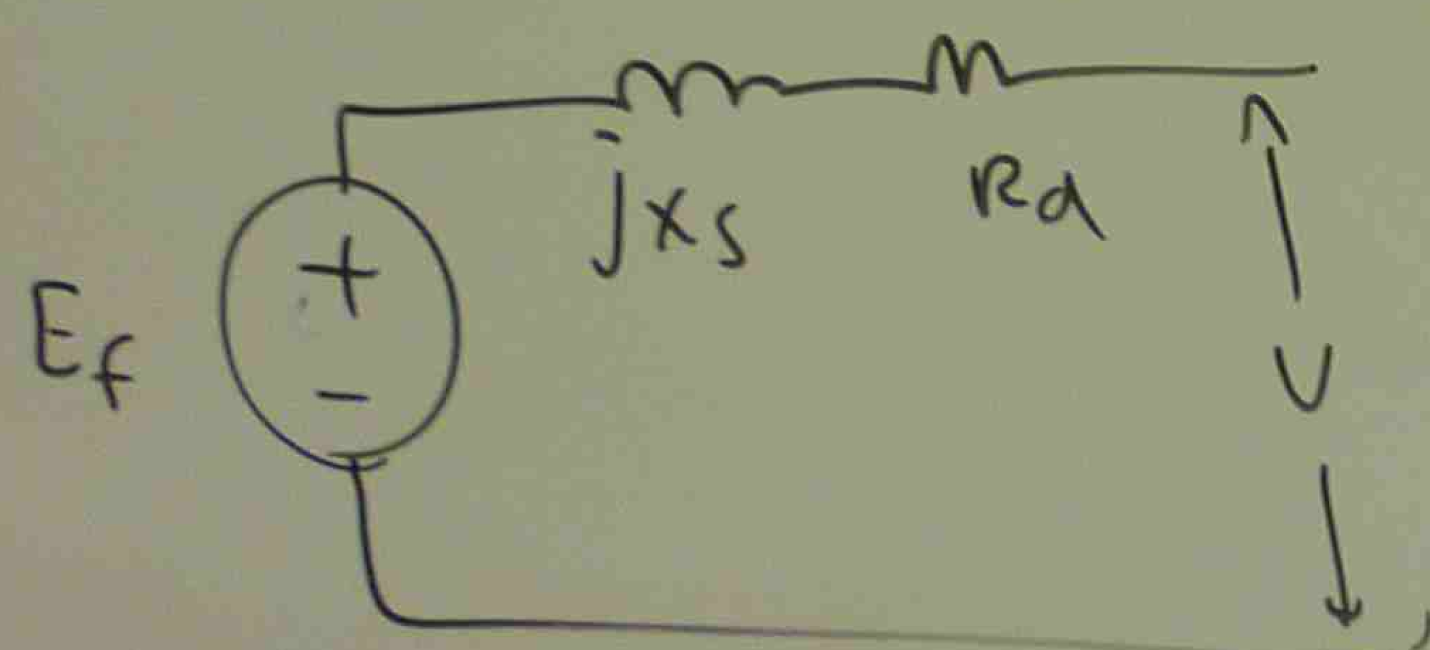
CONSTANT

I_d = DIRECT COMPONENT CURRENT

I_q = QUADRATURE COMPONENT CURRENT

X_d = DIRECT COMPONENT INDUCTIVE REACTANCE

X_q = QUADRATURE COMPONENT INDUCTIVE REACTANCE



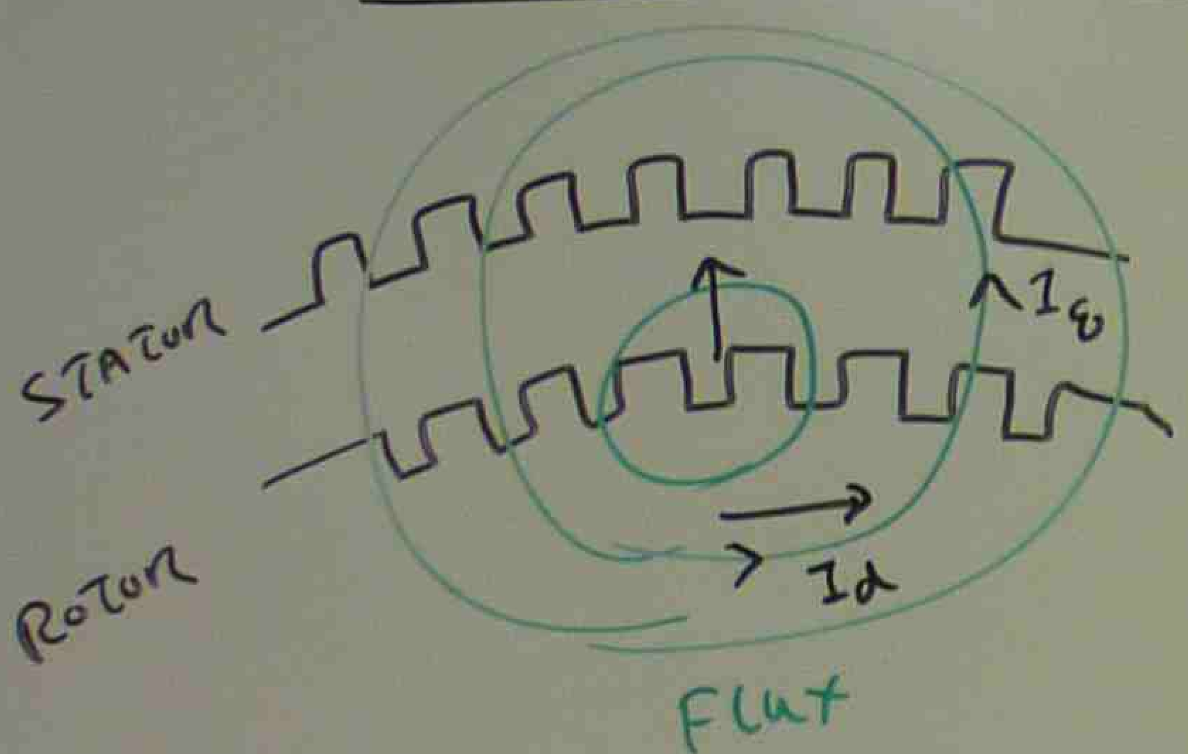
EQUIVALENT CIRCUIT

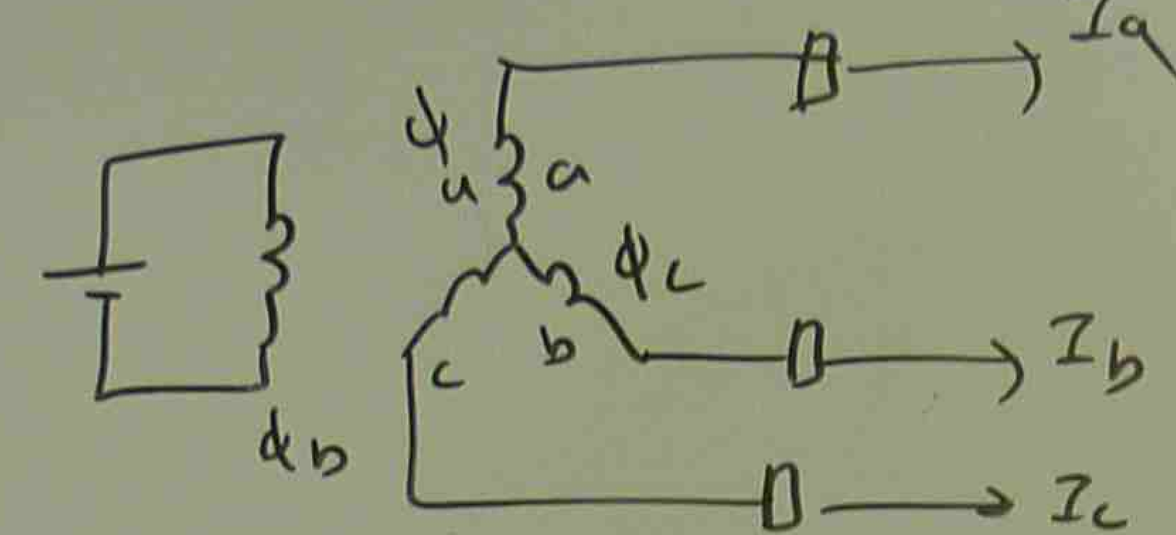
$$I_d = \frac{-R_d V_d + \dots}{X_d X_q - \dots}$$

$$I_q = \frac{X_d V_d + R\dots}{X_d X_q + \dots}$$

ELECTRICAL EQUATION OF SYNCHRONOUS MACHINE

R_a = WINDING RESISTANCE





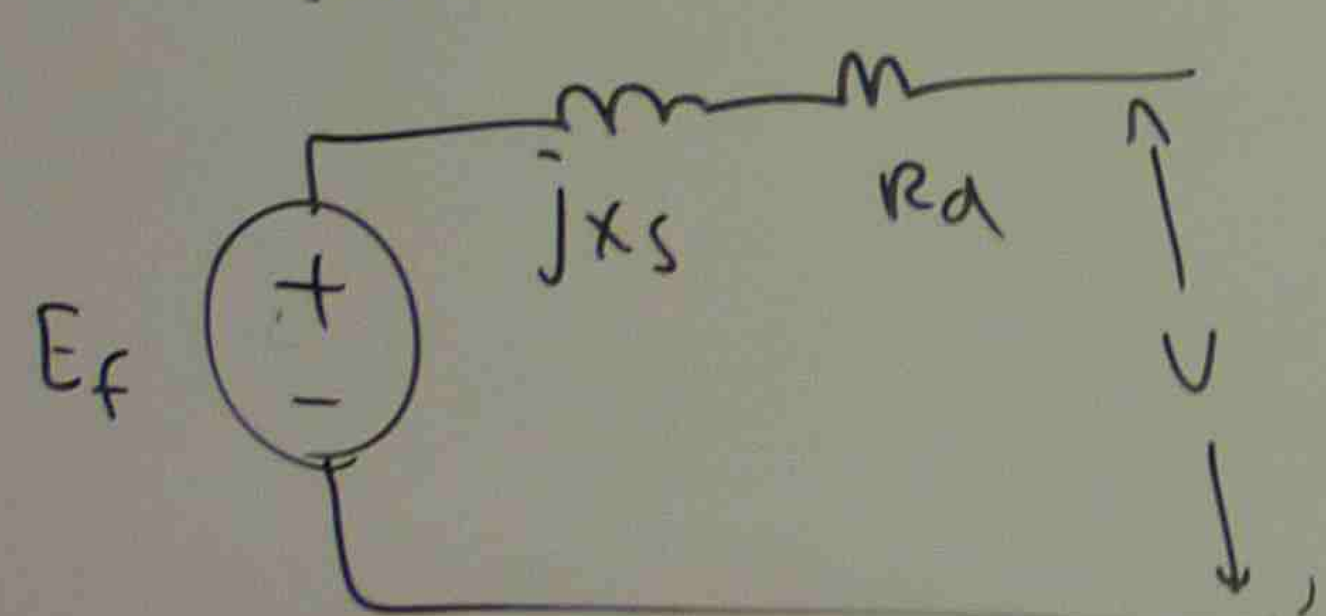
$$I_d = \frac{-R_d V_d + V_q(E_f - V_q)}{X_d X_q + R_a^2}$$

$$I_q = \frac{X_d V_d + R_d(E_f - V_q)}{X_d X_q + R_a^2}$$

$$V = Ri + \frac{d\phi}{dt}$$

$$T = K \frac{2}{3\sqrt{3}} \left[\phi_a (i_b - i_c) + \phi_b (i_c - i_a) + \phi_c (i_a - i_b) \right]$$

K = CONSTANT



EQUIVALENT CIRCUIT

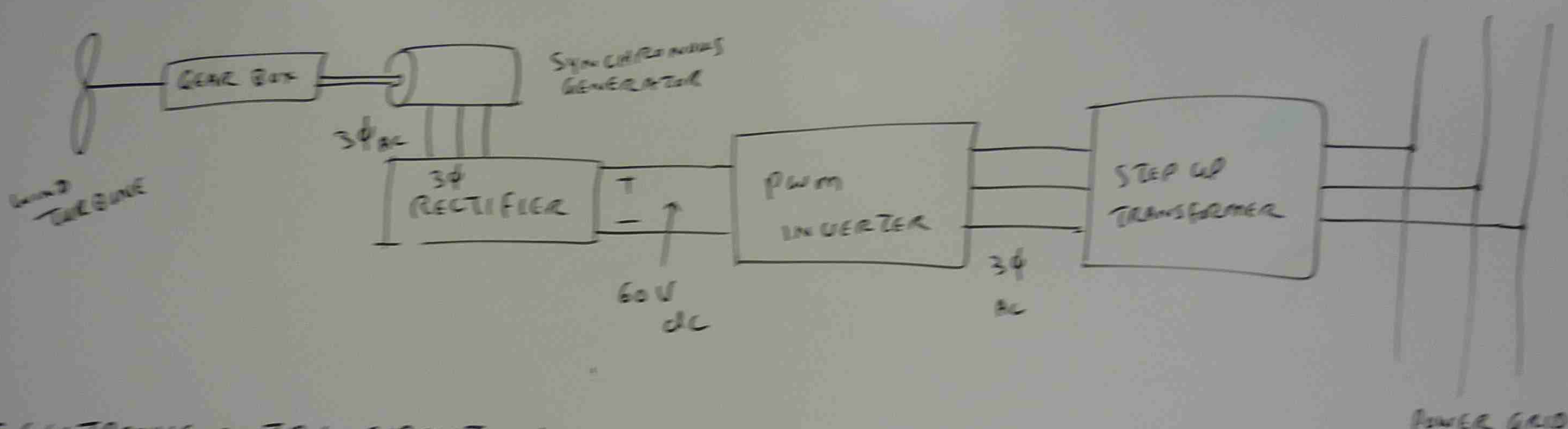
I_d = DIRECT COMPONENT CURRENT

I_q = QUADRATURE COMPONENT CURRENT

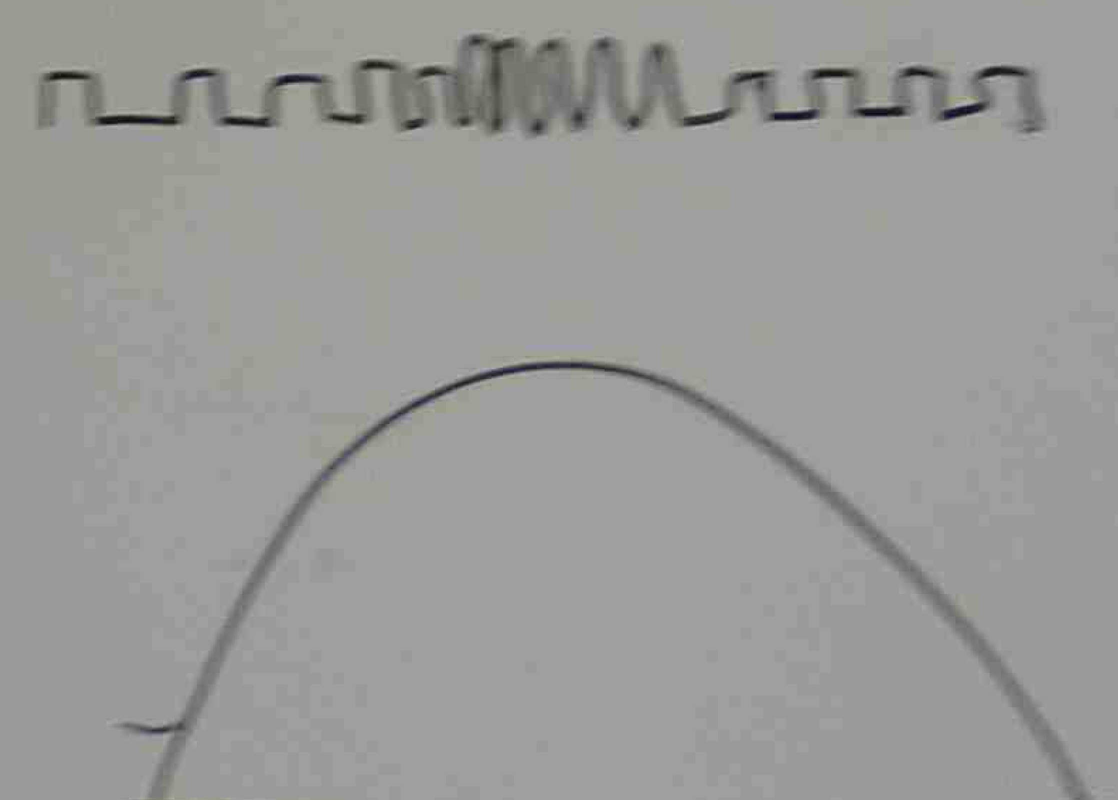
X_d = DIRECT COMPONENT INDUCTIVE REACTANCE

X_q = QUADRATURE COMPONENT INDUCTIVE REACTANCE

POWER QUALITY OF WIND TURBINE GENERATORS



ELECTRONICS CONTROL CIRCUIT IS UTILIZED TO IMPROVE THE POWER QUALITY OF WIND TURBO GENERATOR.



IN ORDER FOR ROTATING MACHINES TO WORK PROPERLY AND NOT TO CAUSE POWER QUALITY PROBLEM, LIMIT FOR MAXIMUM FLUX AND CURRENT DENSITIES MUST BE MET SO THAT NEITHER EXCESSIVE SATURATION NOR HEATING OCCURS.

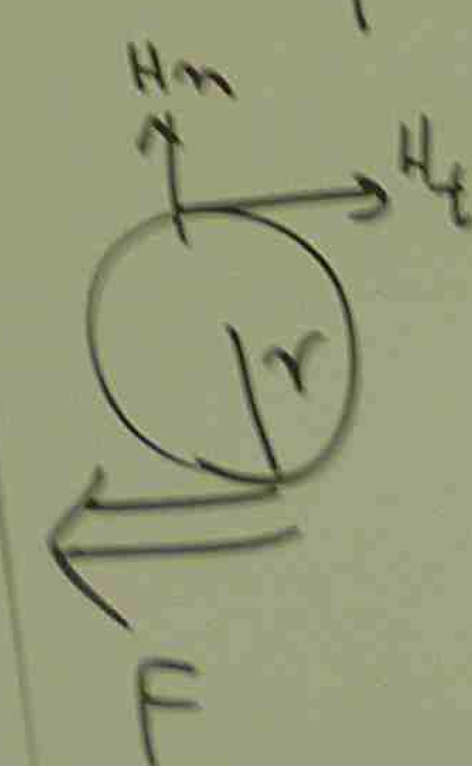
STATOR BACK IRON	STATOR TEETH MAXIMUM VALUE	STATOR TEETH MIDDLE OF TOOTH HEIGHT	SOLID ROTOR	SOLID ROTOR TEETH NEAR WINDING	SOLID ROTOR BACK IRON	SOLID ROTOR CAST IRON
$1 \longrightarrow 1.4$	$1.6 \longrightarrow 1.8$	$1.35 \longrightarrow 1.55$	$1.2 \longrightarrow 1.5$	< 2.4	$1 \rightarrow 1.4$	0.7

NECESSARY CHARACTERISTICS

- SURFACE MUST BE IN AIR
- ARTIFICIAL AIR GAP DOES NOT CAUSE A SIGNIFICANT CHANGE IN THE MAGNETIC FIELD
- SURFACE MAY BE ANY THAT FULLY ENCLOSES THE BODY

$$F = \frac{1}{2}\mu_0\left(H_n^2 - H_t^2\right)$$

INFLUENCED BY LENGTH OF MAGNETIC PATH



F = MECHANICAL FORCE (N)

μ_0 = PERMEABILITY $4\pi \times 10^{-7}$

H_n = NORMAL MAGNETIZING FORCE

H_t = TANGENTIAL MAGNETIZING FORCE

$T = f \times r$ (r = RADIUS OF ROTOR – m)

T = TORQUE (N–m)

...NCES BY
...H OF
...AGNETIC PATH

...ORCE

...OR - m)

m)

HARMONIC MODELLING OF SYNCHRONOUS MACHINES

FREQUENCY CONVERSION PROCESS

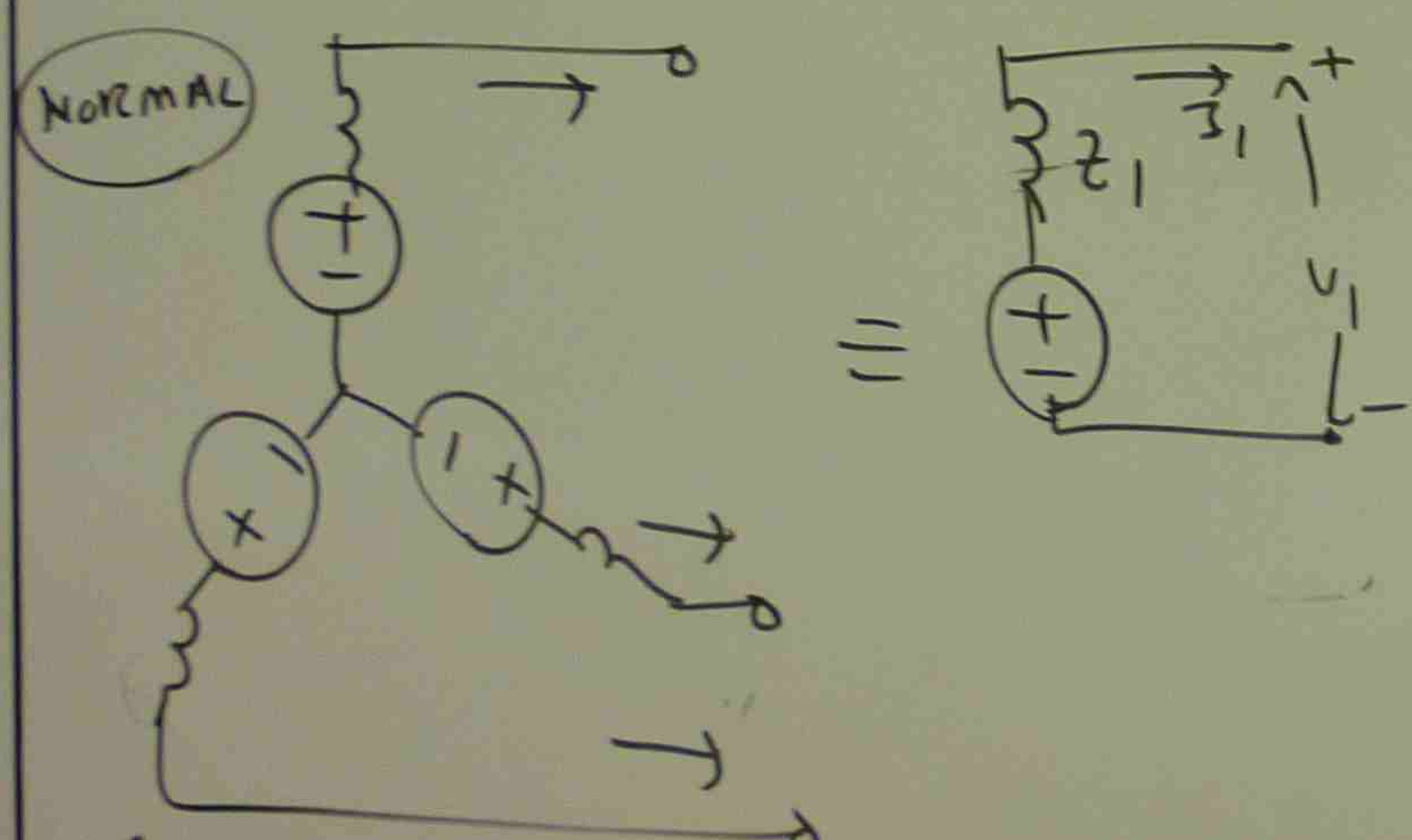
SYNCHRONOUS MACHINE MAY EXPERIENCE A NEGATIVE SEQUENCE CURRENT IN ARMATURE.

SATURATION EFFECT

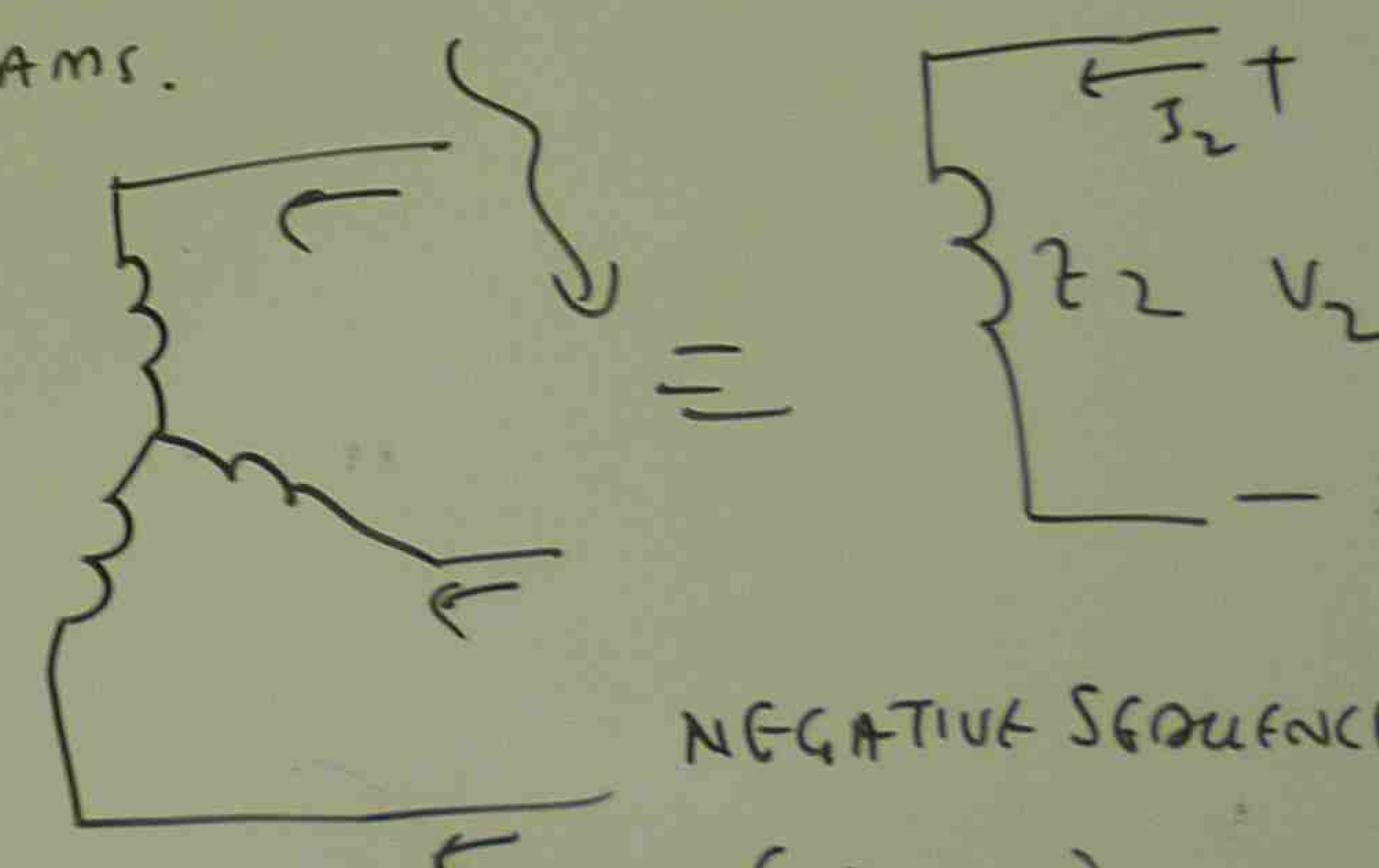
SATURATION EFFECT INTERACTS WITH FREQUENCY CONVERSION PROCESS

MACHINE LOAD FLOW / SYSTEM CONSTRAINTS

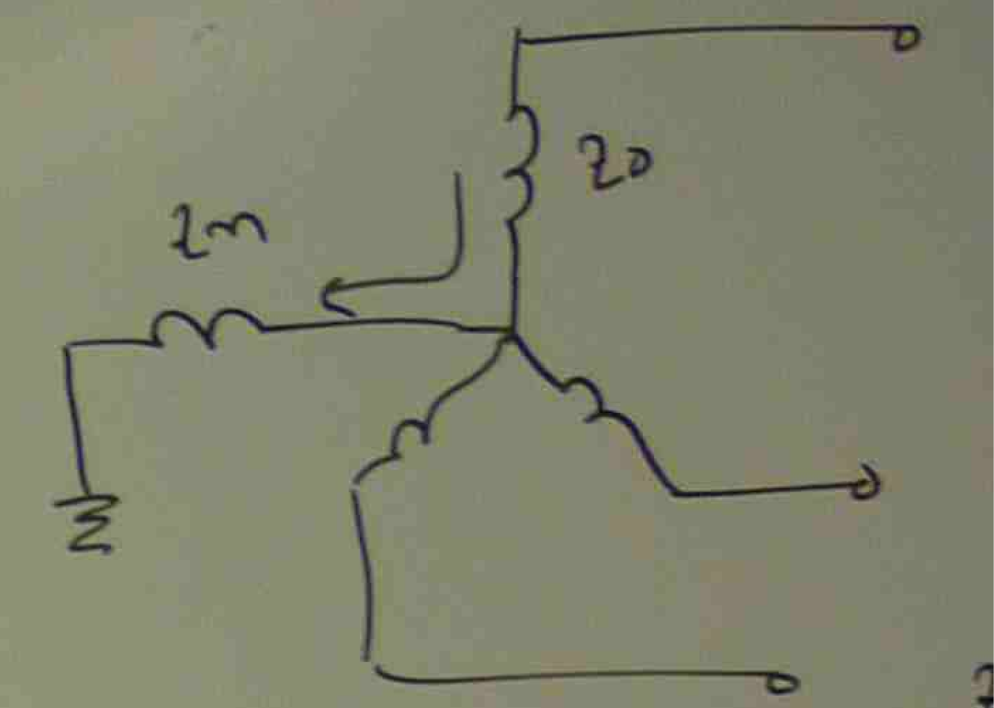
SYNCHRONOUS MACHINE HARMONIC MODELS ARE INCORPORATED IN TO HARMONIC LOAD FLOW PROGRAMS.



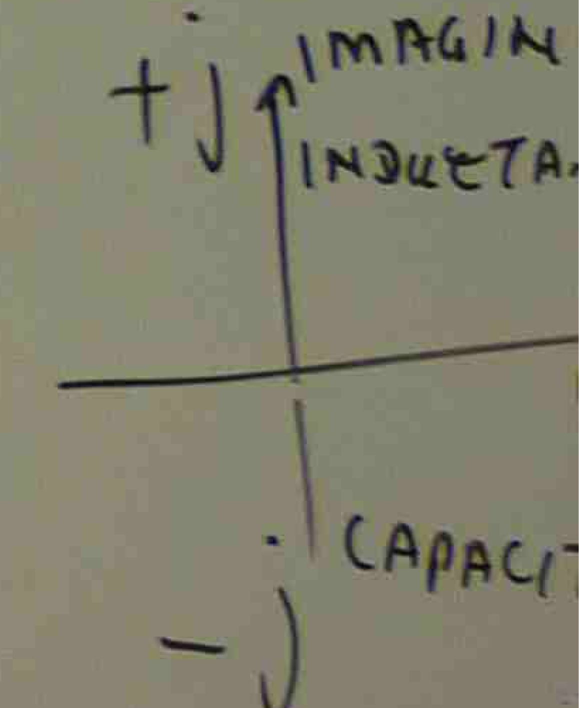
POSITIVE SEQUENCE



NEGATIVE SEQUENCE
(FAULT)



THE GENERATOR MUST ...
DESIGN TO SUSTAIN TH...
TO LINE FAULT (NEG...
GROUND FAULT (ZERO S...
LOAD (POSITIVE SEQ...
TIME LIMIT TO ...



...ONOUS MACHINES

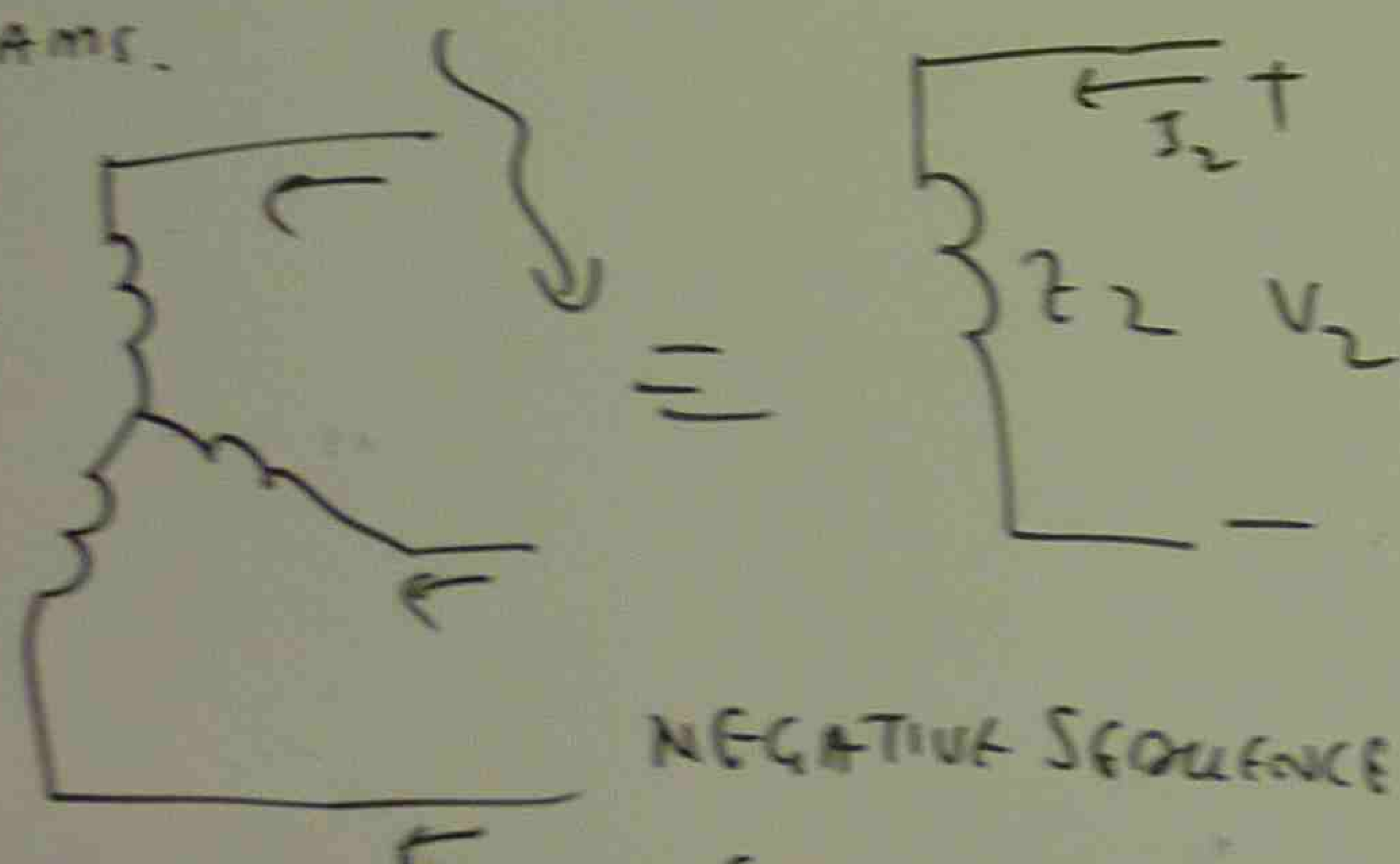
...S

...PERIENCE A NEGATIVE SEQUENCE CURRENT IN

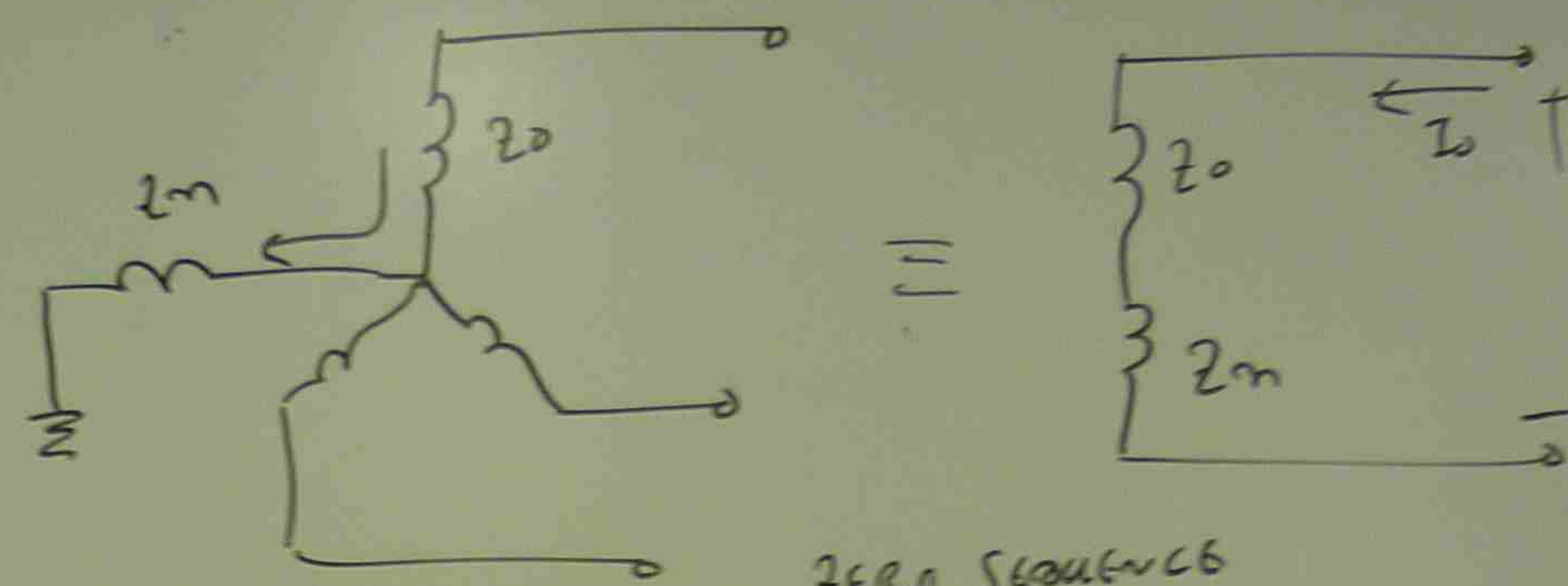
...S WITH FREQUENCY CONVERSION PROCESS

CONSTRAINTS

...NIC MODELS ARE INCORPORATED
... PROGRAMS.



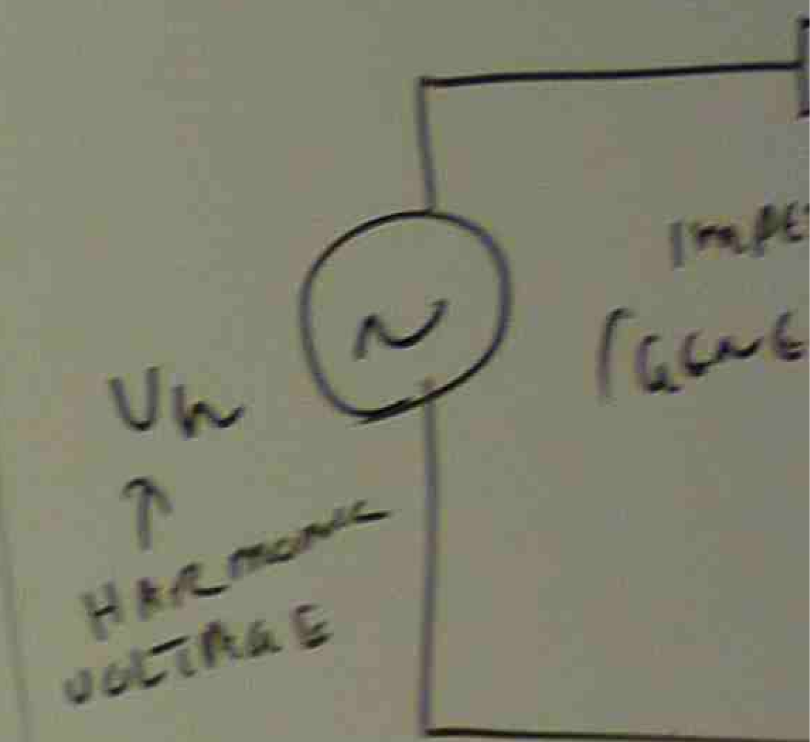
NEGATIVE SEQUENCE
(FAULT)

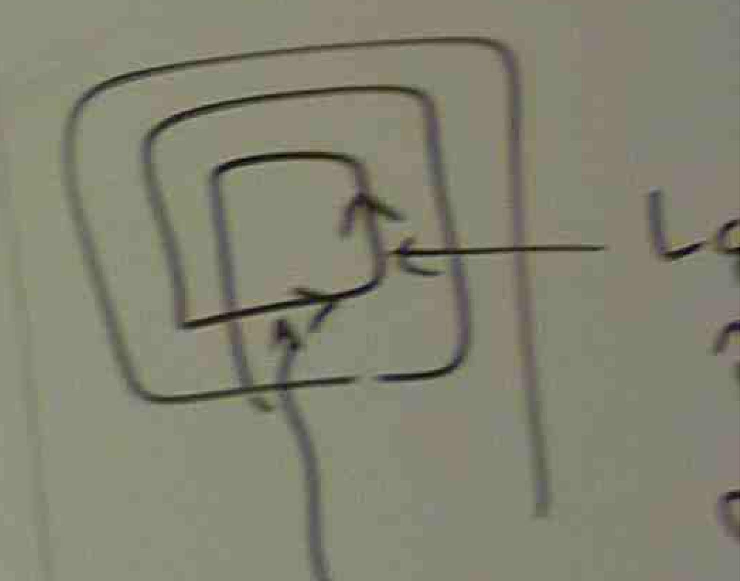


ZERO SEQUENCE
(GROUND FAULT)

THE GENERATOR MUST HAVE APPROPRIATE DESIGN TO SUSTAIN THE POSSIBLE LINE TO LINE FAULT (NEGATIVE SEQUENCE) AND OVER GROUND FAULT (ZERO SEQUENCE) AND OVER LOAD (POSITIVE SEQUENCE) FOR A CERTAIN TIME LIMIT TO RETAIN THE POWER QUALITY

HARMONIC EQUIV...





RA...

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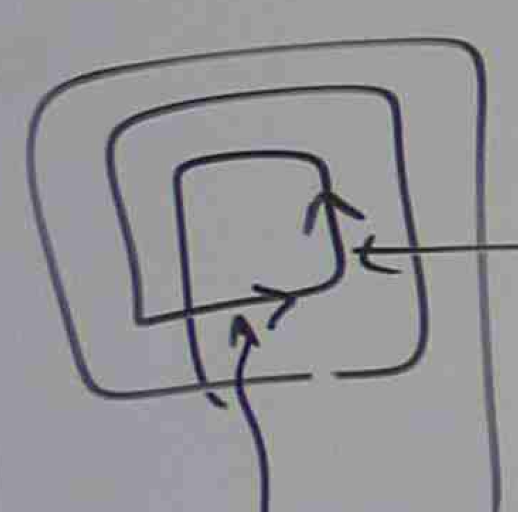
HARMONIC EQUIVALENT CIRCUIT



(HARMONIC CAN FLOW IN TO EXCITATION CIRCUIT & GENERATES THE VOLTAGE INFECTED BY HARMONIC)

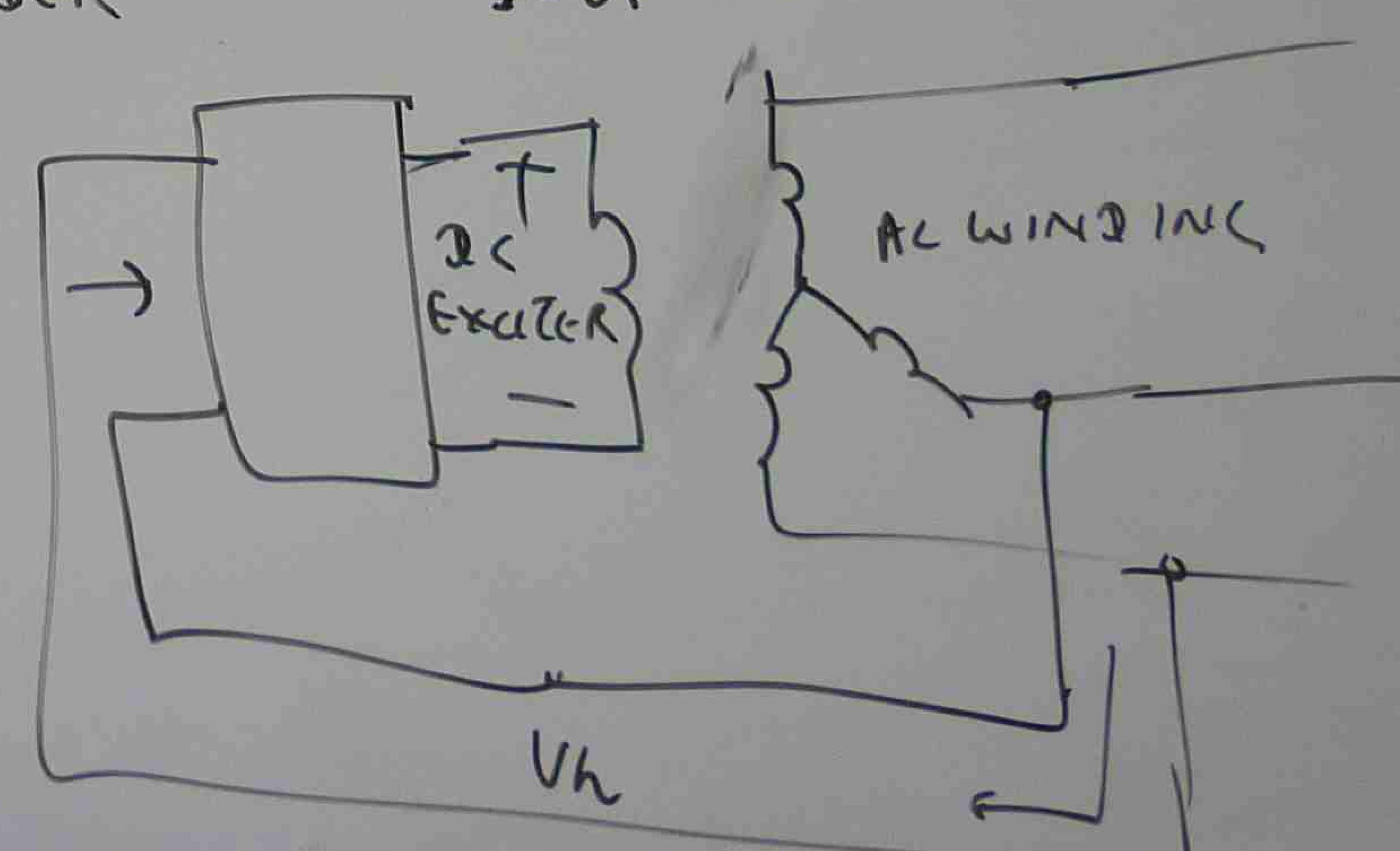
h = HARMONIC ORDER

$\omega = 2\pi f$

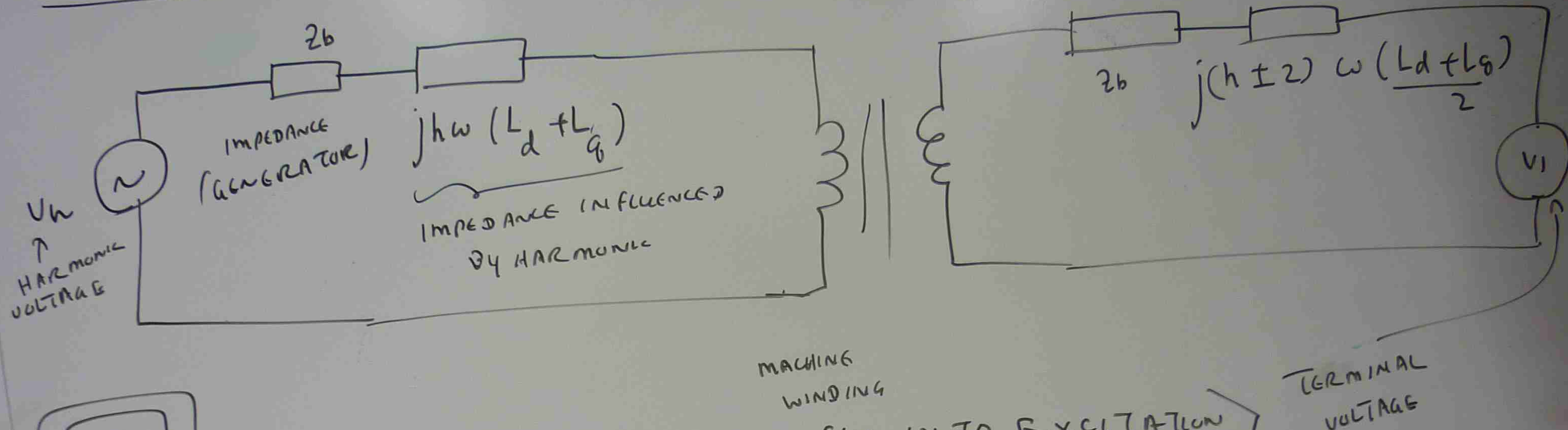
ω: RADIAN/sec, RADIAN FREQUENCY

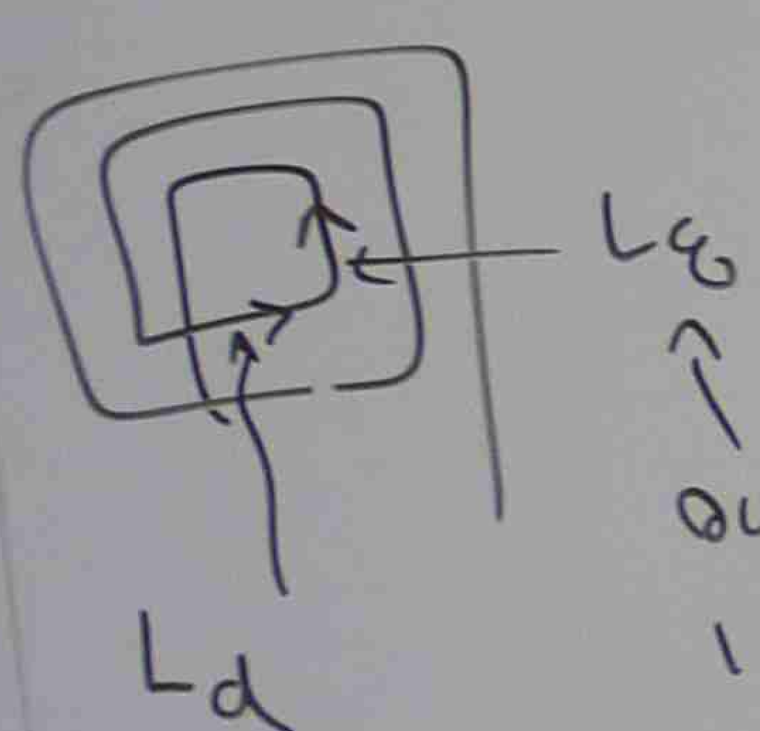
f: FREQUENCY

SELF EXCITATION



HARMONIC EQUIVALENT CIRCUIT





QUADRATURE INDUCTANCE

DIRECT INDUCTANCE

<HARMONIC CAN FLOW INTO EXCITATION CIRCUIT & GENERATES THE VOLTAGE INFECTED BY HARMONIC>

h = HARMONIC ORDER

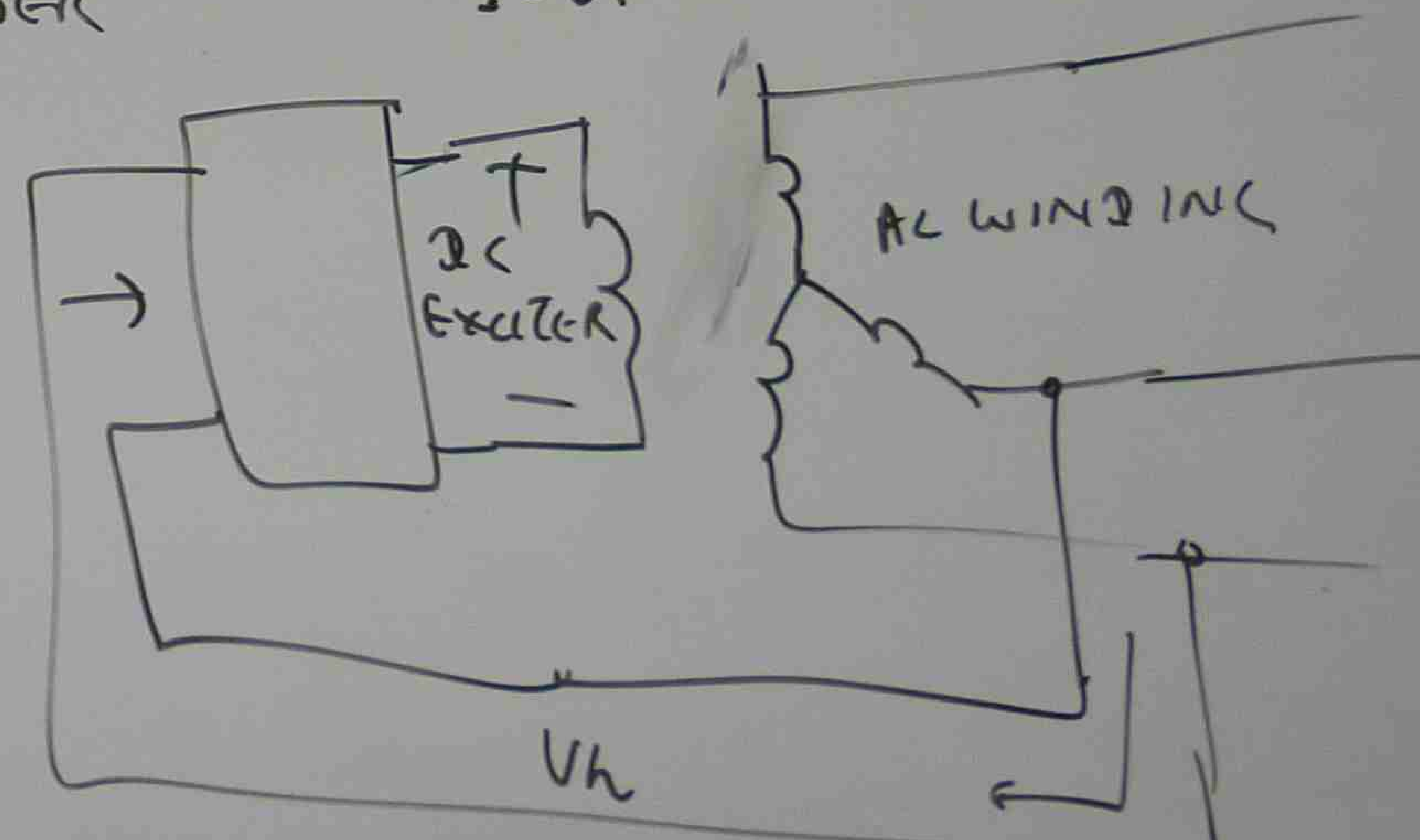
$\omega = 2\pi f$

RADIAN/SEC

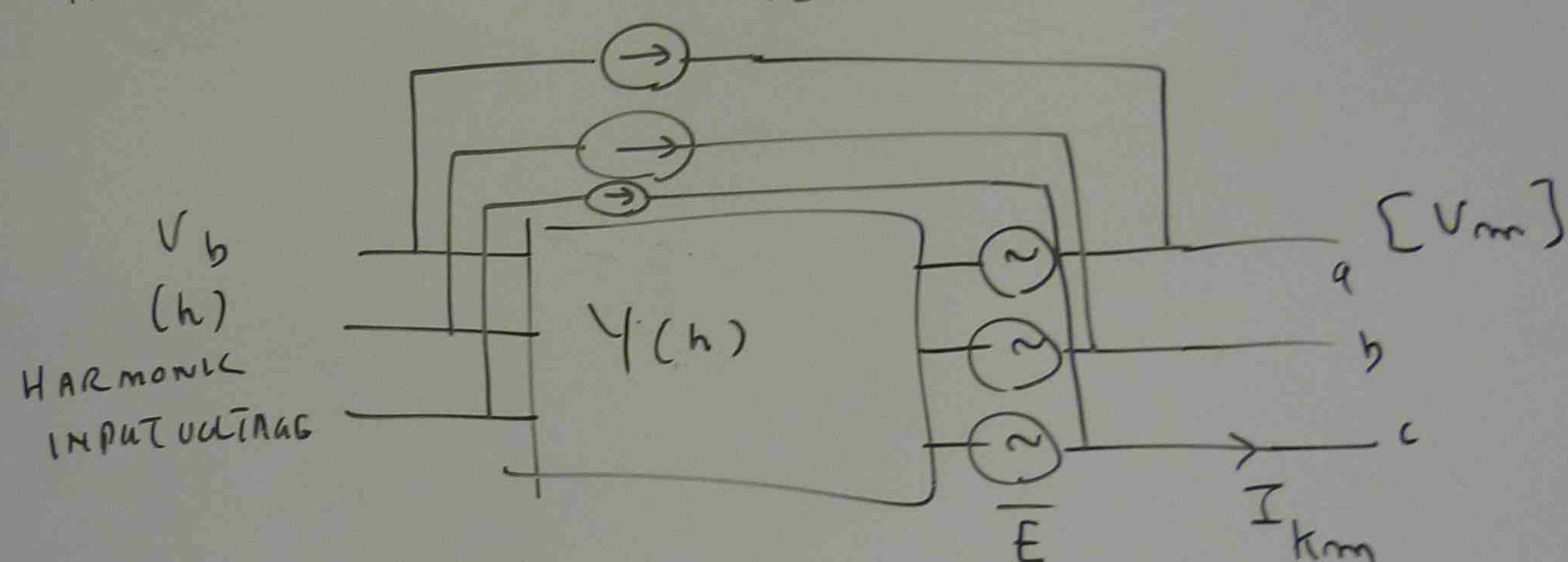
RADIAN FREQUENCY

FREQUENCY

SELF EXCITATION



IN SELF EXCITATION SYSTEM OF GENERATOR, THE HARMONIC COMPONENT IN OUT PUT VOLTAGE CAN FLOW IN TO THE EXCITER SYSTEM AND GENGRATES THE VOLTAGE INFECTED WITH HARMONIC THE HARMONIC MUST BE PROPERLY FILTERED. IN THIS CASE HARMONIC MODEL IS UTILIZED.



↑
LOAD CURRENT

V_m = TERMINAL VOLTAGE

$$Y = \frac{1}{Z}$$

$$\text{ADMITTANCE} = \frac{1}{\text{IMPEDANCE}}$$

↑
ALLOWING THE flow OF CURRENT

HARMONIC MODEL

I (

abc

a, b, c LINE
CURRENT WITH
HARMONIC

ATOR, THE HARMONIC
FLOW IN TO THE EXCITER
INFECTED WITH HARMONIC
FILTERED. IN THIS CASE

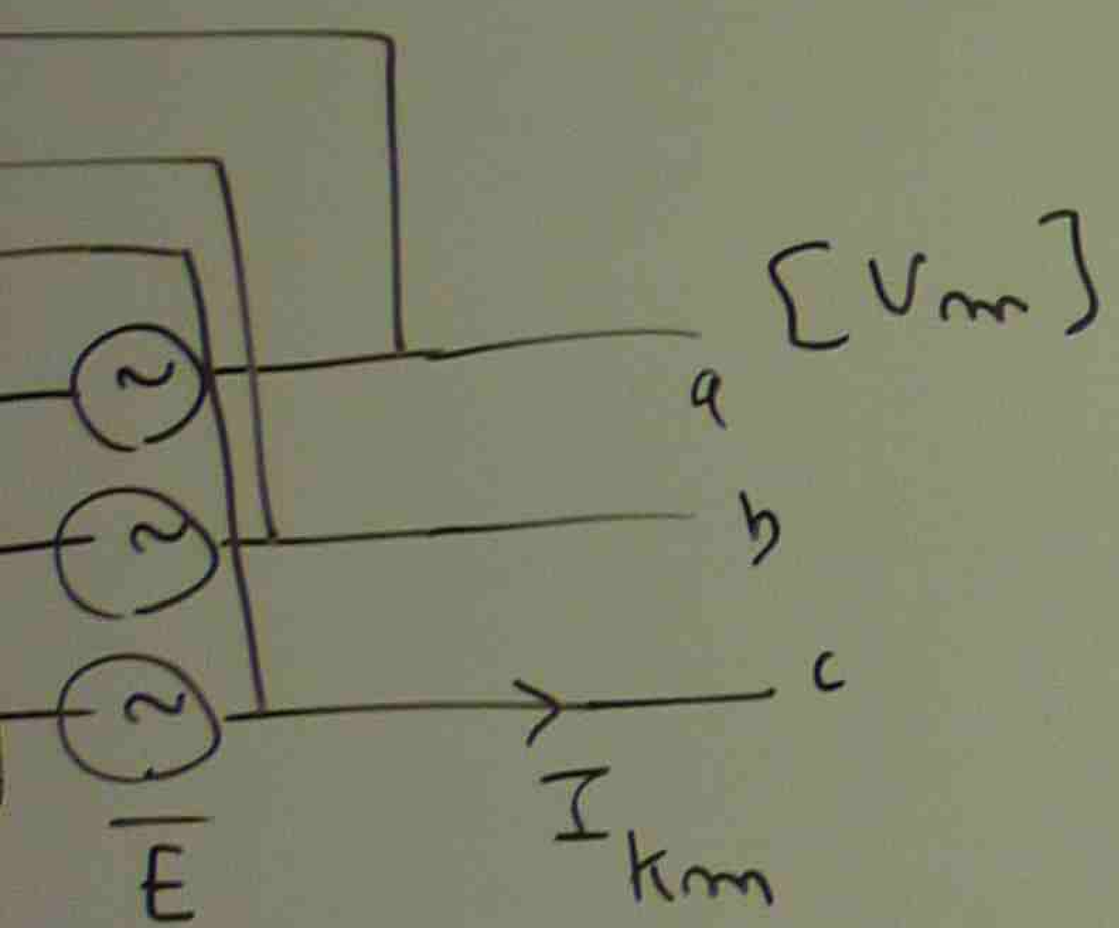
$$I_{abc}(h) = Y(h) \times \left[V_{abc}(h) \right] + I_f(h)$$

a, b, c LINE CURRENT WITH HARMONIC

HARMONIC ADMITTANCE (ABILITY TO ALLOW HARMONIC)

a, b, c LINE VOLTAGE INFLUENCED BY HARMONIC

FIELD EXCITATION CURRENT INFLUENCED BY HARMONIC

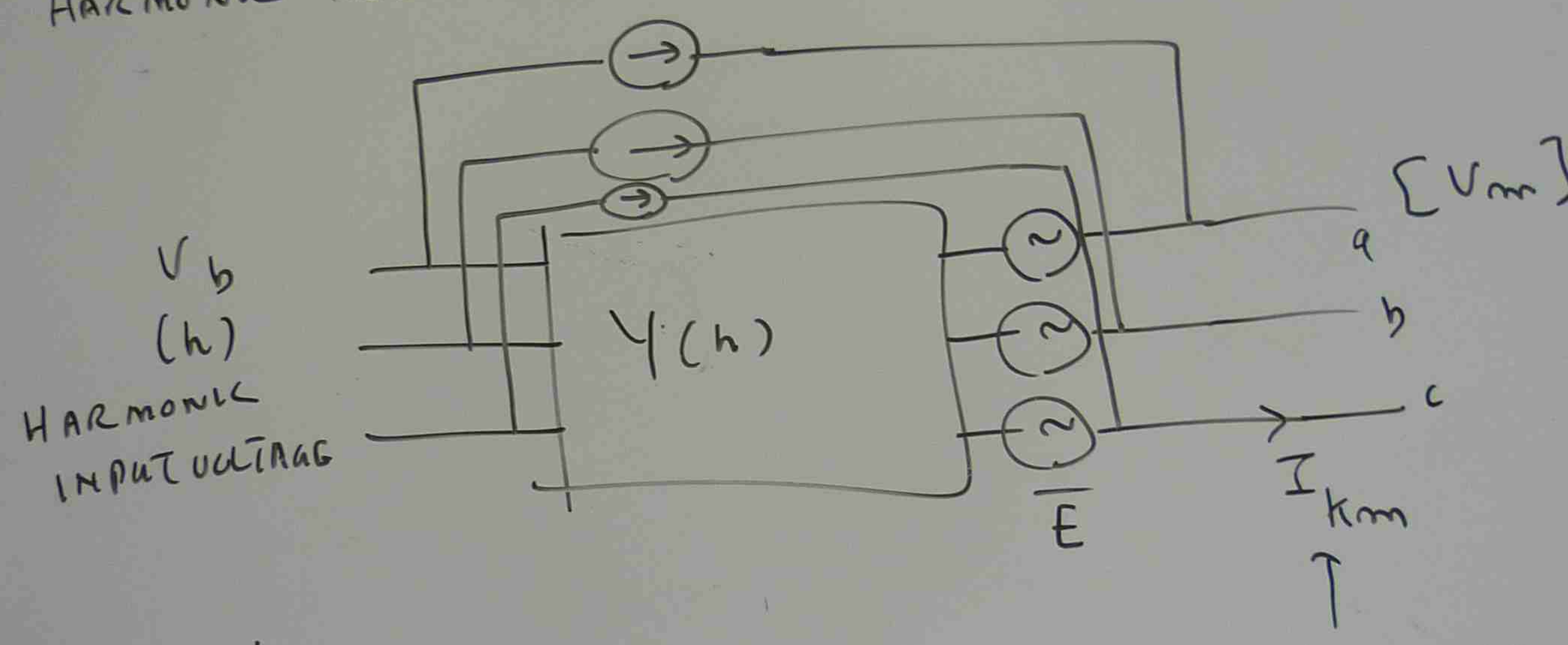


LOAD CURRENT

Vm = TERMINAL VOLTAGE

THE HARMONIC COMPONENT MUST BE FILTERED TO ACHIEVE THE GOOD POWER QUALITY.

IN SELF EXCITATION SYSTEM OF GENERATOR, THE HARMONIC COMPONENT IN OUT PUT VOLTAGE CAN FLOW IN TO THE EXCITER SYSTEM AND GENERATES THE VOLTAGE INFECTED WITH HARMONIC THE HARMONIC MUST BE PROPERLY FILTERED. IN THIS CASE HARMONIC MODEL IS UTILIZED.



V_m = TERMINAL VOLTAGE

$$Y = \frac{1}{Z}$$

$$\text{ADMITTANCE} = \frac{1}{\text{IMPEDANCE}}$$

ALLOWING THE FLOW OF CURRENT

HARMONIC MODEL

$I_{abc}(h) =$

a, b, c LINE CURRENT WITH HARMONIC

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IN THIS CASE

$$I_{abc}(h) = Y(h) \times \left[V_{abc}(h) \right] + I_f(h)$$

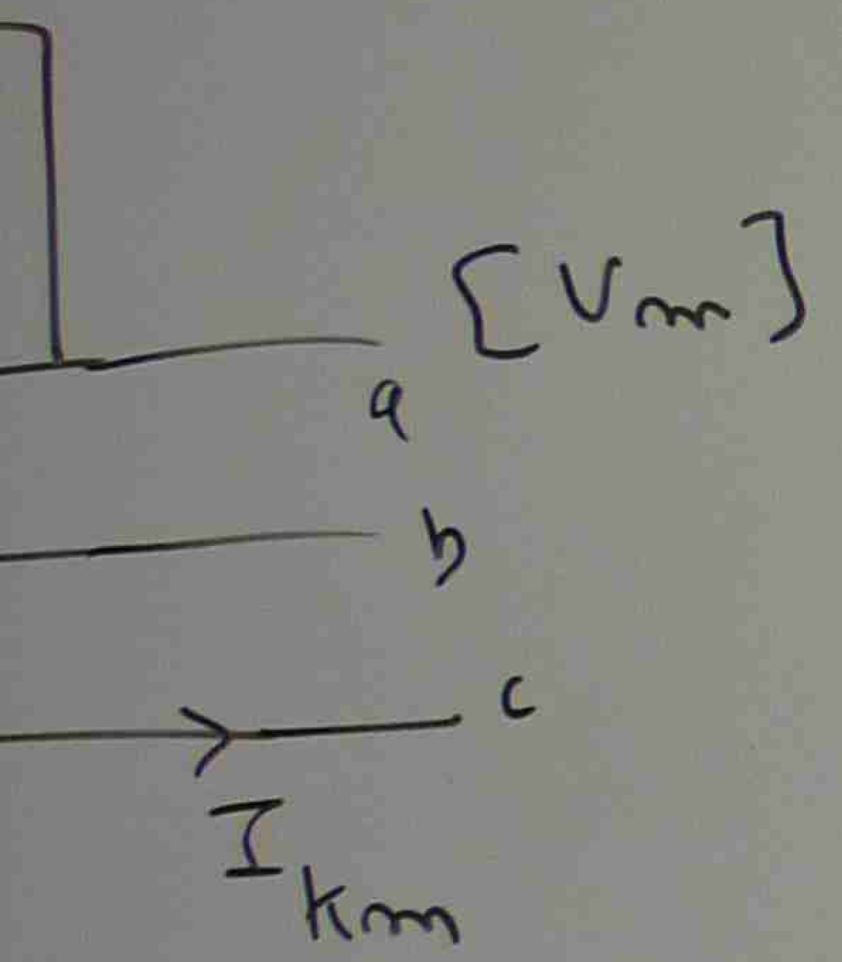
$I_{abc}(h)$: a, b, c LINE CURRENT WITH HARMONIC

$Y(h)$: HARMONIC ADMITTANCE (ABILITY TO ALLOW HARMONIC)

$V_{abc}(h)$: a, b, c LINE VOLTAGE INFLUENCED BY HARMONIC

$I_f(h)$: FIELD EXCITATION CURRENT INFLUENCED BY HARMONIC

THE HARMONIC COMPONENT MUST BE FILTERED TO ACHIEVE THE GOOD POWER QUALITY.



LOAD CURRENT

V_m = TERMINAL VOLTAGE

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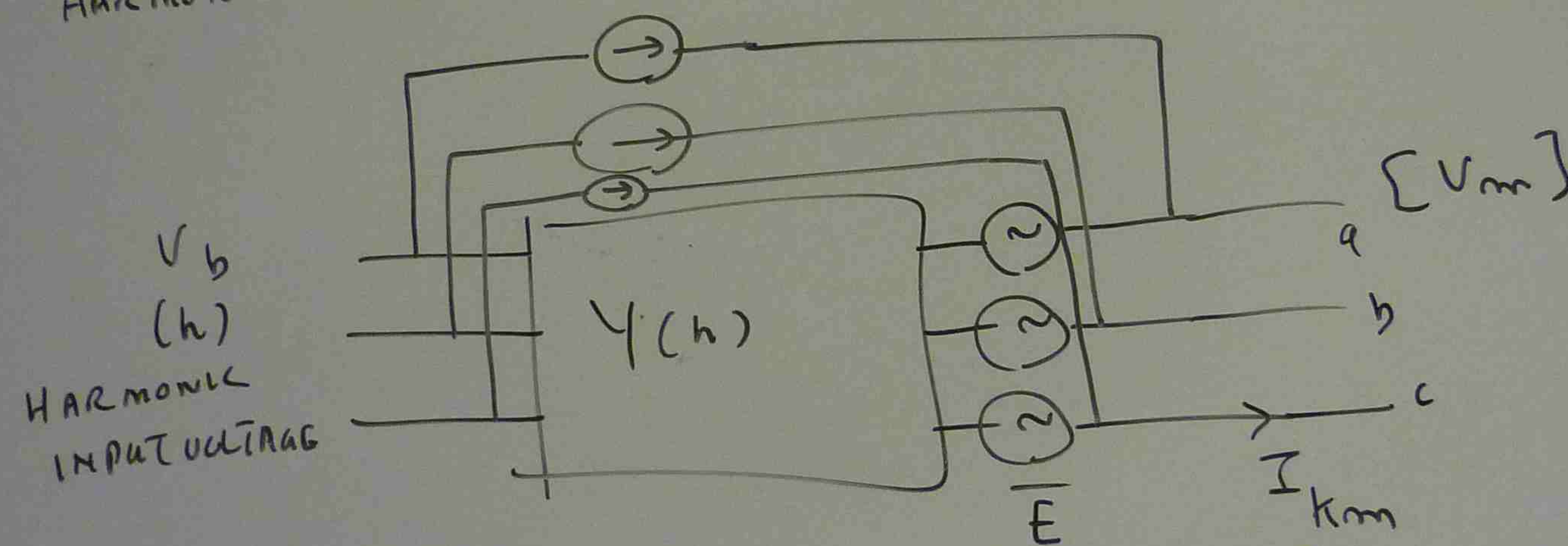
IN SELF EXCITATION SYSTEM OF GENERATOR, THE HARMONIC COMPONENT IN OUT PUT VOLTAGE CAN FLOW IN TO THE EXCITER SYSTEM AND GENERATES THE VOLTAGE INFECTED WITH HARMONIC THE HARMONIC MUST BE PROPERLY FILTERED. IN THIS CASE HARMONIC MODEL IS UTILIZED.



LOAD CURRENT

V_m = TERMINAL VOLTAGE

$$Y = \frac{1}{Z}$$

$$\text{ADMITTANCE} = \frac{1}{\text{IMPEDANCE}}$$

ALLOWING THE flow OF CURRENT

HARMONIC MODEL

$I_{abc}(h) = Y$

a, b, c LINE CURRENT WITH HARMONIC

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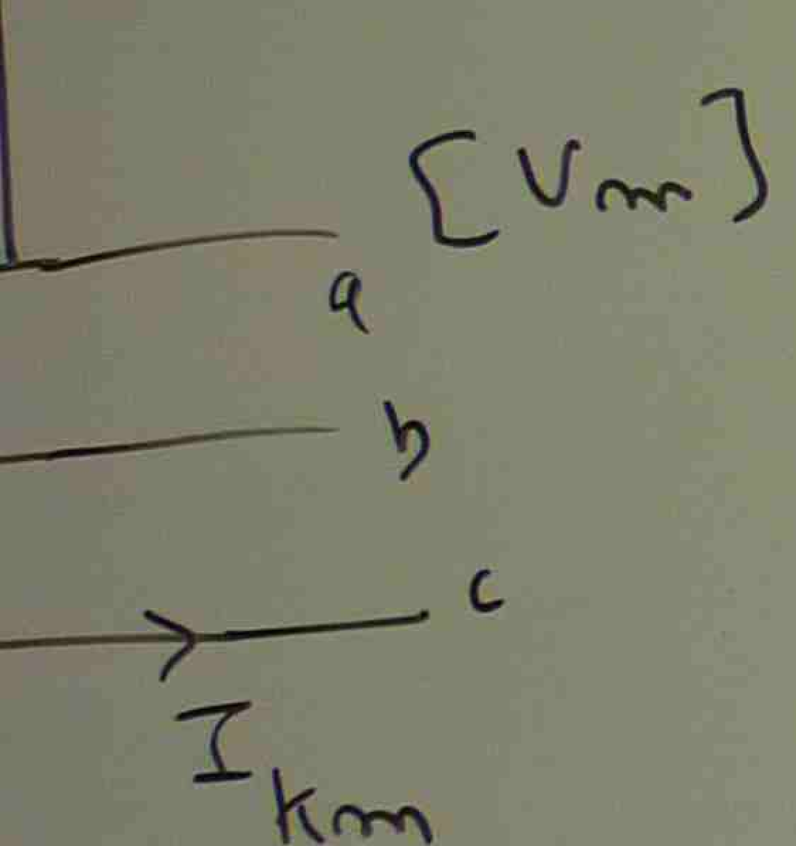

LOAD CURRENT

V_m = TERMINAL VOLTAGE

$$I_{abc}(h) = Y(h) \times \left[V_{abc}(h) \right] + I_f(h)$$

$I_{abc}(h)$: a, b, c LINE CURRENT WITH HARMONIC

$Y(h)$: HARMONIC ADMITTANCE (ABILITY TO ALLOW HARMONIC)

$V_{abc}(h)$: a, b, c LINE VOLTAGE INFLUENCED BY HARMONIC

$I_f(h)$: FIELD EXCITATION CURRENT INFLUENCED BY HARMONIC

THE HARMONIC COMPONENT MUST BE FILTERED TO ACHIEVE THE GOOD POWER QUALITY.

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FIELD EXCITATION CURRENT INFLUENCED BY HARMONIC

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LIFE TIME REDUCTION OF TRANSFORMERS AND INDUCTION MACHINES BY HARMONIC

THE LIFE TIME OF ANY DEVICE IS LIMITED BY THE AGING OF THE INSULATION MATERIAL DUE TO TEMPERATURE. THE HIGHER THE ACTIVATION ENERGY OF ANY MATERIAL, THE FASTER AGING PROCEEDS.

- TEMPERATURE RISES ABOVE THE RATED TEMPERATURE.
- INTERMITTENT OPERATION.
- VIBRATION WITHIN A MACHINE DUE TO LOAD VARIATIONS.
- FAULTS AND SHORT CIRCUITS.

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STATOR WIND...

$j\omega$...

CORE...

EQUIVALEN...

R_{PL} = STATOR...

$j\omega L_{PL}$ = STAT...

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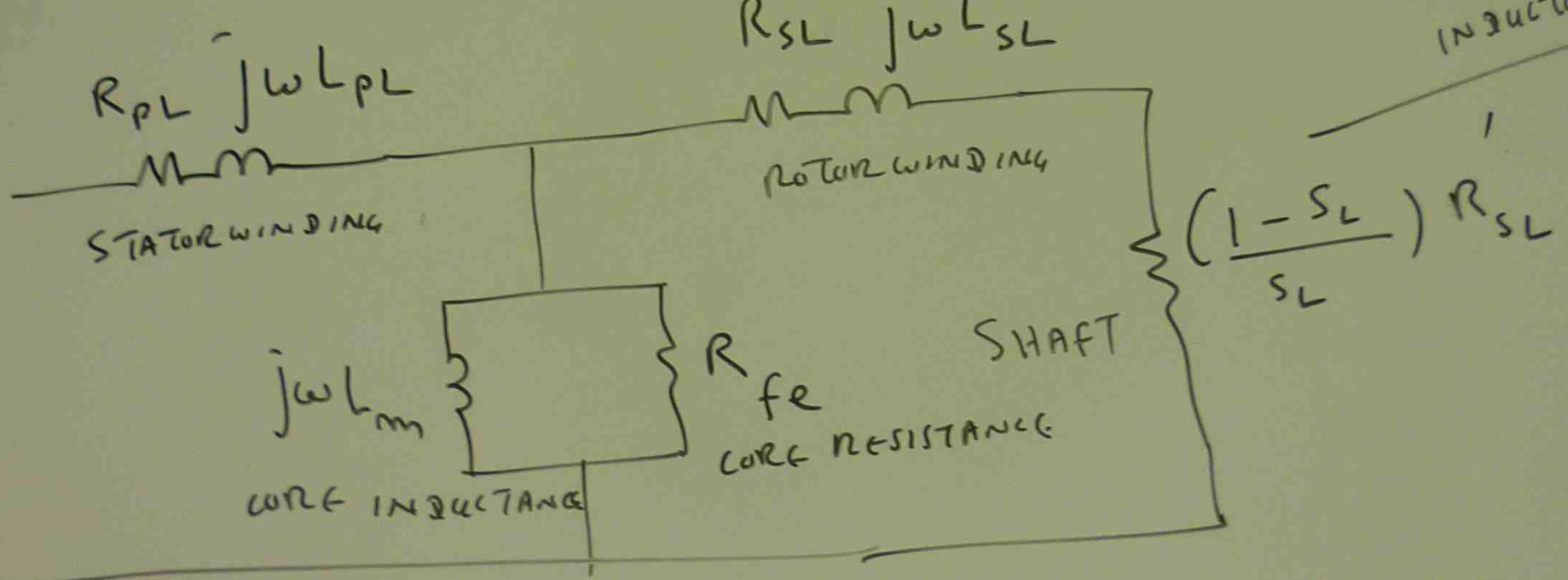
ELEVATED TEMPERATURE RISE DUE TO HARMONIC

$$T = T_{\text{AMBIENT}} + T_{\text{RATED RISE}} + \Delta T_h$$

HARMONIC TEMPERATURE RISE

NORMAL EQUIVALENT CIRCUIT OF INDUCTION MOTOR



1800 1200

$$S_L = \text{SLIP} = \frac{\text{NO LOAD SPEED} - \text{FULL LOAD SPEED}}{\text{NO LOAD SPEED}}$$

1800

EQUIVALENT CIRCUIT FOR INDUCTION MOTOR

R_{pL} = STATOR RESISTANCE

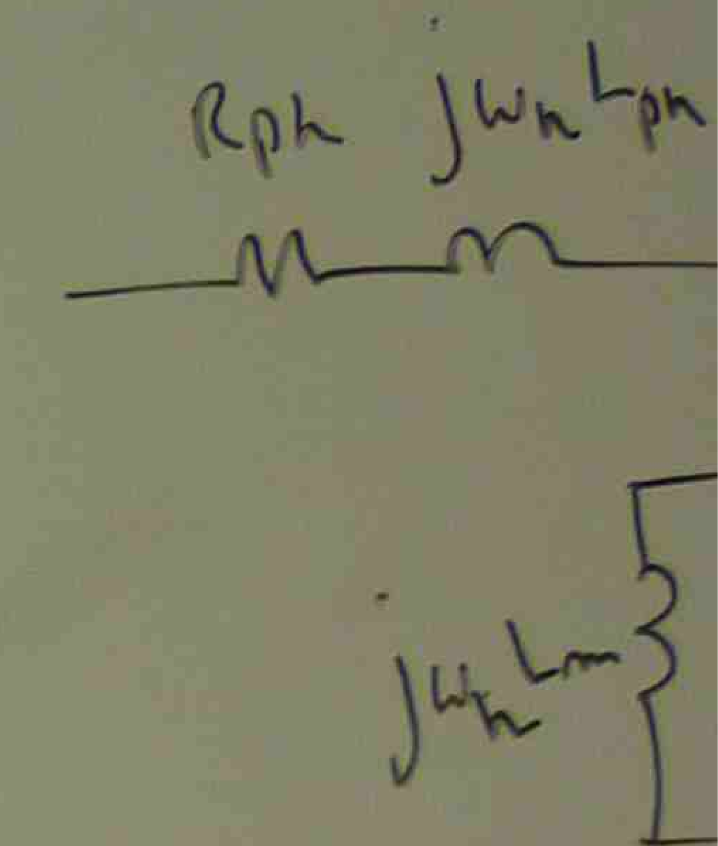
$j\omega L_{pL}$ = STATOR INDUCTANCE

R_{SL} – ROTOR RESISTANCE

$j\omega L_{SL}$ – ROTOR INDUCTANCE

HARMONIC EQUIV

MOTOR

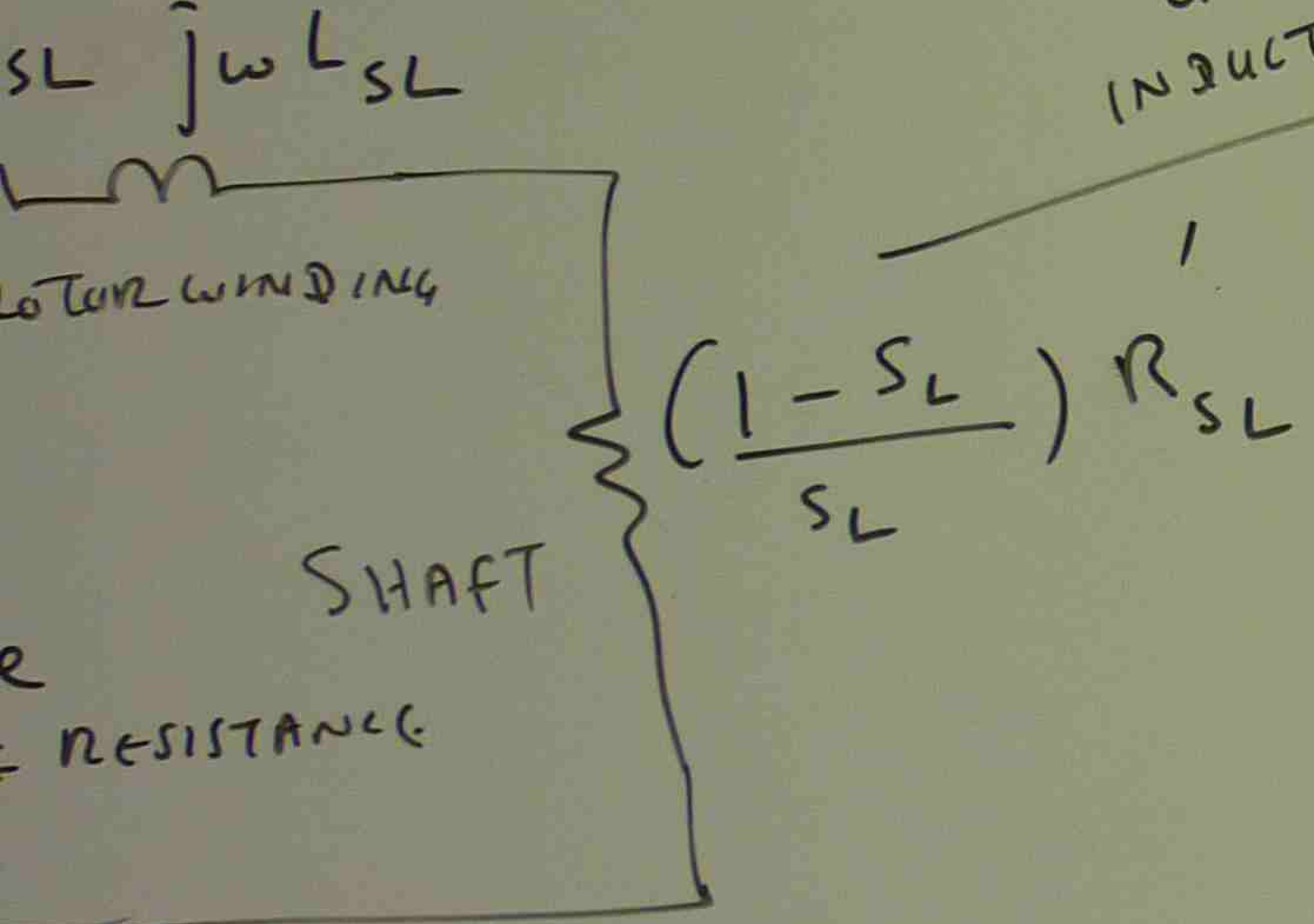


...ISE DUE TO HARMONIC

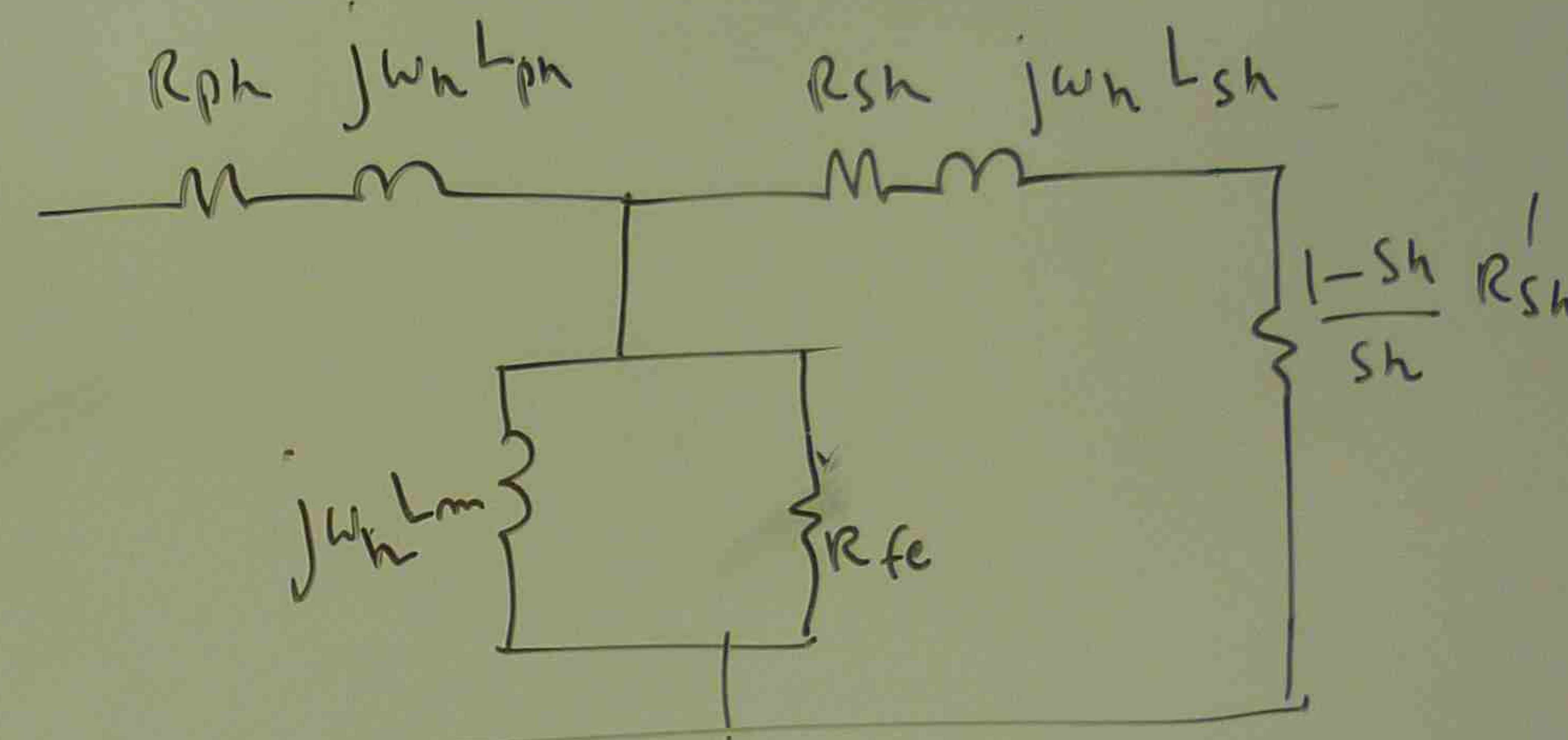
$+ \Delta T_h$ #

HARMONIC TEMPERATURE RISE

NORMAL EQUIVALENT CIRCUIT OF INDUCTION MOTOR



HARMONIC EQUIVALENT CIRCUIT OF INDUCTION MOTOR



$$\Delta T_h = K \sum_{h=2}^{\infty} \frac{1}{h^2} \left(\frac{V_{pk}}{V_{pL}}\right)^{l}$$

1800   1200

$$S_L = \text{SLIP} = \frac{\text{NO LOAD SPEED} - \text{FULL LOAD SPEED}}{\text{NO LOAD SPEED}}$$

1800

h = HARMONIC, $h = 2$ SECOND HARMONIC

V_{pk} = PEAK VOLTAGE

V_{pL} = NORMAL VOLTAGE

...DUCTION MOTOR

...L − ROTOR RESISTANCE

L_{SL} − ROTOR INDUCTANCE

V_{ph1} =

V_{ph2} =

$$k = \frac{\log \left[\frac{\Delta Th_2}{\Delta Th_1} \left(\frac{Vph_1 / VpL}{Vph_2 / VpL} \right) \right.}{\log \left(\frac{h_1}{h_2} \right)}$$

$V_{ph_1} =$ 100 HZ VOLTAGE $\longrightarrow$ $\Delta Th_1 =$ TEMPERATURE RISE (1)

$V_{ph_2} =$ 150 HZ VOLTAGE $\longrightarrow$ $\Delta Th_2 =$ TEMPERATURE RISE (2)

$h_1 =$ 100 HZ - SECOND HARMONIC $\quad h_1 = 2$

$h_2 =$ 150 HZ - THIRD HARMONIC $\quad h_2 = 3$

$V_{PL} =$ NORMAL VOLTAGE

$$l = \frac{\log \left[\frac{\Delta Th_2}{\Delta Th_1} \left(\frac{Vph_1 / VpL}{Vph_2 / VpL} \right) \right.}{\log \frac{h_1}{h_2}}$$