Topics for Today:

• Course Info:
  • Web page: [http://www.ee.mtu.edu/faculty/bamork/ee5220/](http://www.ee.mtu.edu/faculty/bamork/ee5220/)
  • Book, references, syllabus, more are on web page.
  • Software - Matlab. ATP/EMTP [ License - [www.emtp.org](http://www.emtp.org) ] ATP tutorials posted on our course web page
  • [EE5220-L@mtu.edu](mailto:EE5220-L@mtu.edu) (participation = min half letter grade)

• HW#9 - Probs. 9.2, 9.3, 9.4 due today.
• Mid-term: Apr 7-11th time window.
• Term Project - Journal paper review - see review guidelines on web page.
• Transformer modeling - Section 11.1 of text, plus lecture notes
  • Magnetic materials: B-H characteristics
  • Transformer models for EMTP
    • Duality transformations gives correct equivalent circuit
    • Examples for core-form, “shell-form”, single-phase
    • Three phase modeling
• Next - take stock of available ATP transformer models
  • BCTRAN, XFMR models
Duality Transforms

- Ckts: Identical math structure but different physical structure.

NODE EQN $\leftrightarrow$ MESH EQN

IN MAG CkTs - DUAL

MAG Ckt $\leftrightarrow$ ELECT. EQUIV

$R, N, \Phi, \rightarrow V, E, L, I$

$B, H, \rightarrow$ AMPERE'S CIRCUITAL LAW

$NI = \Phi R = \text{MMF} = I$
1) Create Lumped Mag Ckt

2) Transform

\[ L = \frac{N^2}{R} \]

Mesh \quad \rightarrow \quad Node

Node \quad \rightarrow \quad Mesh

\rightarrow

\Rightarrow

\Rightarrow
DUALITY TRANSF. "PAIRS"

\[ N I = \text{MMF} \]
\[ \text{NODE} \leftrightarrow \text{MESH} \leftrightarrow \text{NODE} \]
\[ \text{MESH} \leftrightarrow \text{NODE} \]

\[ R \leftrightarrow I \text{ source} \]

\[ L = \frac{N^2}{R} \]

\[ L = \frac{N^2}{R} \]

\[ I_H \quad \downarrow \]

\[ I_L \]

\[ L_{1H} \quad \quad \quad L_{2H} \]

\[ L_{1L} \quad \quad \quad L_{2L} \]

\[ L_{LM} \]
FLOATING

OTHER EXAMPLES

\[ H_2 \quad R_1 \quad L_1 \quad R_2 \quad L_2 \]
Duality Derivations

Simple XFRM:

Note!: KVL around Mag. Ckt. loop must have same relative signs as currents in KCL dual.

EX. 1
This test is difficult to perform with a typical wattmeter, since it requires the measurement of real power at a relatively low voltage, and the currents for this CT became nonsinusoidal above 30 volts. To avoid this problem, a digital oscilloscope was used to record the voltage and

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Figure 3. Duality Derivation for the CT
circuit calculations, but it is not generally adequate for transient modeling in the EMTP [3].

A cross section view of the CT used in this study is shown in Figure 2. It has a one turn primary and a toroidal core. Since it has concentric windings (the primary is effectively one turn) the circuit of Figure 1 is invalid. Therefore, a

**Figure 2. Cross section view of CT**

This test is difficult since it requires relatively low voltage nonsinusoidal ab digital oscillosce

**Figure 3. Duality**
- Find $B_{\text{MAX}}$
- Pick off $P/\text{kg}$ from curve

$P_{\text{CORE, AVG}} = \text{Mass of Core} \times \frac{P}{\text{kg}}$

$$\overline{P_c} = \frac{V_x^2}{R_c}$$

$\Rightarrow R_c = \frac{V_x^2}{\overline{P_c}}$
CORE LOSS - Watts Per Kilogram

INDUCTION - Kilogausses

50 Hertz
60 Hertz

\[ P_{\text{core}} = \frac{1}{R_0} \]

(\text{ARMCO ORIENTED M-3})

.009" (.23 mm) Thick

CORE LOSS
50 and 60 Hertz
Test: SRA; Parallel; A343
Curve No. 8368
$R_c: \ \ \ \ \ \ \ \ B_{\text{max}} = \frac{E_p}{N A W}$

$B_{\text{max}}: \ c = \frac{d^2 \gamma}{dt^2} = N \frac{d \phi}{dt} = N A d B \frac{dB}{dt}$

if sinusoidal: $B = B_{\text{max}} \sin \omega t$

$e(t) = \frac{NA B_{\text{max}} \omega \cos(\omega t)}{E_p}$
ARMCO ORIENTED M-3
.009" (.23 mm) Thick
D-C MAGNETIZATION CURVE
Test: SRA; Parallel; A596
Curve No. 8371
\[ B = \frac{\Phi}{A} = \frac{2}{NA} \]

\[ J = BAN = \Phi N \]

\[ H = \frac{Ni}{\ell} \]

\[ i_{\text{rms}} = \frac{H \ell}{N} \]

\[ \text{Saturación} \]

\[ V_{\text{rms}} \]

\[ I_{\text{rms}} \]

\[ \lim_{I_{\text{rms}} \to 0} I_{\text{ex}} \]

\[ R_c, L_m \]
ARMCO ORIENTED ELECTRICAL STEELS
.007”, .009”, .011” and .014”
(.18, .23, .27 and .35 mm) Thick

A-C MAGNETOSTRICTION
Magnetostriiction Measured Parallel to Direction of Flux
60 Hertz
Test: SRA; Parallel

Curve No. 7774

Most samples have characteristics falling in the range shown bounded by curves of typical shape.