2006 Wire Development Workshop

Transformer Conductor Requirements

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Transformer Specific Design Issues

Issues

- Non- linear impulse voltage distribution and transferred surges
- Lifetime PD free operation
- Complex dielectric design
- Complex mechanical design for short circuit forces
- Large stressed insulation volume
- Interfaces between solid-liquid-vacuum
- Components and accessories

Requirements

- Cost effective
- Robust/Manufacturable
- 30+ years life

Transformer Market Issues

Total US medium power transformer market is approximately 1300 units annually.

Waukesha Electric builds 500 units annually (50 % with load tap changer).

More than 95 % of the units produced at Waukesha have a de-energized tap changer.

Waukesha Electric annually consumes approximately 4,000 metric tons of copper.

An average unit at Waukesha Electric uses approximately 45,000 meters of copper for the winding set.

Transformer Ratings

System Voltage (k V)	Impulse Voltage 1.2 X 50 μ Sec (kV)	A.C. Withstand 60 Hz (kV)	Current (amps) at 30 MVA level	Portion of Units Built at WES in Voltage Class (%)
Low Voltage				
15 Y (L.V.)	110	34	1154	70
25 Y (L.V.)	150	50	692	15
35 Y (L.V.)	200	70	494	8
High Voltage				
69 Δ (H.V.)	350	140	145	36
115 Δ (H.V.)	550	230	87	32
138 Δ (H.V.)	650	275	72	16
230 Δ (H.V.)	900	395	43	9

Transformer Winding Requirements

Windings must be locked into position to avoid movement and damage during short circuit events.

Wire properties should be uniform throughout the length of the conductor.

Wire used must have sufficient mechanical strength to allow tensioning during winding to avoid displacement of the conductor (i.e. excessive gaps or varying dielectric clearances).

Wire assembly (conductor + backing + insulation) must combine to meet the dielectric requirements of the winding (Turn – Turn, Disc – Disc or Layer – Layer).

All parallel conductors must be equal length (to avoid circulating currents).

Transformer impedance should approximate existing designs to minimize short circuit concerns and to allow paralleling with existing equipment.

Winding Design Procedure

Proprietary design programs optimize losses (both core and winding), sound, design margin and material cost.

Typical starting point is the determination of volts/turn (normal range for this parameter is 70 – 150 volts/turn).

The volts/turn choice defines approximate core diameter and limb height, which in turn defines winding ID and conductor width & thickness.

Required current determines the conductor area. Typical copper current density range is 2 – 4.5 amps/mm^2.

Winding Design Procedure-2

**The copper is sized to store the heat generated during a short circuit without overheating
(< 250 ^{o} C per IEEE requirements).**

- **HTS transformer will also need copper fault winding.**
- **The location of the fault winding must be optimized to reduce potential loss issues**
- **Fault winding may be used to improve dielectric profile of conductor**

The hardness (tensile strength) of the conductor is determined based on the short circuit requirements of the winding.

The width and thickness of the copper conductor is varied in 0.1-mm increments, to optimize space utilization in the active area of the transformer.

Thin conductor improves space factor and reduces mean turn length (reducing total length of conductor needed)

Present designs utilize 2 - 5 coils per core limb.

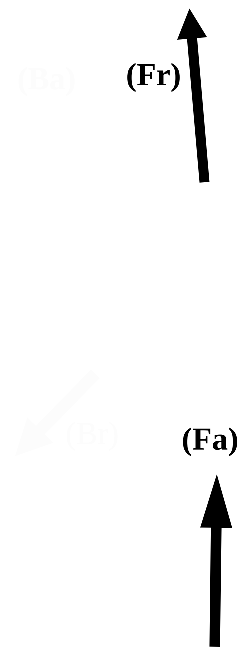
Winding Must Survive Short Circuits

Short Circuit Forces

- Rated current and impedance determine the magnitude of the short circuit forces
- Low impedance leads to increased short circuit forces
- Short circuit forces act both radially and axially
- Short circuits are relatively short duration (~ 2 seconds)

Requirements

- Ability to withstand S.C mechanical stress
- Ability to absorb current without overheating



Conductor Insulation Requirements

REQUIREMENT– Conductor must be insulated to prevent a shorted turn; also between parallel strands

Insulation may be porous to allow impregnation by a liquid dielectric or solid to act as a barrier

Typical operating voltage strand to strand is about 70 volts AC

Typical impulse stress during dielectric test (1.2 X 50 μ sec) is about 400 volts peak

REQUIREMENT– Conductors must have a smooth edge with a radius (preferably a full edge radius)

REQUIREMENT– Conductor surfaces must be completely free of burrs.

Disc Coils are Preferred

Issues with Coil Design

- Past HTS transformer designs used a layer winding which is susceptible to dielectric issues
- Current design of the H.V. coil concentrating on a disc design
- Presently working on reduced tensile strain during transition
- Additional insulation may be added to the discs in certain locations
- Multi-strand low voltage discs are being evaluated
- AC losses must be considered

Requirements

- No loss of conductivity or mechanical strength due to edgewise bending

Disc Coil Design

Each disc contains multiple turns.

Insulation is required between each turn.

No joints– discs are wound outwards, then inwards.

Capacitance reduces impulse dielectric stress at the end(s) of the coils.

Capacitance affects the impedance of the transformer.

REQUIREMENT– Edgewise bends needed for transitions between discs.

Transpositions in LV Coils

Low voltage coils will require multiple parallel strands for higher current.

Multiple parallel strands will require transpositions to maintain identical strand lengths.

Continuously Transposed Cable (CTC) may be used to reduce losses and complexity of the windings

Volts/turn are the same for high & low voltage windings (must maintain proper turns ratio).

Typically there are no taps on the low voltage winding.

Transformer Conductor Requirements

Property	Copper	HTS
Current Density (operating)	2 – 4.5 amps/mm^2	125 amps/mm^2 (J_e)
Operating Current Density (J_c)	N/A	$\geq$ 10,000 amps/mm^2
Overload Capability	100 %	100 %
Bend Radius (mm)	2	50
Current (per strand)	30 – 350 amps	$\geq$ 100 amps
Field	250 mT	150 mT
Cost ($/kA-m)	6 - 10	10 - 20
Available Length	Indefinite (weight limited)	~ 1,000 meters
Operating Temperature	400 ^{o} K	77 ^{o} K