Asia-Pacific
Economic Cooperation

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North American Distribution Transformer Energy Efficiency and Distribution Transformer Energy Efficiency Task Force

Submitted by: IEEE

APEC
VIET NAM
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Workshop on Reducing Losses in Power Distribution Through Improved Efficiency of Distribution Transformers
Jeju, Korea
28 March 2017

Asia-Pacific Economic Cooperation

ASEAN SHINE

Reducing Losses in Power Distribution through Improved Efficiency of Distribution Transformers (EWG 05 2015A)

North American Distribution Transformer Energy Efficiency and Distribution Transformer Energy Efficiency Task Force

28 March 2017 | Jeju, Republic of Korea

Philip J Hopkinson, PE

IEEE Member

ORGANISERS: International Copper Association Southeast Asia, Copper Alliance; CSC China Standard Certification; IIEC International Institute for Energy Conservation

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

1. Introduction
2. Definition of Distribution Transformer
3. Energy Efficiency Evolution
4. Present US Department of Energy Rules
5. Probable time for any rule changes
6. Transformer Loading a key issue
7. Preliminary findings on Loading
8. Proposed improvement to DOE rules
9. Discussion

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Introduction: Phil Hopkinson the speaker

1. 51 years in the transformer industry
2. IEEE Life Fellow, and IEC US TA to IEC TC 14 Power Transformers
3. Engineering Design and Management positions at GE, Cooper/Eaton and Schneider Electric
4. **Currently President & CEO HVOLT Inc.**
5. Long involvement with NEMA
6. **Worked closely with US DOE on Transformer Energy Efficiency since 1991**.

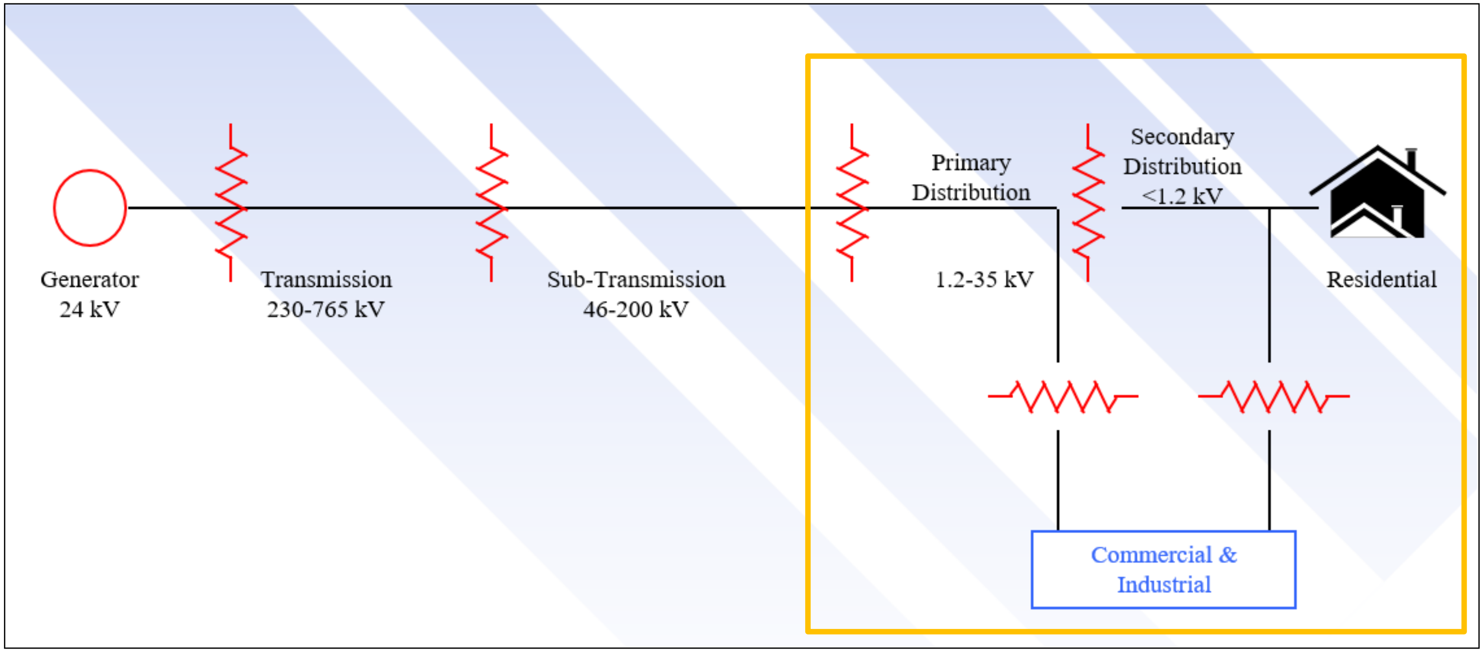
North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer

1. **Stand-alone Transformer** not built in
2. Transformer voltage:
   a) Low (0-1,000 volts) to other Low Voltage
   b) Medium Voltage (> 1,000 volts to 35,000 volts) to Low voltage
3. Power Frequency 60 Hz in North America
4. Power ratings 10 kVA to 833 kVA Single Phase
5. Power ratings 15 kVA to 2500 kVA Three Phase
6. Applications: Residential, Commercial, and Industrial
7. **Many Exclusions: Rectifier, Data Center, Wind, Solar, etc.**

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

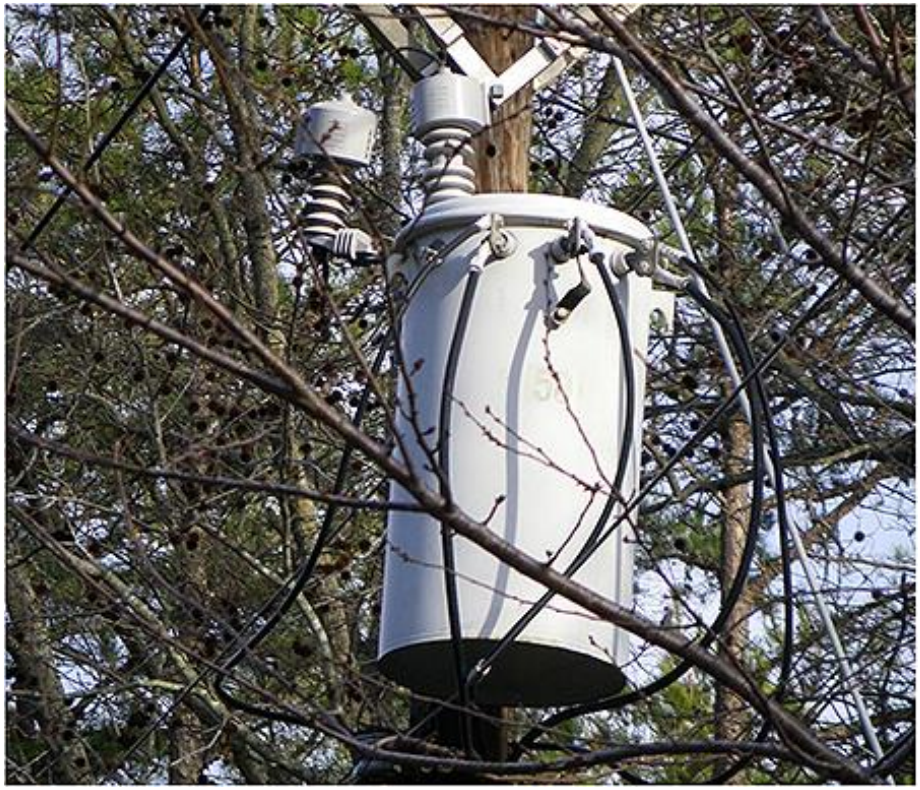
Definition of Distribution Transformer



Distribution Transformers the focus of US Congress for Energy Efficiency improvements

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer



Single Phase Pole Type Transformer

More than 1 million units sold per year in North America and used for Residential, Commercial and Industrial purposes

North American Distribution Transformer Energy **Efficiency** (Philip J Hopkinson, PE)

Definition of Distribution Transformer

Single Phase Pole Type Transformers in a 3-phase configuration for Commercial or Industrial application

37% of power distributed to Residential and 63% to Commercial or Industrial uses.

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer

Single Phase Pad Mount Transformer

More than 0.5 million units sold per year in North America and used mostly for Residential and small Commercial purposes.

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer

Padmounts

Segments: Commercial, Residential, Military, Government

Application: Access to public, outdoor, underground feed

Product Scope: Three phase 75 - 5000 kVA, Liquid filled; Oil, RTemp, Silicone, 5 - 35 kV Primary, Through 5 kV Secondary

Substation

Segments: Industrial, Large commercial

Application: Typically in substation lineup

Product Scope: Three Phase 225 - 10000 kVA, Liquid filled; Oil, RTemp, Silicone, 5 - 35 kV Primary, Through 5 kV Secondary

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer

Three Phase Phase Pad Mount Transformer

More than 20,000 units sold per year in North America and used mostly for Commercial and Industrial purposes

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Not a Distribution Transformer

Three Phase Pad Mount Transformer used as Step-Up

More than 5,000 units sold per year in North America and used mostly for Step-up from Low Voltage (600 volts) to Medium Voltage (typically 34,500 volts).

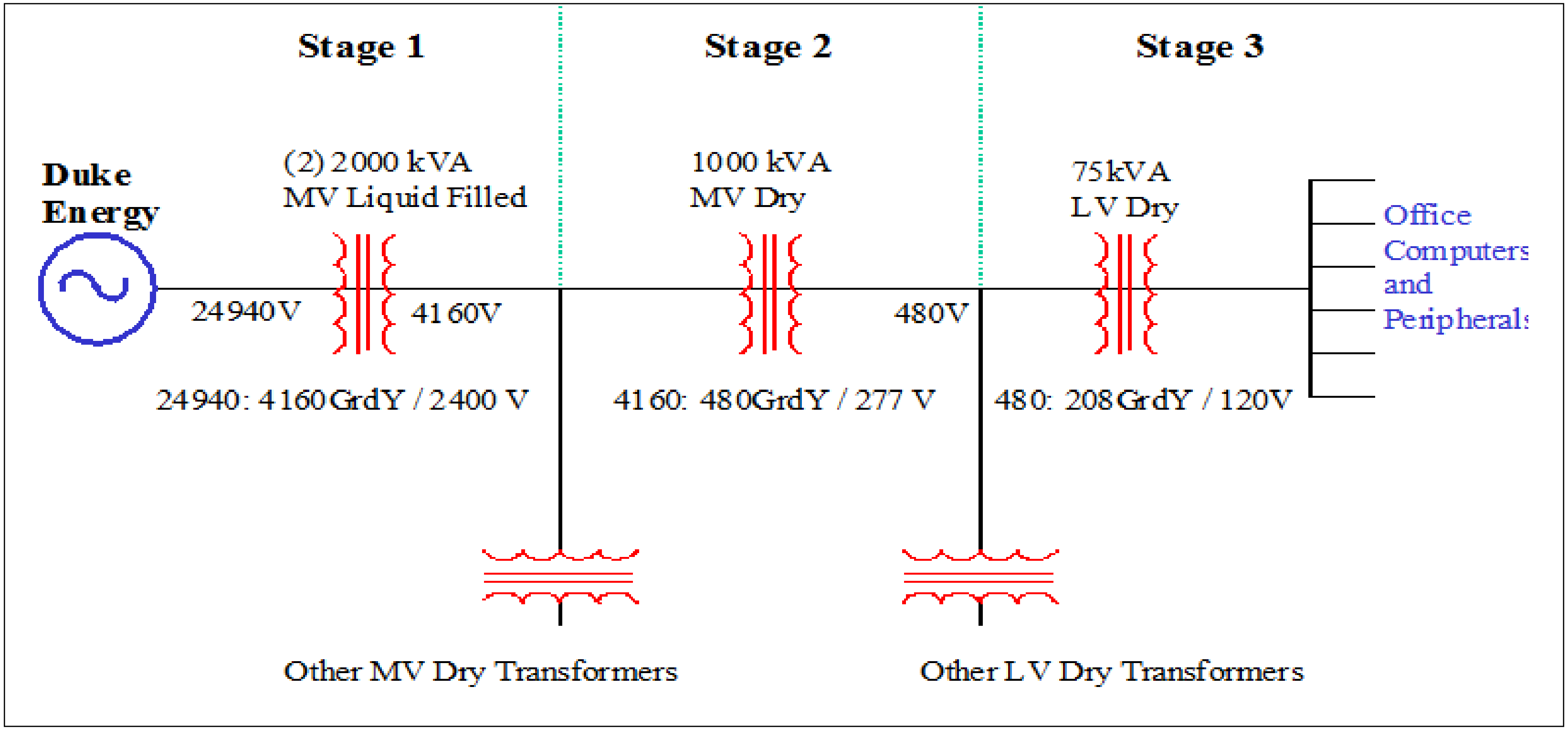
North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer

Network transformer for high density inner city loads

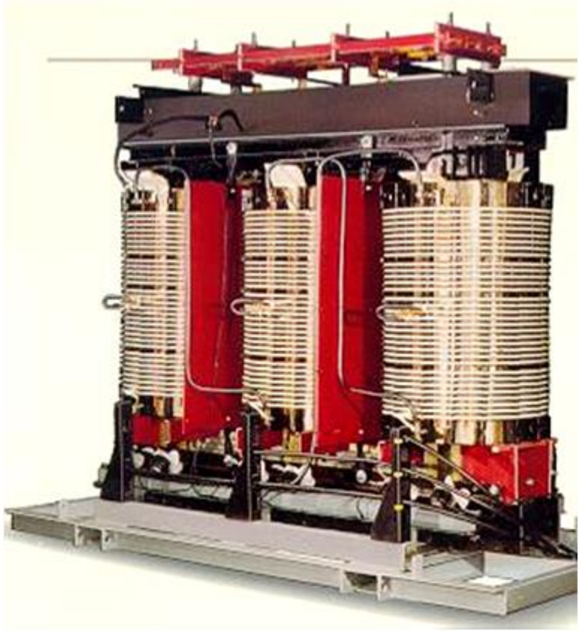
More than 10,000 sold per year

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)



North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer



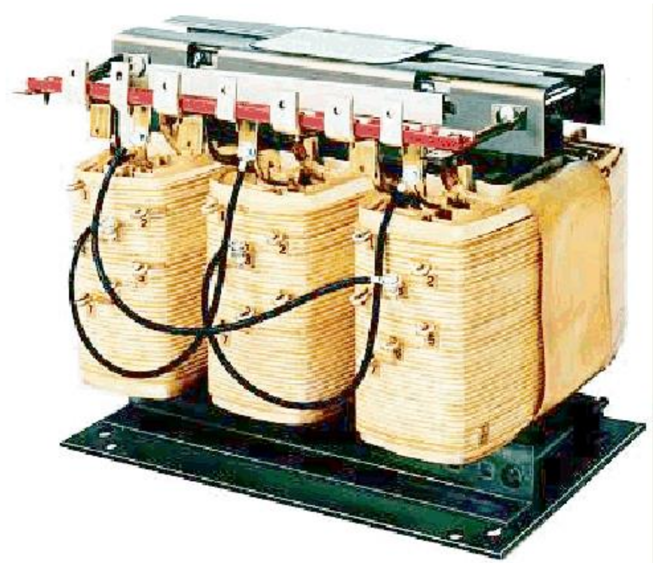
Medium Voltage Dry Type Transformer, VPI and Cast Resin

More than 20,000 sold per year

Most for indoor applications

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Definition of Distribution Transformer



Low Voltage Dry Type Transformer, VPI and Cast Resin

More than 300,000 sold per year

Most for indoor applications

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Distribution Transformer Energy Efficiency evolution

1. 1950's-1970's Losses in tight comfort zone
2. Mid 1970's losses segmentation started using Total Owning Cost Evaluation (Sum of Price + A $/watt * core loss + B $/watt * Load Loss). **Result $0/watt to $12.00/watt!**
3. 1990's US DOE probed Distribution Transformers for energy efficiency improvements
4. 1996 NEMA published TP-1 as voluntary Standard
5. 2007 DOE published first mandatory Standard
6. 2016 DOE published present mandatory standard
7. DOE updates or reaffirms every 5-6 years.
8. **Standards based on Life Cycle Cost minimization**

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Distribution Transformer Energy Efficiency evolution

DOE requirements for all efficiency standards

1. **Do-able without an invention**

2. **Economical and pay for themselves**

3. **Really Save Energy**

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Present DOE Rules mandatory January 1, 2016

1. **Efficiency =100% * (output/(output + losses)**
2. **Medium Voltage Distribution Transformers: Volts > 1,000, < 36,000**
   a) Output = Nameplate kVA *1000 *0.5
   b) 10-833 kVA single phase
   c) 15-2500 kVA 3-phase
3. **Low Voltage Dry Type Transformers: Volts < 1,000**
   a) Output = Nameplate kVA * 1000 *0.35
   b) 15-333 kVA Single Phase
   c) 15-1000 kVA Three Phase

Rules based on Efficiency, not losses

North American Distribution Transformer Energy Efficiency (Philip J Hopkinson, PE)

Assumptions in DOE Rules

1. **Medium Voltage Transformers tested at 50% of Nameplate Load**
2. **All Low Voltage Transformers tested at 35% of nameplate Load**
3. **Test Objective: Simulate losses in service**

RMS Equivalent Load basis of Measure

Distribution Transformer Energy Efficiency Task Force
(Philip J Hopkinson, PE)

3. Liquid Filled Final Rule

Table I.5 Electrical Efficiencies for All Liquid-Immersed Distribution Transformer Equipment Classes (Compliance Starting January 1, 2016)

Standards by kVA and Equipment Class			
Equipment Class 1		Equipment Class 2	
kVA	**%**	**kVA**	**%**
10	98.70	**15**	98.65
15	98.82	**30**	98.83
25	98.95	**45**	98.92
37.5	99.05	**75**	99.03
50	99.11	**112.5**	99.11
75	99.19	**150**	99.16
100	99.25	**225**	99.23
167	99.33	**300**	99.27
250	99.39	**500**	99.35
333	99.43	**750**	99.40
500	99.49	**1,000**	99.43
667	99.52	**1,500**	99.48
833	99.55	**2,000**	99.51
		2,500	99.53

Requires core steel better than M4, low current density
Paybacks > 10 years

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4. Medium Voltage Dry Final Rule

Table I.7 Electrical Efficiencies for All Medium-Voltage Dry-Type Distribution Transformer Equipment Classes (Compliance Starting January 1, 2016)

Standards by kVA and Equipment Class											
Equipment Class 5		Equipment Class 6		Equipment Class 7		Equipment Class 8		Equipment Class 9		Equipment Class 10	
kVA	%	kVA	%	kVA	%	kVA	%	kVA	%	kVA	%
15	98.10	15	97.50	15	97.86	15	97.18				
25	98.33	30	97.90	25	98.12	30	97.63				
37.5	98.49	45	98.10	37.5	98.30	45	97.86				
50	98.60	75	98.33	50	98.42	75	98.13				
75	98.73	112.5	98.52	75	98.57	112.5	98.36	75	98.53		
100	98.82	150	98.65	100	98.67	150	98.51	100	98.63		
167	98.96	225	98.82	167	98.83	225	98.69	167	98.80	225	98.57
250	99.07	300	98.93	250	98.95	300	98.81	250	98.91	300	98.69
333	99.14	500	99.09	333	99.03	500	98.99	333	98.99	500	98.89
500	99.22	750	99.21	500	99.12	750	99.12	500	99.09	750	99.02
667	99.27	1,000	99.28	667	99.18	1,000	99.20	667	99.15	1,000	99.11
833	99.31	1,500	99.37	833	99.23	1,500	99.30	833	99.20	1,500	99.21
		2,000	99.43			2,000	99.36			2,000	99.28
		2,500	99.47			2,500	99.41			2,500	99.33

Requires mitred cores M4 steel and low current density

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5. Low Voltage Dry Final Rule

Table I.6 Electrical Efficiencies for All Low-Voltage Dry-Type Distribution Transformer Equipment Classes (Compliance Starting January 1, 2016)

Standards by kVA and Equipment Class			
Equipment Class 3		Equipment Class4	
kVA	%	kVA	%
15	97.70	15	97.89
25	98.00	30	98.23
37.5	98.20	45	98.40
50	98.30	75	98.60
75	98.50	112.5	98.74
100	98.60	150	98.83
167	98.70	225	98.94
250	98.80	300	99.02
333	98.90	500	99.14
		750	99.23
		1,000	99.28

3 Phase % reduction
29.7
29.2
30.4
30.0
30.0
31.2
29.3
30.0
33.8
35.8
34.5

- 1 Phase efficiencies modest
- 3 Phase efficiencies require very low core loss
- These reductions will have large impacts on the Industry!

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6. LCC and Paybacks in Final Rule

Table I.8 Impacts of Today's Standards on Customers of Distribution Transformers

Design Line	Average LCC Savings 2011$	Median Payback Period years
Liquid-Immersed		
1	72	18.2
2	66	5.9
3	2,753	8.6
4	967	7.0
5	4,289	6.3
Low-voltage dry-type**		
6	N/A*	N/A*
7	1,678	3.6
8	2,588	7.7
Medium-voltage dry-type		
9	787	2.6
10	4,455	8.6
11	996	10.6
12	6,790	8.5
13A	-27	16.1
13B	4,346	12.2

*No customers are impacted by today's standard because there is no change from the minimum efficiency standard for design line 6.
** See section IV.A.3.d for discussion of core construction technique.

DOE Paybacks questionable due to energy cost, selling prices, and cost of funds

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7. Considerations in Final Rule

a) Material prices supposed to reflect 2010-2011
b) **Energy prices that are considerably higher than today's actuals**
c) **Loading remains at 35% for LV and 50% for Medium Voltage**
d) M3 core material and Amorphous
e) Transformer Selling price versus efficiency
f) Dollars cost per watt saved analysis
g) Energy savings versus efficiency levels
h) Payback period versus efficiency
i) Manufacturing Impact
j) Market Impact
k) Core Steel impacts
l) Proposed efficiencies.

1. **All sides wanted M3 Core Material to remain Viable**
2. **Utilities worried about selling price increases**
3. **Considerable concern about rebuild market**

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Examination of Loading

Medium Voltage Transformer Efficiency based on 50% load

1. Initial market data suggested 50% load was good RMS-equivalent load
2. Advocates for low core loss suggest 35-39% load more representative
3. Advocates for low winding loss note many transformers highly overloaded beyond nameplate

IEEE Transformers Committee Taskforce formed to study loading

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Loading findings to date

1. Utilities buy large quantities of transformers that meet DOE efficiency rules and place in stock
2. Transformers drawn from stock as needed
3. Same transformer may go to:
   a) Residential
   b) Commercial
   c) Industrial
4. Some transformers could be lightly loaded
5. Some transformers could be loaded beyond nameplate
6. Utility objective is maximizing utilization of Capital Equipment Investment, not directly on efficiency
7. **Loading limits based on thermals and voltage regulation**

Wide range of loadings evident to date

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Loading findings to date

Pacific Gas & Electric installations standardized but upper limits for Thermals and Voltage Regulation:

Thermals:

- Hot Spot of 190°C for mineral oil or 200°C for natural ester.
- Top Oil of 110°C for mineral oil or 120°C for natural ester.
- Total Aging of 13,140 hours (1 1/2 years of aging in a single year).

Voltage Regulation:

- Voltage drop < 6.5 Volts for transformer secondary
- Flicker drop < 8.0 Volts for transformer, secondary and service
- Flicker drop for transformer and secondary, a total of 6.0 volts or less

Broad limits for loading beyond nameplate

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Data Collection to date from smart meters:

1. Transformer type
2. Power rating
3. Application
4. Hourly readings taken of time and load
5. 24 hours per day and 365 days per year
6. Total of 24 * 365 = **8760 data points per year:**

Initial Findings from RMS-equivalent load summary:

1. **Residential 10% to 78 % of nameplate, 50% average**
2. **Commercial 40% to 80% of nameplate, 60%average**
3. **Industrial varies 40-90% of nameplate, 70% average**

Wide range of loadings evident to date
Average > 50% but peaks > 120% of nameplate

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Thoughts about Transformer losses and efficiency:

1. Core loss is no-load loss and constant at all loads
2. Load loss (winding resistance, eddies and stray) varies as load squared.
3. Total loss = Core loss + Load loss
4. Efficiency = 100% * Output/(Output + Losses)
5. Peak efficiency always at load where core watts=load watts
6. Most manufacturers goal:
   a) Medium Voltage peak =50% load.
   b) Low voltage peak = 35% load

Full Load Loss ratio = Load loss / Core Loss

Medium Voltage transformers ~4:1

Low Voltage transformers ~10:1

Peak efficiency always at load where core loss=load loss

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Closer look at loss ratio (Load Loss / Core Loss) vs. PU Load:

Percent Load	MV Loss ratio	LV Loss Ratio
10	0.04	0.08
35	0.49	1.00
50	1.00	2.04
75	2.25	4.59
100	4.00	8.16
120	5.76	11.76
140	7.84	16.00

Loading beyond nameplate results in high load loss

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Closer look at loss ratio (Load Loss / Core Loss) vs. PU Load:

1. Conventional grain oriented core steels were basis of original DOE standards.
2. New Core materials excellent for high efficiency at low loads.
3. New total loss constraints are excellent additions for all materials and guarantee high efficiency at all loads.

Constraints on Total loss seem appropriate

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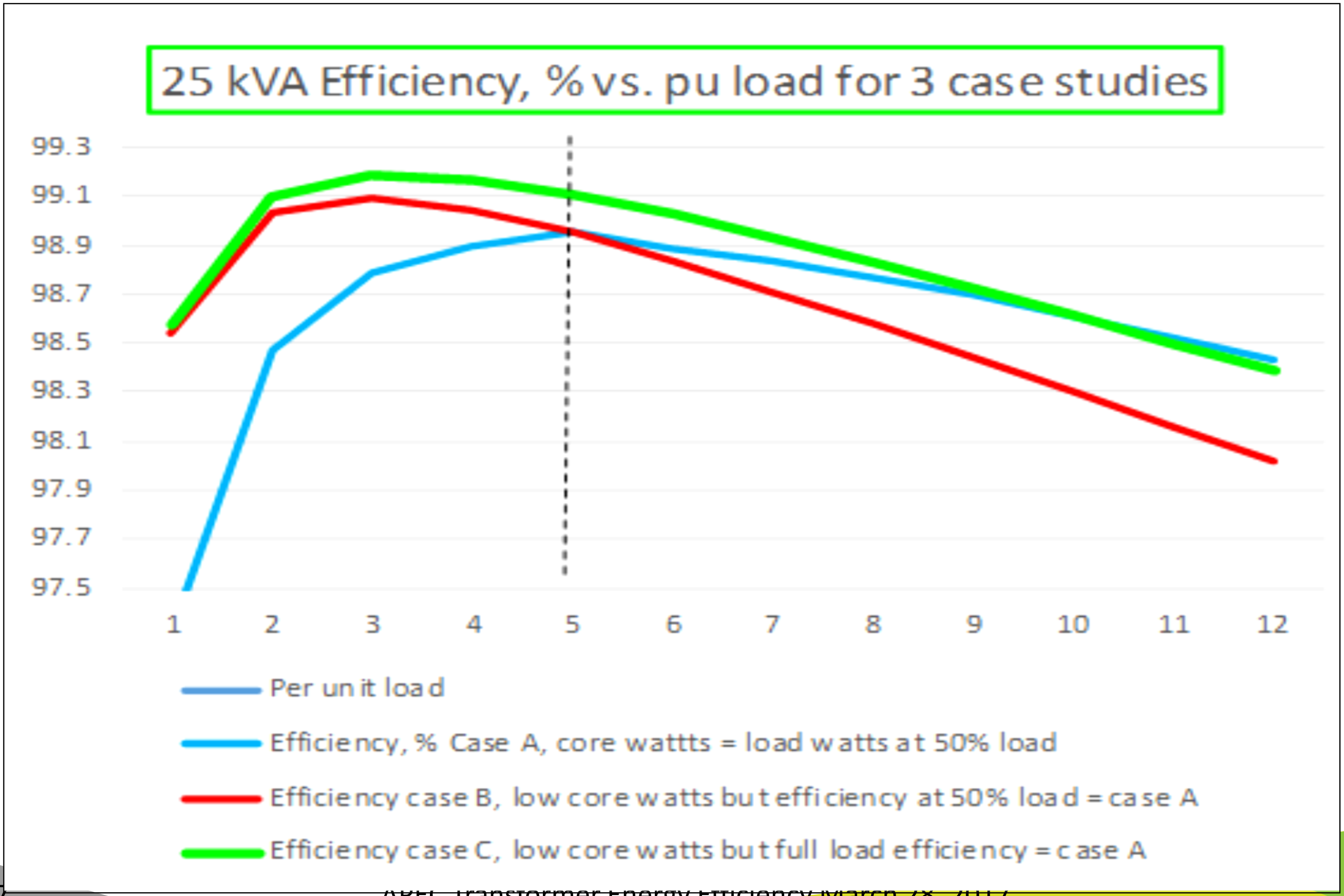
Data Collection to date from smart meters



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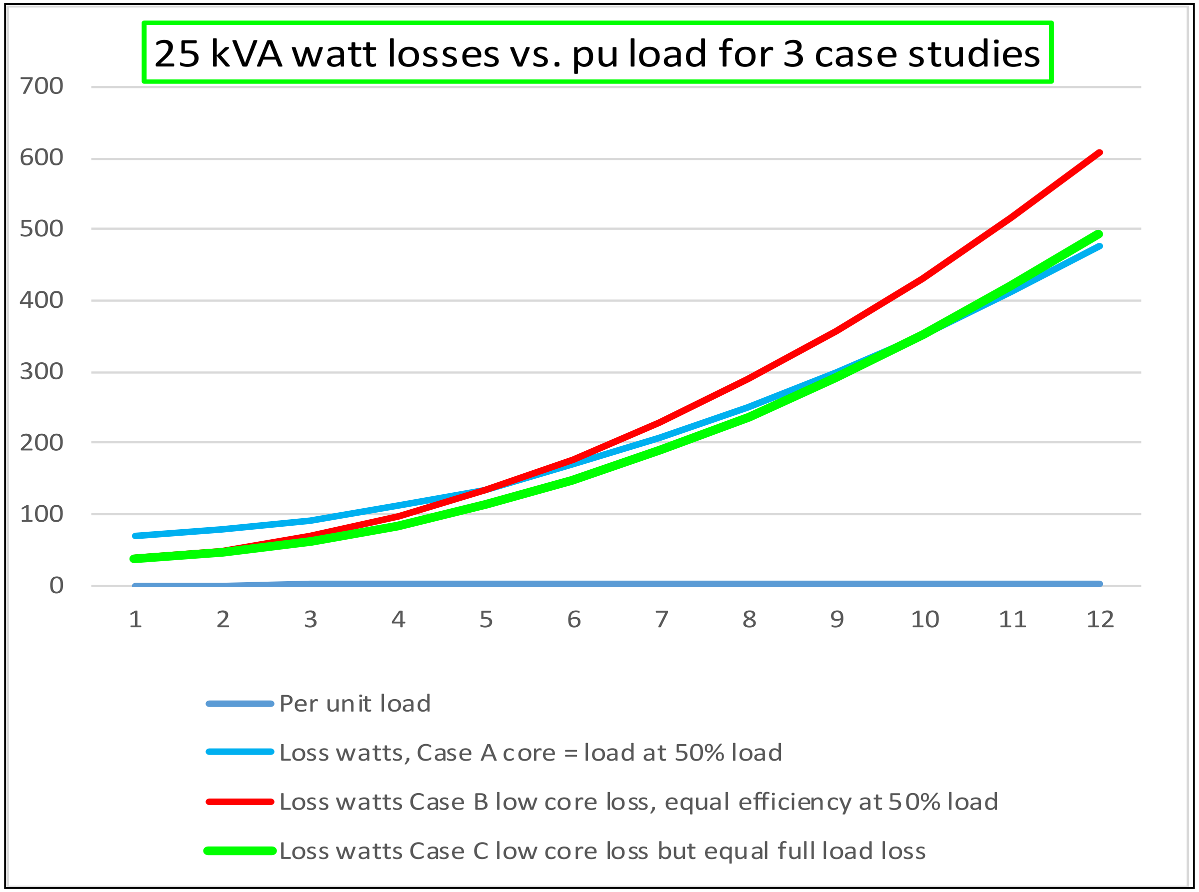

Wide range of loadings evident to date

Distribution Transformer Energy Efficiency Task Force
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Impact of new Total Loss Constraint

1. Basis is total allowable loss at current measurement point for energy efficiency; i.e. at 50% or 35 % load, called "W"
   W= (pu Load) * kVA*1000*(1-PU Efficiency)/Efficiency
2. W/2 is starting assumed load loss.
3. W/2 * (1 /(pu load))^2 / Temperature correction factor = full load loss component = L
4. **Total Loss limit = L + W/2**
5. Suppose real core loss, C, < W/2
6. That is excellent and encouraged.
7. Two constraints must be satisfied.
   a) C < W/2.
   b) L' +C < L+W/2

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Discussion

1. Transformers where core loss = load loss at measurement %load inherently meet this requirement.
2. Transformers with lower core losses are encouraged and save energy at light loads.
3. Transformers with heavy loads do not result in burden to Utility system.