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50 / 60 Hz Frequency Conversion of Measured Transformer Performance Parameters

Outline

- Background
- Survey of presently used factors
- Core Loss
- Exciting Current
- Impedance Voltage
- Load Loss
- Short Circuit Test
- Temperature – Rises
- Sound Levels
- Proposed wording changes in 12.00 and 12.90
- Bibliography

Background

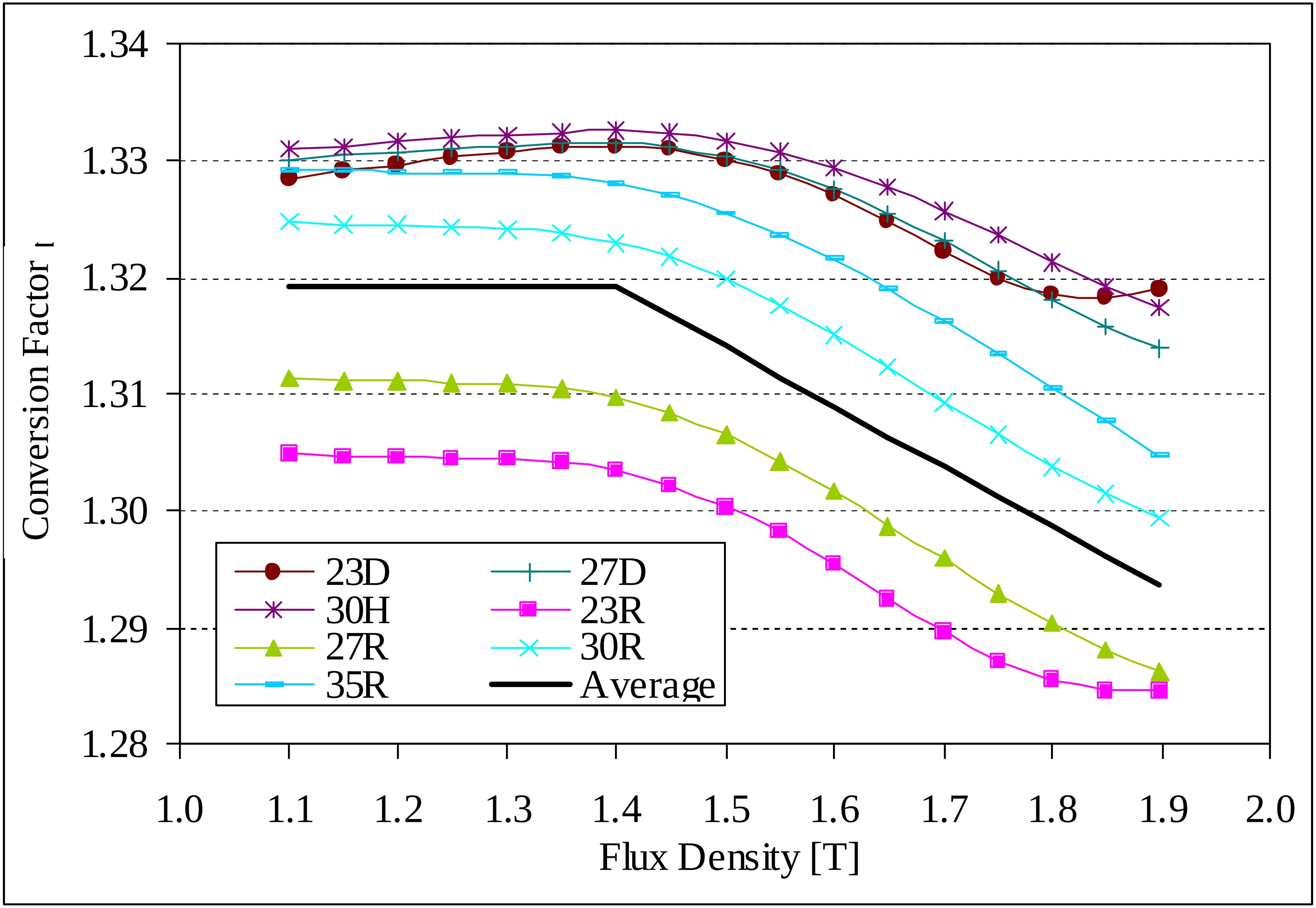
- **Transformers are normally tested at the frequency they will see in service**
- **Transformer suppliers for the NA & other 60 Hz markets may only have 50 Hz test facilities**
  - Only option is to test at 50 Hz and use conversion factors
  - Presently, a wide range of conversion factors are in use
  - No standard today on factors to use
- **Through the IEEE Transformer Standards Committee, users requested that standard conversion factors be developed to be uniformly used amongst suppliers**

Survey of Presently Used 50 to 60 Hz Frequency Conversion Factors

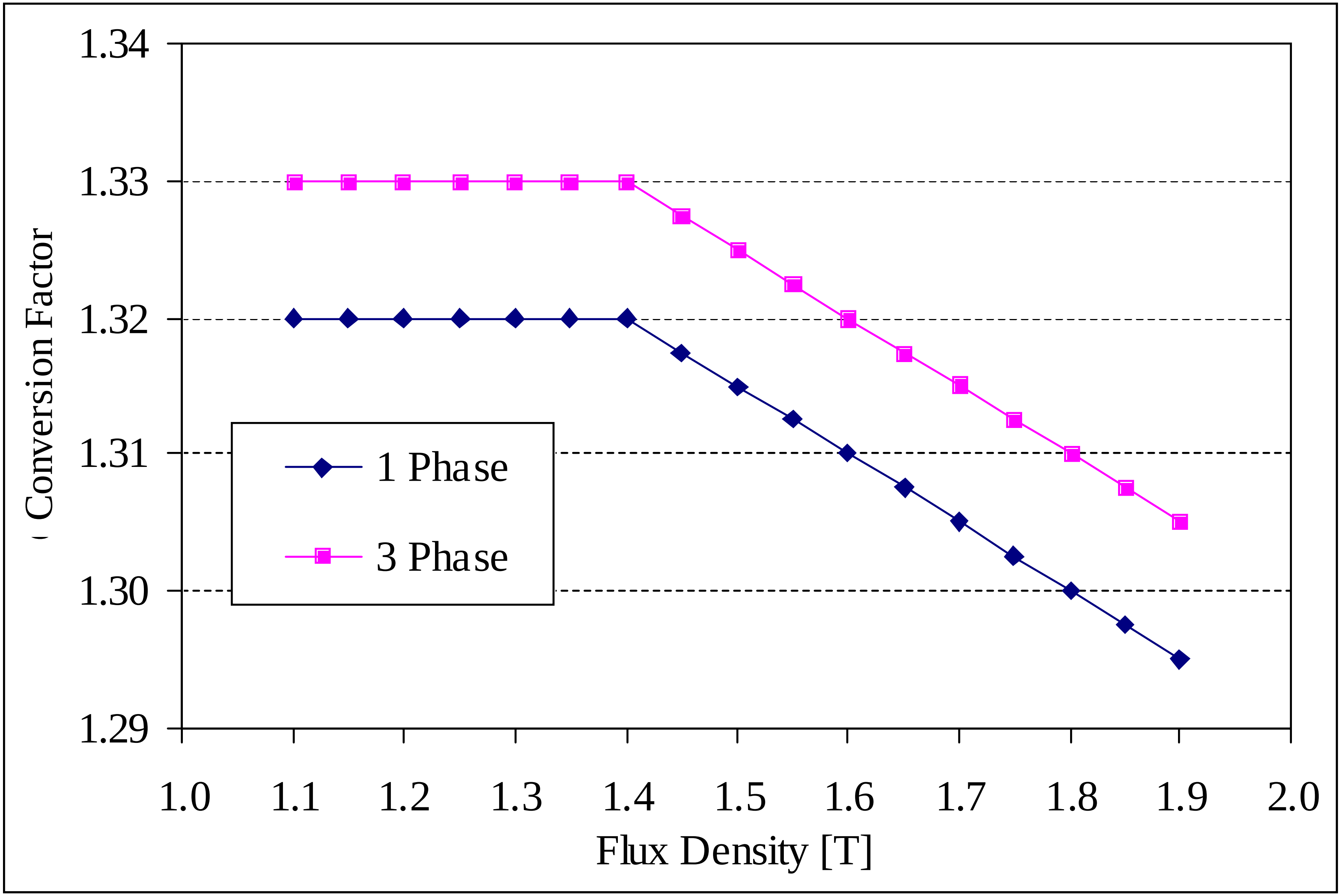
		Core Loss	Exciting Current	Noise	Load Loss	
					Eddy	Stray
Manufacturer	1	1.30	1.20	+2.0 dB	1.31	1.31
	2	1.30	-	0.0 dB	1.44	1.32
	3	f(B, matl)	1.00	+2 dB	1.44	1.16
	4	1.33	-	-	1.44	1.45
	5	f(B, matl)	-	-	1.44	same
	6	-	-	+0.33 dB	-	-
	7	1.31	1.11	+3.0 dB	-	-
	8	1.32	1.00	+3.5 dB	1.44	1.16

No Load Loss

Ratio of Material Iron Loss Values

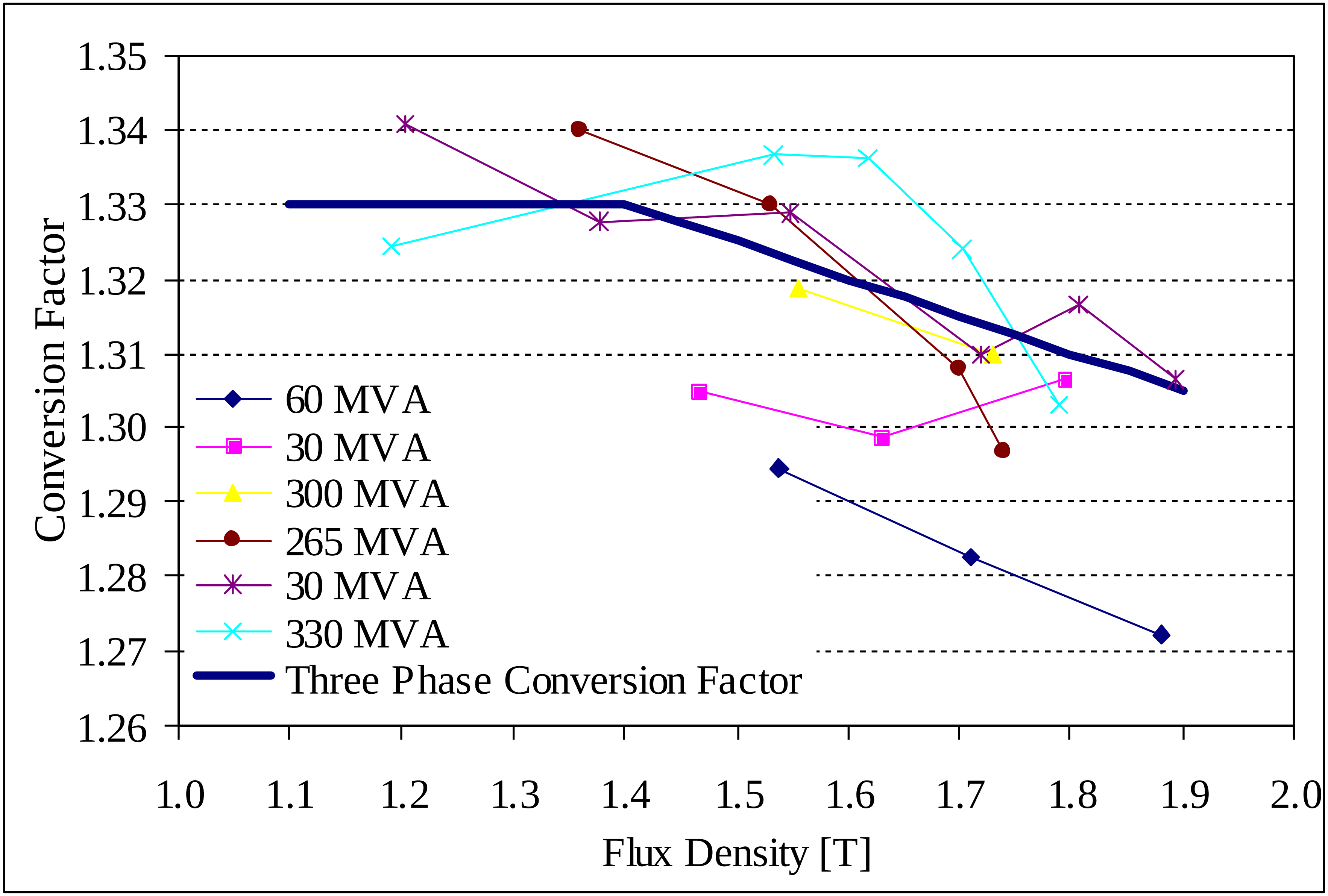


Proposed No Load Loss Conversion Factors



Considering the 1 % higher core loss Building factor at 60 Hz for 3 phase transformers

No-Load Loss Frequency Conversion Factor Verification



B1. No Load Loss & Exciting Current

No Load Loss Conversion Factors (50 to 60 Hz):

Single Phase: $B \leq 1.4T = 1.32$ [38]

$B > 1.4T = 1.32 - 0.05(B-1.4)$ [39]

Three Phase: $B \leq 1.4T = 1.33$ [40]

$B > 1.4T = 1.33 - 0.05(B-1.4)$ [41]

No Load Loss Conversion Factors (60 Hz to 50 Hz):

Single Phase: $B \leq 1.4T = 1/1.32$ [42]

$$B > 1.4T = \frac{1}{1.32 - 0.05 \times (B - 1.4)}$$ [43]

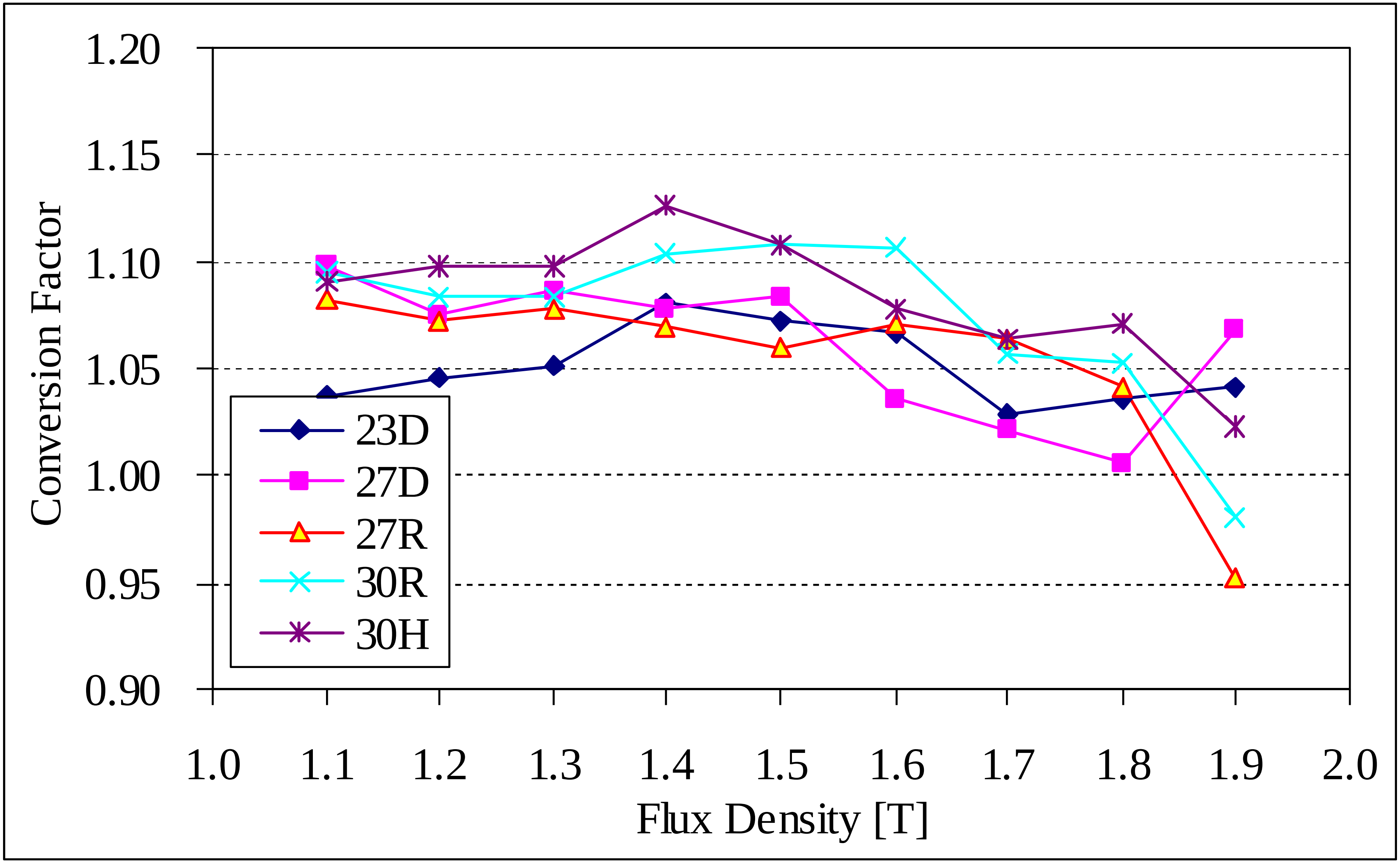
Three Phase: $B \leq 1.4T = 1/1.33$ [44]

$$B > 1.4T = \frac{1}{1.33 - 0.05 \times (B - 1.4)}$$ [45]

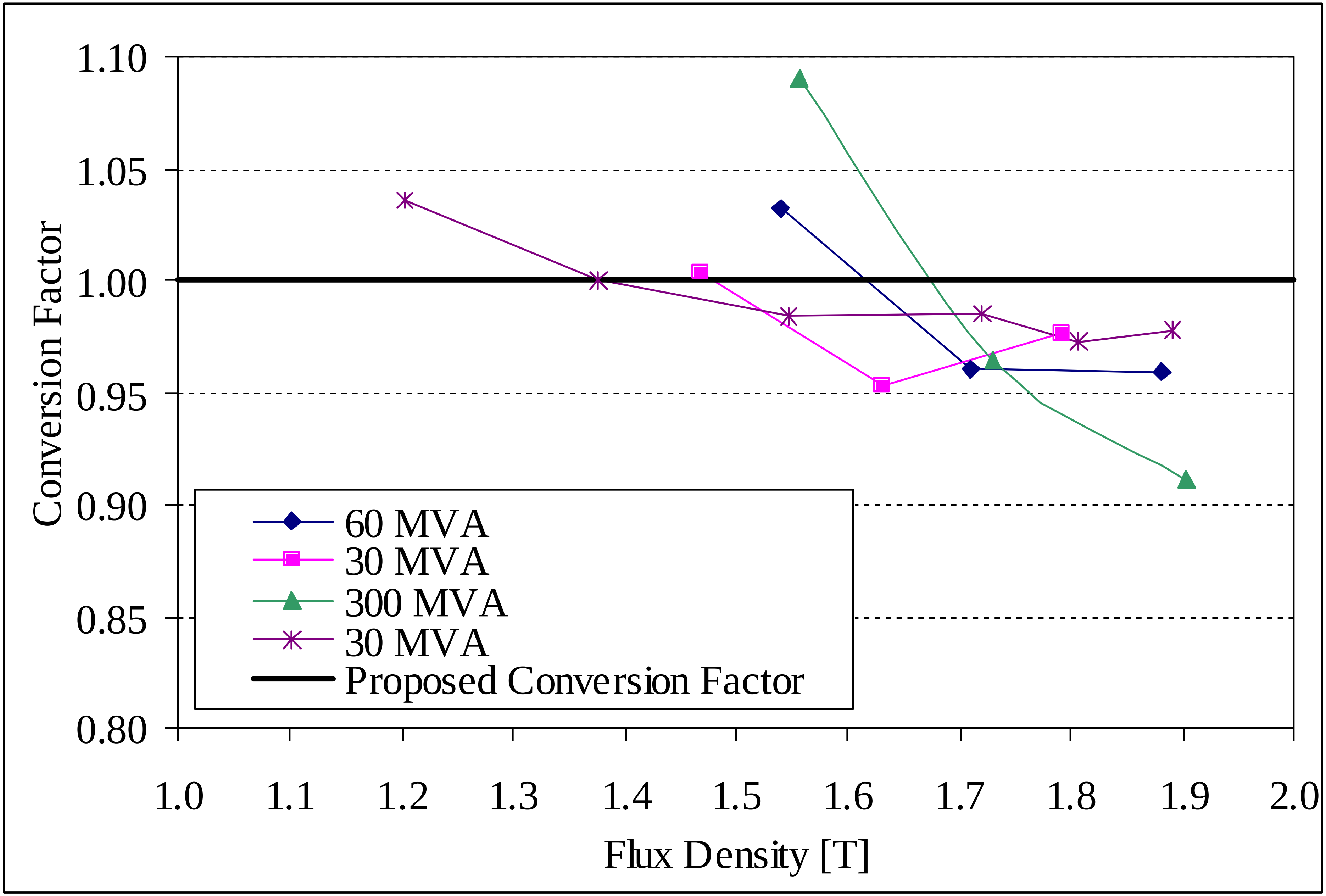
Where B = flux density [T]

Exciting Current

Exciting Current Material Ratios



Exciting Current Measured Conversion Factor



B1. No Load Loss & Exciting Current

Since the value of these conversion factors is an average value for all core materials, this would add 1% uncertainty to the accuracy of the measurement

The exciting current conversion factor is 1.00, thus the measured value of the exciting current does not need to be converted from one to the other frequency.

Example: 50 Hz to 60 Hz Conversion for a Three Phase Transformer

Design Flux Density	= 1.7 T
Rated Voltage at 60 Hz	= 13.8 kV
Voltage applied at 50 Hz = 13.8 x 5/6	= 11.5 kV
Correction Factor = 1.33 - 0.05x(1.7-1.4)	= 1.315
Measured No Load Loss at 50 Hz	= 22.8 kW
Corrected No Load Loss at 60 Hz	= 22.8 x 1.315 = 30 kW
Measured Exciting Current at 50 Hz	= 2.3 A
Exciting Current at 60 Hz	= 2.3 A

Impedance Voltage

Impedance Voltage

- **Impedance voltage made up of resistive and reactive component**

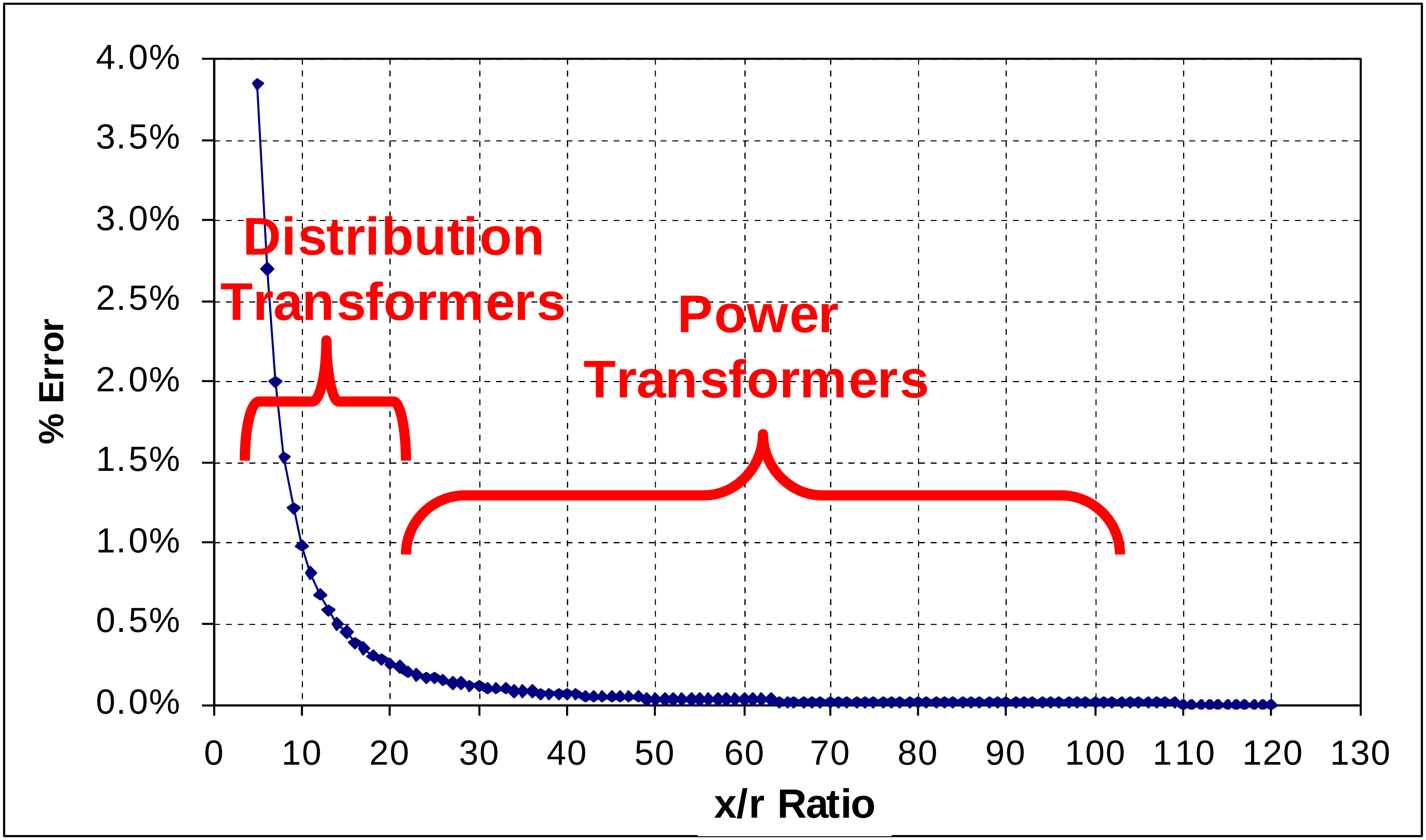
$$E_Z = \sqrt{E_X^2 + E_R^2}$$

- **Reactive component proportional to frequency**
- **Resistive component constant with frequency**
- **Therefore, the impedance voltage will be nearly proportional to frequency if $E_R << E_x$**
  - **x/r ratio is a high number for power transformer**

Typical Range of x/r Ratio

- Actual values gathered for over 100 transformers
  - 12 MVA to 800 MVA
  - Core form and shell form
  - All voltage range
  - GSU versus Auto transformers
  - Whole range of load loss evaluation
- Range of ratio x / r for power Transformers
  - Small power transformers 15 to 40
  - Medium power transformers 35 to 70
  - Large power transformers 40 to 125
- Range of ratio x / r for distribution size Transformers
  - 1 to 20

Impedance – voltage conversion error Versus x/r Ratio



- **Larger error for distribution transformers. However, testing at other than power frequency is rare**

Conclusion for Impedance Voltage

- **Using a 5/6 ratio for voltage is sufficiently accurate for the error involved for Power Transformers**
  - <0.5% for small transformers
  - Negligible for larger transformers

$$v_{50} = v_{60} \cdot \frac{5}{6}$$

- **Distribution Transformers**
  - Cannot simply use the 5/6 ratio
    - Must be sure rated current is applied
  - However, less need for distribution transformers since it is rare for units to be built and tested at non rated frequency

Short Circuit

Short Circuit Freq Conversion Factor

- **Test can be performed using I_{SC}, K factor, and I_{SC} (Peak Asymmetric) values calculated for 60 Hz**
- **Use approximately the 5/6 ratio of the voltage to get the calculated symmetrical and asymmetrical currents**
- **Follow test procedure in the same manner**
- **As per IEC, mechanical & thermal stresses would be nearly equivalent for 50 Hz or 60 Hz**
- **Anyway – most of the short circuit test facilities have both frequencies available for test**

Load Loss

Calculated Ratios for Eddy & Stray Loss

- **For strap conductor, winding eddies are proportional to $[60/50]^{2} = 1.44$**
- **Stray loss components are affected by frequency in two ways:**
  - Distribution of the flux and frequency of the flux
- **Studied effect of frequency on flux distribution & stray loss components for a wide range of transformer sizes and different tank shielding options**

Loss Component	Loss Ratio	
	With	Without
Tank Wall	1.23	1.19
Tank Cover	1.37	1.34
Clamps	1.22	1.23
Tie Plate	1.27	1.29
Total Stray Losses	**1.28**	**1.19**

w/w/o magnetic shielding

Stray Loss Factor Conclusions

- **Overall ratio not sensitive to the distance to tank wall or size of the transformer**
- **Calculated stray loss factors**
  - **No shielding = 1.28**
  - **Magnetic shunts = 1.19**
  - **Conductive shielding = 1.23**
- **Using one single factor of 1.23 for all shielding types would provide sufficient accuracy (Error $\leq$ 1 % in LL)**

Load Loss Conversion factor Verification

(Using 1.23 for stray, 1.34 to eddy + stray)

Loss Component	Value	Tap Position		
		1	3	5
Stray Loss	50 Hz Test X 1.23	54.4	40.3	28.3
	60 Hz Test	55.2	40.7	29.2
	% Deviation	1.6%	0.9%	3.0%
Eddy + Stray Loss	50 Hz Test X 1.34	79.3	63.0	50.0
	60 Hz Test	78.5	62.4	50.8
	% Deviation	-1.0%	-0.9%	1.6%

- **Unit measured at both 50 & 60 Hz**
- **50 Hz values converted to 60Hz**
- **Effect of deviation on total load loss is less than 0.5%**

B2. Load Loss

The following conversion factors shall be used to convert the values of load loss measured at 50Hz to their corrected values at 60Hz.

Conversion values are given below to convert the measured winding eddy and stray loss separately if a magnetic field program was available to calculate at least the winding eddy losses. Otherwise a conversion factor is given below for the sum of winding eddy + stray losses.

Load Loss Conversion Factors – 50 Hz to 60 Hz

Winding Eddy Loss:	1.44
Stray Loss:	1.23
Winding Eddy + Stray:	1.34

Load Loss Conversion Factors – 60 Hz to 50 Hz

Winding Eddy Loss:	$1/1.44$
Stray Loss:	$1/1.23$
Winding Eddy + Stray:	$1/1.34$

B2. Load Loss

Example:

Measured Losses at 50Hz:

Total Load Loss = **142.4** kW

I^2R = 124.6 kW

Winding Eddy+Stray = 17.8 kW

Corrected Losses for 60Hz

Winding Eddy+Stray = 17.8 ×1.34 = 23.9 kW

Total Load Loss = 124.6 + 23.9 = **148.5** kW

Temperature Rise

Temperature Rise - Goal

- **Apply current to produce 60 Hz oil – rise losses**
  - To give the correct 60 Hz total losses (core, I^2R, eddy, stray)
- **Apply current to produce 60 Hz winding – rise losses**
  - To give nearly correct winding losses (I^2R, eddy)
- **Apply cooling that removes the same amount of watts as with a 60 Hz operation**
- **Measure oil – & winding – rises and scan tank temperatures**

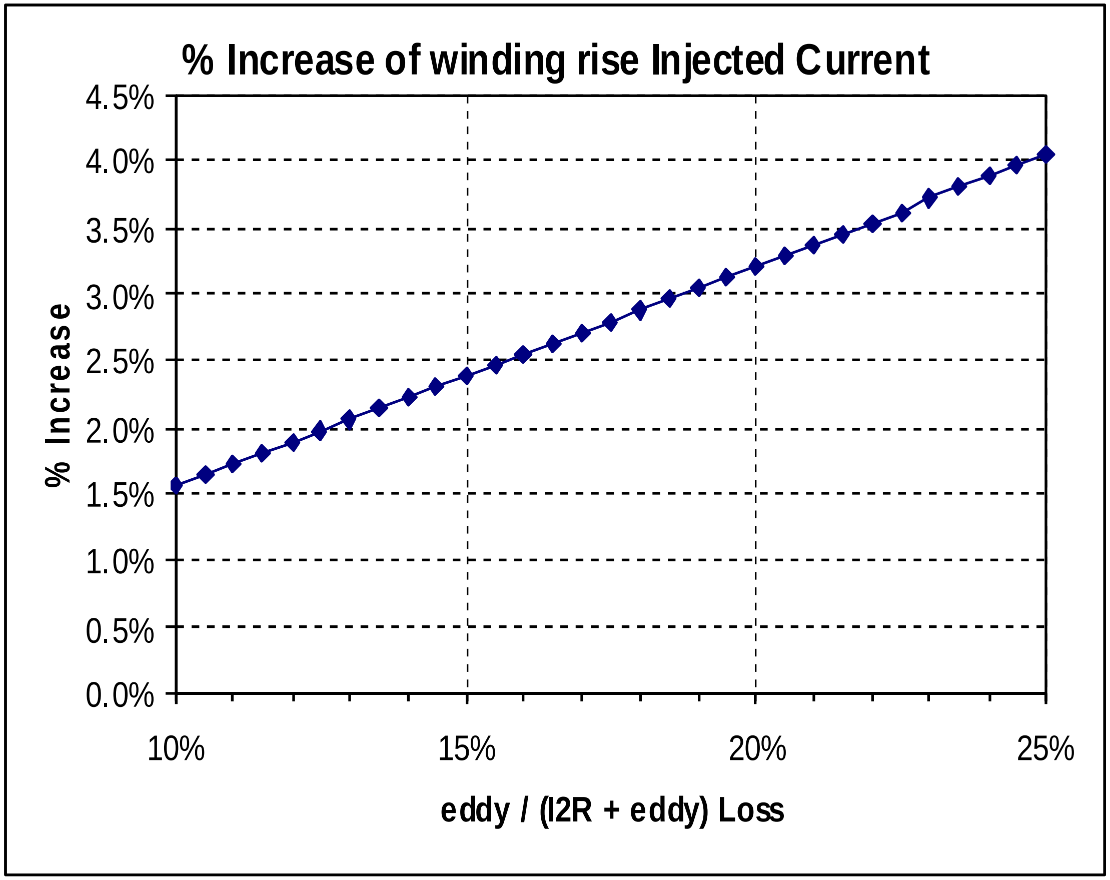
Cooling Equipment Operation

- **Induction motors for pumps and fans will cause reduced cooling performance if operated at 50 Hz**
- **Manufacturer must have adequate 60 Hz supply to operate cooling equipment**

Temperature Rise Tests

- **For the same magnitude of load current:**
  - Winding & total load Losses will be lower at 50 Hz
    - Lower winding, oil, & structural parts temperature rises

- **Current for winding – rise at 50 Hz must be increased by 1.0 – 3.5 % to achieve the required 60 Hz winding rise**



Example

- **Unit designed for 60Hz but to be tested at 50Hz**

Case		A	B	C
Supply Frequency		60Hz	50Hz	50Hz
Current		rated	rated	adjusted
I^2R Loss	kW	124.6	124.6	126.4
Winding Eddy Loss	kW	6.2	4.3	4.4
Winding Loss	kW	130.8	128.9	130.8
Injected Winding Current	A	246.6	246.6	248.4
Increase vs 60Hz	%			0.73%
Winding Gradient	deg C	5.8		
Eddy % of Total		4.7%		3.3%

Injected Current Calculation (During Test)

- **Heat Run Current**

$$I_{SC,50} = I_{SC,60} \cdot \sqrt{\frac{P_0 + \left(P_{I2R} + P_{e+s} \cdot 1.34\right)}{P_0 + \left(P_{I2R} + P_{e+s}\right)}}$$

- **Winding Rise Current**

$$I_{R,50} = I_{R,60} \cdot \sqrt{\frac{P_{I2R} + 1.44 \cdot P_e}{P_{I2R} + P_e}}$$

- $I_{SC,60}$ = heat run current for 60Hz
- $I_{SC,50}$ = adjusted heat run current for 50Hz
- $I_{R,60}$ = rated current for 60Hz
- $I_{R,50}$ = adjusted rated current for 50Hz
- P_0 = meas no load loss at 60Hz
- P_{I2R} = measured ohmic loss at 50Hz
- P_{e+s} = measured winding eddy + stray loss at 50Hz
- P_e = measured winding eddy loss at 50Hz

Injected Current Calculation (Design Stage)

- **Heat Run Current**

$$I_{SC,50} = I_{SC,60} \cdot \sqrt{\frac{P_0 + \left(P_{I2R} + P_e + P_S\right)}{P_0 + \left(P_{I2R} + P_e/1.44 + P_S/1.23\right)}}$$

- **Winding Rise Current**

$$I_{R,50} = I_{R,60} \cdot \sqrt{\frac{P_{I2R} + P_e}{P_{I2R} + P_e/1.44}}$$

- **$I_{SC,60}$ = heat run current for 60Hz**
- **$I_{R,60}$ = rated current for 60Hz**
- **P_0 = no load loss at 60Hz**
- **P_e = winding eddy loss at 60Hz**

$I_{SC,50}$ = adjusted heat run current for 50Hz

$I_{R,50}$ = adjusted rated current for 50Hz

P_{I2R} = ohmic loss at 60Hz

P_S = stray loss at 60Hz

Temperature Rises

- **Measured oil – rise is accurate for rated frequency**
  - Unit will have correct rated frequency loss
  - Does not matter if the winding eddies and stray are not correct
- **Winding – rise would also be accurate**
  - Winding has correct losses so average winding rise should be correct
- **Reported Winding hot – spot temperature rise will be accurate**
- **Directly measured hot – spot temperature rise error = ± 3 C**
  - Caused by different distribution of eddy losses in windings
- **Tank – rise error would be a maximum of 2 C**
  - Worst case would be for high stray loss and/or tank rise in order of 40 C
  - Difficult to correct
  - Add statement to wording

B3. Temperature Rise

The following current multipliers shall be applied to achieve the correct rated frequency loss. The injected current for the initial estimate of the total losses run current shall be adjusted so that the ohmic loss is increased to offset the decreased winding eddy and stray loss with 50Hz operation (although this current is given, the overall requirement is that the correct rated frequency total loss must be achieved). Similarly, the injected current for the winding rise test must be adjusted so that the ohmic loss is increased to offset the decreased winding eddy loss with 50Hz operation.

B3. Temperature Rise

Example:

Calculated total loss run current for 60Hz = 272.0 A

Calculated rated current for 60Hz = 246.6 A

P_0 measured at 50 Hz and converted to 60Hz = 14.4 kW

P_{I2R} = 124.6 kW

P_{e+s} measured at 50 Hz = 17.8 kW

P_e measured at 50 Hz = 4.3 kW

Total Loss Run Current at 50Hz $= 272.0 \times \sqrt{\dfrac{14.4 + (124.6 + 17.8 \times 1.34)}{14.4 + (124.6 + 17.8)}} = 277.2A$

Winding Rise Current at 50Hz $= 246.6 \times \sqrt{\dfrac{124.6 + 1.44 \times 4.3}{124.6 + 4.3}} = 248.4A$

B3. Temperature Rise

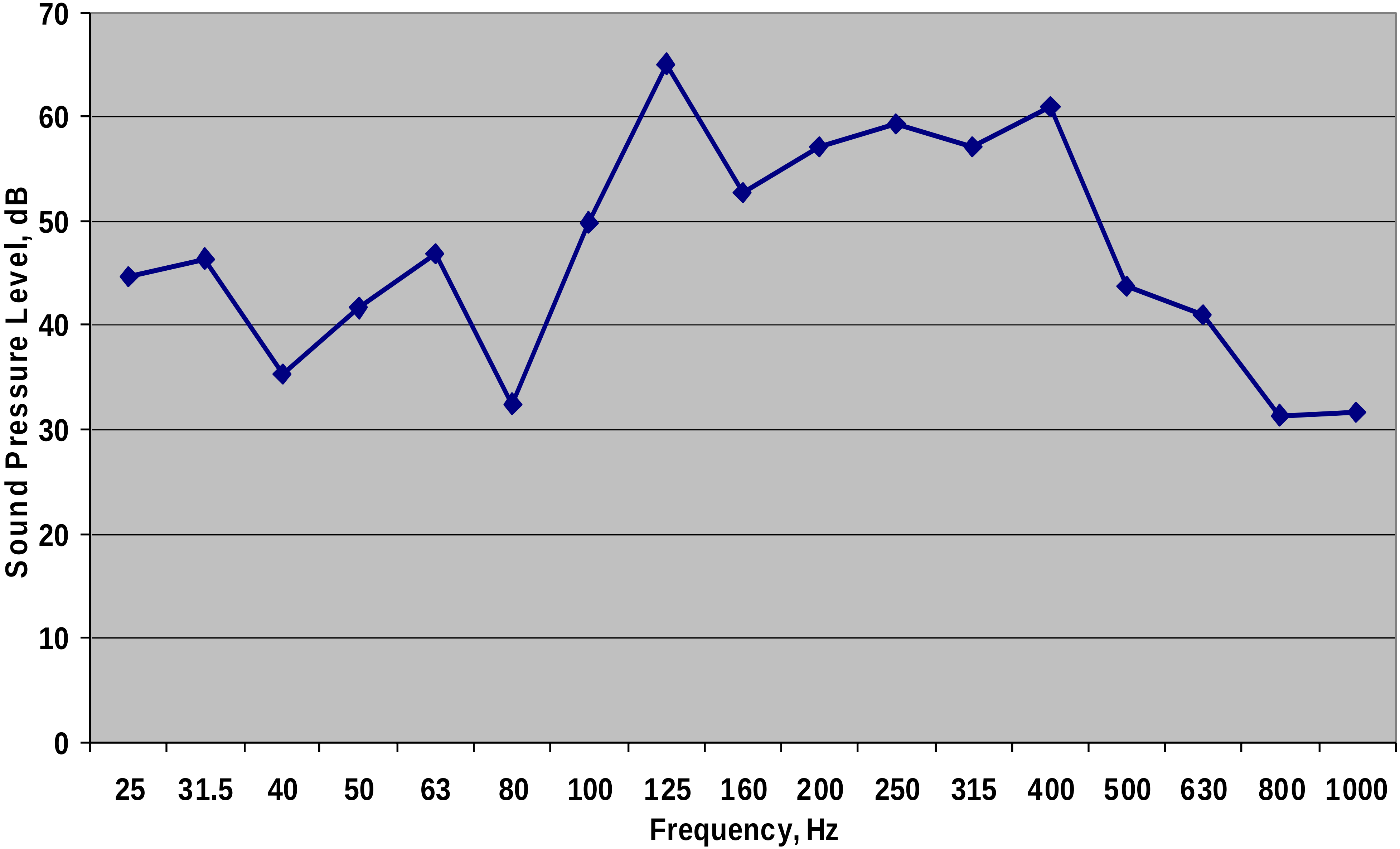
The manufacturer shall provide an adequate supply to operate the cooling equipment at the rated frequency.

The measured average oil and average winding rises will be considered accurate for rated frequency condition since the correct rated frequency losses are applied. It should be noted that direct hot spot temperature measurements (e.g. fiberoptic probes) would need to be corrected for winding eddy losses at the rated frequency.

The measured tank temperature rises could be in error by a few degrees C since the stray losses will not be correct and should thus be noted on certified test reports.

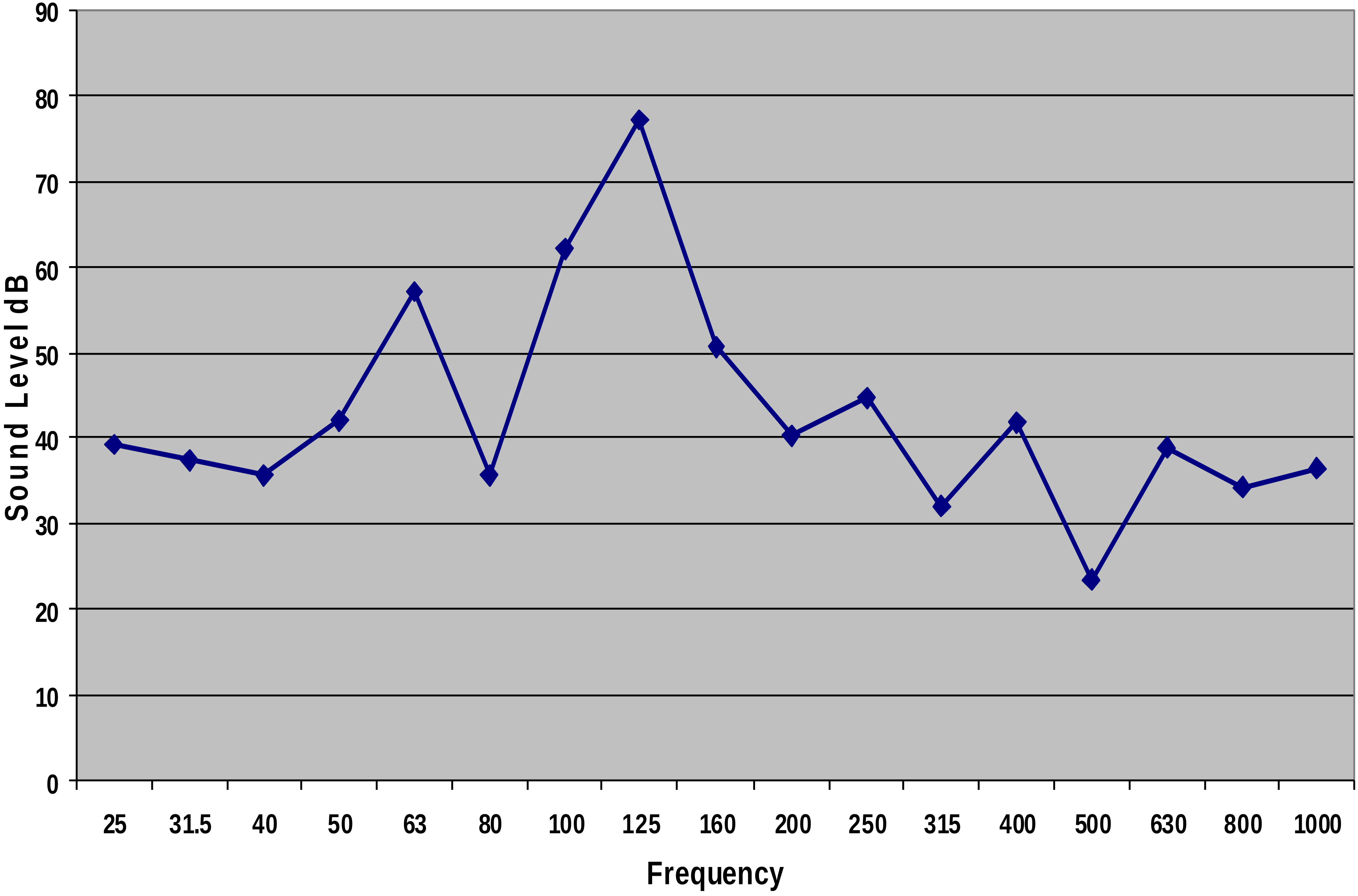
Sound Level

Measured Frequency Spectrum of Core Noise

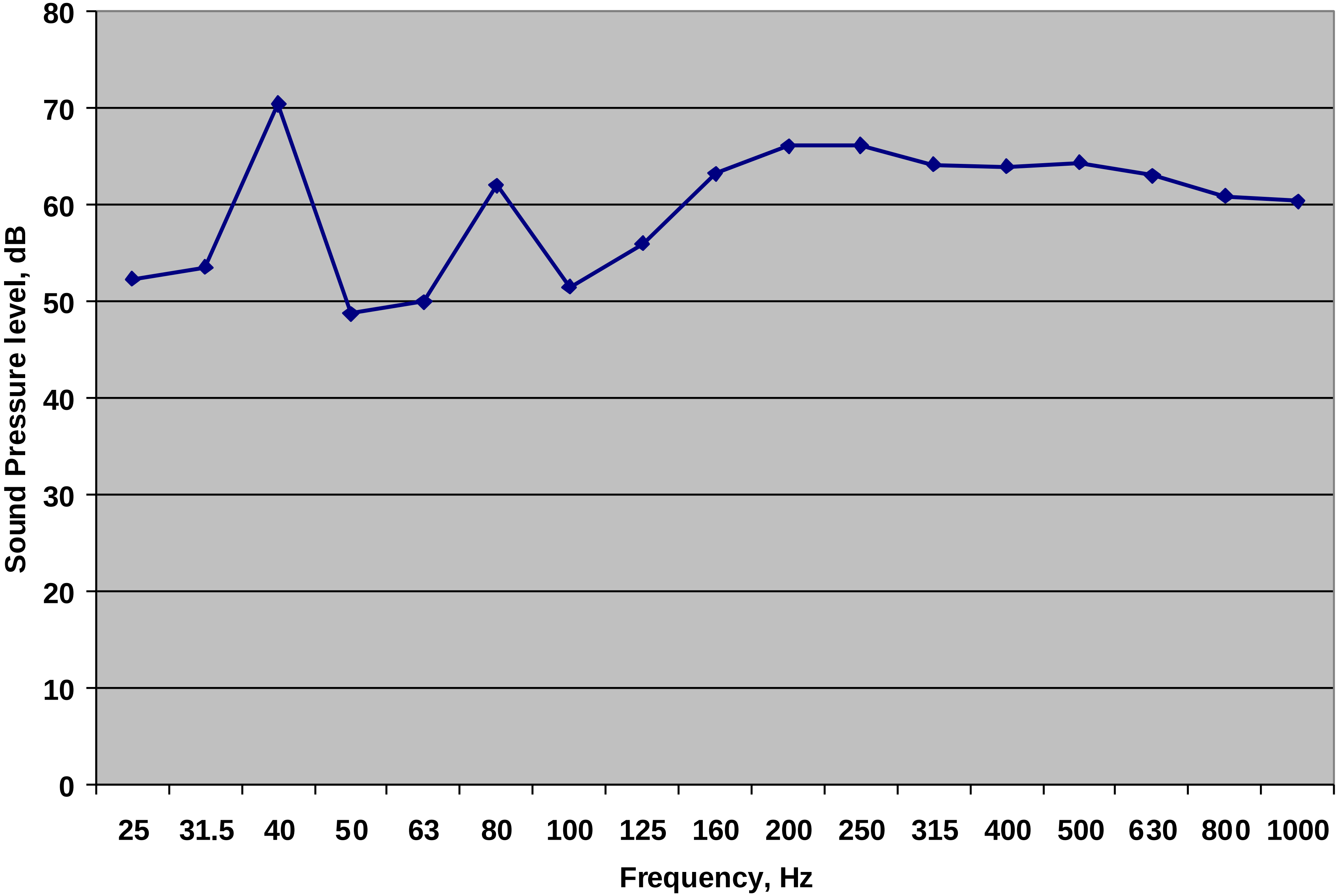


Magnitudes of different Frequency components depend on several design factors

Measured Frequency Spectrum of Load Noise



Measured Frequency Spectrum of Fan Noise



A- Weighting scale

A-weighted frequency correction for one-third octave band sound levels	Corrections (K_j) (dB)
63	–26.2
80	–22.5
100	–19.1
125	–16.1
160	–13.4
200	–10.9
250	–8.6
315	–6.6
400	–4.8
500	–3.2

Theoretical Noise Level Differences

- **Two contributors to the difference:**
  - Difference in Sound Power: Proportional to $(f)^2$ = 20 Log (1.2) = 1.6 dB
  - Difference in A – scale Attenuation = function of frequency component

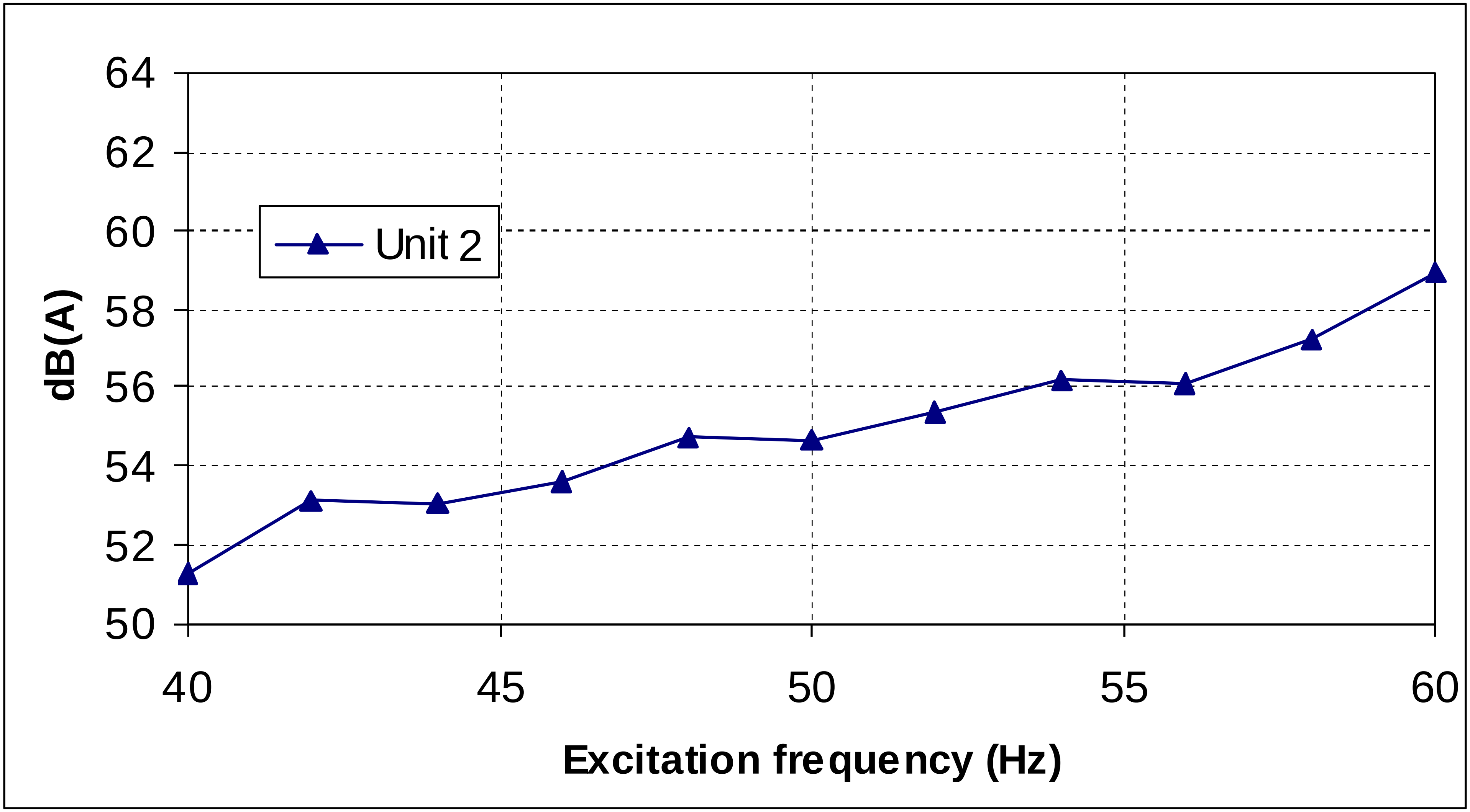
Frequency Hz	Attenuation dB	Difference dB	+ 1.6 dB	Total Difference dB
100	19.1	3.0	1.6	4.6
120	16.1			
200	10.9	2.3		3.9
240	8.6			
300	6.6	1.8		3.4
360	4.8			
400	4.8	1.6		3.2
480	3.2			

• Total dB (A) of core noise is typically determined by the 200 – 400 Hz components
Hence, the average difference in dB (A) should be in the the 3.2 – 3.9 dB range
• Load Noise is dominated by 100 / 120 Hz component, hence difference in dB (A) should be 4.6 dB

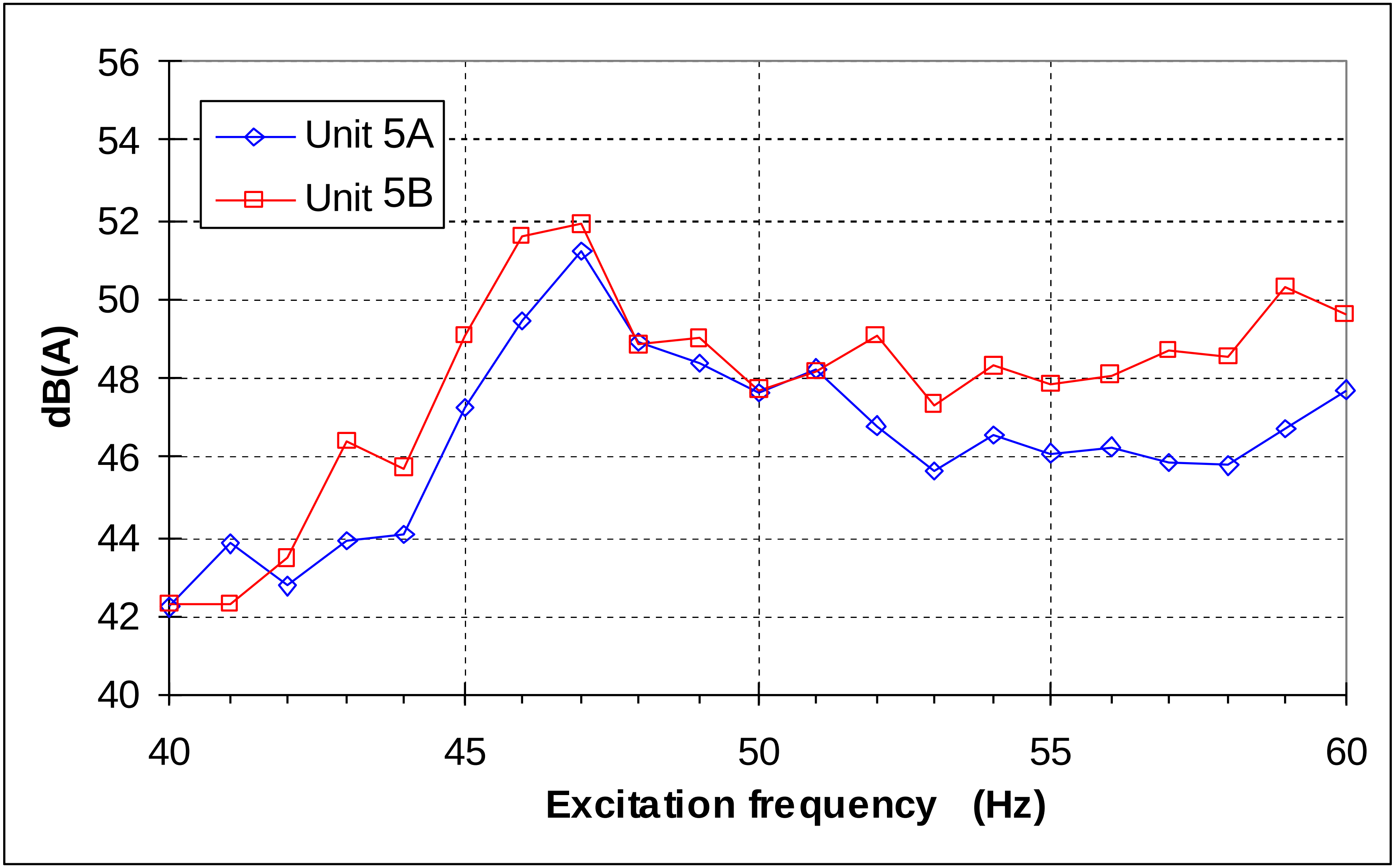
Measured Noise Level Differences

Unit	MVA	Measured Noise		Difference
		50Hz	60 Hz	
1	71	79.7	84.4	4.7
2	63	75.0	79.3	4.3
3	112	72.7	77.9	5.2
4		61.5	67.0	5.4
5A	30	66.0	66.1	0.1
5B		66.1	68.0	1.9
6A	25	72.2	70.5	-1.7
6B		70.6	74.4	3.8
7	40	66.1	74.1	8.0
8	250	80.9	90.3	9.4

Measured Noise Levels In absence of Core Resonance



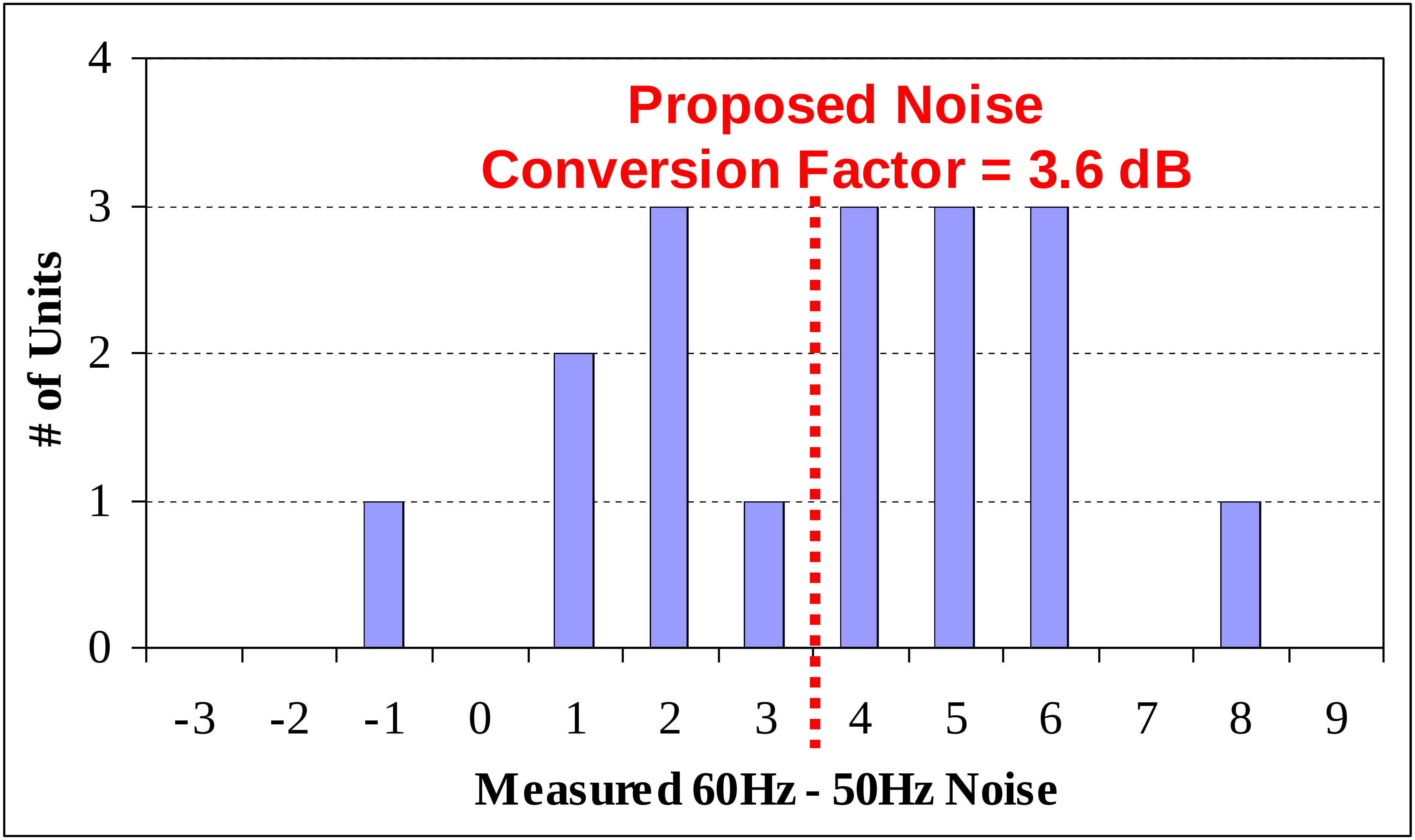
Measured Noise Levels In presence of Core Resonance



Measured Noise-Level differences, other Manufacturers' Data

	Unit	Measured Noise		Difference
		50Hz	60 Hz	
Supplier A	9	38.6	41.2	2.6
	10	43.2	47.1	3.9
	11	36.0	37.2	1.2
	12	45.6	46.2	0.6
	13	38.1	41.5	3.3
Supllier B	14	58.9	60.1	1.2
	15	70.7	76.3	5.6
	16	64.6	69.5	4.9

Measured Noise Level Differences



This is in agreement with the theoretical difference of 3.2 – 3.9 dB range
In absence of core resonance

B5. Audible Sound Emissions

B5.1 A-weighted sound level Conversion

Using these frequency conversion factors requires that the manufacturer verify that neither the core, the windings, nor the tank plates / stiffeners will experience mechanical resonance at the rated frequency. In such a case, the customer and the manufacturer will need to agree on any other adjustments that would be applied to the tested values. If measurements, however, indicate core, tank, or winding resonance at the frequency at which the measurement is being performed, the customer and the manufacturer will need to agree on whether any other adjustment to the tested values would be allowed.

Due to the greater uncertainty and the possibility of resonance frequencies, if the converted measured sound level plus the 2dB uncertainty does not meet the guaranteed value, then verification of the sound level at site may be required.

B5. Audible Sound Emissions

B5.1.1 ONAN (Core) Sound Level Conversion

Voltage should be applied such that the resulting core flux density is equal to the design flux density at the rated frequency of the transformer. For example, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage should be 5/6 of the voltage corresponding to the 60 Hz operation.

The corrected sound level for 60Hz operation is obtained by adding **3.6 dB** to the measured ONAN sound level at 50 Hz. Conversely, the corrected sound level for 50 Hz operation is obtained by subtracting 3.6 dB from the measured sound level at 60 Hz.

B5. Audible Sound Emissions

B5.1.2. ONAF Sound Level Conversion

The measurement will be done with the cooling equipment operated at 60 Hz while the core will be excited with 50 Hz.

Conversion from 50 Hz tested noise levels to corresponding 60 Hz levels

The following will be measured:

$LP_{ONAN-50}$: ONAN Lp at 50 Hz

$LP_{ONAF-50}$: ONAF Lp at 50 Hz with cooling equipment operating at 60 Hz

Calculate:

$LP_{ONAN-60}$: ONAN Lp at 60 Hz = $LP_{ONAN-50}$ + 3.6

Hence, the corresponding ONAF Sound Pressure Level at 60 Hz is:

$$LP_{ONAF-60} = 10 \cdot \log\left[10^{0.1 \cdot LP_{ONAF-50}} - 10^{0.1 \cdot LP_{ONAN-50}} + 10^{0.1 \cdot LP_{ONAN-60}}\right]$$

B5. Audible Sound Emissions

B5.3. Example

Measured Sound Levels at 50 Hz:

$LP_{ONAN\text{-}50} = 59.5$ dB (A)

$LP_{ONAF\text{-}50} = 66.1$ dB (A)

Calculated Sound Levels at 60 Hz:

$LP_{ONAN\text{-}60} = 59.5 + 3.6 = 63.1$ dB (A)

$$LP_{ONAF\text{-}60} = 10 \cdot \log\left[10^{0.1\cdot(66.1)} - 10^{0.1\cdot(59.5)} + 10^{0.1\cdot(63.1)}\right]$$

$$= 67.2 dBA$$

B5. Audible Sound Emissions

B5.1.3 Load Sound Level Conversion

For this test, Impedance Voltage should be applied such that the resulting current in the windings is equal to the rated current of the transformer. For example, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage should be **5/6 of the impedance voltage** for the 60 Hz operation.

The corrected sound level in dB (A) for 60 Hz operation is obtained by adding 4.6 dB to the Load sound level measured at 50 Hz. Conversely, the corrected sound level for 50 Hz operation is obtained by subtracting 4.6 dB from the measured sound level at 60 Hz.

B5. Audible Sound Emissions

5.2 Frequency Spectrum Conversion

The corrected sound levels at the main frequency components of the transformer noise in **dB (A),** for 60Hz operation, are obtained by adding the following values to the measured levels at 50 Hz:

Center Frequency, Hz	< 100 Hz	100 Hz	200 Hz	300 Hz	400 Hz	> 400 Hz
Conversion, dBA	5.5	4.6	3.9	3.4	3.2 Hz	2.5

Conversely, the corrected sound levels at the main frequency components for 50 Hz operation is obtained by subtracting the values in the Table above from the measured sound levels at 60 Hz.

For linear sound level values of the frequency spectrum, a constant value of **1.6 dB** is to be added to all frequency components of the measured frequency spectrum at 50 Hz in order to obtain the corresponding frequency spectrum for the 60 Hz operation. Conversely, the frequency spectrum for 50 Hz operation is obtained by subtracting 1.6 dB from the measured spectrum at 60 Hz.

C57.12.90 Wording for Frequency Conversion Factors

Annex B - (Normative)

Frequency Conversion of Measured Performance Parameters

While it is most **preferred** to perform all tests at the rated frequency, in the event it cannot be done at the rated frequency, then **upon mutual agreement** with the customer at the tender stage or prior to a contract, conversion factors given below shall be used to convert the measured values from the frequency used for measurement to the required rated frequency. The **purpose** of the frequency conversion factors is to have **uniformity amongst the manufacturers** when such cases arise. The below conversion factors are mainly intended for 50 Hz to 60 Hz conversion, however similar 60Hz to 50Hz conversion is also described. The **60 Hz to 50 Hz** conversion factors are essentially the **reciprocal** of the 50 Hz to 60 Hz values.

Annex A - Bibliography

[B6] Ramsis S. Girgis, Barry Beaster, Ed G. teNyenhuis, "*Proposed Standards for Frequency Conversion Factors of Transformer Performance Parameters*", IEEE Transactions on Power Delivery…..