

PRECIPITATOR POWER SUPPLIES USE OF 60 Hz TR's at 400 Hz

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Introduction

Since the 1990's the use of higher frequency Switch Mode Power Supplies (SMPS) has gained increased acceptance in the Electrostatic Precipitation industry. Several High Frequency SMPS systems available operate under resonant mode technology with resonant frequencies in the 20,000 Hz range. Other products, Medium Frequency Power Supplies (MFPS), are available operating in the more modest frequency 400 Hz. Both of these approaches offer the important benefit of decreased voltage (KV) ripple which results in increased average KV and increased average power delivered to the ESP field. In practically all cases, the increased power results in better ESP performance and decreased emissions.

The use of the higher frequency KHz SMPS requires the complete change out of all old 60 Hz components and rerouting of power feeds. The use of the MFPS permits the use of many of the existing components as well as the use of in place power and readout facilities. An important possibility for change over to a 400Hz MFPS system is the potential for the use of the existing 60Hz TR at reduced ratings. A discussion of the implications of such use is offered.

Summary and Conclusions:

A theoretical analysis of the implications of using conventional 60Hz TR at the higher frequency of 400 Hz was conducted. In addition, two (2) different lab tests

were conducted to produce actual loss data from older Research-Cottrell TR's rated at 45KV and 1000 ma. The mathematical analysis indicated that the TR will perform well under the higher frequency but will experience somewhat increased losses. The increased losses from the paper study indicate an increase in loss of from 50% to 100%. Experimental data using sinusoid power yielded an increase of 50%. Experimental data using phase controlled SCR's at 60 Hz and actual TR Controller at 400 Hz yielded an increase in loss of 100%.

The conclusion thus offered is that 60Hz TR may be used at 400 Hz higher frequency providing they are suitably de-rated to preclude over heating. The amount of de-rating necessary depends upon the environment at which the TR is subject to. ***It is recommended that using a 60 Hz TR at 400 Hz can be done up to 50% of its nameplate milli-amp rating. The 50% de-rating results in the unit operating within its design temperature limits. Using the TR above 50% may be possible but it is recommended that temperature rise tests be conducted prior to long term use at such higher ratings.***

ESP Field Ripple Reduction and Time Constants

The charging of an ESP field is essentially a pulsing technology. The KV is pulsed by the power supply. The decay of the KV occurs between pulses and the amount of decay results in ripple, and is a function of the characteristics of the ESP field, as well as the flue gas and the collected particle build up. The ripple magnitude is dependent upon the effective capacitance of the field and the effective resistance of the field. The multiplication of these two parameters is referred to as the time constant and is the time required for the voltage to lose 63% of its value if allowed to decay. For example if the voltage was charged to 100 KV in one such time constant the voltage would decay to 37 KV. The time

constants of a ESP field varies with all operating conditions of the field. A time constant of about 20 to 50 milliseconds is commonly observed. For a field with a 50 msec time constant a 60 Hz TR would yield about 15% P-P ripple and an average voltage of 92 KV. An MFPS, 400 Hz system yields approx 2 % ripple with average of 99 KV and a 3 KHz yields < 1% ripple with an average voltage of 99.8KV. The 3 KHz is used in this discussion since resonate mode SMPS resonate at frequencies of 20,000Hz but actually pulse at a lower rate.

Kilo Hertz SMPS Systems

In order to make use of the higher KHz frequency a complete change over of the TR, CLR and Control is required. The higher frequency SMPS are smaller and lighter then the 60Hz TR's they replace and necessarily integrate the electronics, the power switching transistors (IGBT's) with the step up transformer and rectifier assemblies. The complete package must be mounted as close as possible to the ESP field since long conductor path between the SMPS and the load (ESP Field) cannot be easily tolerated. Because of these requirements, three phase (3 Φ) AC 480VAC feed must be routed to the location of the power supply, which is usually on the roof top of the ESP. Readout and controls for such installations is accommodated through the use of digital communication links between the SMPS on the roof and a convenient location for personnel observation and recording.

400 Hz MFPS Systems

The lower frequency (400 Hz) MFPS provides a modest level of size and weight reduction; not nearly as great as the kilohertz systems. As can be concluded

from the above example MFPS does offer ripple reduction very close to that of the higher frequency units. Often time the need for additional field power is accompanied by a situation where the existing TR is running well below the TR ratings and the TR does have useful life time remaining. In addition this approach permits the use of existing equipment locations and may also permit the use of existing controls and CLR's. The installation can simply consist of removing the SCR assemblies and replacing the SCR assembly with an IGBT inverter system. The question of whether or not the existing TR can be used depends upon many factors, most important of which is the TR current rating and the operating level. Unquestionably the TR rating must be reduced by some level to allow such use at 400 Hz without over heating.

Heat Components for TR's

Most TR's are rated for a 55 °C temperature rise, above ambient of 40 ° C . This is 95 °C or 203 °F if operating in an ambient of 104 °F. The temperature of the TR is a major factor in the resulting life expectancy of the insulating components of the TR and as such the TR itself. Heat generated inside the TR has several components many of which are effected by operating frequency. The heat sources for TR's include the following:

1. IR losses due to resistive component of the transformer winding
2. Total Core loss of the transformer core steel
3. Losses of the high voltage bridge rectifiers and compensation resistors if used.

The losses listed above are the source for the energy that is dissipated inside the TR tank and must be given off by the tank walls and/or radiators. The total

amount of such energy is what dictates the tank surface area needed and as such the tank size that is needed to keep the internal temperature at the required safe level. As a rough estimate one may use the constant of 0.5 watts per square inch area to maintain a 55 deg C rise. Using this number then, a 50,000 watt TR at 95% efficiency would need to dissipate 2,500 watts of heat needing 5,000 square inches of area. Using only the side walls as energy sinks then we would expect a tank dimension of about 2 feet wide by 4 ½ feet high. If a TR design as above did in fact just meet the design temperature rise requirement then any energy loss above the design limit would result in over temperature of the TR under maximum design ambient conditions.

The Items 2 and 3 from above; core losses and rectifier losses constitute a relatively small component to the discussion at hand. The first item, winding Losses, is by far the most significant of the heat considerations of frequency change from 60 Hz to 400Hz. The wires used for both the primary and secondary will be affected by both 'skin effect' and by 'proximity loss'. These wire losses become extremely important for high frequencies, in the kilo-hertz range, and less so for mid-range frequency of 400 Hz. The increased winding losses are the reason why 60Hz TR's must be de-rated if operated at higher frequencies such as 400 Hz.

Rectifier and Voltage Divider Losses

Rectifier losses together with voltage divider loss usually make up a small part of the total losses in the TR. Using the above example these losses would be expected to be in the neighborhood of 150 to 250 watts, which represents less than 10% of the total losses. The rectifier losses consist of a sum of conduction and switching losses. The conduction loss is by far the dominating factor. Since the switching loss is directly related to the frequency, a 400 Hz system would therefore have $400/60 = 6.7$ times the switching loss of 60 Hz but this would still be a very small part of the overall losses and will not be further explored. The conduction losses are simply a multiplication of the voltage drop of the diodes stack, which is about 300 volts. With the secondary current of .5 Amps this results in 150 watts of power loss. The magnitude of the conduction loss is independent of frequency as is the Voltage divider loss, which should be approximately 40 watts.

Transformer Core Loss

The core loss of the TR typically represents 50% of the total transformer losses. For the example under discussion this would be a loss of 1,200 watts. The loss of the core is made up of core eddy currents and core hysteresis. Both of these parameters are affected by the frequency of transformer operation as well as the peak magnetic flux density of the core. If the flux in the core is sinusoidal, the relationship for either winding between its RMS Voltage of the winding E , and the supply frequency f , number of turns N , core cross-sectional area a , and peak magnetic flux density B is given by the universal EMF equation:

$$B_{AC} = \frac{V_{r.m.s}}{4.44 \cdot N \cdot f \cdot A}$$

From this equation it is observed that the AC flux density (B) is inversely proportional to the frequency (f) as well as the number of winding turns (N) and the cross sectional area of the magnetic path (A) which is the transformer core. By increasing frequency from 60 Hz to 400 Hz while maintaining other parameters constant, it is observed that the flux density is decreased by a factor of 60/400 or 0.15. A 60 Hz TR therefore designed for a full voltage Flux density of typically 15 Kilo-Gauss (KG) would have a Flux density of only 2.25 KG at 400 Hz.

Core Eddy Current Loss

Core eddy current losses are circulating current loops within the core laminations caused by differences of magnetic field. Cores are typically made up of silicon steel of lamination thicknesses of .014" or less. Properly assembled core laminations restrict the current path to the area within the lamination thickness (since the steel is coated) to greatly reduce current flow between laminations. The silicon that is added to the steel, typically at 3%, also results in an increase in the resistivity of the steel to reduce the magnitude of eddy current loss.

An approximation of magnitude of eddy currents loss is given by the formula:

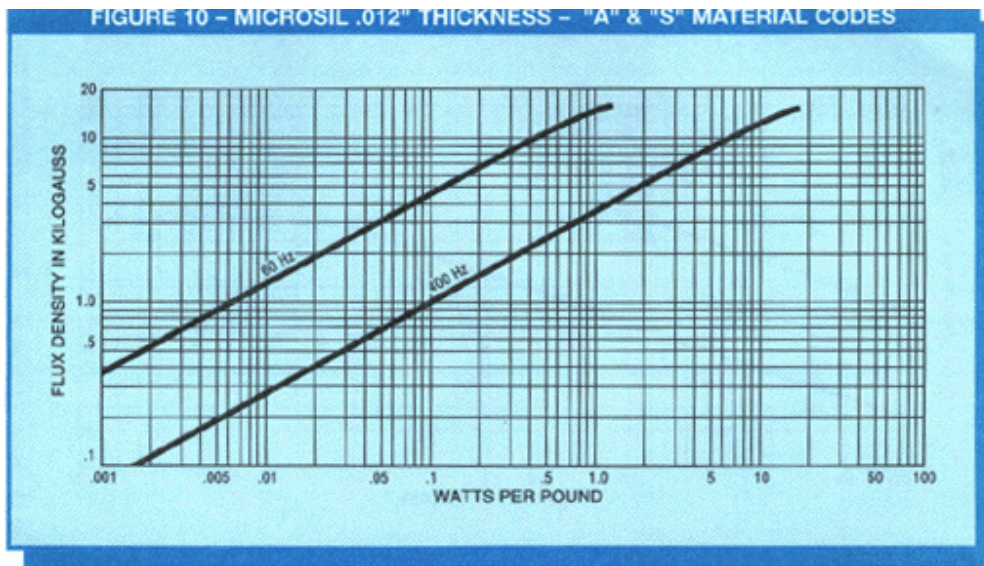
$$P \text{ eddy loss} = (8.4 * \rho * a * b * f^2 * B^2) / \Omega$$

This formula indicates that the eddy loss is directly proportional to the product of the frequency squared and the flux density squared. Since these parameters are inversely related it is seen that eddy current loss within the TR core is not affected by frequency.

Core Hysteresis Loss

The major source of core loss in a transformer is termed hysteresis loss. This is the loss caused by the reversal of the direction of the magnetic domains within the iron core. The hysteresis loss is a function of both the frequency of operation as well as the peak flux density that the core is subject to. As demonstrated above as example a transformer with 15 Kilo-Gauss (KG) at 60 Hz will experience only 2.25 KG at 400 Hz. Unfortunately however, the actual amount of loss due to hysteresis is not a simple mathematical relationship. Although a decrease of flux works to decrease this loss and an increase of frequency works to increase this loss, the relationship is not a simple product. During the design stage of a transformer the designer must reference charts supplied by the manufacturer of the core material to determine the expected core loss.

The chart below is copied from a Magnet Metals Corporation publication.



This chart, although typical, is given for comparison purposes and may not represent that which is used in any given TR but should give visibility of the concept involved.

The chart shows the loss in watts per pound of a specific type of core at both 60 Hz and at 400 Hz. It can be seen that at a given Flux density, say 10 KG, the loss shown for 60 Hz is 0.4 watts per pound and at 400 Hz it is about 6 watts per pound; over ten times the loss! Offsetting this huge increase in power is the decreased flux parameter as was shown however which expected to be only 1.5 KG at 400 Hz ($10 * 60/400 = 1.5$), not the 10 KG as before. If the same chart is now employed to determine the loss at 400 HZ and at 1.5 KG it is determined that the loss is expected to be approximately 0.15 watts per pound, which is considerably less than the 0.4 watts per pound for the 60 Hz excitation.

As referenced above the core loss represents 50% of the example transformer loss. A 37% decrease in core loss from the 60Hz level can be extrapolated as a 750 watt decrease on the core loss contribution toward TR heating.

Transformer Winding Losses

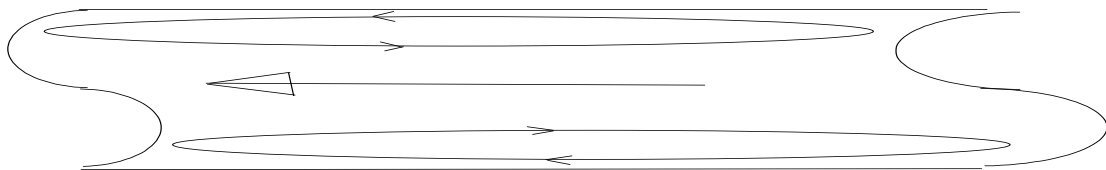
The losses that are experienced in the transformer winding are the main source of concern when increasing the operating frequency of operation. The 400Hz MFPS that have been investigated do use 'hard switching' of an IGBT 'H' bridge which implies a square wave excitation and associated harmonics. In actual application however, a fairly high value CLR is used with MFPS systems that results in a triangular current waveform. This waveform will have some harmonic frequencies above the fundamental of 400 Hz. The harmonics however are considered relatively low and will not be addressed in the following discussion.

It should be noted that 60Hz application TR's that are SCR controlled also present harmonics, and are likewise ignored in this discussion.

The increased losses associated with frequency are caused by the uneven distribution of current through the wire or foil windings of the transformer. The uneven current density effectively decreases the cross section of the wire and as such increases its resistivity and its losses. There are two contributing factors to this phenomena, one termed 'skin effect' and one termed 'proximity effect' both of these parameters are effectively due to eddy currents that are caused to flow on the surface of the conductor down toward the center of the conductor.

'Skin Effect'

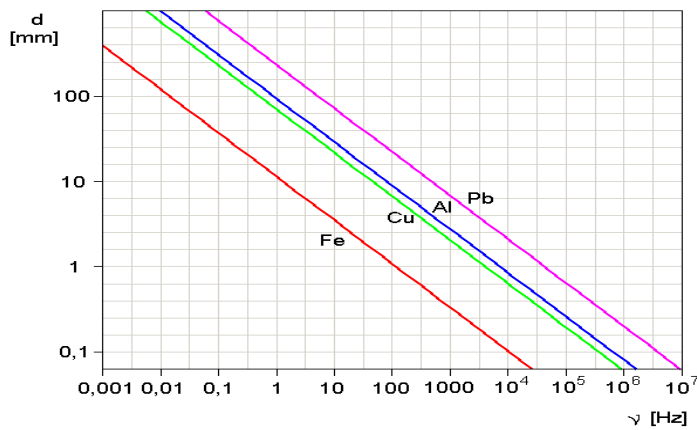
The phenomenon termed 'skin effect' refers to the uneven distribution of current density through an individual conductor as the conductor is considered as an isolated single conductor without the influence of any adjacent conductors. Skin effect is therefore a consideration for any wiring carrying AC current, not just for transformer windings.



The above is a depiction of current flow through a conductor at high frequency. The dark arrow in the center representing the main current flow and the loop paths on the outside showing the skin effect eddy currents. It is observed that the

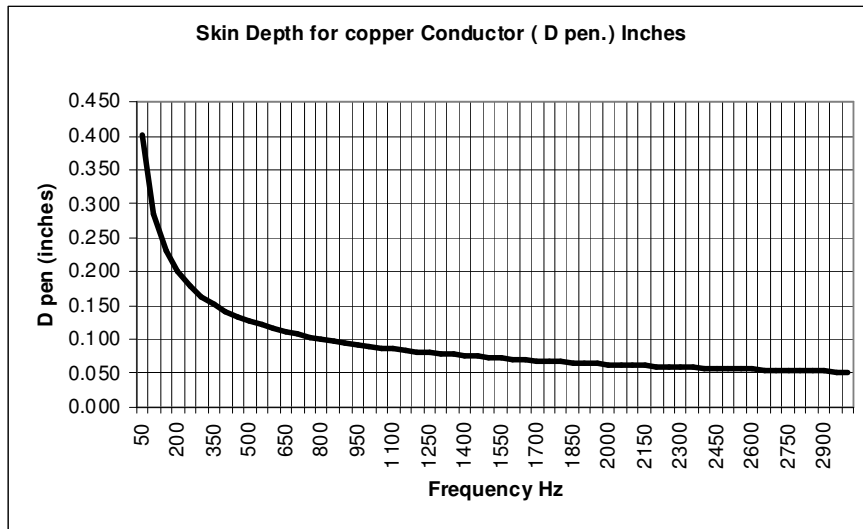
eddy current is in the same direction as the main flow near the surface but in opposing direction nearer the center. The result of this is that the total current flowing is concentrated near the surface of the conductor.

The relationship of frequency and skin penetration depth is shown in the chart below for various materials. It may be observed that the skin effect for copper conductor is slightly worse than the skin effect for aluminum. That is to say that at a given frequency the depth of penetration is deeper for aluminum than it is for copper.



The magnitude of this phenomena for copper wire is approximated by the relationship:

$$D \text{ penetration} = 7.5 / (\text{frequency})^2 \text{ Centimeters} \quad \text{or} \quad D \text{ pen} = 3 / \sqrt{(\text{frequency})} \text{ Inches}$$



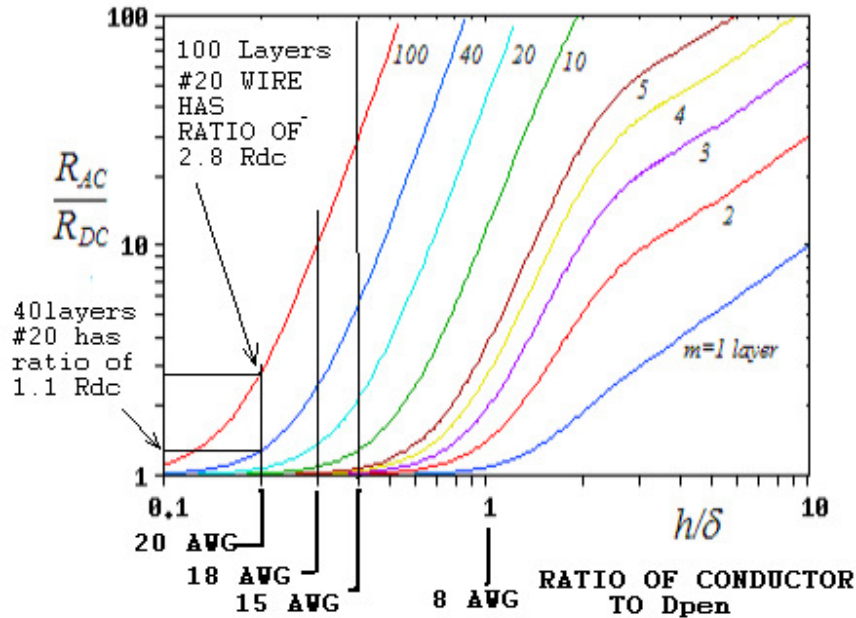
Depth of Penetration for copper on linear scale

For 60 Hz this computes to 0.39 inches and for 400 Hz it computes to 0.15 inches. The parameter D pen is defined as the depth at which the current density is $1/e$ (37%) of the current density at the surface. The skin effect consideration becomes significant when the wire thickness is larger than the D-pen. As a reference point 0.15 inches is approximately the radius of a #4 AWG conductor. Primary windings of a 50 KW transformer may indeed use wire gauge of #4 or larger, however most likely the primary would use a single layer of wire in the #4 range. Because of this, it is speculated that the primary loss increase for a 60Hz TR running at 400Hz would be in the order of +10%. The secondary of such a transformer would typically use wire in the #20 AWG with radius of 0.015" so that simple 'skin effect' on the secondary winding would be negligible for all but the very highest ma rated TR's.

Proximity Effect

Proximity effect is a term that refers to the effect of current density in a conductor in cases where other current carrying conductors are near. In TR transformer design this is certainly the case for secondary windings. As the number of layers of the winding increases, and as the size of the conductor increases, the effective resistance ratio (R_{ac}/R_{dc}) of the conductor is decreased. This is very similar to the 'skin effect' discussed above but is caused not only by the magnetic field of the conductor under analysis but also by conductors close by.

The chart below shows an approximation of proximity effect of rectangular conductors at varied thinness ratios for varied number of conductor layers. The 'X' axis is the ratio of the conductor thickness to the penetration depth (Thickness/ D_{pen}). As shown above the D_{pen} for copper at 400 Hz is calculated to approximately 0.14 inches. P.L. Dowell developed the chart for foil or strip conductors. The effective layer thickness for round conductor wound close together, as with TR's, is 0.83 times the wire thickness. A #20 AWG wire of diameter 0.032" would therefore have a ratio of 0.19 (approximately 0.2).



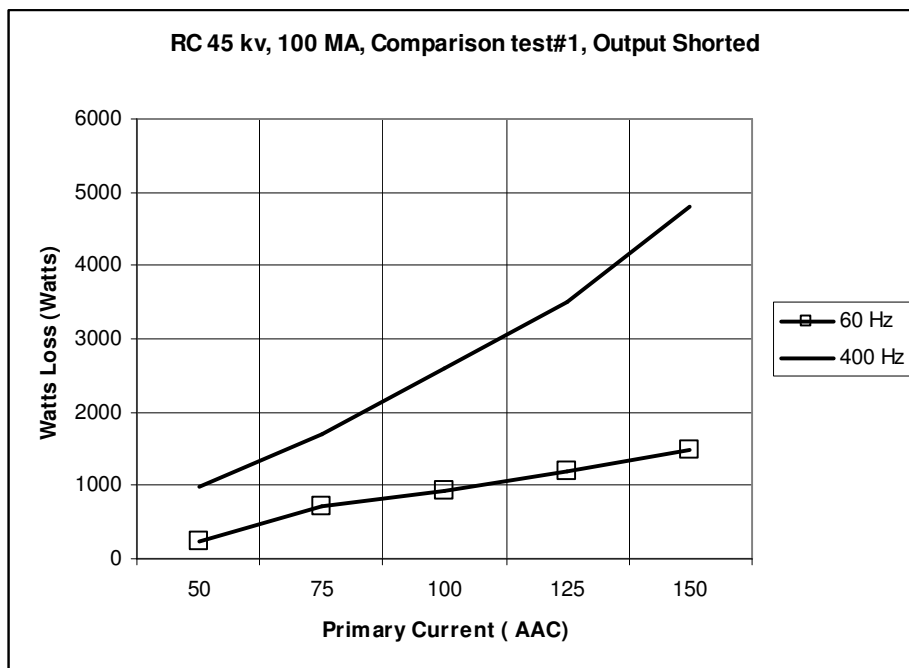
Using the chart above it can be seen that for #20 AWG wire at 40 layers the ratio of DC resistance to AC resistance is about 1.1 to 1. For 100 layers it would be about 2.8 to 1.

A TR of 50Kv and 1000 ma would most likely have less than 40 layers and be approximately #20 AWG. In such case then the losses of the secondary winding could be at a ratio of 1.1 to 1 to as much as 2 to 1, and as such 10% to 100% additional energy loss in the winding can be expected.

For the TR primary winding which often times is wound with multiple turns of foil, additional heat loss will be likewise, and again would be expected to be from a 10% to 100% increase from the DC loss rating. It should be noted that although this effect is present in small scale, even at 60Hz it is rare that the 60Hz TR would take this or winding eddy currents into consideration.

Actual Test Data and Results

Lab tests were conducted using two different TR's, approximately 20 years old, that were sold under the Research-Cottrell label. Tests were conducted by running the same TR under short circuit secondary conditions at the rated current both under SCR 60 Hz control and under MFPS control. The TR's are both rated at 45KV and 1000 ma. Watt loss was measured using a lab type wattmeter connected to the primary voltage and current. The tests were done at different locations by different test teams using different set up.



The above chart is from data taken using a shorted TR output. The primary was driven by a conventional a SCR controlled power feed for the 60 Hz data and a 400 Hz, MFPS controller for the 400 Hz data. The data shows loss at rated current of 4,800 watts at 400 Hz and 1,500 watts at 60 Hz. If the estimated

magnetizing loss is added back in the results show about 2,500 watts at 60 Hz and 5,300 watts at 400 Hz.

A similar test was done at a alternate location using a sine wave excitation for a similar TR. The shorted output readings for that test were approximately 910 watts at 60 Hz verses 2,500 watts at 400 Hz. If the magnetizing losses are again added back the data indicated losses of about 2,000 watts verses 3,000 watts.

CONCLUSIONS:

- **Low ripple advantage gained through the use of Kilo-Hertz ESP Power can largely be achieved through use of lower frequency MFPS systems.**
- **Conventional 60Hz TR's may be operated at the higher frequency of 400 Hz, using MFPS technology providing some TR de-rating is employed.**
- **Mathematic analysis and empirical data indicate that a re-rating factor of 50% will keep TR temperature rise within design limits**
- **A simple temperature rise test measuring top oil temp can give a good indication of additional heating and may permit a lower level of derating.**

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Hank DelGatto is an Electrical Engineer with extensive background in Precipitator control systems and Power Supplies. He holds a BSEE from Clarkson University has worked for several major equipment suppliers in the ESP field. Hank is currently employed as a consultant assisting several companies in R&D efforts.

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