Using 50/60Hz Precipitator TR's with Mid-Frequency Technology

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ABSTRACT:

The objective of this paper is to provide a discussion of technical and commercial consideration that applies when choosing a Power Supply for Industrial Electrostatic Precipitators (ESP's). The paper has focus on Switching power Supplies that operate at high frequencies and those that operate at mid-frequency. Issues addressed include power supply performance increase to realize as well as the cost and reliability that is associated with these technology choices. The paper is offered for the use by Electric Power Generating enterprises as well as other Industrial users of ESP's.

The discussion of the critical issues of performance advantages, ease of installation, cost and reliability should provide valuable information for the selection process EPS power sources for new construction and even more so for replacement and upgrade/improvement projects.

BACKGROUND

Industrial enterprises, such as coal fired electric power generators are under constant pressure to reduce particle and gaseous emissions from the process. ESP's play a major role in capture of particle emissions. The high voltage power source is critical to the efficient operation of ESP's. Line frequency power supplies that use SCR's for power level control have been the technology of choice for over 70 years. Since the 1990's the use of higher frequency Switch Mode Power Supplies (SMPS) has gained wide acceptance in the Electrostatic Precipitation industry, with well over 1,000 installed systems. There are several switching speed technologies that are now available for this use. The use of SMPS has proved to have significant increase in the performance of Electrostatic precipitators. The increase in ESP performance can be over 50%, with 20%-40% improvement in efficiencies typically achieved. There are several SMPS technologies to choose from once the decision to upgrade the line frequency SCR system is made.

PROBLEM ADDRESSED:

When faced with the need to replace or to improve performance of ESP power systems several difficult issues must be considered. The decision maker must choose among the various different suppliers as well as the differing available technologies. All these decision choices have cost and benefit factors. Each enterprise must review and analyze conflicting claims that may be made by competing interests. Many such claims are not accompanied by sufficient supporting science or by verifiable test results. The cost difference between the differing technologies is significant. When the cost of installation and maintenance is considered a ratio of 2:1 can easily be the case. If the solution under consideration is the use of Mid Frequency Power then the existing TR can be used for a significant cost saving. The question of the reliability of a line frequency TR and related components, used at higher frequencies is an important issue to deal with. A focus of this paper is to address those issues and provide good supporting information for the reader.

TECHNICAL REPORT:

The use of SMPS has shown to improve performance of ESP fields in most applications. . The increased efficiency is realized because of the decrease in ripple on the KV voltage that allows higher average KV before spark over occurs. High Frequency SMPS systems available operate under resonant mode technology with frequencies in the 20,000 Hz range. Medium Frequency Power Switching (MFPS), operating in the more modest frequency of 100 Hz to 400 Hz and operate either under resonate mode or more likely under H Bridge switching. The Medium Frequency systems are capable of using existing 50/60 Hz TR's and existing control cabinet locations for significant cost savings

The latest technology of MFPS permits the Energization at selectable frequencies' with advanced power control methods. The original approach for MFPS employed a fixed switch frequency of 400 Hz worked well for applications where the ESP field ran at levels below 70% of TR rating. The recent introduction of advanced MFPS technology uses a multitude of frequencies over the 100-400Hz range. The different operating frequencies allow the TR and CLR to balance the precipitator performance against the ability of the existing TR and the existing CLR to operate at or near the milliamp nameplate rating without degradation of the expected TR life span.

Factors influencing Transformer life span expectancy.

The first of two factors is related to temperature rise caused by excessive heat generated by the transformer core and windings. The second is over voltage and/corona discharge within the windings of the transformer or between high voltage conducting components in the TR tank. Both the over temperature and corona result in the breakdown of the transformer insulation system. The insulation system includes the layer insulation material as well as the dielectric fluid (transformer oil) in the tank.

Analysis of advanced MFPS use of 60Hz TR has indicated that neither of the above life cycle factors significantly affect existing TR's as they are converted to MFPS. In addition, both of the above factors are easily monitored by periodic tests and measurements of TR's in actual operation. Since the conversion process from Phase Control SCR to MFPS IGBT can be accomplished with relative ease. Low cost trial runs with appropriate monitoring can result in high reward at minimal risk.

MFPS TECHNOLOGIES:

The first of the two technologies uses an increased exciting frequency of up to 400 Hz and controls power level delivered to the TR primary by variation of the duty cycle of the AC power feed. This technique is commonly referred to as Pulse Width Modulation (PWM). This technology is widely used for smaller power supplies, presents challenges when used with ESP power levels. With MFPS/PWM the TR transformer and the CLR are actually powered at 400 Hz as compared to the normal design frequency of 60 Hz. The higher frequency causes the combined impedance of the CLR and the TR to increase by a factor of 6.6. The increased impedance may require that the CLR be replaced with a CLR of lower inductance if maximum TR power is required. The MFPS allows the PWM to run at a high degree of conduction, akin to increasing the impedance of the CLR on a conventional set to improve the form factor. Normally the use of 400 Hz TR excitation should be limited to applications where the TR can be limited to about 60%-70% of nameplate rating. Often this level is the maximum level that is possible, for the ESP field characteristics.

The second advanced MFPS technology presents a constant 100% duty cycle wave form to the TR primary and controls the power level delivered to the TR primary by effectively modulating the average amplitude of the primary power signal. This modulation is accomplished by creating a high frequency PWM pulse within the base frequency which is typically 100 Hz. The modest frequency increase (100Hz vs. 60Hz) can make full use of the existing TR milliamp ratings without any detrimental results. The frequency increase of 1.6 x does result in significantly increased system impedance such that CLR change out would be necessary only under the rare condition where both rated KV and rated ma is to be delivered to the ESP field.

Installation of MFPS is retrofitted into existing installations by installing the control electronics in the same space previously used by the older controller and the SCR power Block. The size of the retrofit equipment is approximately the same as the 60 Hz components replaced. The system requires a 3 Phase feed into the cabinet which is usually easily available. The circuit breakers and the contactor that are used switch the line frequency power feed to the Inverter and are not subject to the higher frequency. The existing feedback signals, the circuit breakers, contactors and panel meters are utilized in keeping the change over simple and economical. The MFPS conversion may require the CLR used for 60 Hz to be replaced by a smaller value so as to maintain required system impedance.

Figure 1 shows depictions of a 400 Hz PWM signal at 30% power level and 60% power level. The positive and the negative pulse width is varied to alter the power level delivered to the TR primary. At 30% level the ‘On’ time is 30% of the half cycle for the positive and negative polarities giving alternating pulses of .000375 seconds. When at the 60% level the pulse width is .00075 seconds.

A second and improved method, **Figure 2**, of using higher frequency control of ESP TR’s is to power the TR with a 100% duty cycle square wave of modulated amplitude. This method allows the TR/CLR system to run at a frequency much closer to the design frequency of 60 Hz. This technology controls the effective amplitude of the square wave by dividing the positive and the negative half cycles into segments. The segments within the 100 Hz signal are then pulse width modulated such that the energy within the pulses is controlled, while the transformer, because of the series inductance, responds as an amplitude modulated square wave excitation. Upon inspection of Figure 2 it can be seen that the resulting power signal that is applied to the TR primary winding is approximately sinusoidal without sharp rise time associated with SMPS signals.

FIGURE 1

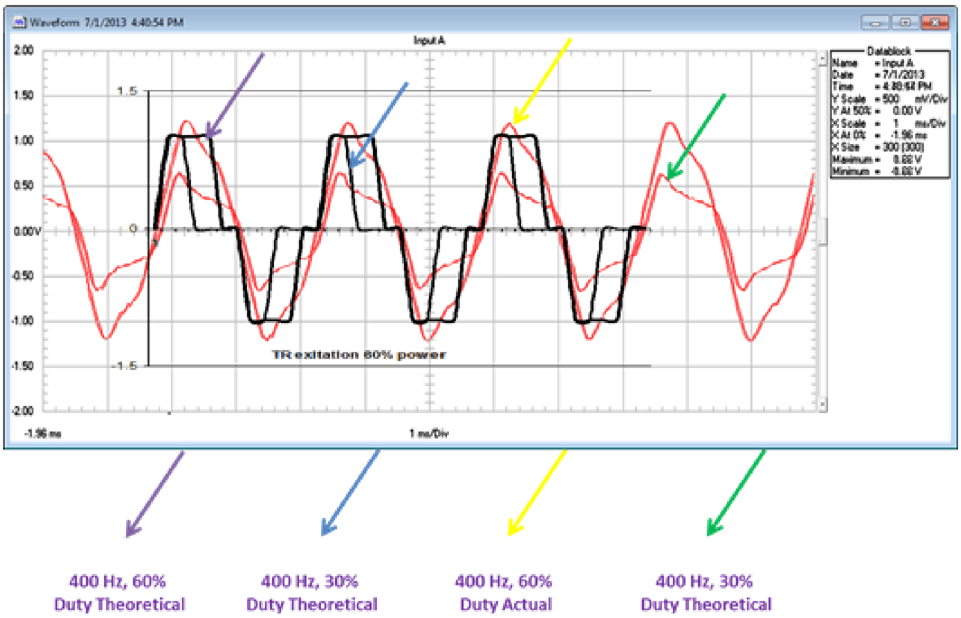

Figure 1 above shows actual scope traces from a working system superimposed upon theoretic curves generated by formula. The horizontal axis is 1 ms/div and the vertical axis shown as +/- 2 volts for relative reference only. The black traces are the theoretical curves of a 400Hz PWM signal at different duty cycles and the red curves are actual scope traces of the voltage across the primary winding of the TR. The difference in the theoretic vs. actual is due to the CLR in the circuit as well as parasitic capacitance of the TR.

FIGURE 2

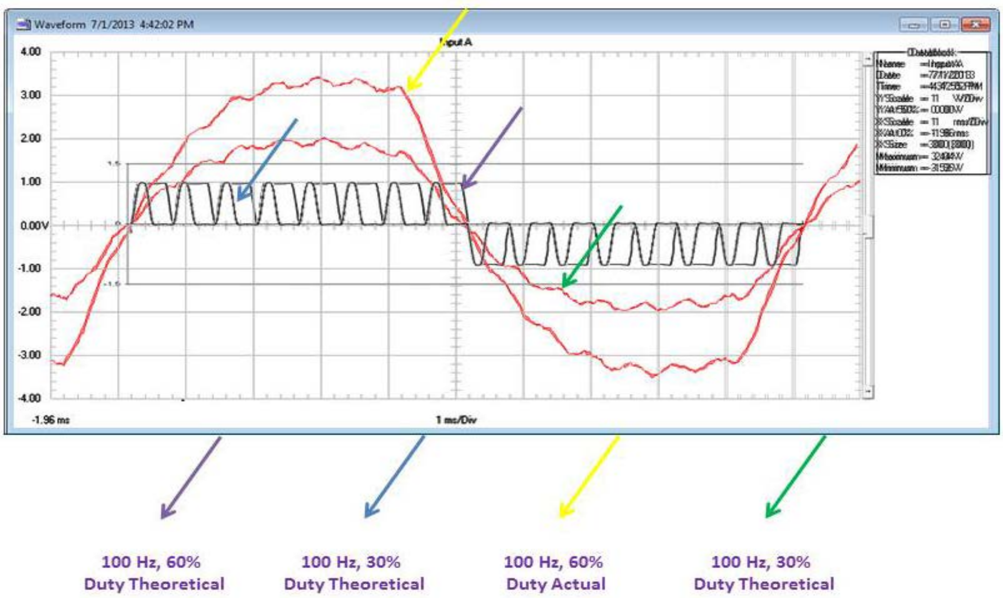

Figure 2 above shows actual scope traces from a working system superimposed upon theoretic curves generated by formula. The horizontal axis is 1 ms/div and the vertical axis shown as +/- 4 volts for relative reference only. The traces are the theoretical / actual curves of a 100Hz Power signal modulated at 1,600 Hz. The signals are depicted at different power levels. The red curves are actual scope traces of the voltage across the primary winding of the TR. The difference in the theoretic vs. actual is due to the CLR in the circuit as well as parasitic capacitance of the TR.

PREDICTING TR LIFE EXPECTANCY

The life expectancy of power transformers varies, however 30 to 50 years of service is typical. The primary mode of transformer failure occurs when the TR system insulation can no longer withstand the stress imposed upon it during operation. Transformers used on ESP applications deteriorate due to electrical and mechanical stresses during normal and transient conditions. Degradation actually starts from the first day the TR is energized. The deterioration of the layer insulation of the transformer secondary windings is a common failure mode. The isolation, which is typically Kraft paper, is subject to mechanical abrasion caused by transient conditions such as ESP sparking. In addition the insulation is degraded by the voltage stress level as well as the temperature at which the material is operated.

A critical parameter to consider in the discussion of using 60Hz transformers at higher frequency is the possibility of additional heat that may result. Transformer designers include consideration for the energy losses within the transformer tank, which must be dissipated by the tank surface areas.

The losses consist of:

(1) Transformer winding losses
(2) Transformer Core losses,
(3) Heat loss by the internal rectifiers and voltage divider.

To obtain a highly accurate estimate of heat generation from the windings, the winding losses are the most complex calculation of the above factors. The winding losses are made up of a resistive component and a 'skin effect/proximity' component. The core losses are made up of eddy current losses and hysteresis losses. The losses from the diodes and the voltage divider resistors are not discussed since the change in heat loss from frequency increase from 60 to 100 or 400 is extremely small as compared to the other TR heat source losses. There is some small increase in heat loss from the switching losses of the diodes yet these are negligible.

Transformer Core Loss

The core loss of the TR typically represents 50% of the total transformer losses. The losses are the result 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 the 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:

$$B_{AC} = Vr.m.s \times 10^8/4.44.N.f.A$$

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:

$$P\ eddy\ loss = (8.4 * p * a * b * f^2 * B^2) / \Omega$$

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 subjected to.

As demonstrated in the above 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.

FIGURE 3

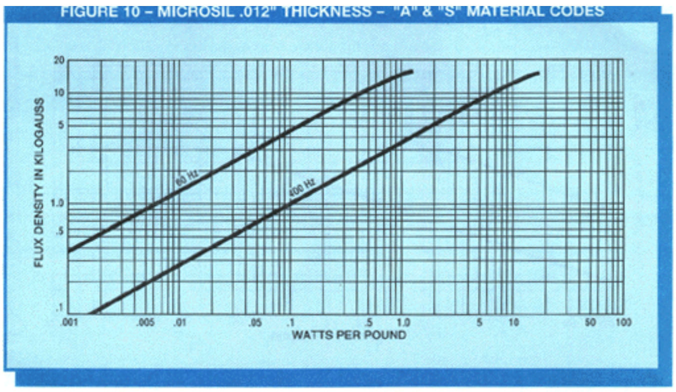

Figure 3 above is a plot of core flux density vs. energy loss at 60Hz and 400 Hz. This chart from Magnetic Metals Corp publication.

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 used 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.

Transformer Winding Losses

The losses that are experienced in the transformer windings are the main source of concern when increasing the operating frequency of operation. The 400Hz MFPS's that have been investigated 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.

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. This effect is related to the frequency of the current within a given conductor. At high frequencies the current is concentrated around the perimeter of the wire.

FIGURE 4

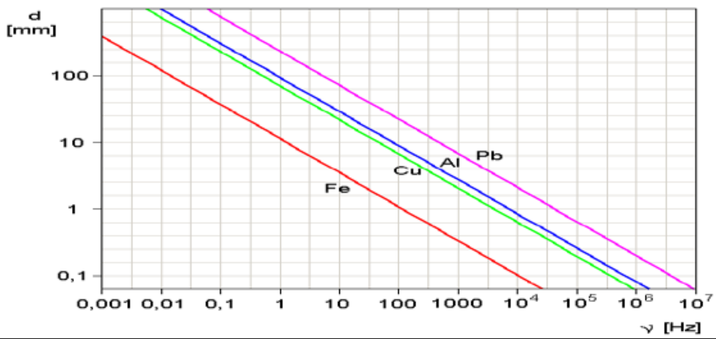

Figure 4 shows the skin effect penetration for metals at differing frequencies.

The magnitude of this phenomena for copper wire in approximated by the relationship: D penetration = 7.5 / (frequency) ² Centimeters or D pen = 3 /√(frequency) Inches. The skin effect consideration becomes significant when the wire thickness is larger than the D-pen. A 400 Hz signal penetration of 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. For higher power TR's the primary loss increase for a 60Hz TR running at 400Hz would be in the order of +10%. The secondary of TR's would typically use wire in the #20 AWG with radius of 0.015" so that 'skin effect' on the secondary winding would be negligible.

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 transformer rectifier design this is certainly the case for secondary windings. As the number of layers of the winding increase, and as the size of the conductor increase, the effective resistance ratio (Rac/Rdc) 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. In the frequency ranges of 60Hz, 100 Hz or 400Hz the proximity effect loss is negligible.

CONCLUSIONS:

1. The conversion from line frequency power to SMPS power will almost always increase the power and efficiency of an ESP field.
2. The use of Medium Frequency permits the use of the line frequency TR's as well as many of the existing components of the 50/60Hz system to be replaced
3. The CLR that is part of the ESP power system serves to eliminate fast rising/falling edges of wave form such that corona and heat effect internal to existing TR's is negligible.
4. The latest innovation in technology permits SMPS running at 100 Hz and as such permit full power output of existing TR's in a vast majority of applications.
5. The use of 60/50 Hz TR's at amplitude modulated 100 Hz excitation will have no effect on life cycle of existing components

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