# M I Cable: Improving Reliability and Range in Medium Voltage High Temperature Applications

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Paper No. PCIC-(do not insert number)

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***Abstract*** – The advancement of medium voltage Mineral Insulated (MI) Cables and horizontal drilling technologies has increased opportunities for use of long MI Cables in oil well lengths of several thousand meters. The long lengths, high power requirements, high temperature exposure, and smaller cable size driven by economics are all challenges to the reliability and life expectancies of MI Cable applications.

This paper presents a patent-pending system, control process, and method for extending both the reliability and range of application of long MI electrical cables in high temperature environments, such as down-hole heaters in thermal assisted oil production and flow assurance applications.

*Index Terms* — MI Heater Cable, Flow Assurance, Thermal Assisted Oil Production, Permittivity, Capacitive Reactance, Dielectric Safety Factor, Dielectric Max Rating, PWM Drive, Sine Wave Filter.

## I. INTRODUCTION

Mineral Insulated (MI) Cables have been used for years in electrical heating applications such as flow assurance and oil reservoir production. Recent advancements in manufacturing technology of MI Cables have extended applications that were once limited to 600 volts, now to medium voltage operation approaching 5000 volts. The increased voltage capability enables longer heated wells and higher thermal energy injection rates, thereby improving the value of MI Cable electrical heating with respect to other thermal technologies.

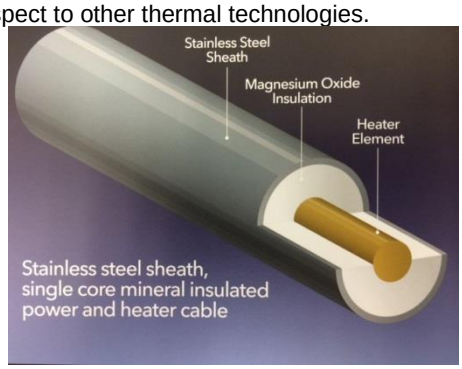



Fig. 1 - MI Cable

Cable size, length, and heat injection rate are important parameters that can affect the project viability of specific applications. The economic drivers of smaller, longer, and higher wattage cable, however, directly conflict with drivers for cable reliability: smaller cable size implies less MgO insulant with a lower voltage withstand; longer cable length for a given size & wattage means higher operating voltage and reduced dielectric safety factor; with higher wattage comes higher operating temperature and associated decrease in cable insulant impedance.

The theoretical and mathematical *Analysis* of the effect of each of these parameters on cable insulant impedance and dielectric safety factor is presented, followed by *Demonstration Data* of these concepts, then a proposed *Description of Mitigation Methods* for the compromised parameters and temperature associated dielectric degradation, then *Validation Data* of the proposed mitigation methods, and *Conclusions* reached.

## II. ANALYSIS

### A. Cable Size & Capacitance Effect on Cable Impedance

The following is a derivation of capacitance and impedance formulas specific to single conductor MI cable:

The MI cable MgO insulation shunt impedance (Z) has two components: Resistance (R) and Reactance (X). As the inductive reactance of the insulation is negligible compared to its resistance and capacitive reactance, the impedance magnitude formula can be simplified as:

$$|Z| = \sqrt{\left(R^2 + \left(-1/(2\pi f C)\right)^2\right.} \quad (1)$$

where

| | |
|---|---|
| R | Shunt resistance, Ω |
| f | operating frequency, Hz |
| C | Shunt Capacitance, F |

The geometric form of MI cable is coaxial and its shunt capacitance is defined as:

$$C = \frac{\varepsilon_r \varepsilon_o \, 2\pi L}{\ln\left(\frac{r_o}{r_i}\right)} \quad (2)$$

where

| | |
|---|---|
| $\varepsilon_r\varepsilon_o$ | permittivity; |
| L | cable length; |
| $r_O$ | MgO outer radius; |

$r_I$ cable conductor radius.

By observation it is clear that the ratio of insulation outer radius to conductor radius (insulation internal radius), affects the cable Capacitance. For a given conductor size, decreasing the MgO thickness, for example to achieve a smaller overall diameter cable, causes cable capacitance to increase.

One last substitution of (2) into (1) presents the contribution of both permittivity and frequency into the impedance magnitude (3):

$$|Z| = \sqrt{\left(R^2 + \left(-\frac{\ln\left(\frac{r_o}{r_i}\right)}{(2\pi f(\varepsilon_r \varepsilon_o 2\pi L)}\right)^2\right.} \quad (3)$$

An important observation from (3) is the effect of cable size and capacitance on the capacitive reactance component of impedance; specifically as cable size decreases, shunt capacitance increases, and the shunt impedance of cable MgO insulant decreases. *A lower Capacitance and higher Impedance is good for cable reliability and life. Thus, not only do larger diameter cables have an increase in insulation thickness which leads to higher shunt resistance, generally the capacitance is lower which increases shunt impedance*.

Section III.A. shows characterizations of different cable sizes reinforcing these concepts

B. Cable Size & Length Effect on Operating Voltage & Dielectric Safety Factor

With horizontal drilling and MI cable manufacturing advancements, MI heater cable lengths of several thousand feet are being considered for oil production applications. While a detailed discussion of the application of these cables is beyond the scope of this paper, a general discussion will aid the reader in understanding the interaction of the factors influencing the application. Generally speaking, the MI cables under discussion are applied as downhole heaters for increased oil production. As heater cable size goes up, the wellbore necessary for containment of the cables, as well as any production equipment, goes up as well, along with associated wellbore costs. As well length increases, these increased costs become substantial, and are a driving influence for the use of physically smaller heater cables.

Additionally, as wellbore length increases, the necessary operating voltage for a fixed thermal injection rate (watts / meter) increases. This leads to a conflict between smaller cable size, and the associated lower voltage withstand level, and increasing voltage.

When examining the optimum cable size for an application, it is important to establish a safe maximum steady state operating voltage to ensure a reliable, long life cable installation.

One method for quantifying the voltage risk of cable size is to establish a *dielectric safety factor* based on the design operating peak voltage and the dielectric maximum voltage rating. The design operating peak voltage for a single conductor coaxial cable may be calculated as follows:

$$\sigma_{design} = V \Big/ [r_i * ln(r_o/r_i)] \quad (4)$$

where

| | |
|---|---|
| $\sigma_{design}$ | design operating peak voltage; |
| $V$ | system operating voltage; |
| $r_I$ | cable conductor radius; |
| $r_O$ | insulation outer radius. |

For a three-phase cable, V represents Volts line-to-neutral; i.e. $V = V_{L-N} = V_{L_L} \Big/ \sqrt{3}$

*Dielectric Safety Factor* is calculated as follows:

$$SF = \sigma_{max} / \sigma_{design} \quad (5)$$

where

| | |
|---|---|
| $SF$ | dielectric safety factor; |
| $\sigma_{max}$ | dielectric max rating; |
| $\sigma_{design}$ | dielectric design rating. |

The dielectric maximum voltage rating of MgO varies with temperature. For a conservative comparison of cable designs, a value representative of the maximum operating temperature of the application should be used. Other factors that affect the max rating are the quality and compaction of the MgO which vary by manufacturer. **Error! Reference source not found.** shows the decrease in dielectric strength of the MgO insulation for a typical cable.

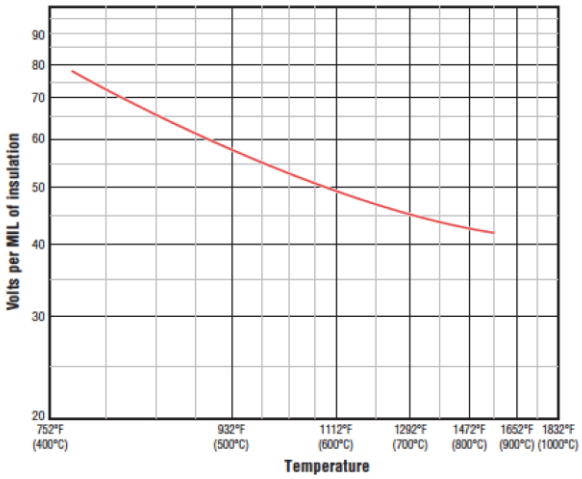



Fig. 2 - Dielectric Strength vs. Temperature [1)]

From **Error! Reference source not found.**, a dielectric max rating reference point of 57 V/mil @ 500ºC will be used for calculation of dielectric safety factor in Section III, Table 2 and Section V, Table 5.

C. Temperature Effect on Cable Impedance

The dielectric strength of MI cable as a function of temperature is well established. (see Fig. 2) Similarly, the insulation resistance of MI cable varies with temperature as shown in Fig. 3, again for a typical cable.

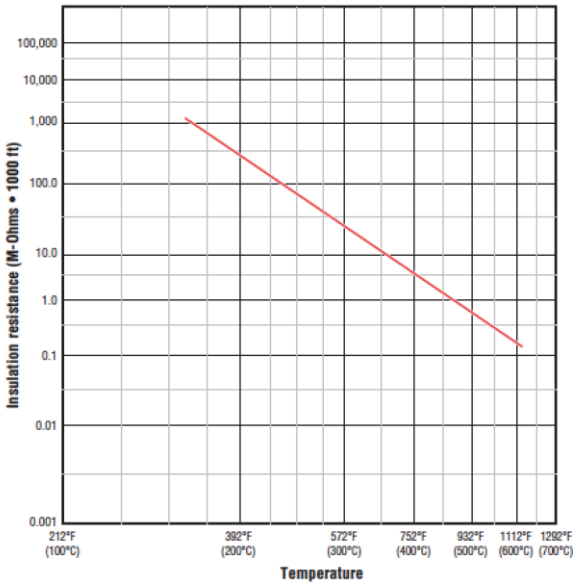



Fig. 3 - IR vs. Temperature [1)]

For a particular application, the characteristics of the specific cable under consideration should be known. This is particularly important as the limits of the cable are being pushed. In order to obtain this characterization for medium voltage cables operating at the upper limits of cable capability, the authors conducted impedance vs. temperature laboratory characterization tests of various MI cable samples.

From these tests, and from subsequent dielectric withstand tests, it was observed that the impedance change in MgO cables at higher temperatures (200ºC - 600ºC range) is predominately due to the decreases in capacitive reactive as opposed to a decrease in insulation resistance. This becomes strikingly clear as the temperature of the insulation approaches a transition temperature, where the impedance of the cable is no longer dominated by high capacitive reactance, but begins to be supported by a lower insulation resistance value.

Wilson states that "Below 400ºC the 50 Hz Impedance is predominately capacitive. In the intermediate region, the transition temperature, at which the resistance and capacitive components are equal, can be regarded as an indication of powder quality since the higher the transition temperature the higher the DC resistance". [2]

For the studied samples, the transition temperature was near 600ºC, while Wilson's observed transition temperature was near 400ºC. Wilsons measurements were of MgO powders @ 70% compaction whereas the authors' tests were on samples with >80% compaction. This higher compaction rate was at least one of the factors contributing to the higher powder quality of the author's samples.

It is important to understand the contributions to this decaying impedance with temperature in order to offer solutions for improving MI cable reliability in high temperature environments, such as in down-hole oil well heater applications. The following connects prior research data with the author's observed data to demonstrate the temperature effect on cable capacitance and impedance.

**Error! Reference source not found.** shows the increase in permittivity of MgO crystals as observed by Thorp et al. Single crystal samples can be equated to a nearly perfect "powder quality" for the MgO. It is observed that permittivity of the MgO increases exponentially as the temperature of the sample approaches 600ºC.

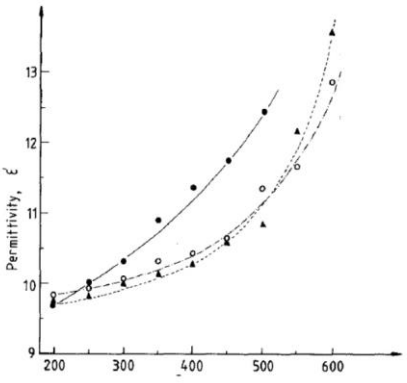



Fig. 4 - Permittivity vs. Temp [3)]

The data on MgO crystals closely corresponds to the measured data for 80% compacted MgO powder in the cables tested, Fig. 5.

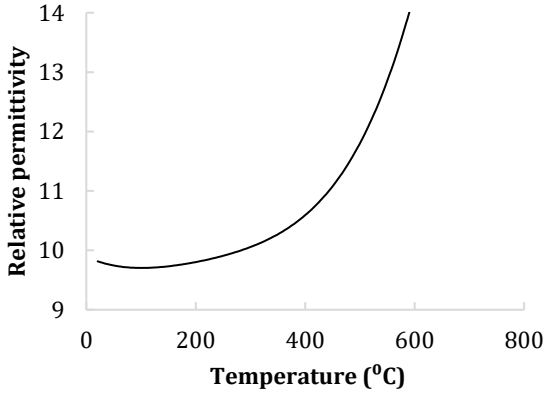



Fig. 5 - Permittivity vs. Temp

This permittivity increase with temperature directly increases capacitance, as shown in (2) and decreases overall impedance as shown in (3). Specifically as permittivity increases exponentially, capacitance increases exponentially, and the impedance of cable MgO insulant decreases exponentially. This allows additional leakage current from the center conductor to the outer

metallic sheath, and can eventually lead to insulation failure, though not the typical “breakdown” type failure associated with polymeric insulation materials. The leakage current increases local temperatures, which further reduces impedance locally.

In addition to failures from the additional leakage current, partial discharge effects damage the insulation characteristics of the MgO.

Chaikin states “Excessive device capacitance could also cause leakage current failure … Partial Discharges are the source of *Erosion Breakdown* which affects the long term life of an insulator…. Partial Discharge cycles may occur many times during the positive and negative peaks. In applications, if this happens with sufficient magnitude over time, arcing in the voids will degrade the insulation, even producing tree-like patterns in the dielectric that lead to failure. This effect is called Erosion Breakdown.”[4)]

Since MgO compaction of good quality Mi Cable is in the 80%-85% range, there are sufficient trapped air voids dispersed in the insulant material to support partial discharge activity under the right conditions. This mechanism is enhanced in insulation materials with relatively high permittivity, such as MgO powder. In these materials, the permittivity of the insulating material acts as a field intensifier for the localized electric field inside the voids.

Because of this effect, the localized electric field intensity **‘ε’** at the air voids can easily exceed the breakdown voltage of air which is 3000 V/mm (@ ambient); **‘ε’** is a multiple of the applied Voltage/mm times the ratio of MgO permittivity to air voids permittivity; as MgO permittivity exponentially increases with temperature, while the permittivity for air is relatively temperature independent, the localized field intensity in the voids increases exponentially with temperature as well.[5)] This can create the PD condition for erosion breakdown.

The temperature/pressure effect plus the geometry of the air voids makes for a complicated if not impossible quantitative analysis of PD and therefore is beyond the scope of this paper. However, this presents an opportunity to develop PD testing as an indicator of MI cable quality and perhaps to determine the dielectric maximum voltage rating.

For the cables tested, no Partial Discharge activity occurred with the cables at 450ºC or below. Fig. 4 and Fig. 5 show he results of partial discharge testing of a medium voltage MI cable sample tested at 500º and 550ºC respectively. The increase in PD, both in magnitude and in number of discharges is apparent.

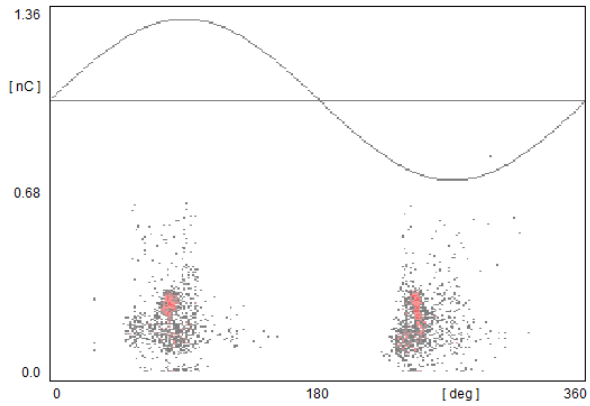



Fig. 4 - Partial Discharge at 500ºC

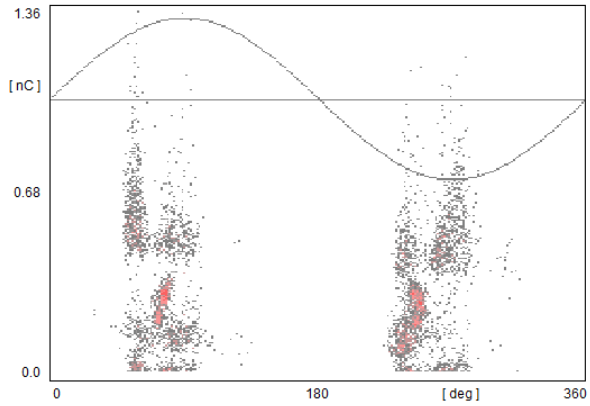



Fig. 5 - Partial Discharge at 550ºC

D. Frequency Effect on Cable Impedance

Another important observation from the impedance magnitude formula shown in (3) is the frequency effect on impedance.

If the operating system frequency can be lowered, it increases the capacitance reactance and increases the impedance magnitude. This is can be an effective countermeasure to:

1) Offset the negative effects of higher cable capacitance due to smaller cable size imposed by some applications
2) Offset the capacitance associated with increased permittivity of high operating temperature environment
3) Offset the reduced dielectric safety factor caused by longer heater applications requiring higher operating voltage; this is accomplished by way of increasing the impedance by lowering the frequency with other parameters held constant, effectively increasing the dielectric max voltage

Section V. discusses examples of frequency effect on cable impedance

## III. DEMONSTRATION DATA

A. Cable Size & Capacitance Effect on Cable Impedance

**Error! Reference source not found.** lists capacitance and impedance values for three different MI cables to demonstrate effect of cable size on capacitance and impedance, as measured during laboratory tests. *The 0.85" OD cable has 22% more capacitance and 43% less impedance than the 1.0" cable.* Additionally, the 1.0" OD cable has a larger ratio of MgO to conductor radius than the 1.2" cable and therefore has lower capacitance.

TABLE I
CAPACITANCE & IMPEDANCE VALUES

| | | **1.2" OD** | **1.0" OD** | **0.85 " OD** |
|---|---|---|---|---|
| MgO Outer Diam. [$D_O$] | mils | 1000 | 810 | 650 |
| Core Diameter [$D_I$] | mils | 325 | 250 | 250 |
| Ratio of [$r_O$] to [$r_I$] | | 3.1 | 3.2 | 2.60 |
| 22ºC Capacitance [C]: | pF/m | 0.47 | 0.45 | 0.55 |
| ***% Capacitance ↑*** | % | | | **22%** |
| 60Hz Cap Reactance | | 5.64 | 5.90 | 3.36 |
| 60Hz Impedance | | 7.54 | 8.03 | 4.58 |
| ***% Impedance ↓*** | % | | | **43%** |

B. Cable Size & Length Effect on Operating Voltage & Dielectric Safety Factor

Table 2 lists dielectric and safety factor values for three different MI cable OD sizes for an 8000 ft long cable application requiring a 4500 V operating system to achieve a 250 W/ft heat rate.

TABLE 2
LONG HEATER EXAMPLES

| 3000 Ft Overburden + 5000 Ft @ 250 W/ft / 250 mil Cases | | | | |
|---|---|---|---|---|
| **OD** | | **1.2"** | **1.0"** | **0.85"** |
| **Operating Volts** | $V_{L-L}$ | 4500 | 4500 | 4500 |
| $\sigma_{design}$ | $\sigma_{design}$ | 15.0 | 17.7 | 21.8 |
| **Dielectric max** | $\sigma_{max}$ | 57 | 57 | 57 |
| **Safety Factor @ 60 Hz:** | $S_{F(60)}$ | **4** | **3** | **3** |
| $S_{F(60)}$ **≥ 10?** | | **NO** | **NO** | **NO** |

Note that none of the three cases have a safety factor even close to the desired minimum of 10 which raises reliability concerns. The conventional mitigation options involve reducing the operating voltage by shortening the heater length and/or reducing the Watt/ft heat rate OR increasing the MgO thickness which makes the cable size larger; any of these options affect a project's viability. A better solution is needed.

C. Temperature Effect on Cable Impedance

**Error! Reference source not found.** lists capacitance reactance and impedance values for three different MI cables to demonstrate effect of operating temperature on capacitance and impedance. *Note the average impedance decrease of 25% from ambient temperature to 500ºC.*

TABLE 3
TEMPERATURE EFECT ON IMPEDANCE

| | 1.2" OD | | 1.0" OD | | 0.85" OD | |
|---|---|---|---|---|---|---|
| | 22ºC | 500ºC | 22ºC | 500ºC | 22ºC | 500ºC |
| **Cap. Reactance @ 60Hz** | 5.64 | 4.32 | 5.90 | 4.52 | 3.36 | 2.57 |
| **Impedance @ 60Hz** | 7.54 | 5.71 | 8.03 | 5.98 | 4.58 | 3.41 |
| *% Impedance ↓* | | 24% | | 26% | | 25% |

## IV. DESCRIPTION OF MITIGATION METHODS

*A.* Dielectric Safety Factor

MI heater cable applications should be designed with a minimum V/mil Safety Factor to ensure the peak operating voltage is well below the dielectric max voltage rating for the expected temperature range of operation. The dielectric rating vs. temperature varies according to insulant quality and manufacturing process, thus a minimum safety factor of ten is suggested.

*B.* Modeling to Optimize Cable Configuration

Modeling of cable configurations with formulas presented here, in particular insulant outer radius to conductor radius ratios is an effective method for identifying high capacitance/low impedance causal contributors to poor dielectric safety factor and is an important step in optimizing the cable configuration and size for the application.

*C.* Patent-pending System for Extending Reliability & Range of Application of Long MI Electrical Cables

This system enables low frequency operation for mitigation of issues presented in this paper not possible with conventional 60 hertz operation. The *System* employs a new application of existing technology custom configured and arranged as represented in Fig. 6 below.

The *System* comprises a control process to optimize the setting of the operating frequency of the power supply, such as a voltage source pulse-width modulation (PWM) variable speed drive, and the application of a sine wave filter (SWF) on the output of the power supply. Based on voltage, current, and temperature feedback provided to an external controller (PLC or DCS) from the SWF output

and the cables, the external controller provides a voltage set point to the PWM drive to regulate power to the MI Cable.

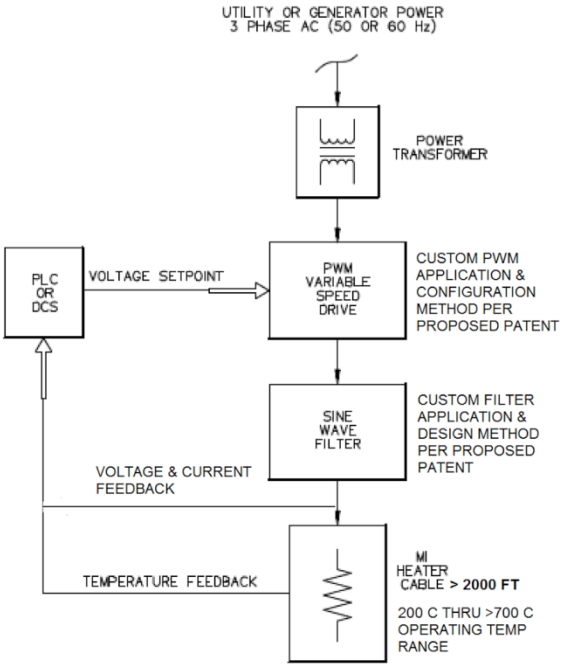



Fig. 6 – Mitigation System Sketch

The *System, Control Process,* and *Method* incorporate the following features:

1) An optional power transformer to match system voltage to PWM Drive input voltage & power rating
2) A three phase voltage source inverter producing a three phase alternating current using one of many available PWM control algorithms; a standard PWM Drive typically used on fan and pump applications is custom configured by de-coupling Voltage from Frequency thereby enabling a variable voltage output at a fixed operating frequency
3) The PWM Drive minimum continuous operating frequency at full nameplate rated voltage and amperes is at least 1.5 Hz; to improve operating life of drive power components a minimum operating frequency configuration of 6 Hz is recommended
4) The PWM Drive must be capable of configuration to operate at a permanent fixed carrier frequency; the selected optimized carrier frequency must not result in de-rating of the PWM Drive's nameplate output voltage and ampere ratings
5) A full sine wave filter (SWF) placed on the Drive output to the cables is custom designed for the optimal PWM Drive carrier frequency; the SWF eliminates reflective or standing wave voltages and voltage excursions created by the PWM Drive carrier frequency that would otherwise result in cable MgO dielectric breakdown and heater cable failure
6) Hall Effect type sensors are carefully selected and specified for accurate low frequency measurement of voltage and current; transducer outputs are connected to the external controller (PLC or DCS) for metering, control, and Operator display & historization. Heater temperature measurements via Type K thermocouples and/or Fiber Optic cable are connected to the external controller as well.
7) The external controller (PLC or DCS) converts the Operator's desired heater wattage (power) set-point to a voltage output signal to the PWM Drive. Custom program logic includes algorithms for power measurement, heater control, and protection.
8) In event of a single cable failure, the *System* is designed to recover with two phase operation at up to two-thirds of original maximum heater capacity; the PWM Drive is capable of two-phase operation at full voltage & current ratings and the external controller has custom program logic for metering, control, & protection in two phase mode

## V. VALIDATION DATA FOR LOW FREQUENCY SOLUTIONS

**Error! Reference source not found.** is repeated from Section III.C. with the addition of 6 hertz impedance values to evaluate the effectiveness of low frequency operation as a mitigation to low impedance values due to high operating temperature:

TABLE 4
LOW FREQUENCY IMPEDANCE FACTORS

| | 1.2" OD | | 1.0" OD | | 0.85" OD | |
|---|---|---|---|---|---|---|
| | 22°C | 500°C | 22°C | 500°C | 22°C | 500°C |
| **Cap. Reactance @ 60Hz** | 5.64 | 4.32 | 5.90 | 4.52 | 3.36 | 2.57 |
| **Impedance @ 60Hz** | 7.54 | 5.71 | 8.03 | 5.98 | 4.58 | 3.41 |
| **Impedance @ 6 Hz:** | 56.63 | 43.38 | 59.25 | 45.37 | 33.74 | 25.84 |
| $\Delta T$ $\%Z\downarrow$ | | 24% | | 26% | | 25% |
| Impedance ↑ Factor **w/ 6 Hz** | 7.5 | 7.6 | 7.4 | 7.6 | 7.4 | 7.6 |
| % Impedance ↑ **w/6 Hz** | 751% | 760% | 738% | 759% | 737% | 757% |

*Changing the operating frequency from 60 hertz to 6 hertz improves the MI cable impedance by a factor of seven and is a very effective means for offsetting the average 25% impedance reduction at elevated temperature operation.*

Table 5 is repeated from Section III.B. with the addition of 6 hertz impedance values to validate the effectiveness of low frequency operation as a mitigation to poor safety factor due to cable size, length, and high operating voltage. A conservative Impedance factor improvement of 5 (vs. 7 determined above) is used as a multiplier to the dielectric max rating for 6 Hz operation basis Ohm's Law; i.e. for a given max conduction current if the impedance is increased 5 fold then so is the voltage

TABLE 5
LOW FREQUENCY SAFETY FACTORS

| 3000 Ft Overburden + 5000 Ft @ 250 W/ft / 250 mil Cases | | | | |
|---|---|---|---|---|
| | **OD** | **1.2"** | **1.0"** | **0.85"** |
| **Operating Volts** | $V_{L-L}$ | 4500 | 4500 | 4500 |
| **$\sigma_{design}$** | $\sigma_{design}$ | 15.0 | 17.7 | 21.8 |
| **Dielectric max V/mil @ 60 Hz @ 500C** | $\sigma_{max}$ | 57 | 57 | 57 |
| **Safety Factor @ 60 Hz:** | $S_{F(60)}$ | **4** | **3** | **3** |
| **$S_{F(60)} \geq 10$ ?** | | **NO** | **NO** | **NO** |
| **Safety Factor @ 6 Hz:** | $S_{F(6)}$ | **19** | **16** | **13** |
| **$S_{F(6)} \geq 10$ ?** | | **YES** | **YES** | **YES** |

*Changing the operating frequency from 60 hertz to 6 hertz is a very effective mitigation to poor Dielectric Safety Factor due to cable size, length, and high operating voltage.*

## VI. CONCLUSIONS

Smaller, longer cables coupled with high operating temperature, and high operating voltage reduces the dielectric safety factor and can affect MI cable reliability & life. These characteristics should be considered and properly mitigated in the design stage.

One mitigation method is to use the patent-pending process explained here with a low operating frequency such as 6 Hz.

The specific advantages are:

1) Mitigate capacitance effect of small cable sizes
2) Mitigate high temperature effect of permittivity & capacitance on cables in the 200C to 600C range with up to a sevenfold impedance improvement
3) Mitigate low dielectric safety factor caused by high operating voltage required with long cable length & high wattage applications by increasing the dielectric maximum voltage rating at low frequency
4) Prevent overvoltage failure of MI Cable with sine wave filter

The significance of this work is the promotion of medium voltage electric heater cable technology as an environmentally friendly alternative to other thermal assisted production & flow assurance technologies in the oilfield.

Further work should include development of an MI Cable aging model with variables of voltage, temperature and frequency. Also, development of PD testing as an indicator of MI cable quality with consideration of the inception voltage level as the dielectric maximum voltage rating.

## VII. NOMENCLATURE

$|\mathbf{Z}|$ Impedance magnitude (Ω).
R Resistance (Ω).
$X_C$ Capacitance Reactance (Ω).
f operating frequency (Hz).
C Capacitance (F).
$\varepsilon_r\varepsilon_o$ permittivity.
L cable length (m).
$r_O$ MgO outer radius (mil).
$r_I$ cable conductor radius (mil).
$\sigma_{design}$ design operating peak voltage (V/mil).
$\sigma_{max}$ dielectric max rating (V/mil).
$S_F$ dielectric safety factor.
$S_{F(6)}$ dielectric safety factor @ 6 hertz.
$S_{F(60)}$ dielectric safety factor @ 60 hertz.

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## IX. VITAE

**Lee Bourgeois, E.E.**, received his BSEE from Louisiana State University in 1979. He spent 2 years with Louisiana Power & Light Company (LP&L) providing operating and maintenance support of steam turbine generator controls and major electrical systems for Waterford Generating

Station. He relocated to the Louisiana Convent Refinery where over the next 25 years under ownership of Texaco, followed by Star Enterprises, and then Motiva Enterprises, held various power & instrumentation engineering roles, including lead E&I Engineer for major projects at both Convent & Norco, Louisiana Refineries. He then relocated to Shell E&P's Unconventional Group in Houston, Texas where he provided power, controls, & automation engineering front-end development support for various down-hole heating system projects for 4 years. Lee then retired from Shell and established a consulting business primarily focusing on down-hole electric heat technology with clients including Athabasca Oil Corp., American Shale Oil Co., and ConocoPhillips. He also provides electrical consulting for the petrochemical industry and presently has Motiva Enterprises as a client for its three gulf coast refineries. He is a member of IEEE.

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Dr. Durham is a Senior Member of IEEE and is registered as a Professional Engineer in numerous states. His work experience is broad, and encompasses all areas of the power industry. His technical emphasis has been on all aspects of power systems from electric generating stations, to EHV transmission systems, to large-scale distribution systems and power applications for industrial locations. He is an internationally recognized author; having received several awards from technical and professional organizations such as the IEEE, and has published magazine articles on multiple occasions. Dr. Durham's extensive client list includes the development of a broad spectrum of forensic, electrical and facilities projects for many companies. He also is involved with the audit of market participants in competitive utility markets to ensure that these facilities are adhering to the rules of the market.

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