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TITLE: Prediction of Heating Power in Magnetic Pipe Conducting Large AC Current with High Frequencies Up to 200Hz

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ABSTRACT BODY:

Digest Body: In direct electrical heating system (DEHs), which is developed for subsea process to safeguard well stream through pipelines to topside process platform or shore. The production pipeline is also acts as an active conductor conducting large AC current to generate heat. The heating source is conductive and hysteresis power losses in the pipe. Currently, the all implemented DEHs operate at 50Hz. There is a potential to further improve the heating capacity of the DEHs by operating the system at higher frequency so that the same power can be achieved at lower current. Consequently, the cross-session of the power cable can be reduced. Furthermore, operation in higher frequency directly results in better system utilization and less AC corrosion of the pipeline. This will further reduce the installation and operational cost and increase the system lifetime. For DEHs design it is critical to predict the heating power as function of input current and frequency so that proper frequency and current can be selected correspondingly. This paper analytically evaluate the heating power as functions of current and frequency based on experimentally measured material properties such as mass density, conductivity, B-H curve and hysteresis B-H loop energy. To verify the analytical results, both FEM simulation and prototype test are performed.

Current distribution
Comparing to the conducting current in the carbon steel pipe, generally in several hundred amperes, the displacement current is the pipe is negligible. The current distribution in the pipe is therefore determined by
$\nabla^2 J=j\omega\mu\sigma J$ (1)
The permeability of carbon steel is a nonlinear function of magnetic fields. To solve the problem analytically, it is common to assume an effective constant permeability uniformly over the pipe and this will be discussed later in detail.

The solution of (1) for an isolated thick tubular conductor can be derived as
$P_R=k_R I_{rms}^2\sqrt{(\mu f)}$ (2)
where $k_R=1/(2r_o\sqrt{(\pi\sigma)})$ (3)

Hysteresis power loss
Due to the varied electric field produced by the AC current in the pipe, magnetic field in the pipe also varies, which causes hysteresis loss that is part of the heating power. The dissipated hysteresis energy per unit volume (or weight) in one cycle is the area enclosed by the hysteresis loop of B-H curve. The area and shape of the B-H loop is dependent on maximum magnetic field. This hysteresis B-H loop of the pipe is measured at laboratory in DC condition (< 0.003Hz) to eliminate the influence from eddy current loss. So the hysteresis energy is independent of frequency. Hysteresis energy in a magnetic material is usually expressed as a function of the maximum flux density B_{max}
$E_{hys}=k_h B_{max}^{k_p}$ (4)
where k_h and k_p are material dependent constants, and k_p as “Steinmetz coefficient” is generally near to 1.6.

The hysteresis power in unit length can be evaluated by integrating the hysteresis energy over the pipe volume and multiplying frequency f and mass density ρ as
$P_{hys}=2\pi\rho f\int rE_{hys}dr$ (5)

Based (1) and (5), the hysteresis power in the pipe can be derived and finally expressed as
$P_{hys}=k_c I_{rms}k_p\mu^{(k_p-0.5)}\sqrt{f}$ (6)

where $k_c=2r_o k_h \rho\sqrt{(\pi/\sigma)}/(k_p(\sqrt{2}\pi r_o)^{k_p})$ (7)

Effective permeability

As given in (2) and (6), both the conductive and hysteresis powers are a function of effective permeabililty in addition to frequency and input current, so the effective permeability should satisfy following two conditions:
1) The effective permeability should be acceptable for both conductive and hysteresis power loss calculations.
2) The effective permeability should be obtainable based on the measured permeability and the input current of the pipe.

An effective permeability as function of input current has been derived here and the result is shown in Fig.(1) ,where the effective constant relative permeability used for the analytical calculation is plotted as function of the maximum magnetic flied that is determined by the input peak current.

Result verification

To verify the result, both FEM simulation and prototype test are carried out for a specific case, a 12” carbon steel pipe having tube thickness of 17.1mm where the current varies between 300 and 1000 A, and the frequency between 50 to 200Hz. A rod example is made of the pipe for measuring the properties. The results are expressed as resistance per km ($R=P/I_{rms}^2$) and presented in Fig.(2)

Conclusion

An analytical method to predict the heating power in magnetic pipe is derived, in which the heating power is expressed in terms of operating frequency and input current. Effective permeability for the analytical calculation is also derived based on measured B-H curve of the magnetic material and its value is determined by the peak input current. The analytical results are compared with FEM simulation and prototype test, and they match each other satisfactorily. More detail will be presented in final paper, including proximity effect.

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KEYWORDS: magetic pipe, Direct electric heating, effective permeabililty, heating power.

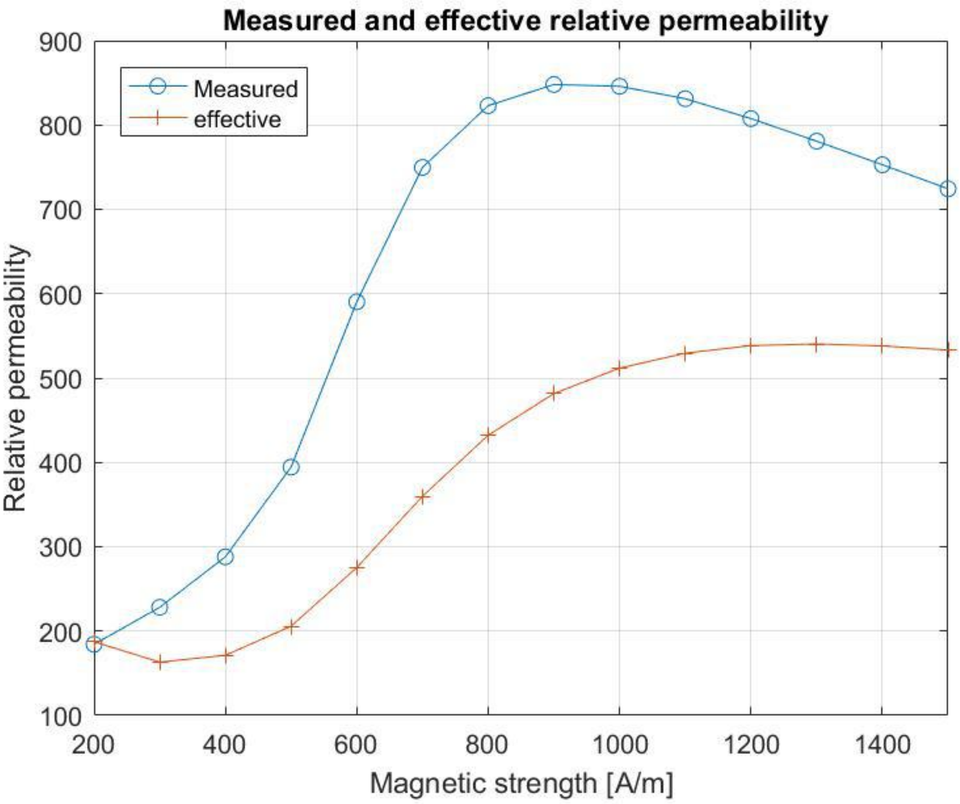

Fig.1 Measured relative permeabilily and effective relative permeabilily in carbon steel

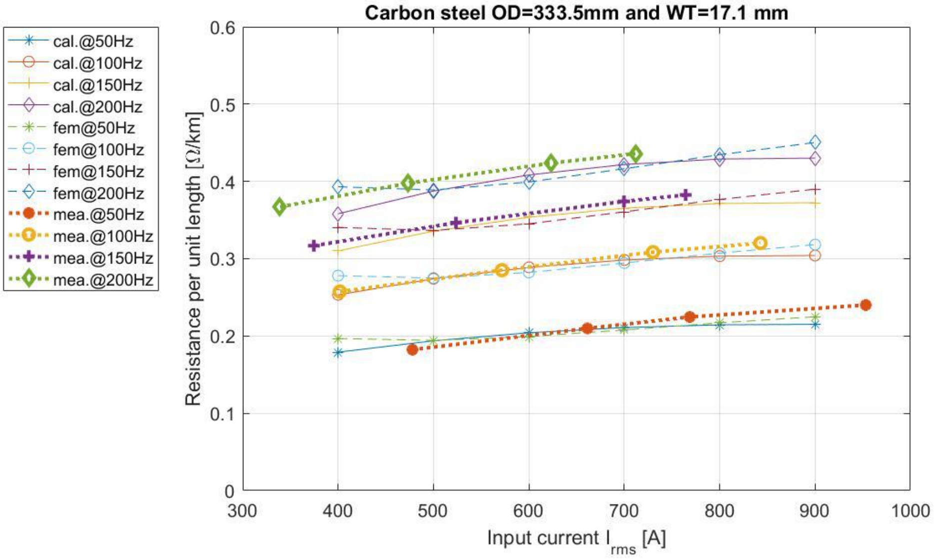

Fig.2 Comparison of analytical calulated, FEM simulated and measured power loss in terms of resistance as function of input current in the carbon steel pipeline.

IMAGE CAPTION: Fig.1 Measured relative permeabilily and effective relative permeabilily in carbon steel Fig.2 Comparison of analytical calulated, FEM simulated and measured power loss in terms of resistance as function of input current in the carbon steel pipeline.

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