Improving the Performance Of LF/MF Transmitter Installations

John Pinks
Chief Engineer Emeritus
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Nautel Limited
10089 Peggy's Cove Road,
Hackett's Cove, NS, Canada B3Z 3J4
T.+1.902.823.2233 F.+1.902.823.3183
info@nautel.com

U.S. customers please contact:
Nautel Maine, Inc.
201 Target Industrial Circle, Bangor ME 04401
T.1.207.947.8200 F.1.207.947.3693
info@nautel.com

e-mail: support@nautel.com
www.nautel.com

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SUMMARY

The United States Coast Guard operates a nationwide network of medium frequency transmitters to augment the GPS System by supplying correctional data to localized users. Operating in the frequency band 282-325 kHz at a power level of 1 kW, they are required to provide a field strength of 75 micro volts per meter at a range of 200 kilometers. This technical paper addresses a specific problem, whereby variations in the antenna system cause variations of the field strength at the specified range.

BACKGROUND

2.1 TYPICAL ANTENNA TYPES

Radio transmitters which operate in the LF/MF frequency band utilize antennas that are much shorter than an optimal height. This causes the antenna input impedance to approximate a high capacitive reactance in series with a low value resistive term. Standard antenna matching arrangements series resonate this capacitive reactance with a loading coil and transform the resulting low resistance to the required 50 ohm load for the transmitter. Input impedances vary widely depending upon the transmitter power rating and the operating frequency. Typically installations with power ratings of 100 watts or less utilize very short antennas with input impedances in the order of 10 - j 2000 ohms. These can have antenna efficiencies as low as 1% or less and very narrow bandwidths. At higher powers, more money is typically spent erecting taller antenna structures which have input impedances in the range 5 - j 200 ohms. These systems can have efficiencies as high as 50% or more but also have limited bandwidth. Antenna tuning units often utilize a servo system to maintain accurate tuning of the loading coil to compensate for weather related variations of the antenna's reactive term. The resistive part of the antenna's input impedance includes the antenna's radiation resistance which is directly related to the antenna's effective height, in series with loss resistance components representing the loading coil and the antenna's ground plane. The antenna efficiency can be expressed directly as the ratio of the radiation resistance R_R divided by the total resistance R_T.

Conversion of the resistive term of the antenna input impedance to the required 50 ohms, is typically achieved using a ferrite cored transformer with tapping positions which are adjusted at the time of installation to suit conditions at the site. The fundamental assumption has been that the resistive term does not exhibit a wide variation and a reasonable match is maintained during changing weather conditions. In many installations, however, it has been determined that changes in the ground plane loss resistance occur with the water content of the soil in the immediate proximity of the ground plane radials. This is particularly true where the length and quantity of the radials are less than optimum. This is often the case due to restrictions of plot size or the prohibitive cost of the copper wire. Leakage currents flowing on the surface of the antenna's high voltage insulators which vary with moisture, salt and ice build-up represent an additional series loss resistance which can cause a significant variation of the resistive term.

2.2 HIGH EFFICIENCY TRANSMITTERS REQUIRE A WELL MATCHED LOAD

Modern transmitters are designed to be highly efficient, hence reducing the need for large cooling surfaces in their output amplifiers. It follows that their outputs must be properly matched to the designed load impedance, typically 50 ohms, so that reflected power which causes heat dissipation in the final amplifier, is maintained at a safe level. Some transmitters are designed to shut off if the reflected power becomes excessive or, in the case of Nautel equipment, to reduce their output power to maintain the reflected power below a critical safe value.

In order to maintain a constant radiated power and hence a constant field strength, it is necessary to maintain a constant antenna current. This will not be achieved by keeping a perfect match alone, because the changing resistive loss component will cause the antenna current to vary even though the transmitter output power remains constant. The technique proposed by this paper will automatically retain a good match and will also monitor the antenna current and use feedback to stabilize its value. In order to accomplish this, the transmitter must have the ability to increase or decrease its output power in response to the current feedback signal whilst maintaining a safe operating condition.

3 ESTIMATING THE PERFORMANCE CHARACTERISTICS OF ANTENNAS PRESENTLY USED BY US COAST GUARD

The following theoretical analysis examines the specific United States Coast Guard task of providing a field strength of 75 micro volts per meter at a range of 200 kilometers at locations throughout the USA using two particular antenna types. The analytical methods used are based upon the technical paper " NDB Antennas" prepared in 1989 by Nautel's Chief Engineer John R. Pinks. For simplicity, the analysis is performed at 300 kHz. Frequencies in the range 282 - 325 kHz would exhibit only slight variations from the calculated results.

3.1 RHON 45G, 90 FT. TOP LOADED ANTENNA

This antenna, used extensively by the US Coast Guard, comprises a base insulated, 90 ft guyed tower, utilizing three top loading guys each 65 ft long. The ground plane uses 36 radials 150-180 ft long.

Capacitance of tower
= 90 x 5.5 pf
= 495 pf

Capacitance of top loading
= 3 x 65 x 1.5
= 292 pf

Total Capacitance of Antenna = 787 pf

Antenna Capacitive reactance

$$= \frac{1}{2\pi fC}$$

$$= \frac{10^9}{2\pi \times 300 \times 787}$$

= 674 ohms

Antenna Effective Height (H_E)

$$= 90\left[1 - \frac{1}{2}\left[\frac{C_{TOWER}}{C_{TOTAL}}\right]\right]$$

$$= 90\left(1 - \frac{1}{2}\left[\frac{495}{787}\right]\right)$$

= 90 x 0.685

= 61.7 ft.

Antenna Radiation Resistance (R_R)

$$= 160\pi^2\left(\frac{H_E}{\lambda}\right)^2$$

$$= 160\pi^2\left(\frac{61.7}{3280}\right)^2$$

= 0.559 ohms

Assuming that the Q value of the Antenna Tuning Unit's loading coil

Q_C = 300

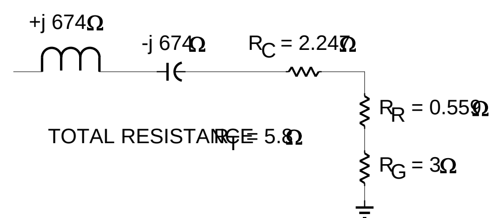
then its loss resistance

$$R_C = \frac{X_C}{Q_C}$$

$$= \frac{674}{300}$$

= 2.247 ohms

If we assume a ground plane loss resistance of 3 ohms, the equivalent circuit of the antenna becomes



$$\text{Efficiency} = \frac{R_R}{R_T}$$

$$= \frac{0.559}{5.8}$$

= 0.0964 or 9.64%

For a transmitter output power of 1000 watts and using the loading coil Q of 300. Radiated power is 94.6 watts. This is 10.15 dB below 1 kW.

The resulting overall Q_A value for the antenna

$$Q_A = \frac{X_C}{R_T}$$

$$= \frac{674}{5.8}$$

= 116.2

Antenna 3 dB Bandwidth

$$= \frac{f_o}{Q_A}$$

$$= \frac{300}{116.2}$$

= 2.58 kHz

Sideband Attenuation at a bandwidth of 1.3 kHz

$$A_{S_{1.3\ kHz}} = 10\log_{10}\left(\frac{1}{1+Q_A{}^2\left(\frac{2f_m}{f_o}\right)^2}\right)$$

where

2fm = 1.3 kHz and f_O = carrier frequency

$$\therefore A_S = 10\log_{10}\left(\frac{1}{1+Q_A{}^2\left(\frac{2f_m}{f_o}\right)^2}\right)$$

= -0.978 dB

i.e., The bandwidth at –1 dB is 1.3 kHz.

It is possible to improve the Q value of the loading coil to approximately 500 by the use of Litz wire. This would reduce its loss resistance to 1.35 ohms producing a total antenna resistance value of 4.91 ohms. The antenna efficiency would improve to a value of 0.113 (11.3%) and the radiated power for 1 kW input would increase to 113 W or 9.47 dB below 1 kW. This would give an antenna Q of 137.3 and a -3 dB bandwidth of 2.18 kHz or signal attenuation at 1.3 kHz of 1.3 dB. It is understood that a -1 dB bandwidth 1.3 kHz is desirable for future increases in data rates, hence the reduction of ATU coil loss resistance seems to be of dubious benefit.

3.2 GWEN 299 FT. TOP LOADED TOWER

This antenna, also used extensively by the U.S. Coast Guard, comprises a base insulated, 299 ft. high tower utilizing 12 - 105 ft. long top loading guys. The ground plane uses 36 radials 150 - 180 ft. long.

Capacitance of tower
= 299 x 5.5 pf
= 1644 pf

Capacitance of top loading
= 12 x 105 x 1.3
= 1638 pf

Total Capacitance of Antenna = 3282 pf

Antenna Capacitive reactance

$$= \frac{10^9}{2\pi x 300 - 3282}\, ohms$$

= 161.6 ohms

Antenna Effective Height H_E

$$= 299\left(1-\frac{1}{2}\left[\frac{1644}{3280}\right]\right)$$

= 299 x .749

= 224 ft.

Antenna Radiation Resistance R_R

$$= 160\pi^2 x\left(\frac{224}{3280}\right)^2$$

= 7.365 ohms

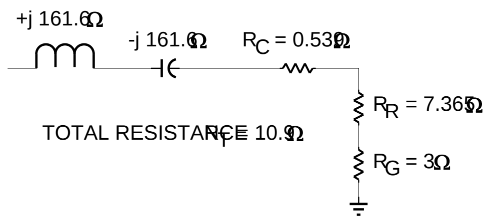
If the Loading Coil Q factor (Q_C) = 300

then its loss resistance R_C

$$= \frac{161.6}{300}$$

= 0.539 ohms

If we again assume a ground plane loss resistance of 3 ohms, the equivalent circuit of the antenna becomes



Efficiency = $\frac{R_R}{R_T}$

= $\frac{7.365}{10.9}$

= 0.676 or 67.6%

For a transmitter output power of 1000 watts

Radiated Power
= 676 watts or 1.7 dB below 1 kW

The resulting overall Q Value for the antenna

= $\frac{X_C}{R_T}$

= $\frac{161.6}{10.9}$

= 14.8

Hence Antenna -3 dB bandwidth

= $\frac{300}{14.8}$

= 20.23 kHz

4. ESTIMATING THE REQUIRED RADIATED POWER

The International Telecommunications Union Publication ITU-R P.832-2 is widely used to predict ground wave field strength throughout the world. Figure 35 of this publication shows ground conductivity expressed in milli-mho/meter (mS/m) for various regions within the United States. The areas mainly on the east coast and on the northern west coast are shown to have the lowest conductivity (2-4 mS/m) and hence will require the greatest radiated power in order to meet the specified signal strength of 75 micro-volts per meter at a range of 200 kilometers.

A more detailed map of Estimated Effective Ground Conductivity used by the Federal Aviation Administration more closely with ITU-R P.832-2 showing the worst conductivity being 2 to 4 mS/m.

Figure 23 of ITU-R P.832-2 shows the field strength in micro-volts per meter (right side vertical scale) for a radiated power of 1 kW at various ranges (horizontal scale). Curves are shown for various ground conductivities expressed as S/m at a frequency of 300 kHz. These can be co-related to the maps using the following table:

Soil Type	mS/m from maps	S/m of curves on Fig 23
Low salinity seawater	5000	5
Very wet ground	30	3×10^{-2}
Wet ground	10	10^{-2}
Medium Dry ground	3	3×10^{-3}

The radiated power that is necessary to achieve a given field strength at a given range for a frequency of 300 kHz can be read from the curves of Fig 23 of ITU-R P.832-2 for a given soil conductivity. For example, the curve representing the conductivity of 3 mS/m intersects the 200 km distance at a point that is 12.5 dB.

In tabular form, the required radiated power is above the horizontal grid at 75 micro-volts per meter. This indicates that the required radiated power is 12.5 dB below 1 kW or 56.2 W. Similarly, for the higher conductivities of 10 mS/m and 30 mS/m, the required radiated powers are -20 dB ref 1 kW (10 watts) and -22.5 dB ref 1 kW (5.6 watts) respectively.

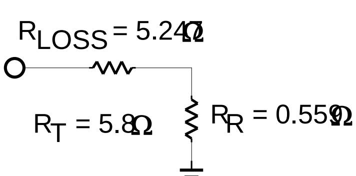
Soil Conductivity	Radiated Power required Rel 1 kW	Radiated Power Required
mS/m = 2-4	-12.5 dB	52.6 watts
mS/m = 8-10	-20 dB	10 watts
mS/m = 30	-22.5 dB	5.6 watts

The estimate for radiated power from the Rhon antenna is 96.4 watts. This is only 2.3 dB above the required level in the areas which have soil conductivities of 2-4 mS/m, leaving a slim margin of safety.

It is likely that additional loss resistance, which will undoubtedly occur during weather related conditions, will cause the field strength to fall below the required level.

5. CHANGES TO ANTENNA EFFICIENCY CAUSED BY INCREASING LOSS RESISTANCE

Changes to the resistive term of the antenna impedance caused by insulator leakage and ground plane resistance changes cause a mismatch at the transmitters terminating impedance. Taking the critical example of a Rhon antenna operating in the areas where the conductivity is 2-4 mS/m, the simplified equivalent circuit becomes



The antenna current (I_A) can be calculated from the expression

$I_A^2 \times R_T = 1000$ watts

Hence

$$I_A = \sqrt{\frac{1000}{5.8}}$$

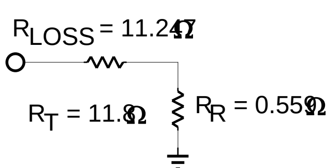
= 13.13 Amps

And Power Radiated = $I_A^2 \times R_T$

= $13.13^2 \times R_R$

= 96.37 watts

An increase of the loss resistance value by say, an additional 6 ohms, even if the transmitter power remained constant, which is unlikely, would change the equivalent circuit to



Now I_A^2 x 11.8 = 1000 watts or

$$I_A = \sqrt{\frac{1000}{11.8}}$$

= 9.03 Amps

Hence Radiated Power is reduced to 9.03^2 x 0.559 = 47.3 watts

In order to maintain a constant antenna current, the transmitter power must be increased to a value of

P = 13.13^2 x 11.806 = 2035 watts

The relationship between the resistance change to the required transmitter power to maintain a constant antenna current is such that twice the resistance requires twice the power. Three times the resistance requires three times the transmitter power, etc. Nautel believes that increases in the resistive input impedance of up to 100% (representing a VSWR of 2:1) can be expected. Consultation with the FAA, who utilize a less sophisticated current stabilization system with over 300 Nautel NDB transmitters located in the U.S.A, suggests that a variation of at least 50% commonly occurs with their low power installations.

6. PROPOSED SOLUTION

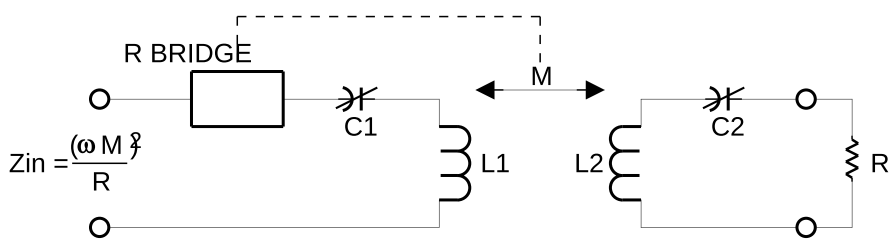
The solution proposed by Nautel includes two fundamental changes which will result in both a much more stable field strength and an improved error rate for the transmitted data.

6.1 First, a stage will be added in the Antenna Tuning Unit input, which automatically adjusts the matching, such that a resistive 50 ohm impedance is always presented to the transmitter output. A bridge circuit will compare current and voltage samples and activate a servo system which varies the mutual coupling between two resonant coils. This servo system will be inhibited when the loading coil servo is active.

A functional block diagram for this arrangement is shown below. Its operation is based upon the fact that the mutual coupling between two resonant inductors can be varied to create a varying transformation ratio without introducing a reactive term at the input.

C1/L1 and C2/L2 are adjusted for resonance at the carrier frequency.

Mutual inductance M is adjusted by the servo system such that Zin = 50Ω for varying values of R.



This feature alone will not solve the problem as the antenna current will still vary in proportion to the total antenna resistance for a fixed input power (or input voltage).

6.2 Second, a DC voltage proportional to the antenna current will be fed back to the existing remote power level control in the Nautel transmitter, to stabilize the preset value of the antenna current.

6.3 The proposed solution required the use of a transmitter which has both the ability to automatically vary its output level and which has a suitably high maximum power rating. As shown earlier, the 1 kW systems used in the low soil conductivity areas (2-4 mS/m) on the map do not have a large margin of excess available power and may require upgrading. On systems installed in areas of higher ground conductivity, a 1 kW maximum power level may be entirely adequate.

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References

International Telecommunications Union. Recommendation ITU-R P.368-7, Ground-Wave Propogation Curves for Frequencies between 10 kHz and 30 MHz. 1992.

International Telecommunications Union. Recommendation ITU-R P.832-2, World Atlas of Ground Conductivities. 1999.