Standing Wave Ratios in the FM Broadcast Band

THE GATES RADIO CO., QUINCY, ILLINOIS

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Published By

GATES RADIO COMPANY

Quincy, Illinois
November 1948

INTRODUCTION

The purpose of this treatise is to call to your attention the fact that an impedance mismatch between a transmitter and the transmission line to the antenna or between the antenna and the transmission line, or both, is just as possible at 100 megacycles as at 1000 kilocycles and has effects that are even more serious.

The problem of standing wave ratios in transmission lines (the result of impedance mismatch) is an old one. On ordinary or standard broadcast frequencies it is common practice to couple devices having different impedances by means of a network of inductances and capacitors. A common item of this nature is the antenna tuning unit used to match the transmission line impedance to that of the antenna impedance.

At FM broadcast frequencies (100 megacycles) antennae are of a considerably different design and do not lend themselves to matching to transmission lines by the same type of circuits and components that are used on the low frequencies. In most cases the antennae for FM frequencies are designed by the manufacturer to match properly to the standard transmission lines now in use, the impedance of which is 51.5 ohms. In cases where standing waves result due to mismatch of impedances, the antenna must be readjusted by the manufacturer or in accordance with his instructions.

There are several methods used to determine that standing waves exist in the system. These are explained in the section of the treatise entitled ''Standing Wave Measuring Methods''. Ordinary means of determining that there are standing waves (observation of RF current meters at either end of the transmission line, for example) are ineffective because meters are not yet developed that will operate satisfactorily at FM broadcast frequencies.

Here follows a simplified explanation of why standing waves exist:

An analogy of the development of standing waves might be that of a beam of light going through a clear piece of glass. If the beam is projected at an angle of 90° to the surface of the glass most of the light passes on through and very little is reflected. If, however, the glass is treated so it becomes a mirror most of the light will be reflected and very little will pass through. Similarly, if a transmission line is connected at each end to devices that are pure resistances that equal the surge impedance of the line, -- all the current put into the line at one end will come out of the line at the other end. If, however, the antenna end of the line has a termination that is not a pure resistance or that is not equal to the impedance of the transmission line only a portion of the energy will come out of the line and the rest will be reflected. The amount of reflection is dependent upon the amount of mismatch.

The reason that reflection takes place even if a pure resistance is used (but unequal to the impedance of the line) is because of distributed capacity or inductance present as an inherent characteristic of any transmission line. It is also true that if the load consists of resistance along with either capacity or inductance reflections will take place. These reflections add and subtract to the sine wave of the transmitted voltage in the transmission line and result in standing waves, the ratio of which is dependent upon the amount of reflection which, as we have seen, is in turn dependent upon the amount of mismatch.

Practically speaking, the only way to reduce standing waves to a reasonable ratio (1.2 to 1) is to have the antenna impedance match that of the transmission line. The following treatise discusses ways of determining whether standing

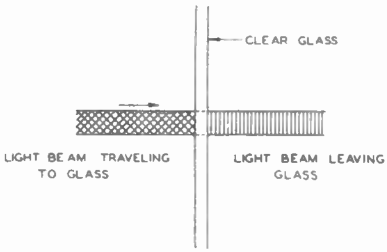


FIG 1

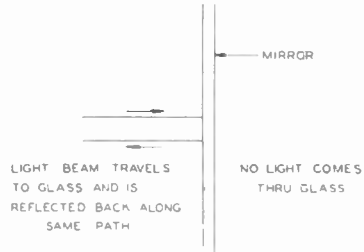


FIG 2

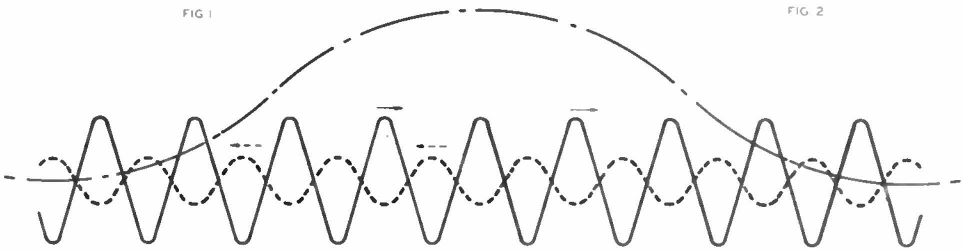


FIG. 3

These drawings illustrate, as well as possible, the action of light to provide an analogy to explain the reasons for existence of standing waves. Figs. 1 and 2 show the action a light beam on clear glass and also a mirror. Fig. 3 shows a transmitted or incident wave (solid line), (the beam of light projected on to the mirror), the reflected wave (dotted line) of lesser value than the incident wave because of losses in the system, and the standing wave (dashed line) which results because of interaction of the incident and standing waves.

Illustrations such as Fig. 3 can only illustrate the approximate relationship existing between incident, reflected and standing waves because the phase relationship between the incident and reflected waves is actually constantly changing and therefore the amplitude of the standing wave is constantly changing. The proportions of each wave are also not found in practice but serve very well for illustrative purposes.

waves do exist. Obviously the remedy for standing waves is to obtain an antenna that does match the line. Most antennae used in the FM broadcast band cannot be adjusted without the knowledge and experience of a highly skilled laboratory engineer from the manufacturer of the antenna manufacturer's plant and the use of instruments not ordinarily obtainable or used in the field. Accordingly, in case of trouble consult the manufacturer of your antenna about having the proper adjustment or replacement made. Do not attempt to do it yourself.

DEFINITION OF STANDING WAVES

If a transmission line is terminated into an impedance (Z_L) equal to the surge impedance of the line (Z_O) there will be no energy reflected back toward the transmitting source. In other words all the transmitted energy will be dissipated in the load impedance Z_L. We may then write the equation $Z_O = Z_L$ fulfilling this condition.

If the transmission line is not terminated into an impedance equal to its own surge impedance part of the energy will be reflected back toward the transmission source. The reflection coefficient can be expressed as:

$$\text{Reflection Coefficient} = \frac{\dfrac{Z_L}{Z_O} - 1}{\dfrac{Z_L}{Z_O} + 1} \ *$$

The incident wave is the outgoing wave moving toward the load end.

The reflected wave is the wave reflected back from the load and travelling toward the transmitting source.

The ratio of reflected to incident waves, existing at some particular point on the transmission line, is frequently expressed in terms of what is called the standing wave ratio. This can be defined as the ratio of the sum E_{max} of the amplitudes of the two wave trains when they are in phase to the sum E_{min} of their amplitudes when they are in phase oppo-

*By permission from "Radio Engineering" by F. E. Terman Chap. 4, Sec. 4-2, Copyrighted 1947. McGraw-Hill Book Company., Inc.

sition. We may express this as:

$$\text{Standing Wave Ratio (VSWR)} = \frac{E_{max}}{E_{min}}$$

If by means of a slotted line and a voltmeter, we are able to measure the voltage by sliding this device along the line, we would find when there is a standing wave present that the voltmeter will not indicate a steady value but one which goes from a minimum to a maximum. The ratio of the maximum reading to the minimum reading will be our standing wave ratio. It is common practice to express this in units greater than one.

DETRIMENTAL EFFECTS OF STANDING WAVES

The detrimental effects of standing waves are numerous. Since it is obviously beyond the scope of this pamphlet to discuss all of these effects, discussion will be confined to the most common ones.

Power Loss in Transmission Lines

Blueprint A-4647 shows the relation of the loss in a transmission line with a given standing wave ratio to a line having unity standing wave ratio. For example, assume a transmission line having a loss calculated at 200 watts. If upon installation a standing wave ratio of 4 is found to exist, by referring to the chart, it is found that the line losses are 2. In this particular installation if this standing wave ratio is allowed to exist the actual transmission line losses will be on the order of 400 watts.

This added dissipation probably will consist largely of copper, dielectric and connector losses. If this should be an open wire line, then radiation losses would be added to these.

Damage to Transmission Lines

Standing waves usually cause damage to transmission lines of the coaxial type in one or more of the following ways:

(a) Broken insulating support beads.
(b) Arcing and subsequent damage to both line and insulators.
(c) Over-heating of the conductors.

The safe power capabilities of coaxial line decreases sharply with the increase in standing wave ratio. Blueprint A-4646 illustrates how the capability is decreased.

Mismatch Presented to the Transmitter

FM transmitters are designed to work most efficiently into some definite given load. RMA recommendations are 51.5 ohms.

With standing waves present in the transmission line, there is little probability that the transmitter output termination will look into the proper 51.5 ohm impedance. The actual impedance will be of a complex value consisting of both resistance and either capacitive or inductive reactance. This is usually expressed in the rectangular form. For example, a given installation might reflect an impedance at the transmitter end of 50 +j30.

Obviously a pi matching network, such as a two stub tuner, may be used at this point to properly match the transmitter to the line, but this still will not alleviate the attendant evils of standing waves in the transmission line. Since there is a good possibility of a change in the standing wave due to weather and other similar conditions at the antenna, the stub tuner would of necessity require readjustment to meet the new set of conditions.

From this it appears a matching stub tuner to bring the input impedance of the transmission line, with the standing wave condition, to the correct 51.5 ohm impedance value is merely the addition of further evils.

An FM transmitter designed and adjusted for operation into a 51.5 ohm load can be expected to have its output effectively reduced according to the standing wave ratio as shown in blueprint A-4648.

The actual amount of this reduction will depend on the position of the standing wave at the input point of the transmission line. This will cause a variation between the minimum and maximum lines on the chart.

High standing wave ratios may also result in damage to the transmitter. Insulators, tubes and other components may be damaged due to arcs occurring where high impedance and voltage points result.

Error Introduced in the R. F. Output Meter Reading

The R. F. Output meter reading will vary by an amount depending on the magnitude of the standing wave and/or its position at the measuring point. This will be true regardless of whether it is a voltage or current indicating instrument.

Since the impedance at the effective measuring point will vary as stated above, the reading will be subject to an error falling some place in between lines A and B on blueprint A-4649.

COMMON CAUSES OF STANDING WAVES

There are numerous causes and conditions which will contribute to a standing wave condition in a transmission line, however, the below are some of the most frequent sources of trouble:

Antenna not Properly Resonated

An antenna having the correct terminating impedance will cause standing waves when incorrectly tuned to the operating frequency. The magnitude of the standing wave ratio will be dependent on the amount of mis-tuning. Mis-tuning will cause reactance (inductive or capacitive) to appear in series with the normally resistive load the antenna would present to the transmission line. The antenna manufacturer's instructions should be followed in adjusting the antenna.

Improper Antenna Termination Connections

The antenna manufacturer's installation instructions will usually go into this phase. However, one steadfast rule if adhered to will be of considerable help. All connections should be as short as physically possible, firm and tight electrically and not introduce any change in surge impedance.

Improper Termination Due to Incorrect Antenna Impedance

The manufacturer's literature will state the impedance of the antenna and/or the impedance at the associated balancing on matching section. This impedance must be equal to the surge impedance of the line.

Adjustment of the associated balancing or matching section may be necessary in the field for the particular installation, due to the presence of the tower or other structures near the radiating element. Consultation of the manufacturer's instructions or field engineer is advisable before attempting any adjustments.

Poor or Incorrect Electrical Joint in Transmission Line

A poor electrical joint in the transmission line will effectively introduce a resistance in series with the load, and cause standing waves. A break in the outer conductor which does not maintain the constant relationship between the inner and outer conductor is equivalent to the insertion at this point of a series inductance, even though there is D.C. continuity. This will, of course, likewise introduce standing waves.

Points where sections are bolted together may be offenders on the two above counts. Firm contact on the coupling bullets of the inner conductors and the flanges should be maintained.

Broken Beads in Transmission Line

Broken beads in the transmission line will result in some disturbance of the characteristic surge impedance since this dielectric figures materially in the characteristic surge impedance as does the ratio of inner to outer conductor ratio. This figures important enough that the coaxial cable manufacturers usually recommend cutting only midway between beads. Broken beads may also allow sagging of the inner conductor with a subsequent change in the characteristic surge impedance of that particular section of line.

Any discontinuity or change in impedance will result in standing waves.

Water or Moisture in Transmission Line

Water or moisture in the transmission line will upset the surge impedance. Moisture on the support beads serve to change the power factor and effective dielectric constant of these supports. Needless to say, the voltage breakdown of the beads is dangerously weakened.

If water should collect in a low portion of the line, it may either furnish a low resistance path effectively shorting the inner to the outer conductor or change the surge impedance due to the dielectric constant of the water being greater than air. Water also serves as a highly dissipative medium in absorbing the radio frequency energy.

Impedance Discontinuity in the Transmission Line

Impedance discontinuity in the transmission line may occur in many different ways.

(a) Broken beads
(b) Sagging inner conductor
(c) Poor joints
(d) Cutting of the transmission lines at other than points mid-way between beads
(e) Defective expansion joints or sections.
(f) Improperly compensated right angle junction boxes.
(g) Too short taper on reducer sections.

Care in installation and careful observance of the manufacturer's instructions and recommendations will usually prevent standing waves from originating at these points.

STANDING WAVE MEASURING METHODS

Of the numerous methods of measuring standing wave ratios in transmission lines, there still does not exist any easy accurate method in the field. Method #4 given below is perhaps the easiest, but this requires special equipment not ordinarily available in the field.

(1) The slotted line method has been in use for a number of years. For this method the lines are slotted over one or more wave lengths. By means of a probe moved along this line at a constant pre-determined penetration depth and a voltmeter (one of the most common R. F. voltmeters consists of a germanium crystal and 0-1 mil D.C. meter), the voltage is measured every ten or fifteen electrical degrees (Appx. 3 inches at FM frequencies), and plotted on graph paper. The variations of E_{min} to E_{max} can then be fairly accurately calculated. The bead spacing of the coax should be noted with respect to the measuring points to enable compensating for the electrostatic concentration at bead points.*

(2) A variation of the above method consists of drilling a series of holes approximately 3 inches apart along the line for two or more wavelengths. An R. F. Voltmeter with probe such as Model WV-75A voltohmyst, may then be used to obtain the readings at the measuring points. This should be plotted as in method one for the most accurate results.

(3) A further variation of the above which may be used in 3-1/8 inch and larger lines, consists of inserting miniature spark plugs (such as used in model airplanes) at 3 or 4 inch intervals in the outer conductor. These may be part of a permanent installation as they will permit pressuring the line.

Care must be exercised in alignment of the plugs since the finger points should all face in the same plane and direction.

*To obtain the most accurate measurements, the effect of the detector non-linearity and the probe reflection error must be taken into consideration. "Techniques of Micro Wave Measurements", Sec. 10-17 cover this along with useable curves. This is Volume 11 of "The Radiation Laboratory Series", published by McGraw Hill Book Company.

(4) Perhaps the easiest method in the field consists of breaking the line and inserting some form of directional coupler. A directional coupler is a device which will measure the amplitude of the outgoing energy and also the amplitude of the reflected energy traveling in the opposite direction, hence the name directional coupler.

Since directional couplers are of fairly recent design, there is not a great amount of literature available that is directly applicable to FM frequencies.* Various names are employed throughout the industry as well as individual trade names. ''Impedance Monitor'' and ''Reflectometer'' are probably the most popular and descriptive of the units.

One unit available on the market is the Model MM200 Micromatch, manufactured by M. C. Jones Electronics Company, North Main Street, Bristol, Connecticut.

This unit may be inserted in the line and reads directly on individual meters both the standing wave ratio and power.

(5) Short Circuited Line Method. This method has been popularized by Phillip H. Smith.

Measurements are made on the line with the load connected. The load is then removed and the direction and amplitude of

*1. ''Electrical Communication'', March, 1947, Page 94

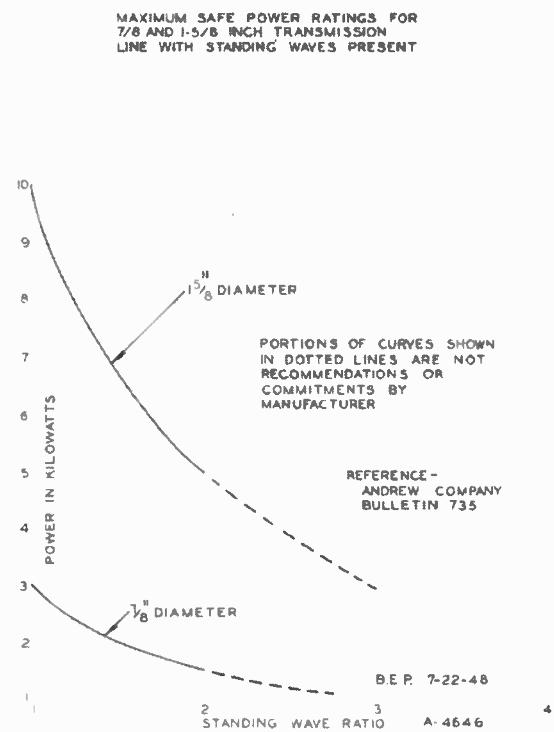
2. U. S. Patent #2,443,097 issued to Radio Corporation of America.

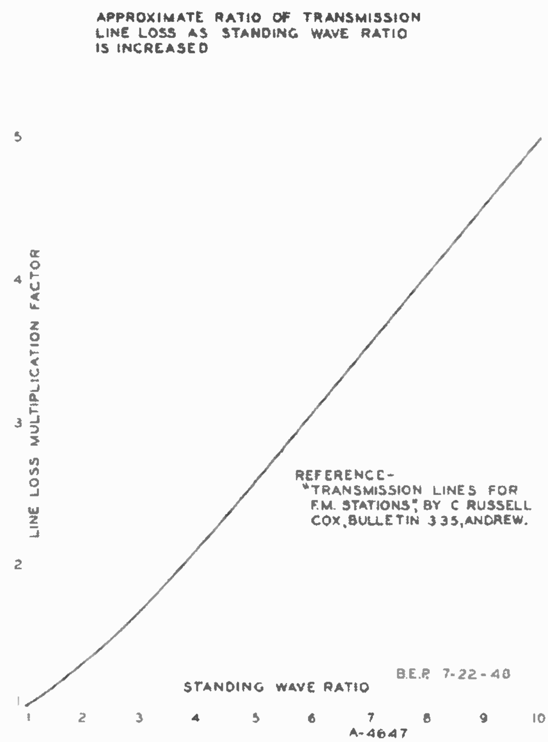
3. ''A Method of Determining and Monitoring Power and Impedance at High Frequencies'', by J. F. Morrison and E. L. Younker, IRE Proceedings, February, 1948.

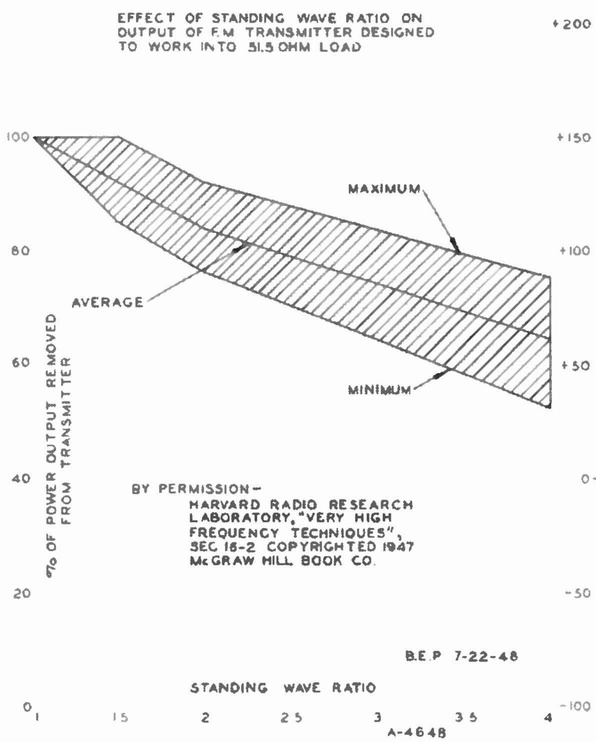
the voltage shift is again measured. By means of the Smith chart* the impedance as well as VSWR can be calculated.

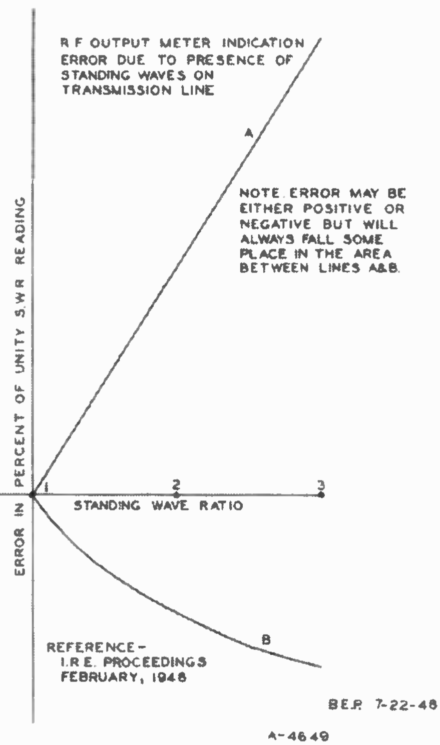
(6) Spectrum Analyzer. One of the newest and latest instruments on the market for determining standing waves is a spectrum analyzer, called "Megamatch", built by Kay Electronics. By means of an oscilloscope, and a sweep generator with marker frequencies, the desired frequency spectrum is swept. The pattern appearing on the scope indicating the degree of mismatch.

*"Transmission Line Calculator" by Phillip H. Smith, Electronics, January, 1944
"Techniques of Microwave Measurements", Radiation Laboratory Series, Montgomery, Page 625.


MAXIMUM SAFE POWER RATINGS FOR 7/8 AND 1-5/8 INCH TRANSMISSION LINE WITH STANDING WAVES PRESENT
POWER IN KILOWATTS
1 5/8" DIAMETER
7/8" DIAMETER
PORTIONS OF CURVES SHOWN IN DOTTED LINES ARE NOT RECOMMENDATIONS OR COMMITMENTS BY MANUFACTURER
REFERENCE - ANDREW COMPANY BULLETIN 735
B.E.P. 7-22-48
STANDING WAVE RATIO
A-4646


APPROXIMATE RATIO OF TRANSMISSION LINE LOSS AS STANDING WAVE RATIO IS INCREASED
LINE LOSS MULTIPLICATION FACTOR
REFERENCE - "TRANSMISSION LINES FOR F.M. STATIONS", BY C RUSSELL COX, BULLETIN 335, ANDREW.
B.E.P. 7-22-48
STANDING WAVE RATIO
A-4647


EFFECT OF STANDING WAVE RATIO ON OUTPUT OF F.M TRANSMITTER DESIGNED TO WORK INTO 51.5 OHM LOAD
% OF POWER OUTPUT REMOVED FROM TRANSMITTER
MAXIMUM
AVERAGE
MINIMUM
BY PERMISSION - HARVARD RADIO RESEARCH LABORATORY, "VERY HIGH FREQUENCY TECHNIQUES", SEC 16-2 COPYRIGHTED 1947 McGRAW HILL BOOK CO.
B.E.P 7-22-48
STANDING WAVE RATIO
A-4648


R F OUTPUT METER INDICATION ERROR DUE TO PRESENCE OF STANDING WAVES ON TRANSMISSION LINE
ERROR IN PERCENT OF UNITY S.W.R READING
A
B
NOTE ERROR MAY BE EITHER POSITIVE OR NEGATIVE BUT WILL ALWAYS FALL SOME PLACE IN THE AREA BETWEEN LINES A&B.
STANDING WAVE RATIO
REFERENCE - I.R.E. PROCEEDINGS FEBRUARY, 1948
B.E.P. 7-22-48
A-4649

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