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WAVE PROPAGATION ON R.F. TRANSMISSION LINES

PUBLISHED 1969

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1. INTRODUCTION.

1.1 In the publication ETP 0026 'Characteristics of R.F. Transmission Lines', reference is made to the use of R.F. lines for transferring energy from one point to another with minimum loss. This type of line is sometimes called a 'non-resonant' transmission line. It is terminated in its characteristic impedance to keep reflection loss to a minimum, and to ensure maximum transfer of energy from line to load.

1.2 In other applications, electrically short sections of R.F. transmission lines are used as circuit elements, or as resonant circuits for oscillators and for the construction of filters, particularly in the H.F., V.H.F. and U.H.F. ranges. This type of line is terminated in an impedance not equal to its characteristic impedance, and is called a 'resonant' transmission line. Energy is reflected from the termination and standing waves are set up along the line. When terminated in either an open circuit or a short circuit, all the energy reaching the end of the line is reflected, and the line may be designed to exhibit the characteristics of either a series or a parallel resonant circuit. Alternatively, a short section of line may be designed to behave as either an inductor or a capacitor, or be used as an impedance matching device.

1.3 This publication discusses the propagation of electrical energy along a transmission line, with particular reference to incident, reflected and standing waves on lines with different terminations. The characteristics and impedance variations of resonant line sections are also discussed. Impedance calculations are covered in the publication ETP 0389 'The Smith Chart for R.F. Transmission Lines'. Specific applications of these principles are detailed in other publications.

E.T.S. 14/0828

2. PROPAGATION OF ELECTROMAGNETIC FIELDS.

2.1 ELECTROMAGNETIC FIELDS. When a voltage is applied to a transmission line, current flows in the line and an electromagnetic field is set up about the conductors. This field has two components:

- The field associated with the voltage, called the electric or E-field, which tends to exert a force on an electric charge (such as an electron or ion) placed in its vicinity. Electric lines of force are sometimes called E-lines.

- The field associated with current, called the magnetic or H-field, which tends to exert a force on a magnetic pole (such as is associated with a magnet or a wire with current flowing in it) placed in its vicinity. Magnetic lines of force are sometimes called H-lines.

The E-field is at right angles to the H-field and both are at right angles to the line conductors.

For example, Fig. 1a shows a battery connected to a two wire transmission line. Electrons flow in the circuit in the directions shown by the arrows. An E-field is set up along the line due to the p.d. between the conductors and an E-field is established around each conductor due to the electron movement.

Fig. 1b shows an end view of the E-field and H-field about the conductors looking toward the battery end. The arrows indicate the directions of the two fields.

Fig. 1c shows a side view of the fields. It is conventional to represent the E-field by arrows, which point from a more positive to a more negative voltage point. Neglecting line losses, the p.d. (and, therefore, the intensity of the E-field) between the line conductors is the same at all points along the line. This is indicated by drawing the arrows evenly spaced and of equal thickness.

In Fig. 1c, the H-field is shown in cross-section. The symbol:

- • indicates H-lines in the direction out of the paper;
- × indicates H-lines in the direction into the paper.

The direction of these lines can be established by the left-hand rule for electron flow. In the diagram, the symbols are evenly spaced and of the same size to indicate an even distribution of H-field along the length of line.

2.2 WAVE PROPAGATION ALONG A TWO WIRE LINE. When an alternating voltage is applied to a two wire R.F. transmission line, an alternating current flows in each conductor and a varying electromagnetic field is set up about the conductors. The R.F. energy transmitted along the line is not confined to the line conductors but is contained in the electric and magnetic fields surrounding them, the wires merely serving to guide the fields. The electromagnetic field travels along the line in the form of a 'travelling wave' of electrical energy (called an electromagnetic wave) at a velocity of propagation less than the maximum velocity of 300×10^6 metres per second which is the velocity in free space. The actual velocity depends on the characteristics of the particular line.

The left-hand diagrams of Fig. 2 give a physical picture of propagation of electromagnetic fields on a line which is longer than one wavelength at the applied frequency. The right-hand diagrams indicate graphically the variations in intensity of the E-field and H-field (and the voltage and current values) as a function of distance along the line at selected instants of time. For simplicity, sine waves are considered in this and following examples, because complex waveshapes are too complicated for study purposes.

Fig, 2a indicates the condition at the generator end of a two wire line on which travelling waves have been established, at the instant that the R.F. generator is developing its maximum voltage.

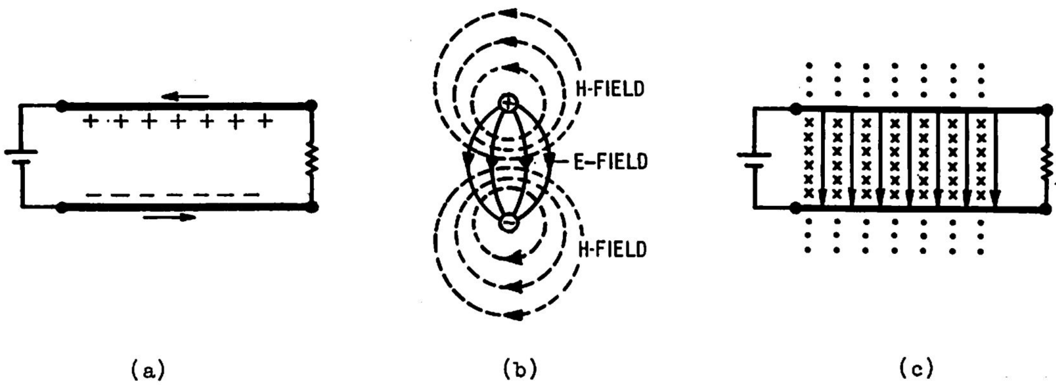


FIG. 1. FIELDS PRODUCED ABOUT LINE CONDUCTORS.

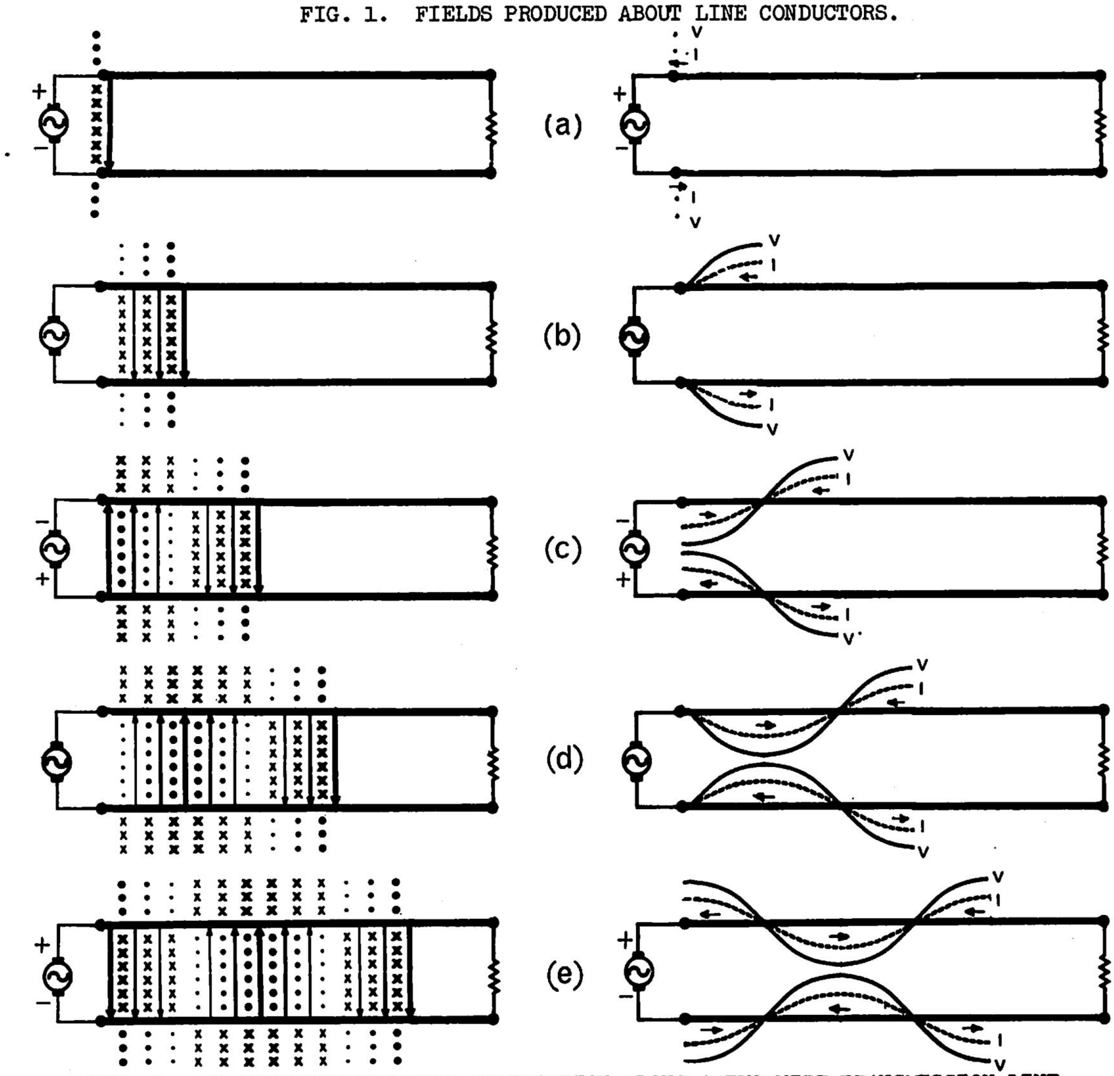


FIG. 2. ELECTROMAGNETIC WAVE PROPAGATION ALONG A TWO WIRE TRANSMISSION LINE.

Under its influence, electrons move in the conductors adjacent to the generator in the directions shown by the arrows. The value of this current is determined by the generator voltage and the input impedance (Zin) of the line.

As the Zin of an infinitely long line or any length of line terminated in its Zo is purely resistive at radio frequencies, the current is in phase with the voltage; and their associated fields are also in phase. At the instant indicated, the current (I) and voltage (V) values are maximum at the input end of the line, and this is indicated graphically in the right-hand diagram. (The ratio V/I is equal to the characteristic or surge impedance of the line).

One-quarter cycle later (Fig. 2b), the generator voltage falls to zero. No p.d. exists between the conductors and no electrons are moving in the line at the input end. During this time, however, the original fields have travelled one-quarter wavelength along the line, at which point the voltage and current values are a maximum. The variation in intensity of the E-field along the line is indicated by the variation in thickness of the arrows. The variation in intensity of the H-field is indicated by the size of the symbols for the H-lines shown in cross-section.

Figs. 2c, 2d and 2e indicate the conditions for successive quarter cycle intervals of time. Note that the fields are in opposite directions in different sections of the line at the same instant. The fields at any point on the line alternately build up to a maximum in one direction, fall to zero, then rise to a maximum in the opposite direction and fall to zero again, with each cycle.

2.3 COAXIAL TRANSMISSION LINE. For simplicity, most of the diagrams in this publication show two wire transmission lines and the voltage and current conditions are shown for one conductor only. (The waves on the other conductor of a two wire line are similar but in opposite phase relationship). The information also applies to coaxial lines. The similarity between a section of two wire line and a coaxial section is seen by rotating one conductor of a two wire line to form a cylinder around the inner conductor (Fig. 3).

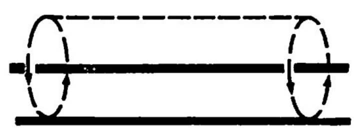


FIG. 3. DEVELOPMENT OF COAXIAL LINE

Fig. 4a shows a battery connected to a coaxial transmission line (shown in cross-section). Electrons flow in the centre conductor and outer sheath in the directions shown by the arrows. An E-field is set up along the line between the centre and the outer conductors due to the p.d. between them. An H-field is set up around the centre conductor due to the electron movement.

Fig. 4b shows an end view of the E-field and H-field looking towards the battery end. The arrows indicate the directions of the two fields which are at right angles to each other and also at right angles to the centre conductor.

Fig. 4c shows a side view of the fields, using the convention stated in para. 2.1. Neglecting line losses, the intensity of the E-field is the same at all points along the line, and the H-field is evenly distributed along the length of line.

The left-hand diagrams in Fig. 5 give a physical picture of the wave propagation of an alternating electromagnetic field along a coaxial line, and the right-hand diagrams indicate graphically the variations in intensity of the E-field and H-field (and the voltage and current values). The comments given in para. 2.2 for a two wire line apply generally to these diagrams.

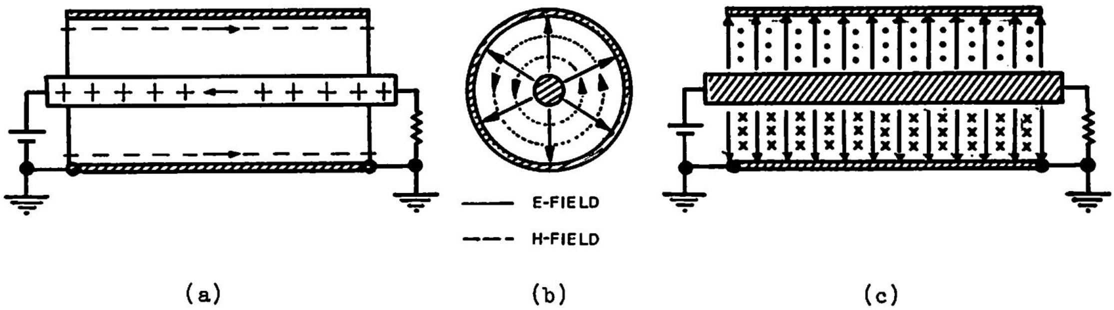


FIG. 4. FIELDS PRODUCED ALONG COAXIAL LINE

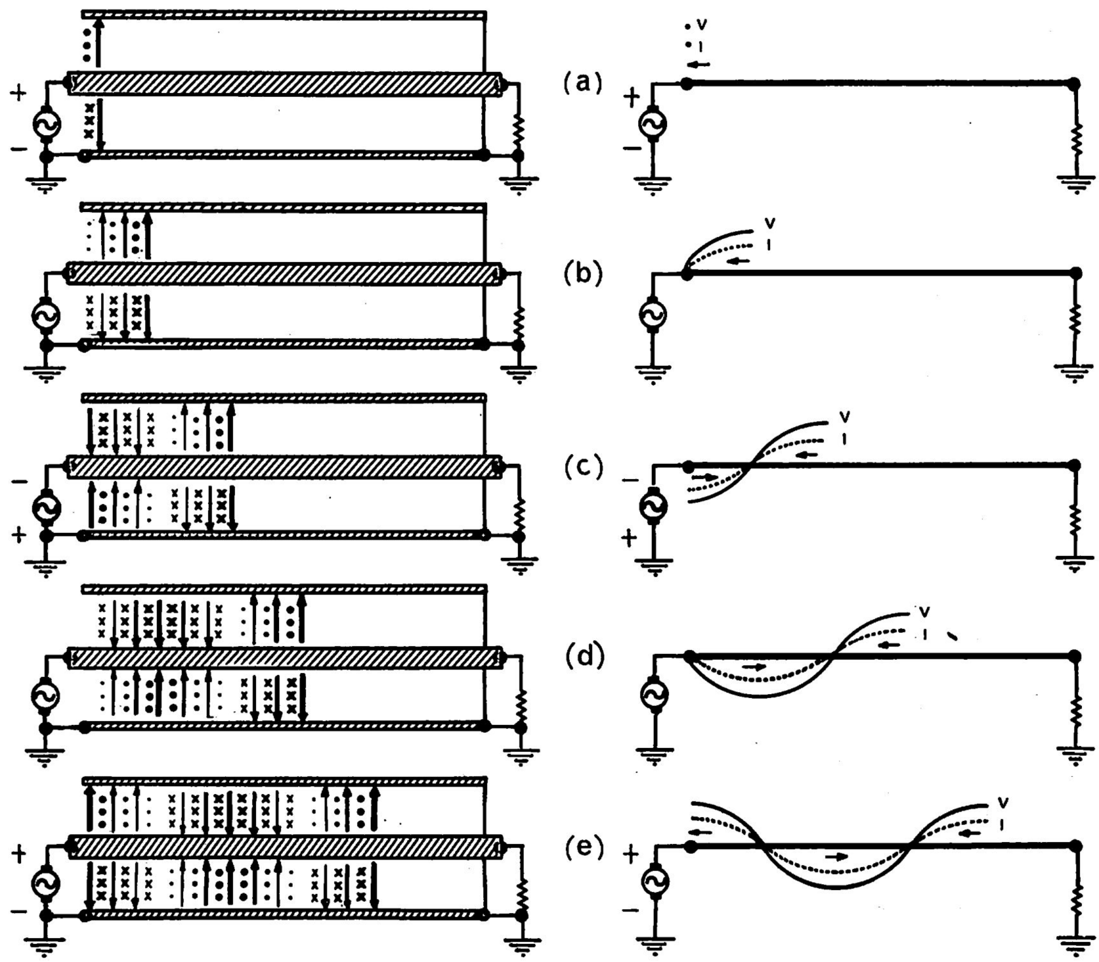


FIG. 5. ELECTROMAGNETIC WAVE PROPAGATION ALONG A COAXIAL TRANSMISSION LINE.

NON-RESONANT TRANSMISSION LINES

3. LINE TERMINATED IN ITS CHARACTERISTIC IMPEDANCE.

3.1 TRAVELLING WAVES. Fig. 6 shows a source of R.F. energy supplying a sine wave voltage to a transmission line, which is terminated in a resistive load (R_T) that matches the Zo of the line. As the successive cycles of alternating voltage are applied to the line, an alternating current flows. The electrons constituting the current do not make a complete journey around the circuit as in the d.c. case, but merely oscillate backwards and forwards about their normal position. Electrical energy is transmitted along the line in a manner similar to that in which sound energy is transmitted through a conducting medium.

The travelling waves of voltage and current, with their associated fields, progressively move down the line from the source to the load, and the transmitted energy (except for line losses) is completely absorbed by the load).

Figs. 6a to 6i show the travelling waves of voltage and current on a transmission line $2\frac{1}{4}\lambda$ long for successive $\frac{1}{8}\lambda$ or 45° intervals of time.

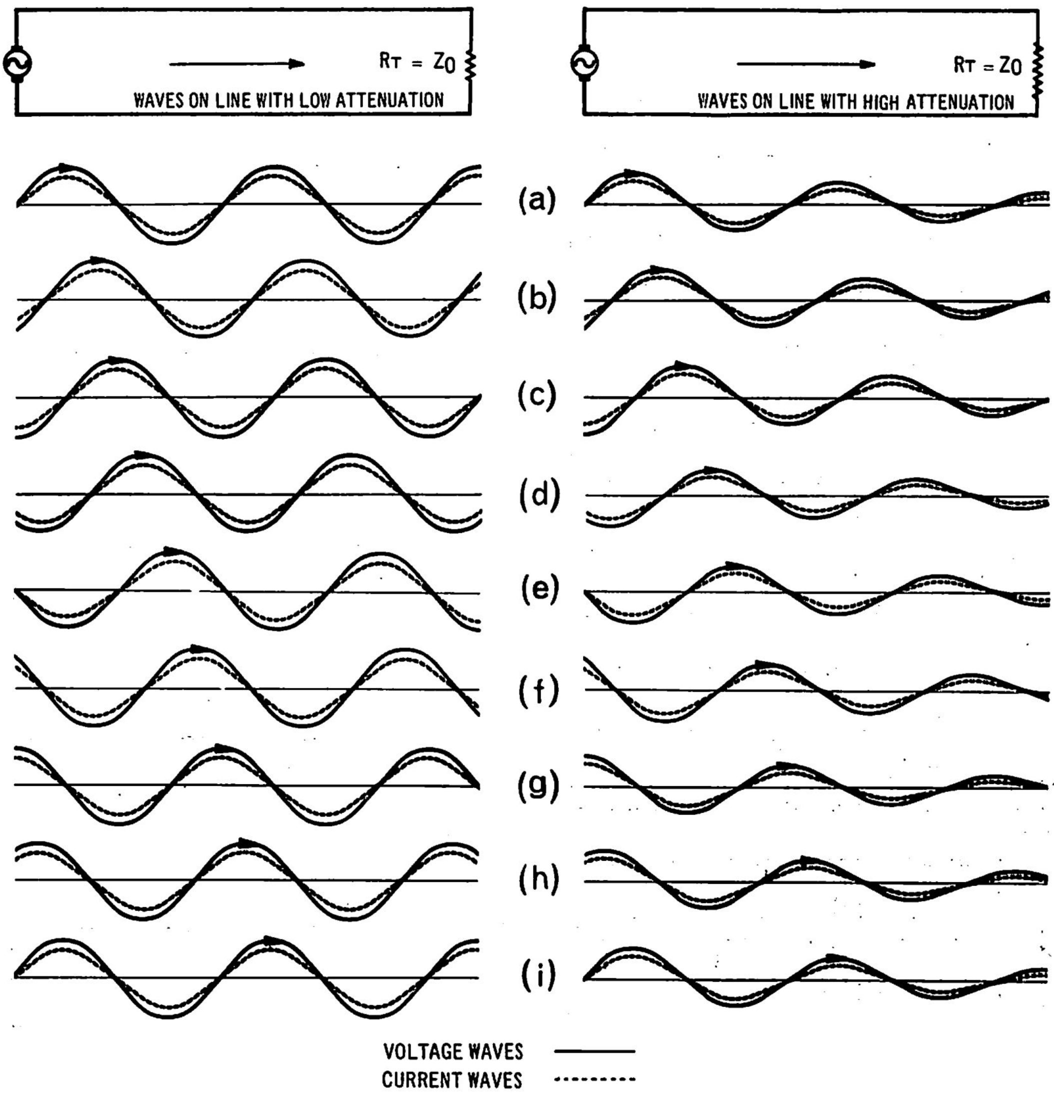
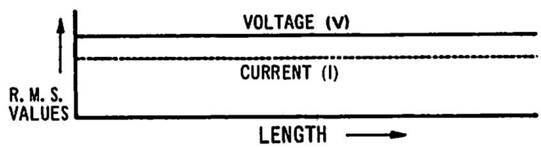


FIG. 6. TRAVELLING WAVES ON LINES TERMINATED IN THEIR Zo.

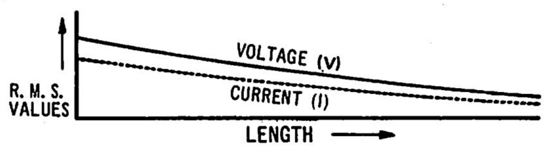
The left-hand diagrams apply to a line with very low attenuation in which the amplitudes of the waves do not decrease to any noticeable degree, as they travel along the line. The right-hand diagrams show the progressive reduction in amplitude of the waves on a line with high attenuation. In each case, the Zin of the line is purely resistive and equal to its Zo. The waves of voltage and current are in phase at any point along the line.

3.2 R.M.S. VALUES OF TRAVELLING WAVES. As the waves travel along a line, the instantaneous values of voltage and current at any point vary from zero to maximum and back to zero in alternate directions. The r.m.s. value of voltage can be observed by connecting an alternating voltmeter across the line at any point. Similarly, the r.m.s. value of current can be observed by connecting an a.c. ammeter in series with the line at any point.

Fig. 7 shows graphs of the r.m.s. values of voltage and current waves plotted at all points along the line. On lines with negligible attenuation, the r.m.s. values of voltage or current are the same at all points (Fig. 7a). On other lines, the values progressively decrease due to attenuation (Fig. 7b).



(a) With very low attenuation.



(b) With high attenuation.

FIG. 7. VOLTAGE AND CURRENT VALUES ON A LINE TERMINATED IN ITS Zo.

3.3 IMPEDANCE AT A POINT ALONG A LINE. In the case of an infinitely long line or any length of line terminated in its Zo, the ratio of the R.F. voltage to the current measured at any point is constant and independent of the attenuation of the line. This ratio determines the value of impedance which would be measured if the line were cut at that point and a measurement made between the two conductors looking towards the output end. At radio frequencies, the value of this impedance remains constant at all points along the line and is purely resistive (V and I are in phase), being equal to the Zo ($= \sqrt{L/C}$) of the line. (Fig. 8).

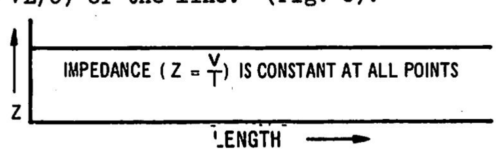


FIG. 8. IMPEDANCE OF LINE TERMINATED IN ITS Zo IS CONSTANT AT ALL POINTS.

3.4 SUMMARY. When an R.F. signal is applied to a transmission line terminated in its Zo:

- Waves of voltage and current, which are in phase, travel along the line in the form of an electromagnetic wave.
- The ratio of the r.m.s. values of voltage and current is constant at all points along the line, and is equal to the Zo of the line.
- All the energy arriving at the receiving end is absorbed by the load and none is reflected.

4. OPEN CIRCUITED LINES.

4.1 REFLECTION. When energy is transmitted in the form of waves through a medium, a reflection of energy occurs when any form of discontinuity is encountered in the medium. For example, ripples on a pool of water are reflected when they strike the bank. When reflection occurs, the part of the wave travelling towards the reflection point is called the 'Incident Wave' and the part of the wave travelling away (reflected) from the reflection point is called the 'Reflected Wave'. In the transmission of electrical energy, reflection is caused by discontinuities such as open circuits, short circuits and impedance mismatches in the transmission path.

4.2 REFLECTION CAUSED BY OPEN CIRCUIT. When a sine wave voltage is applied to an open circuited transmission line which has negligible attenuation, incident waves of voltage and current, which are in phase, travel along the line from the generator to the open end. Since no energy is absorbed by an open circuit, all the energy arriving at the open circuit is reflected back towards the generator. At the instant the energy arrives at the open circuit, the reflected voltage has the same amplitude as, and is in phase with the incident voltage. Also, at this instant, the reflected current has the same amplitude as, but is in reverse phase to the incident current.

The phase relationships between the reflected and incident waves at the open circuited end, may be remembered from the following:

- No current flows through an open circuit, therefore the incident and reflected current waves must be out of phase in order to cancel.
- Maximum voltage is developed across an open circuit, therefore both voltage waves must be in phase.

4.3 GRAPHS OF INCIDENT AND REFLECTED WAVES. The form of reflection which occurs on an open circuited transmission line can best be considered by examining the graphs of Fig. 9, which show progressively the reflection occurring after an incident wave of voltage and current arrives at the open end of the line. The left hand diagrams show the voltage waves and the right hand diagrams show the current waves. For simplicity, the conditions are shown on a single conductor transmission line only. However, it should be remembered that these waves exist simultaneously on both conductors of a two wire transmission line. The waves on the other conductor of a two wire line are similar but opposite in phase relationship.

Fig. 9a shows the incident and reflected waves at the instant the incident wave reaches the open end of the line. The voltage wave is at its maximum value and is commencing to be reflected in phase. The current wave is also at its maximum value but is commencing to be reflected with a reversal in phase.

In Fig. 9b, the incident waves have travelled 45° in time, and the reflected waves have also travelled 45° in time, but back towards the source.

Fig. 9c shows the condition a further 45° later in time. This process continues until the reflected waves reach the generator end as shown in Fig. 9d. Assuming that the source impedance equals the Zo of the line, all the reflected energy is dissipated in the source impedance. When these impedances are not matched, some reflected energy is returned back to the open circuited end, producing repeated reflections on the line.

Fig. 9e to 9j show the instantaneous conditions for successive $\frac{1}{8}\lambda$ or 45° intervals of time.

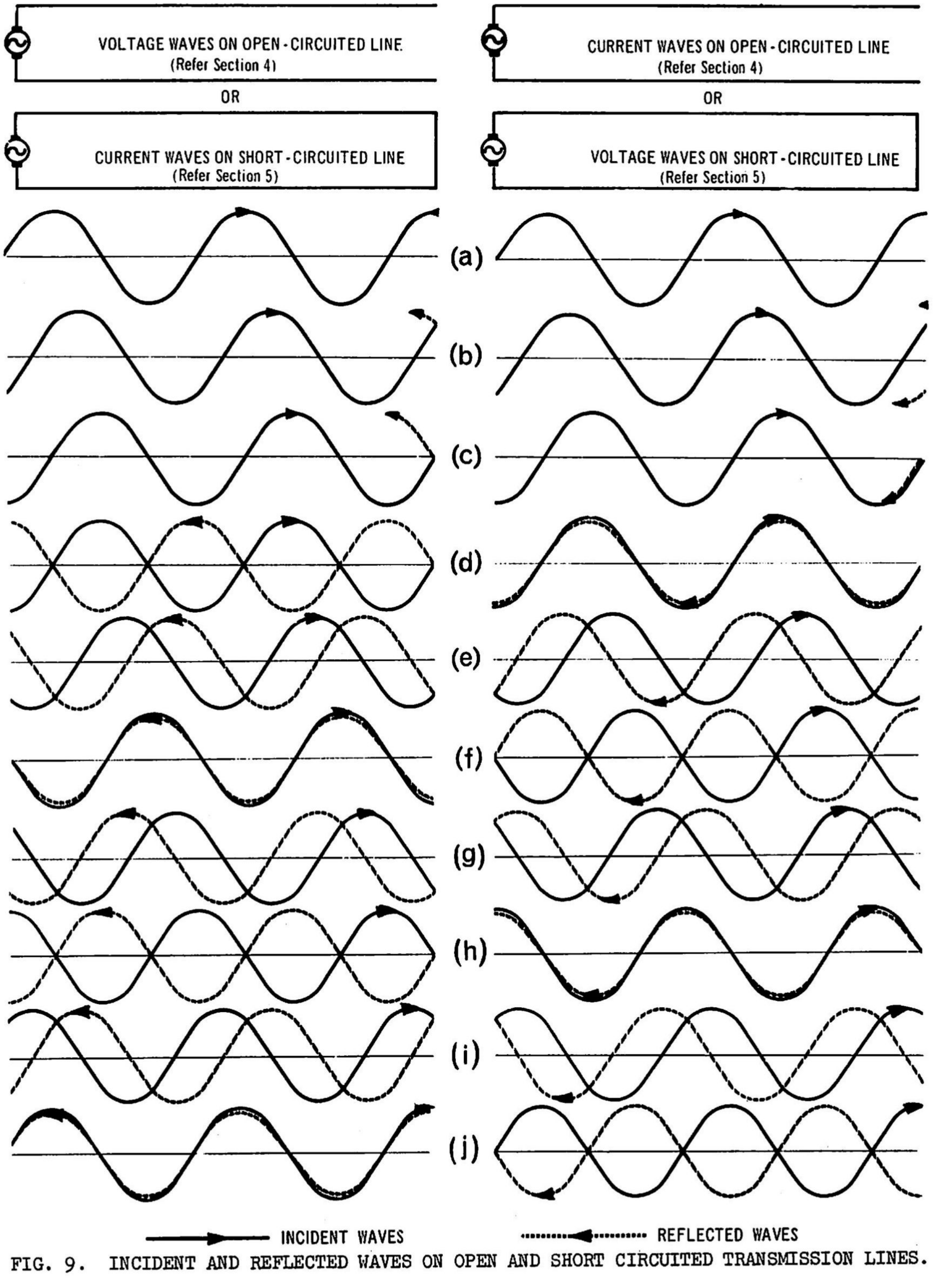


FIG. 9. INCIDENT AND REFLECTED WAVES ON OPEN AND SHORT CIRCUITED TRANSMISSION LINES.

4.4 SUMMARY. On an open circuited transmission line:

- None of the energy arriving at the end of the line is absorbed, and all of this energy is reflected. This sets up reflected waves of voltage and current which travel back along the line in the opposite direction to the incident waves.
- The waves are reflected without change in amplitude or shape from the open end. The voltage wave commences to be reflected in phase and the current wave in opposite phase from the open end.
- Assuming negligible attenuation, the incident and reflected waves have the same amplitude along the line.

4.5 STANDING WAVES. When reflection occurs on a transmission line, the resultant voltage (or current) waveform produced on the line at any instant is the sum of the incident and reflected waves at that instant. A study of the resultant voltage and current waves over a period of time indicates that they rise from zero to a maximum, fall to zero again, and reverse about the same points. The points of zero and maximum displacements are always the same. Fig. 10 shows this condition in more detail.

Fig. 10a (left hand side) shows the incident and reflected voltage waves at one instant on an open circuited line $2\frac{1}{4}\lambda$ long at the applied frequency. The resultant voltage wave at this instant is indicated in red. It is at its maximum instantaneous value.

Fig. 10a (right hand side) shows the incident and reflected current waves on this line at the same instant. These waves cancel at all points on the line and the current wave is at its minimum or zero instantaneous value.

Fig. 10b shows the condition 45° later in time when the incident waves have moved $\frac{1}{8}\lambda$ down the line towards the short circuit, and the reflected waves $\frac{1}{8}\lambda$ back along the line towards the generator. At this instant the resultant voltage wave is collapsing, but the resultant current wave is building up.

Figs. 10c to 10i show the wave conditions for successive $\frac{1}{8}\lambda$ or 45° intervals of time.

Fig. 10j shows a composite picture of the resultant waveforms over a period of one cycle. Note that, at certain points on the line (for example, at the open circuited end, and at points $\frac{1}{2}\lambda$, 1λ, $1\frac{1}{2}\lambda$, etc. back from the open end), the resultant voltage varies between zero and maximum in both directions. At other points $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, $1\frac{1}{4}\lambda$, etc., back from the open end, the resultant voltage is always zero.

Conversely, the resultant current is always zero at the open circuited end and at points $\frac{1}{2}\lambda$, 1λ, $1\frac{1}{2}\lambda$, etc., back from the open end. It varies between zero and maximum in both directions at points $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, $1\frac{1}{4}\lambda$, etc., back from the open end.

Thus, the resultant voltage and current waves produced on a line when reflection occurs, appear to be stationary and not travelling; and are referred to as 'Standing Waves' of voltage and current respectively.

We can measure the r.m.s. (or average or peak) values of the voltage standing wave by connecting an alternating voltmeter between the line conductors at various points. Similarly, the current standing wave values can be measured by connecting an a.c. ammeter in series with the line at various points. Fig. 10k shows the variations due to the voltage and current standing waves, that would be observed as the test equipment is moved from one end of the line to the other. Note the cyclic variation of the voltage and current readings when standing waves exist.

The minimum points of a standing wave are called nodes; and the maximum points are called anti-nodes.

WAVE PROPAGATION ON R.F. TRANSMISSION LINES

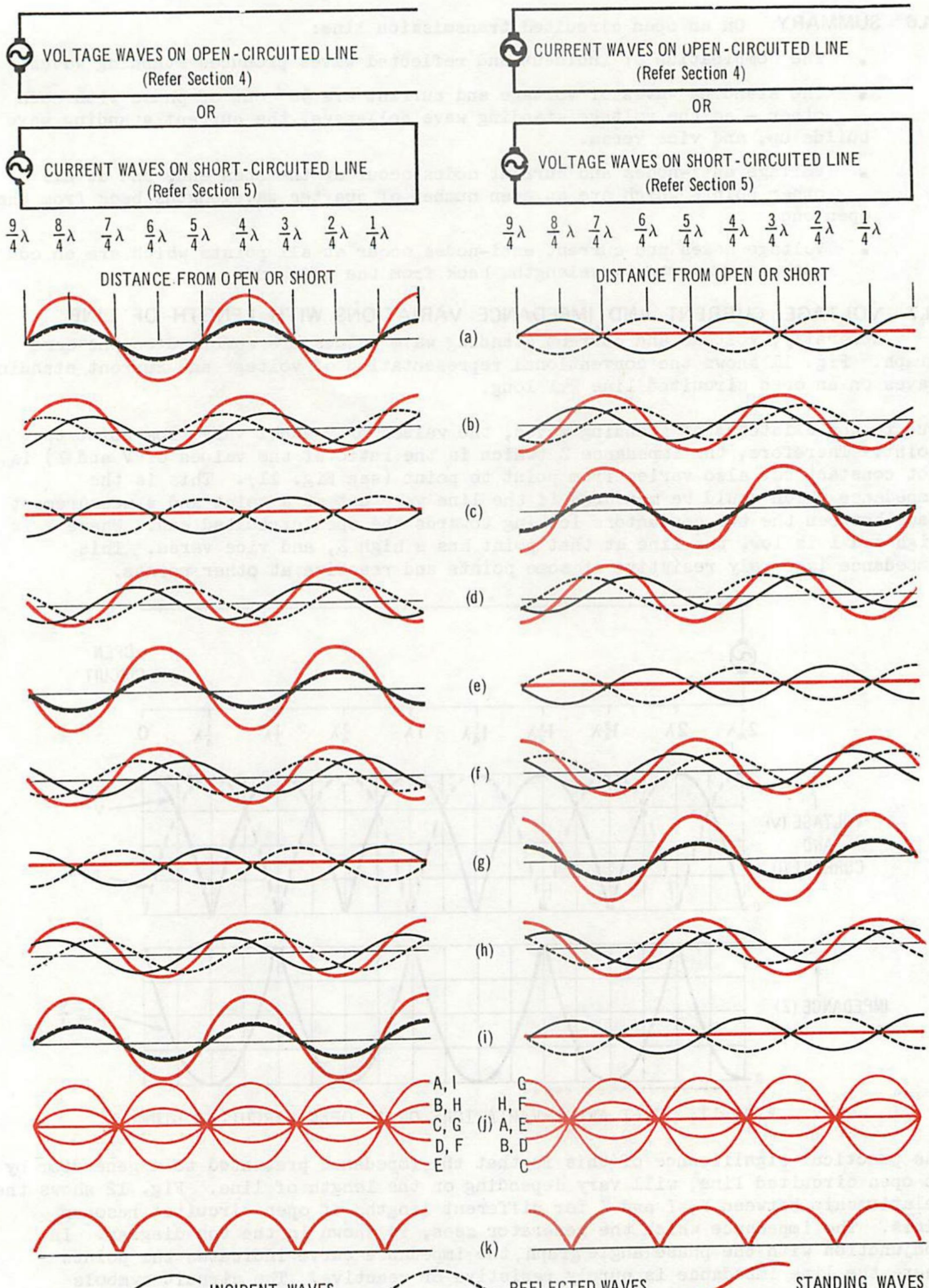


FIG. 10. STANDING WAVES ON OPEN AND SHORT CIRCUITED TRANSMISSION LINES.

4.6 SUMMARY. On an open circuited transmission line:

- The combination of incident and reflected waves produces standing waves.
- The standing waves of voltage and current are 90° out of phase with each other - as the voltage standing wave collapses, the current standing wave builds up, and vice versa.
- Voltage anti-nodes and current nodes occur at the open end, and at all other points which are an even number of quarter wavelengths back from the open end.
- Voltage nodes and current anti-nodes occur at all points which are an odd number of quarter wavelengths back from the open end.

4.7 VOLTAGE, CURRENT AND IMPEDANCE VARIATIONS WITH LENGTH OF LINE. Generally, voltage and current standing wave values are combined on the same graph. Fig. 11 shows the conventional representation of voltage and current standing waves on an open circuited line $2\frac{1}{4}\lambda$ long.

Due to the existence of standing waves, the values of V and I vary from point to point. Therefore, the impedance Z (which is the ratio of the values of V and I) is not constant but also varies from point to point (see Fig. 11). This is the impedance which would be measured if the line were cut at a point and a measurement made between the two conductors looking towards the open circuited end. Where V is high and I is low, the line at that point has a high Z, and vice versa. This impedance is purely resistive at some points and reactive at other points.

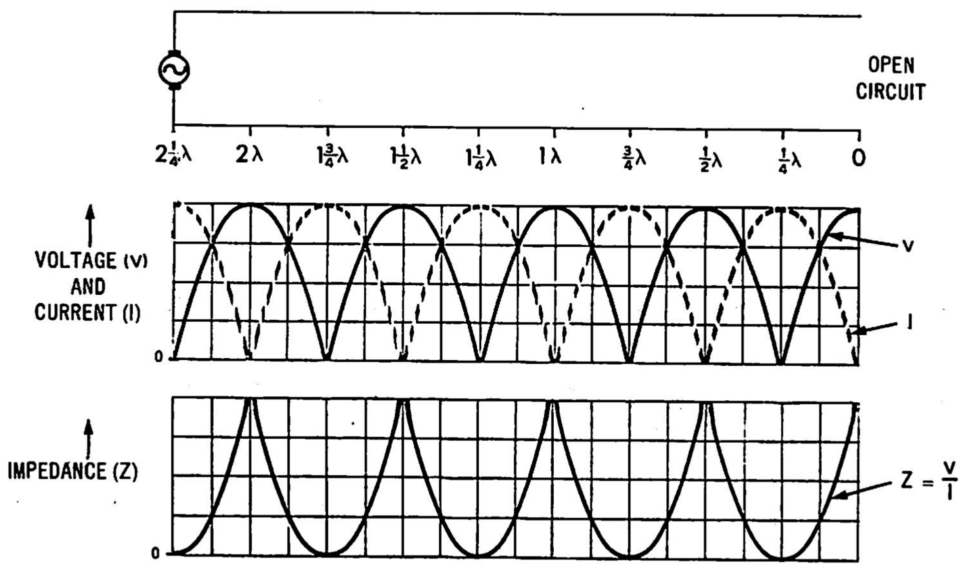


FIG. 11. V, I AND Z VARIATIONS ON AN OPEN CIRCUITED LINE.

The practical significance of this is that the impedance presented to a generator by an open circuited line, will vary depending on the length of line. Fig. 12 shows the relationship between V, I and Z for different lengths of open circuited resonant lines. The impedance which the generator sees, is shown in the top diagram. In conjunction with the phase angle graph, the impedance curve indicates the points where the line impedance is purely resistive or reactive. The circuit symbols indicate the equivalent electrical circuits for different lengths of line.

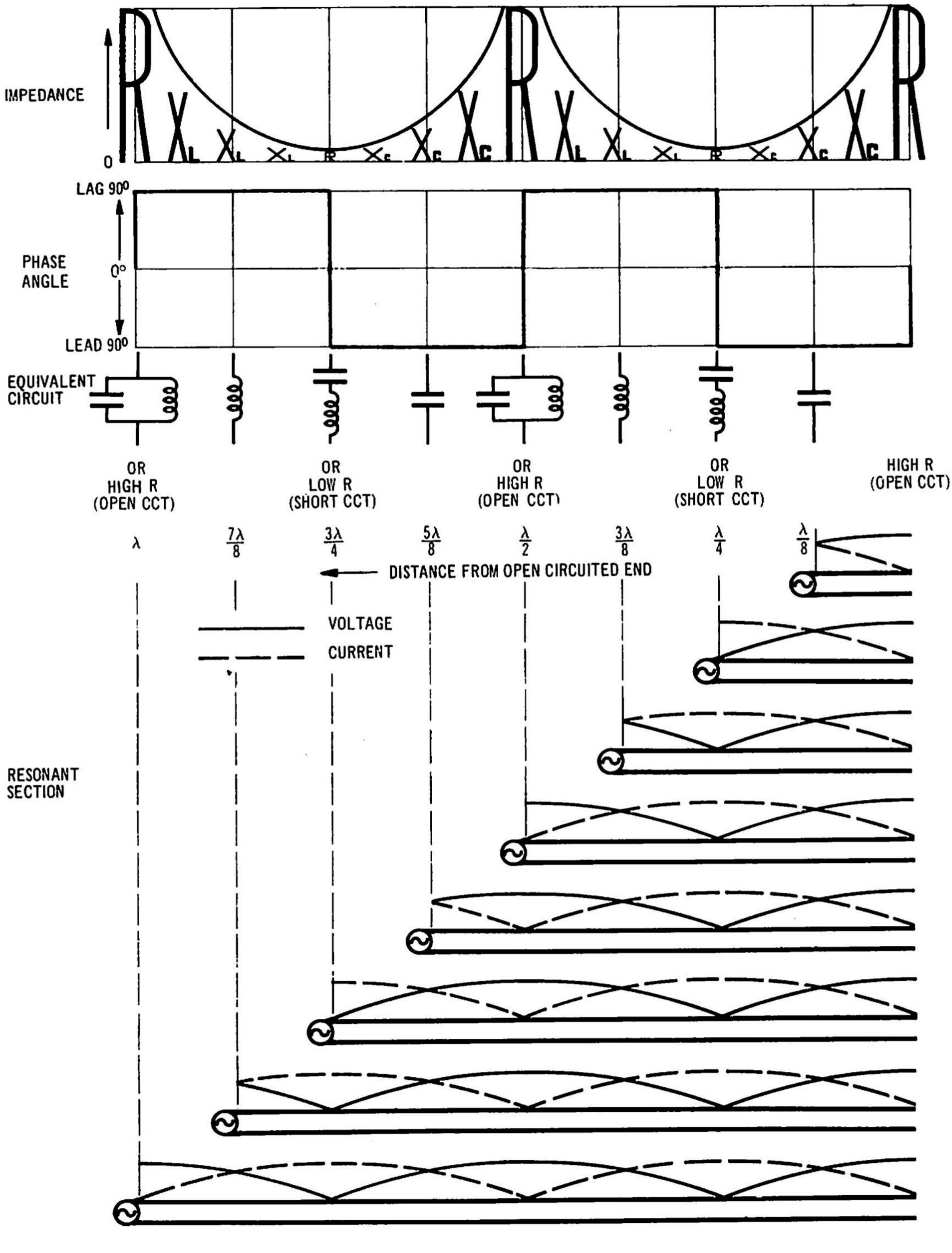


FIG. 12. CHARACTERISTICS OF OPEN CIRCUITED LINES.

At all odd quarter wave points ($\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, etc.) measured from the output (open circuited) end of the line, V is minimum, I is maximum and Z is equivalent to a very low resistance, prevented only by small circuit losses from being zero. A generator connected to an open circuited resonant line section an odd number of quarter wavelengths long sees very low impedance, or, in effect, the generator sees a short circuit. These lines can be considered as exhibiting the characteristics of a conventional series resonant circuit.

At all even quarter wave points ($\frac{1}{2}\lambda$, 1λ, etc.), V is maximum, I is minimum and Z is equivalent to a very high resistance. A generator connected to a line an even number of quarter wavelengths long sees, in effect, an open circuit. These lines can be considered as exhibiting the characteristics of a parallel resonant circuit.

Resonant open lines may also be used to act as nearly pure capacitances or inductances. An open line acts:

- as a capacitance when less than $\frac{1}{4}\lambda$;
- as an inductance between $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$;
- as a capacitance between $\frac{1}{2}\lambda$ and $\frac{3}{4}\lambda$;
- as an inductance between $\frac{3}{4}\lambda$ and 1λ; and so on.

5. SHORT CIRCUITED LINES.

5.1 REFLECTION CAUSED BY SHORT CIRCUIT. When an R.F. generator is connected to a short circuited transmission line which has negligible attenuation, in-phase incident waves of voltage and current travel along the line from the generator to the short circuited end. Since no energy is absorbed by a short circuit, all the energy arriving at the short circuit is reflected back towards the generator. At the instant the energy arrives at the short circuit, the reflected current has the same amplitude as, and is in phase with the incident current. Also, at this instant, the reflected voltage has the same amplitude as, but is in reverse phase to the incident voltage.

The phase relationships between the reflected and incident waves at the short circuited end, may be remembered from the following:

- No voltage exists across a short circuit, therefore the incident and reflected voltage waves must be out of phase in order to cancel.
- Maximum current flows through a short circuit, therefore both current waves must be in phase.

5.2 GRAPHS OF INCIDENT AND REFLECTED WAVES. The graphs in Fig. 9 (on page 9) show the incident and reflected waves on a short circuited transmission line with negligible attenuation. In this case, the left hand graphs show the current waves and the right hand graphs show the voltage waves.

5.3 STANDING WAVES. As in the case of the open circuited line, the reflected voltage and current waves occurring on a short circuited line also produce standing waves. These waves are shown on the graphs in Fig. 10 (on page 11). For a short circuited line, the left hand graphs show the current waves and the right hand graphs show the voltage waves.

5.4 SUMMARY. On a short circuited transmission line:

- All the energy arriving at the end of the line is reflected. The waves are reflected without change in amplitude or shape. The current wave commences to be reflected in phase and the voltage wave in opposite phase from the short circuited end.

- The combination of the incident and reflected waves produces standing waves. The standing waves of voltage and current are 90° out of phase with each other.

- Voltage nodes and current anti-nodes occur at the short circuited end and at points an even number of quarter wavelengths back from the short circuit. Voltage anti-nodes and current nodes occur at points an odd number of quarter wavelengths back from the short circuit.

5.5 VOLTAGE, CURRENT AND IMPEDANCE VARIATIONS WITH LENGTH OF LINE. Fig. 13 shows the conventional representation of V and I and resultant impedance variations on a short circuited line $2\frac{1}{4}\lambda$ long at the applied frequency. Note that the distribution of V and I is opposite to that for the open circuited line.

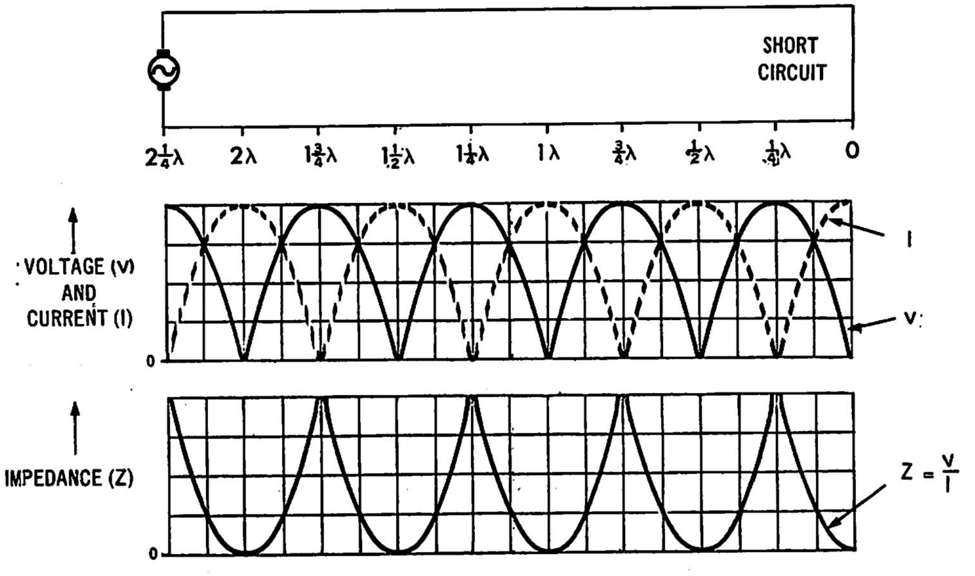


FIG. 13. V, I AND Z VARIATIONS ON A SHORT CIRCUITED LINE.

5.6 The characteristics of short circuited resonant line sections are shown in Fig. 14, and compared with open circuited lines in Section 6.

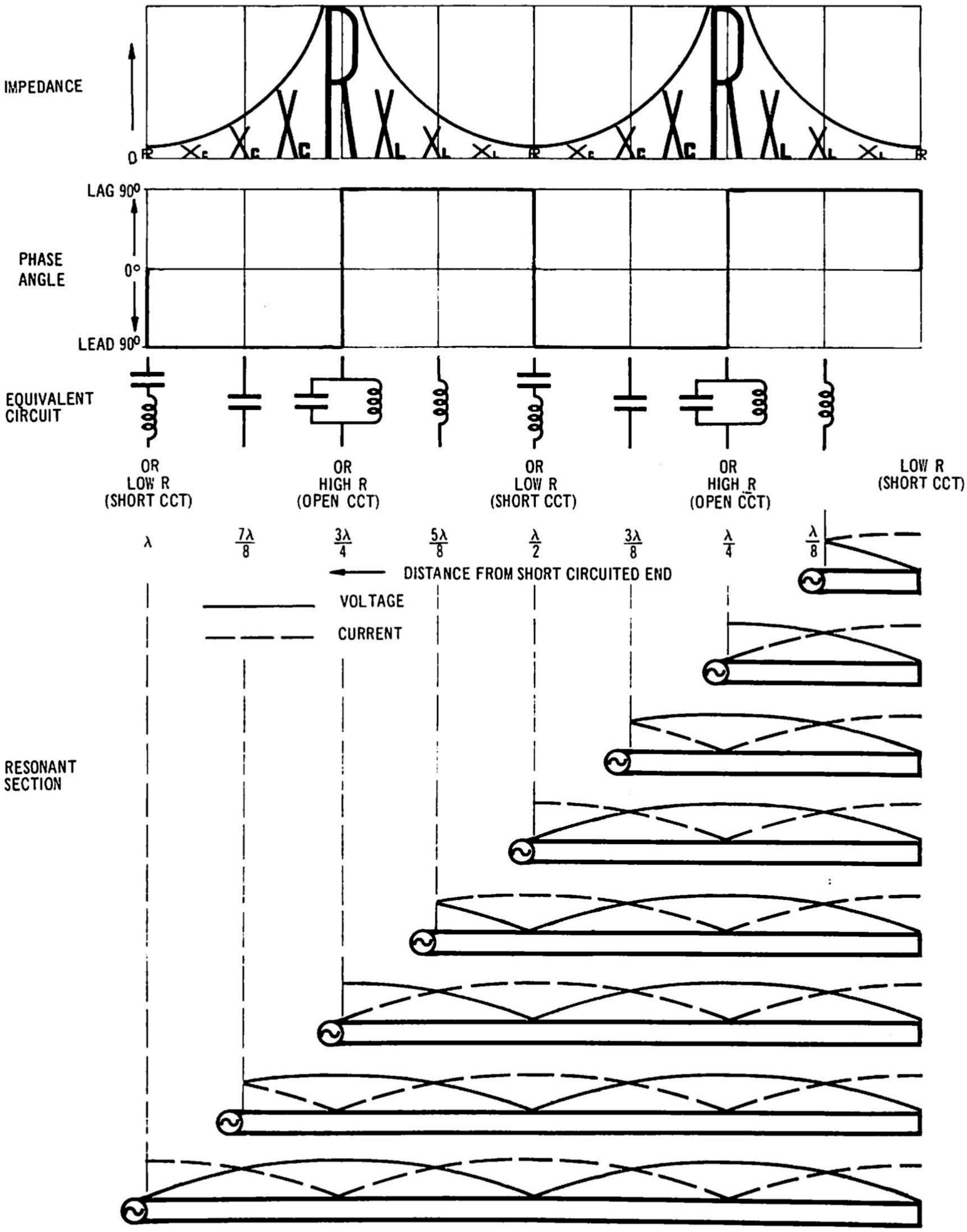


FIG. 14. CHARACTERISTICS OF SHORT CIRCUITED LINES.

6. SUMMARY OF OPEN AND SHORT CIRCUITED LINES.

6.1 GENERAL. In practice, electrically short sections of open or short circuited R.F. transmission lines are used, particularly in the H.F., V.H.F. and U.H.F. ranges, to exhibit the characteristics of a resonant circuit or a reactance. For this application, the line is designed to have negligible attenuation. The following paragraphs summarise the behaviour of these lines.

6.2 INCIDENT AND REFLECTED WAVES.

- Incident waves of voltage and current which are in phase, travel along the line towards the open or short circuited end.

- All the incident energy is reflected from the end of the line, and reflected waves of voltage and current travel back along the line in the opposite direction to the incident waves.

- Assuming negligible attenuation, the incident and reflected waves of voltage (or current) have the same amplitude along the line.

- The waves are reflected from the open or short circuited end without change in amplitude or shape.

- In the open circuited line, the voltage wave commences to be reflected in phase and the current wave in opposite phase from the open end. In the short circuited line, the voltage wave is reflected in opposite phase and the current wave in phase from the short circuited end.

6.3 STANDING WAVES.

- The combination of incident and reflected waves produces standing waves.

- The standing waves of voltage and current are 90° out of phase with each other. As the voltage standing wave collapses, the current standing wave builds up, and vice versa.

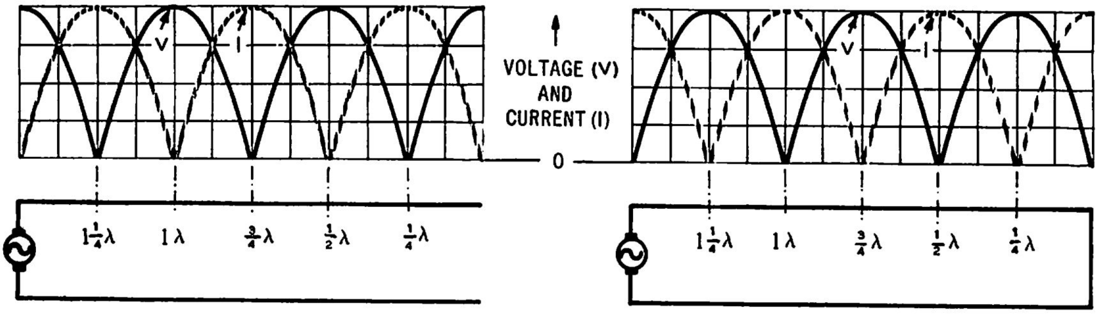
- Assuming the source impedance matches the Zo of the line, the standing wave values of voltage (and current) vary between a maximum equal to twice the incident values and practically zero.

- The maximum values are called anti-nodes, and the minimum values are called nodes.

- Voltage (or current) anti-nodes are spaced $\frac{1}{2}\lambda$ apart, and occur between the voltage (or current) nodes which are also $\frac{1}{2}\lambda$ apart.

- In the open circuited line (Fig. 15a), voltage anti-nodes and current nodes occur at the open end and at points an even number of quarter wavelengths back from the open circuit. Voltage nodes and current anti-nodes occur at points an odd number of quarter wavelengths back from the open circuit.

- In the short circuited line (Fig. 15b), voltage nodes and current anti-nodes occur at the shorted end and at points an even number of quarter wavelengths back from the short circuit. Voltage anti-nodes and current nodes occur at points an odd number of quarter wavelengths back from the short circuit.



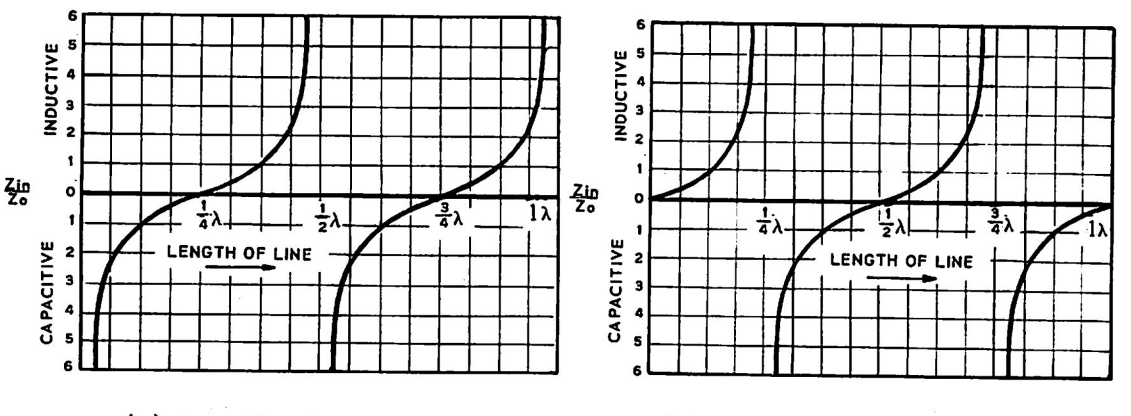
(a) Open Circuited Line.

(b) Short Circuited Line.

FIG. 15. VOLTAGE AND CURRENT STANDING WAVES.

6.4 IMPEDANCE VARIATIONS. The input impedance (Zin) of a line depends on the ratio of the standing wave values of V and I at the input end. It varies between the extremes of a very low and a very high value, and may be purely resistive or reactive.

Depending on its electrical length, an open or short circuited line may behave as a parallel resonant, series resonant, inductive or capacitive circuit. Fig. 16 shows the variation of input impedance for open and short circuited lines with electrical lengths up to 1λ. These graphs are repeated for lines longer than 1λ. The graphs have the vertical ordinates expressed numerically in terms of the ratio of Zin and Zo for the particular line. Thus, for lines $\frac{1}{8}\lambda$, $\frac{3}{8}\lambda$, $\frac{5}{8}\lambda$, $\frac{7}{8}\lambda$, etc., this ratio is 1 and the reactive value in ohms of Zin equals the resistive value in ohms of Zo.



(a) Open Circuited Line.

(b) Short Circuited Line.

FIG. 16. INPUT IMPEDANCE VARIATIONS VERSUS LENGTH OF LINE.

Table 1 summarises the input impedance variations for different lengths of lines. These characteristics repeat when multiples of $\frac{1}{2}\lambda$ are added.

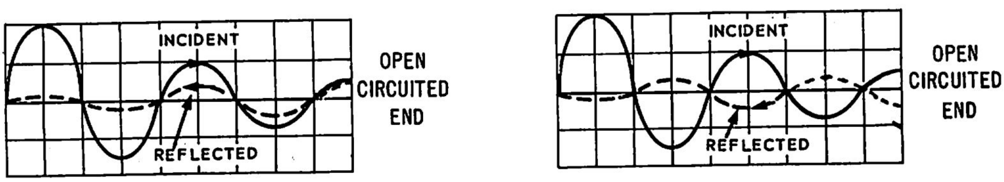
Length of Line	Zin of Open Circuited Line	Zin of Short Circuited Line
Less than $\frac{1}{8}\lambda$ $\frac{1}{8}\lambda$ $\frac{1}{8}\lambda - \frac{1}{4}\lambda$	Capacitance Capacitance Capacitance	Inductance Inductance Inductance
$\frac{1}{4}\lambda$	Resistive - looks like a series resonant, a low resistance or a short circuit.	Resistive - looks like a parallel resonant, a high resistance or an open circuit.
$\frac{1}{4}\lambda - \frac{3}{8}\lambda$ $\frac{3}{8}\lambda$ $\frac{3}{8}\lambda - \frac{1}{2}\lambda$	Inductance Inductance Inductance	Capacitance Capacitance Capacitance
$\frac{1}{2}\lambda$	Resistive - looks like a parallel resonant, a high resistance or an open circuit.	Resistive - looks like a series resonant, a low resistance or a short circuit.

TABLE 1. SUMMARY OF INPUT IMPEDANCE VARIATIONS.

7. EFFECT OF LINE ATTENUATION ON STANDING WAVES.

7.1 Another application of an open or short circuited transmission line is to provide a termination designed to dissipate high power, for example, the open wire termination for a rhombic transmitting aerial. In practice, a short circuited line which is a number of wavelengths long, is generally used. It is constructed of G.I. wire to provide high attenuation.

7.2 **OPEN CIRCUITED LINE.** Fig. 17 shows the incident and reflected waves at one instant on an open circuited line $2\frac{1}{4}\lambda$ long, which has high attenuation.



(a) Voltage Waves. (b) Current Waves.

FIG. 17. INCIDENT AND REFLECTED WAVES ON AN OPEN CIRCUITED LINE WITH HIGH ATTENUATION.

The incident wave of voltage (or current) is attenuated as it travels down the line. The reflected wave has the same amplitude as the incident wave at the open circuited end and is similarly attenuated as it travels back along the line to the sending end. Note that the voltage wave is reflected in phase and the current wave in opposite phase from the open circuit. When the attenuation of the line is sufficiently high, the amplitude of the reflected wave which arrives at the sending end, is negligible.

The standing wave pattern on this type of line can be analysed in the same manner as described in Section 4 for open circuited lines. Fig. 18 shows the standing wave pattern and resultant impedance variations. (Compare these graphs with those shown in Fig. 11 on page 12, for an open circuited line with negligible attenuation).

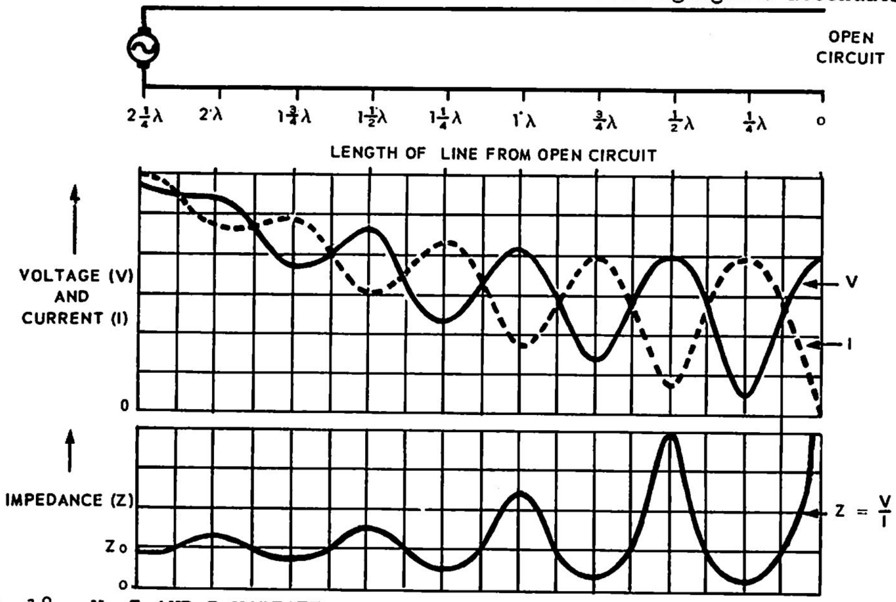
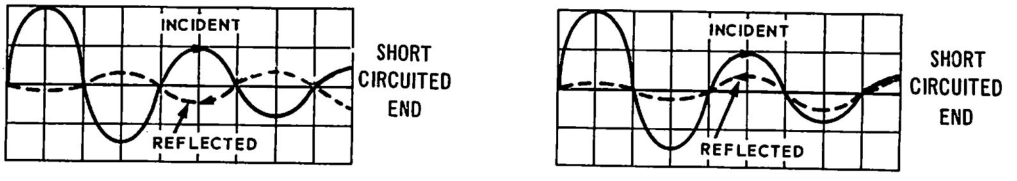


FIG. 18. V, I AND Z VARIATIONS ON AN OPEN CIRCUITED LINE WITH HIGH ATTENUATION.

Towards the open circuited end, the values of the incident and reflected waves are similar, and the standing wave effect and impedance variations are most pronounced.

Voltage anti-nodes and current nodes occur at the open end and at points an even number of quarter wavelengths back from the open circuit. Voltage nodes and current anti-nodes occur at points an odd number of quarter wavelengths back from the open circuit. Towards the input end, the value of the reflected wave is very small due to the high attenuation of the line; and so the standing wave effect is negligible. The Zin is approximately equal to the Zo of the line.

7.3 SHORT CIRCUITED LINE. Fig. 19 shows the incident and reflected waves at one instant on a short circuited line $2\frac{1}{4}\lambda$ long, which has high attenuation.



(a) Voltage Waves. (b) Current Waves.

FIG. 19. INCIDENT AND REFLECTED WAVES ON A SHORT CIRCUITED LINE WITH HIGH ATTENUATION.

Both incident and reflected waves of voltage and current are attenuated as they travel along the line. Note that the voltage wave is reflected in opposite phase and the current wave in phase from the short circuit. Due to the high line attenuation, the amplitude of the reflected wave is negligible at the sending end.

Fig. 20 shows the standing wave pattern and resultant impedance variations on this type of line. (Compare these graphs with those shown in Fig. 13 on page 15, for a short circuited line with negligible attenuation).

The standing wave effect and impedance variations are most pronounced towards the short circuited end. Voltage nodes and current anti-nodes occur at the shorted end and at points an even number of quarter wavelengths back from the short circuit. Voltage anti-nodes and current nodes occur at points an odd number of quarter wavelengths back from the short circuit. The standing wave effect is negligible towards the input end, and the Zin is approximately equal to the Zo of the line.

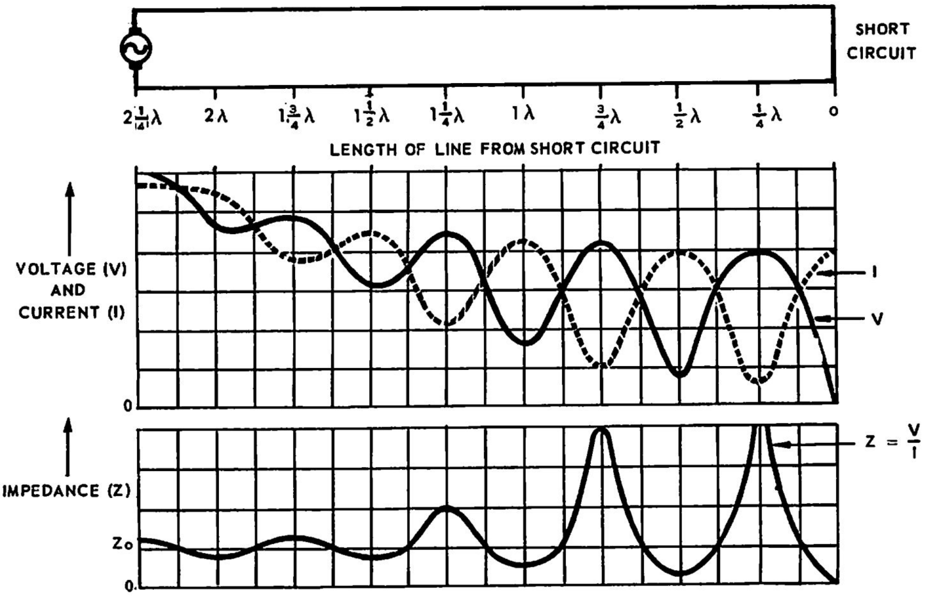


FIG. 20. V, I AND Z VARIATIONS ON A SHORT CIRCUITED LINE WITH HIGH ATTENUATION.

8. LINES TERMINATED IN RESISTIVE OR REACTIVE LOADS.

8.1 A large variety of terminations may be used for R.F. lines. Each type of termination has a particular effect on the standing wave pattern on the line. From the nature of the standing wave pattern, we can determine the type of termination which produces the waves. This section summarises the effects of different line terminations.

8.2 **INFINITELY LONG LINE.** In the theoretical case of an R.F. generator connected to an infinitely long transmission line, no standing waves are produced, because the signal never reaches the end of the line and, therefore, cannot be reflected. The values of the incident waves of voltage and current measured at points along the line gradually decrease due to line attenuation. The ratio of voltage to current, however, remains constant; and is equal to the Zo of the line.

8.3 **LINE TERMINATED IN ITS Zo.** When a line of any finite length is terminated in a resistive load that matches the Zo of the line, the incident signal is completely absorbed by the load. As in the case of an infinitely long line, no reflections or standing waves are produced. The values of the incident waves gradually decrease due to line attenuation as they move down the line; but on relatively short lines, the attenuation is usually small enough to be disregarded. The ratio of voltage to current at the input end, (that is, the input impedance) is constant and equal to the Zo of the line, irrespective of the length of line.

When measurements show that there are no standing waves on a line, we can conclude that the line is correctly terminated in its Zo and that all the incident energy is absorbed by the load.

8.4 LINES TERMINATED IN OPEN CIRCUIT OR SHORT CIRCUIT. For these terminations, all the incident energy arriving at the end of the line is reflected and standing waves are set up as described in Sections 4 and 5.

For lines with very low attenuation, the standing wave values vary between maximum and practically zero. Theoretically, the input impedance varies between zero and infinity depending on the length of line and, between these limits, it is either an inductive or capacitive reactance.

For lines with high attenuation, the effects are somewhat similar but, as described in Section 7, the maximum and minimum values are not constant along the line. The variations are more pronounced at the open or short circuited end and become less as we move back along the line towards the input end.

By determining the positions and values of the voltage and current standing waves, particularly towards the end of the line, we can determine whether the line is open or short circuited. For example:

- Maximum voltage and minimum current occur at the end of an open circuited line.
- Minimum voltage and maximum current occur at the end of a short circuited line.

8.5 LINES TERMINATED IN PURE RESISTANCE NOT EQUAL TO Zo. For these terminations, some of the incident energy is absorbed by the terminating resistor (R_T) and the remainder is reflected. Standing waves which have maximum and minimum values at the terminating end, are set up in the same manner as on open or short circuited lines. Because the amplitudes of the reflected waves are less than those of the incident waves, the standing waves do not fall to zero nor rise to twice that of the incident waves.

Figs. 21a and 21b show typical standing wave and impedance variation patterns on lines with negligible attenuation, when R_T is approximately three times Zo and one-third of Zo respectively.

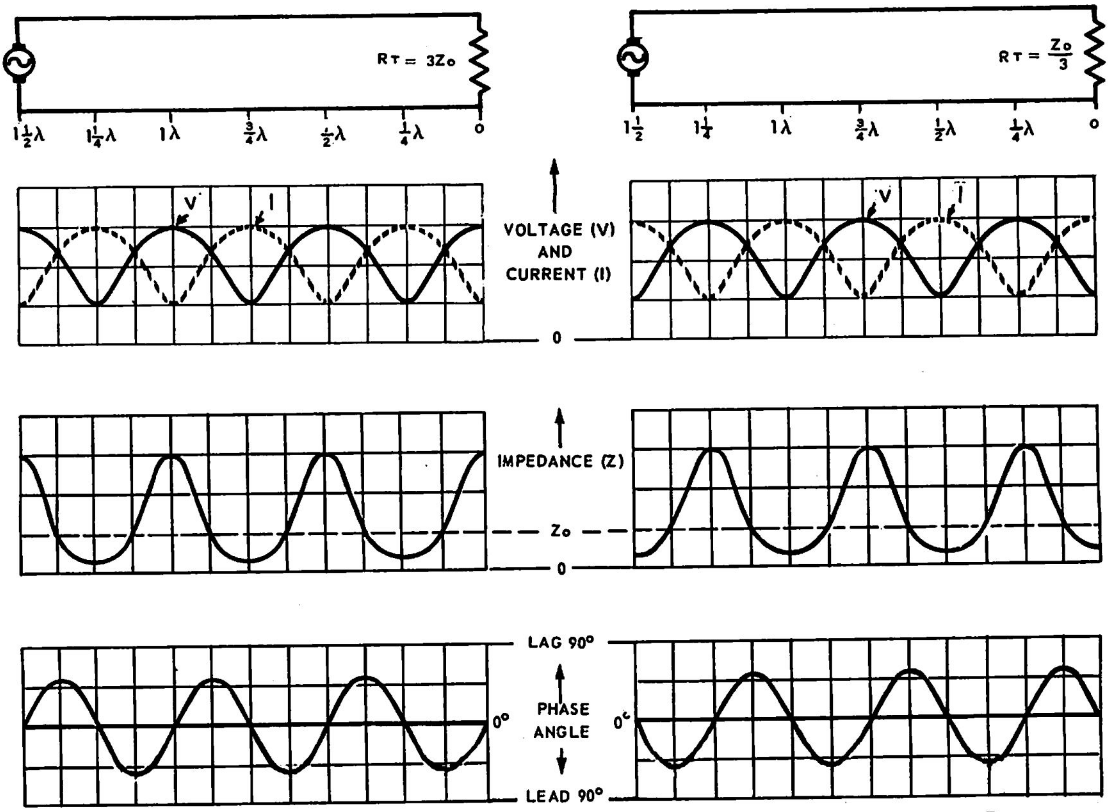
For lines with high attenuation, the standing wave effect and impedance variations are most pronounced towards the terminating end but follow the trend of the graphs shown in Section 7, becoming progressively less towards the input end of the line.

Referring to Fig. 21a, for R_T greater than Zo:

- when the value of R_T is increased progressively towards an open circuit, more energy is reflected, and the standing wave pattern approaches that of an open circuited line;
- when the value of R_T is decreased progressively towards the Zo of the line, less energy is reflected, and the standing wave pattern approaches that of a line terminated in its Zo.

Referring to Fig. 21b, for R_T less than Zo:

- when the value of R_T is decreased progressively towards a short circuit, more energy is reflected and the standing wave pattern approaches that of a short circuited line;
- when the value of R_T is increased progressively towards the Zo of the line, less energy is reflected, and the standing wave pattern approaches that of a line terminated in its Zo.



(a) Line terminated in R_T = 3 Zo. (b) Line terminated in $R_T = \frac{Zo}{3}$.

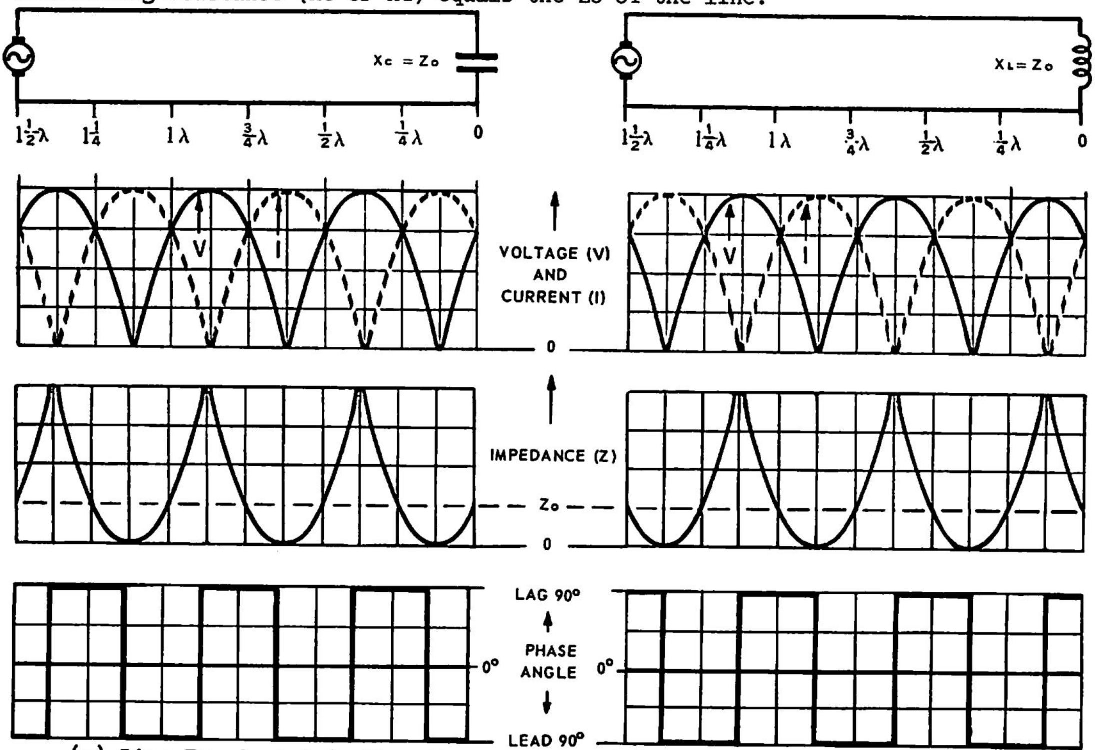
FIG. 21. BEHAVIOUR OR LINES TERMINATED IN PURE RESISTANCE (R_T) NOT EQUAL TO Zo.

Table 2 summarises the input impedance variations for different lengths of lines. These characteristics repeat when multiples of ½λ are added.

Length of Line	Zin when R_T > Zo	Zin when R_T < Zo
Less than ¼λ	Complex impedance - capacitive (R - jX)	Complex impedance - inductive (R + jX)
¼λ	Pure resistance with value less than Zo. $Zin = \frac{Zo^2}{R_T}$	Pure resistance with value greater than Zo. $Zin = \frac{Zo^2}{R_T}$
¼λ - ½λ	Complex impedance - inductive (R + jX)	Complex impedance - capacitive (R - jX)
½λ	Pure resistance = R_T.	Pure resistance = R_T.

TABLE 2. SUMMARY OF INPUT IMPEDANCE VARIATIONS.

8.6 LINE TERMINATED IN A PURE REACTANCE. When the line is terminated in either a pure capacitance or a pure inductance, the load absorbs no energy and all is reflected. The standing wave values vary between maximum and zero along the line, but they do not have their maximum and minimum values at the terminating end. For example, Figs. 22a and 22b show the conditions for a low attenuation line when the terminating reactance (X_C or X_L) equals the Zo of the line.



(a) Line Terminated in Xc = Zo.   (b) Line Terminated in XL = Zo.

FIG. 22. BEHAVIOUR OF LINES TERMINATED IN PURE REACTANCE (X_C OR X_L) = Zo.

The standing wave patterns in Fig. 22 are shifted one way or the other along the length of line, depending on the value of X_C or X_L. For example:

- When X_C or X_L is increased progressively above the value of Zo, the standing wave patterns tend towards the open circuit condition. The voltage standing wave value increases and the current standing wave value decreases at the termination. We can consider the graphs in Fig. 22a as shifting towards the left, and those in Fig. 22b towards the right.

- When X_C or X_L is decreased progressively below the value of Zo, the standing wave patterns tend towards the short circuit condition. The voltage standing wave value decreases and the current standing wave value increases at the termination. We can consider the graphs in Fig. 22a as shifting towards the right, and those in Fig. 22b towards the left.

Note that, at points an odd number of quarter wavelengths from the termination, the line impedance is purely reactive but it is opposite in effect (for a capacitive load, the line impedance is inductive, and vice versa). At points an even number of quarter wavelengths from the termination, the line impedance is purely reactive and identical in all respects with the terminating reactance.

For lines with high attenuation, the standing wave effect and impedance variations are most pronounced towards the terminating end, but follow the trend of the graphs shown in Section 7, becoming less towards the input end.

8.7 LINE TERMINATED IN A COMPLEX IMPEDANCE. When a line termination has both resistive and reactive components, the standing wave pattern may be considered as being a combination of the standing waves resulting from the resistance and from the reactance considered separately. These components vary the standing wave pattern as discussed in paras. 8.5 and 8.6 respectively.

9. SUMMARY OF ¼λ AND ½λ SECTIONS.

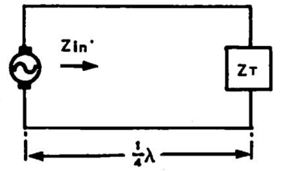
9.1 Quarter-wave or half-wave resonant line sections are commonly used in many R.F. transmission line applications, for example, R.F. switching, impedance matching, converting from balanced to unbalanced impedance or vice versa. The characteristics of these sections are summarised below.

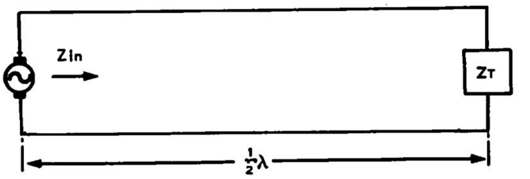
9.2 QUARTER-WAVE SECTION. The impedance (Zin) presented to a generator by a ¼λ section (or any line which is an odd number of quarter wavelengths long) varies with different terminations (Z_T), as shown in Table 3. Note that a ¼λ section always 'inverts' its load, for example:

- an open circuit appears as a short circuit to the generator;
- a short circuit appears as an open circuit;
- a resistance load higher in value than the Zo of the line looks like a resistance lower than the Zo, and vice versa;
- an inductance load looks like a capacitance, and vice versa.

9.3 HALF-WAVE SECTION. The impedance (Zin) presented to a generator by a ½λ section (or any line which is an even number of quarter wavelengths long) is equal to the impedance of the termination (Z_T), as shown in Table 4. Note that a ½λ section always 'repeats' its load, for example:

- an open circuit appears as an open circuit to the generator;
- a short circuit appears as a short circuit;
- a resistance load looks like a resistance of the same value;
- an inductance load looks like an inductance of the same value, etc.





Zin looks like ...	When Z_T is ....
a short circuit	an open circuit
a low resistance	a high resistance
a high resistance	a low resistance
an open circuit	a short circuit
a capacitance	an inductance
an inductance	a capacitance
an impedance (R - jX)	an impedance (R + jX)
an impedance (R + jX)	an impedance (R - jX)

TABLE 3. A ¼λ SECTION 'INVERTS' ITS LOAD.

Zin looks like ..	When Z_T is ...
an open circuit	an open circuit
a high resistance	a high resistance
a low resistance	a low resistance
a short circuit	a short circuit
an inductance	an inductance
a capacitance	a capacitance
the same complex load (R ± jX)	a complex load (R ± jX)

TABLE 4. A ½λ SECTION 'REPEATS' ITS LOAD.

10. STANDING WAVE INDICATORS.

10.1 Several methods are used to measure the current or voltage at any point on a transmission line, and to observe the existence of standing waves. In using these methods, remember that the H-field around a line varies directly with the line current, and the E-field varies directly with the line voltage.

10.2 **CURRENT MEASUREMENT ON OPEN WIRE LINES.** To measure the current at any point on an open wire line:

- connect an a.c. ammeter in series with the line (Fig. 23a); or
- place a loop of wire connected to an a.c. ammeter, in the magnetic field surrounding one of the conductors (Fig. 23b).

FIG. 23. MEASURING CURRENT ON OPEN WIRE LINES.

To measure current standing waves on an open wire line, such as that feeding a transmitting aerial, the method shown in Fig. 23b is used. A typical arrangement (called a 'trolley meter') consists of an insulating frame fitted with wheels so that it may be run along the line while maintaining a constant coupling. This frame carries a coil or pick-up loop inductively coupled to one side of the line. An e.m.f. is induced and a thermocouple or rectifier type R.F. ammeter in series with the coil, reads relative values of current at points along the line. A potentiometer or variable resistor is connected in series to protect the meter and to adjust the maximum reading to a convenient value. The ammeter reads maximum at the current anti-nodes and minimum at the current nodes.

When making these measurements the current in each wire is checked by turning the trolley round so that the loop is coupled to each wire in turn. If the currents in the two wires differ by more than a few per cent, a serious unbalance exists and the generator, load and line are examined for unbalance. Operation in the unbalanced condition usually means loss of energy due to radiation from the transmission line.

10.3 **VOLTAGE MEASUREMENT ON OPEN WIRE LINES.** To measure the voltage at any point on an open wire line:

- connect an alternating voltmeter or a neon lamp across the line (Figs. 24a and 24b); or
- capacitively couple a sensitive alternating voltmeter to the line (Fig. 24c); or
- connect one end of a $\frac{1}{4}\lambda$ section of line across the transmission line, and the other end to an a.c. ammeter. (Fig. 24d).

When a neon lamp is connected across the line, the greater the voltage, the brighter the lamp will glow. An E-field will make a neon lamp glow, even when it is not directly connected to the line, provided that the field is strong enough. On lines carrying high power, the neon lamp need only be placed in the vicinity of the line.

Trolley meters may be constructed to indicate voltage standing waves on an open wire line. In this case, an alternating voltmeter is capacitively coupled between the two sides of the line.

A basic requirement of voltage standing wave indicators is that they possess a very high impedance, so that they do not load (take energy from) the line being measured. A relatively low impedance voltage indicator would upset the normal characteristics of the line and cause reflections due to the change in impedance at the point of connection. The $\frac{1}{4}\lambda$ section shown in Fig. 24d is a high impedance indicator suitable for voltage measurements on an open wire line. In this device, an a.c. ammeter forms an effective short circuit across the $\frac{1}{4}\lambda$ section. This 'reflects' a very high impedance at the other end of the section which is connected across the transmission line (see para. 9.2) and very little energy is dissipated by the $\frac{1}{4}\lambda$ section. When the section is moved along the line, the ammeter reads maximum at the voltage anti-nodes and minimum at the voltage nodes.

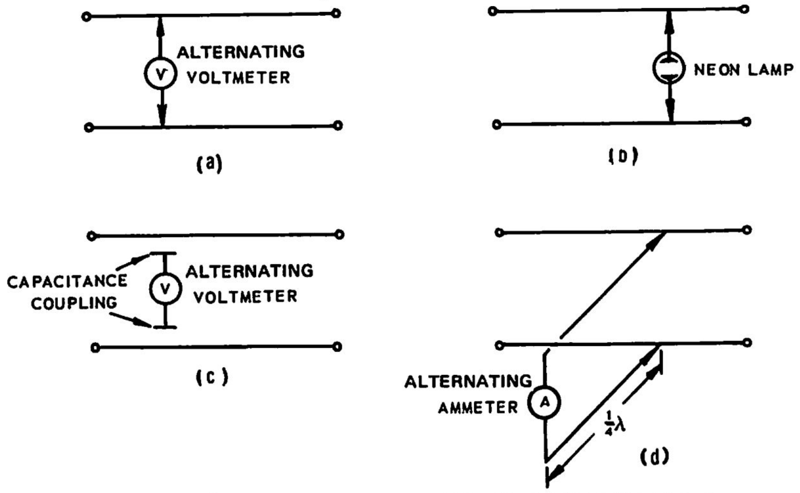


FIG. 24. MEASURING VOLTAGE ON OPEN WIRE LINES.

10.4 VOLTAGE MEASUREMENT ON COAXIAL LINES. For standing wave measurements on coaxial lines (where the H-field and E-field are confined), a section of the line is constructed with a narrow slot in the outer conductor (Fig. 25). A probe is a slender rod at a shallow depth, not far enough to touch the centre conductor. The probe is a slender rod which acts as an aerial and is excited by the E-field parallel to it. It is unaffected by the H-field. The slot is at least $\frac{1}{2}\lambda$ long so that one maximum and one minimum can be observed. The narrow slot does not reduce the effectiveness of the coaxial line because the currents flow in the outer conductor parallel to the slot. With this arrangement, the coupling is small and very little energy is extracted by the probe.

The R.F. energy induced in the probe is rectified, amplified and read on a d.c. meter. When the probe is moved along the line, the meter reads maximum at the voltage anti-nodes and minimum at the voltage nodes.

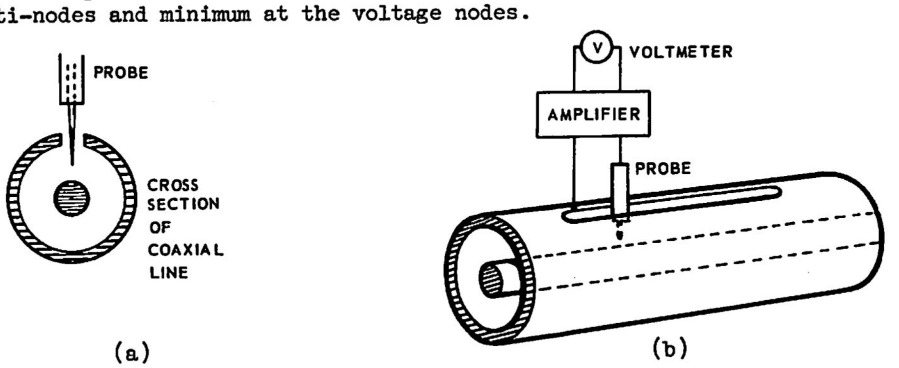


FIG. 25. MEASURING VOLTAGE ON COAXIAL LINES.

11. STANDING WAVE RATIO.

11.1 The character of the voltage (or current) standing wave distribution on a transmission line is generally described in terms of the standing wave ratio. The importance of the standing wave ratio arises from the fact that it can be easily measured experimentally. It indicates directly the extent to which reflected waves exist on a line and the degree of impedance mismatch between line and load. This measurement is important when a line is used to transfer energy from one point to another with minimum loss. In this case the line should be terminated in its Zo. Any impedance mismatch produces losses due to reflection.

11.2 **THE VOLTAGE STANDING WAVE RATIO (VSWR)** is the ratio of maximum voltage reading at a point on a line, to the value of minimum voltage ¼λ distant.

$$VSWR = \frac{Vmax}{Vmin}$$

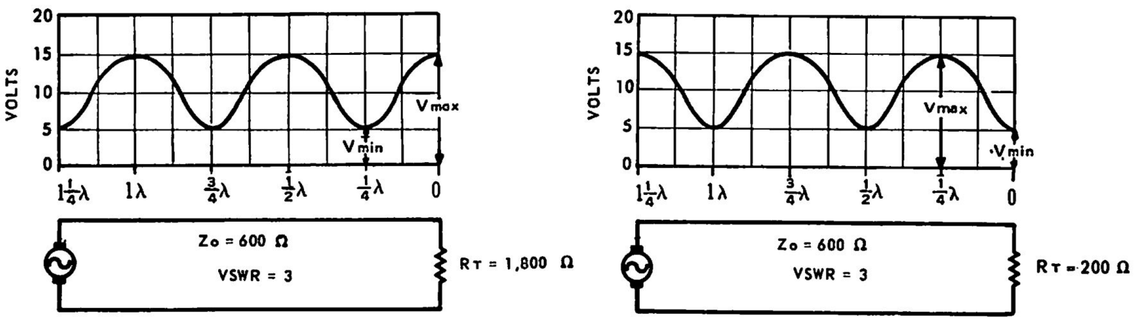
Alternatively, the VSWR may be measured in terms of maximum and minimum current. For a particular line, the VSWR is the same value, whether defined in terms of either voltage or current distribution.

The value of VSWR depends on the ratio of the terminating resistance (R_T) to the Zo of the line:

$$VSWR = \frac{R_T}{Zo} \quad or \quad \frac{Zo}{R_T}$$

The formula is given in two ways because it is customary to put the larger number in the numerator, so that the ratio will not be fractional.

For example, Fig. 26 indicates typical standing wave voltage variations on a line.



(a) (b)

FIG. 26. VSWR ON A TRANSMISSION LINE.

In each figure, the maximum voltage is 15 V and the minimum voltage is 5 V, producing a VSWR of 3:1, more simply expressed as a VSWR of 3. This indicates that R_T is either three times or one-third Zo, depending on the relative voltage measurement (maximum or minimum) at the load.

In Fig. 26a, as the voltage at the load is a maximum value, the load is resistive and is three times the value of Zo. When Zo = 600 ohms, R_T = 1,800 ohms.

In Fig. 26b, as the voltage at the load is a minimum, the load is resistive and is one-third the value of Zo. When Zo = 600 ohms, R_T = 200 ohms.

(Reverse reasoning applies when the current variations are considered).

The VSWR also gives an indication of the relative amplitudes of the reflected and incident waves. For example, a VSWR of unity denotes the absence of a reflected wave, and a very high VSWR indicates that the reflected wave is almost as large as the incident wave. Theoretically, the VSWR is infinite when the line is terminated in an open circuit, a short circuit or a pure reactance.

In terms of incident voltage (Vi) and reflected voltage (Vr):

$$VSWR = \frac{Vi + Vr}{Vi - Vr}$$

For example, the voltage variations in Fig. 26 are produced by Vi = 10 V and Vr = 5 V. Substituting in the above formula, these values give a VSWR of 3.

11.3 REFLECTION COEFFICIENT (Symbol ρ). The amount of energy reflected because of mismatch can be expressed by the reflection coefficient (or reflection factor) which is equal to the ratio of the reflected voltage (Vr) to the incident voltage (Vi). Reflection coefficient can also be expressed in terms of the terminating resistance (R_T) and the characteristic impedance of the line (Zo). It is equal to the difference between these two values divided by their sum.

$$\rho = \frac{Vr}{Vi} = \frac{R_T - Zo}{R_T + Zo}$$

For a line terminated in its characteristic impedance (R_T = Zo), ρ is calculated as zero. This means that none of the incident voltage is reflected.

For an open circuited line, $R_T = \infty$, and $\rho = \frac{\infty}{\infty} = +1$. This means that all the incident voltage is reflected in phase.

For a short circuited line, $R_T = 0$, and $\rho = -1$. All the incident voltage is reflected and the minus sign signifies that it is reflected in opposite phase.

When a 600 ohms transmission line is terminated in a 75 ohm non-reactive load:

$$\rho = \frac{75 - 600}{75 + 600} = -\frac{525}{675} = -0.78.$$

The amplitude of the reflected voltage wave is 0.78 or 78% of the amplitude of the incident voltage wave and it is reflected in opposite phase.

The relationship between VSWR and ρ is .... $VSWR = \frac{1 + \rho}{1 - \rho}$

As an exercise, transpose this formula to get .... $\rho = \frac{VSWR - 1}{VSWR + 1}$

An approximation for ρ when the VSWR is low (say, less than 1.5) is:

$$\rho = \tfrac{1}{2}\,(VSWR - 1)$$

The relationship between ρ and VSWR is shown graphically in Fig. 27.

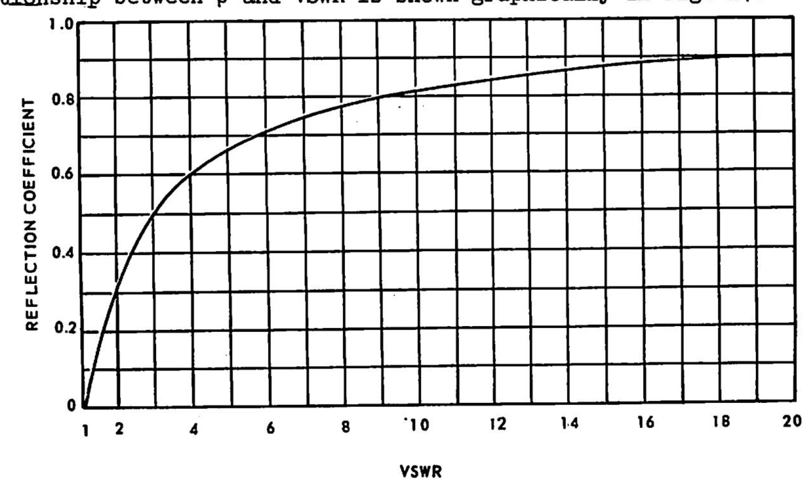


FIG. 27. RELATIONSHIP BETWEEN ρ AND VSWR.

11.4 RETURN LOSS. is a common method of expressing the degree of mismatch between the terminating impedance and the Zo of the line. It indicates the dB ratio of the incident power (that is, the power that would be absorbed in the termination under correctly matched conditions) to the power reflected from the termination, and is expressed in the formula:

$$\text{Return Loss (dB)} = 10 \log \frac{\text{Incident Power}}{\text{Reflected Power}}$$

In terms of the incident voltage (Vi) and the reflected voltage (Vr):

$$\text{Return Loss (dB)} = 20 \log \frac{\text{Incident Voltage}}{\text{Reflected Voltage}}$$

$$= 20 \log \frac{Vi}{Vr} = 20 \log \frac{1}{\rho}$$

This formula can be expressed in terms of R_T and Zo, by substituting $\frac{R_T - Zo}{R_T + Zo}$ for ρ:

$$\text{Return Loss (dB)} = 20 \log \frac{R_T + Zo}{R_T - Zo}$$

For correctly matched conditions (R_T = Zo), none of the incident power is reflected and the return loss is, theoretically, infinite.

For a mismatch condition, the value of return loss depends on the degree of mismatch; it is high for a small mismatch and low for a large mismatch.

For extreme mismatch conditions, with either a short or open circuit termination, all the incident power is reflected and the return loss is, theoretically, 0 dB.

EXAMPLE NO. 1. A 600 ohm transmission line is terminated in a non-reactive load of 1800 ohms. Calculate:

(a) the VSWR on the line near the output end;
(b) the voltage reflection coefficient at the load;
(c) the return loss in dB at the load.

SOLUTION.

(a) VSWR

$$= \frac{R_T}{Zo}$$

$$= \frac{1{,}800}{600} = \underline{3.0}$$

(b) Reflection Coefficient (ρ)

$$= \frac{R_T - Zo}{R_T + Zo}$$

$$= \frac{1{,}800 - 600}{1{,}800 + 600} = \underline{0.5}$$

(c) Return Loss (dB)

$$= 20 \log \frac{1}{\rho}$$

$$= 20 \log \frac{1}{0.5}$$

$$= 20 \log 2$$

$$= 20 \times 0.3 = \underline{6 \text{ dB}}$$

Answers (a) 3.0; (b) 0.5; (c) 6 dB.

Similarly, in the above problem, a non-reactive load of 200 ohms gives a VSWR of 3, a reflection coefficient of -0.5 and a return loss of 6 dB.

Alternatively, in the above problem, use the formulas for ρ in terms of VSWR, and for return loss in terms of R_T and Zo.

11.5 REFLECTION LOSS is the dB ratio of the incident power to a load, to the power absorbed by the load. It is expressed in the formula:

$$\textit{Reflection Loss (dB)} = 10 \log \frac{\textit{Incident Power}}{\textit{Absorbed Power}}$$

$$= 10 \log \frac{\textit{Incident Power}}{\textit{Incident Power} - \textit{Reflected Power}}$$

In terms of the incident voltage (Vi) and the reflected voltage (Vr):

$$\textit{Reflection Loss (dB)} = 10 \log \frac{Vi^2}{Vi^2 - Vr^2}$$

Dividing throughout by Vi^2, we get:

$$\textit{Reflection Loss (dB)} = 10 \log \frac{1}{1 - \frac{Vr^2}{Vi^2}} = 10 \log \frac{1}{1 - \rho^2}$$

This formula can be expressed in terms of R_T and Zo, substituting $\frac{R_T - Zo}{R_T + Zo}$ for ρ.

$$\textit{Reflection Loss (dB)} = 10 \log \frac{(R_T + Zo)^2}{4R_T Zo}$$

For correctly matched conditions, (R_T = Zo), the absorbed power equals the incident power and the reflection loss is, theoretically, 0 dB.

For a mismatch condition, the value of reflection loss depends on the degree of mismatch; it is low for a small mismatch and high for a large mismatch.

For extreme mismatch conditions, with either a short or open circuit termination, none of the incident power is absorbed and the reflection loss is, theoretically, infinite.

EXAMPLE NO. 2. A VSWR of 3 exists on a transmission line near the output end. Calculate:

(a) the reflection coefficient at the load;
(b) the reflection loss in dB at the load.

SOLUTION.

(a) Reflection Coefficient (ρ)

$$= \frac{VSWR - 1}{VSWR + 1}$$

$$= \frac{3 - 1}{3 + 1} = \frac{2}{4} = \underline{0.5}$$

(b) Reflection Loss (dB)

$$= 10 \log \frac{1}{1 - \rho^2}$$

$$= 10 \log \frac{1}{1 - (0.5)^2}$$

$$= 10 \log \frac{1}{1 - 0.25}$$

$$= 10 \log \frac{1}{0.75}$$

$$= 10 \log 1.33$$

$$= 10 \times 0.125 = \underline{1.25\ dB}$$

Answers: (a) 0.5; (b) 1.25 dB.

11.6 RELATIONSHIP BETWEEN VSWR, RETURN LOSS AND REFLECTION LOSS. The formulas quoted earlier in this Section give an indication of the relationship between VSWR, reflection coefficient, return loss and reflection loss. This relationship is directly concerned with the relative impedances of the line and the load. In practice, measurements can be made to determine the VSWR on an R.F. transmission line from which the reflection coefficient, return loss and reflection loss can be calculated. Fig. 28 shows in graph form the values of return loss and reflection loss for different values of VSWR.

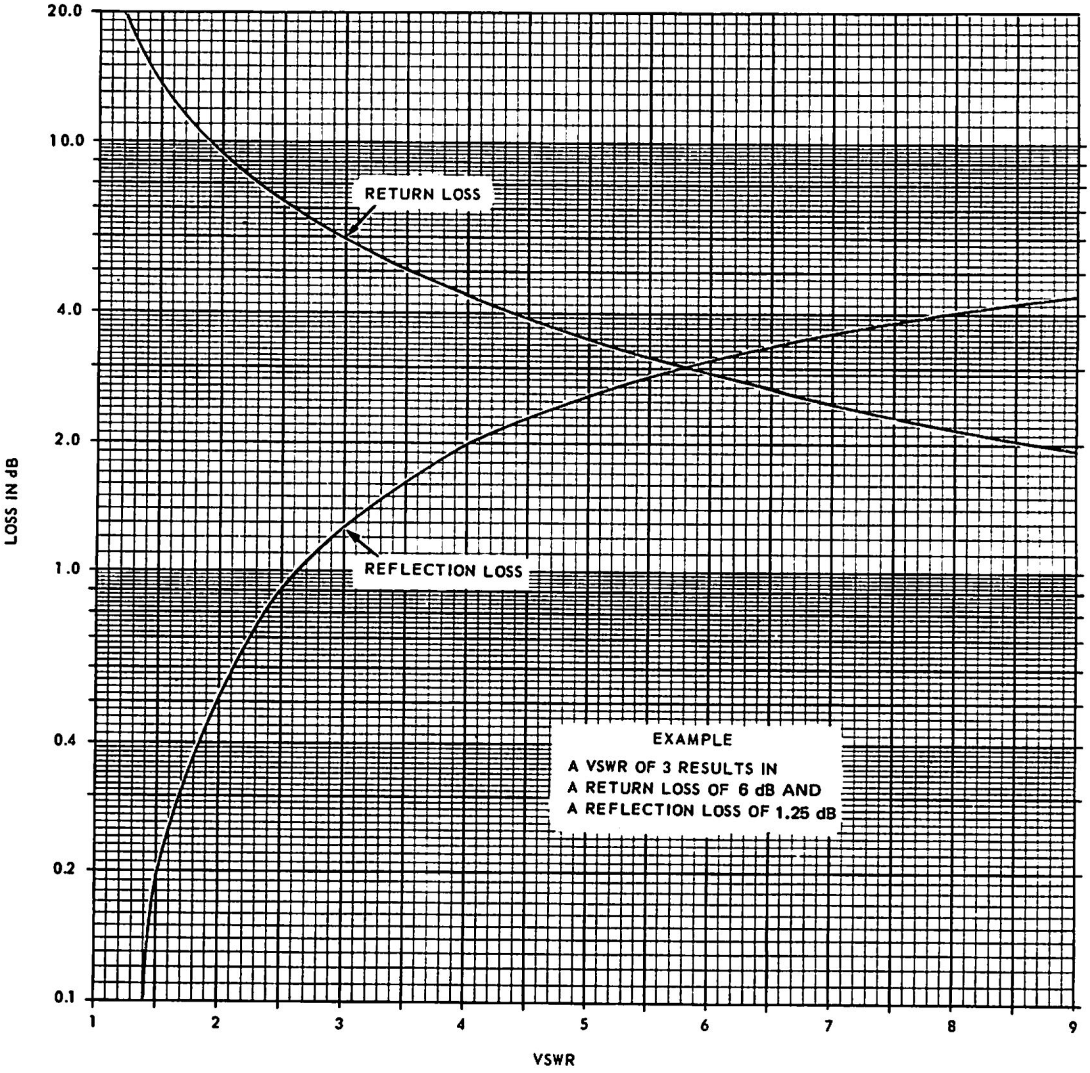


FIG. 28. RELATIONSHIP BETWEEN VSWR, RETURN LOSS AND REFLECTION LOSS.

This relationship may also be expressed in chart form and associated with the Smith Chart used for transmission line calculations. (Refer publication ETP 0389 - 'The Smith Chart for R.F. Transmission Lines'). To summarise:

- Return loss values give an indication of the degree of impedance mismatch and the VSWR on the line. A high return loss indicates negligible mismatch and a low VSWR. Return loss figures do not numerically indicate how much loss is caused due to an impedance mismatch.
- Reflection loss values indicate numerically the actual loss caused due to the impedance mismatch. A low reflection loss is associated with negligible mismatch and a low VSWR.

12. VSWR ON LINES WITH ATTENUATION.

12.1 The mathematical formulas given in Section 11 can be applied to lines with attenuation. From the following examples, it is important to note that when standing waves exist on a line with attenuation, the VSWR varies from a minimum value near the input end of the line to a maximum value near the termination.

12.2 **LINE TERMINATED IN ITS Zo.** Fig. 29 shows an R.F. generator matched to a 600 ohm line terminated in its Zo. All the energy arriving at the output end is absorbed by the termination. No voltage is reflected and no standing waves exist on the line.

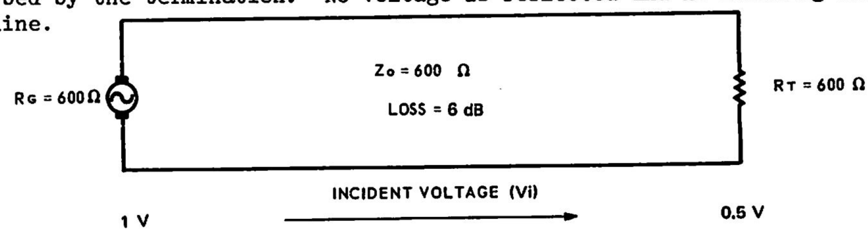


FIG. 29. LINE TERMINATED IN ITS Zo.

Assume that the input voltage is 1 V and the line loss is 6 dB. The incident voltage across the load is, therefore, 0.5 V. (Loss of 6 dB indicates a voltage ratio of 2 : 1 across equal resistances).

Using the formula VSWR = $\frac{Vi + Vr}{Vi - Vr}$ where Vr is zero, we calculate that the VSWR near both input and output ends of the line is 1. This line has a VSWR of unity along its entire length.

Other calculated values (at the load) are:

Reflection coefficient is zero.
Return Loss is infinite.
Reflection Loss is 0 dB.

12.3 **LINE TERMINATED IN SHORT CIRCUIT OR OPEN CIRCUIT.** Fig. 30 shows the line referred to in Fig. 29 terminated in a short circuit. Under these conditions, no energy is absorbed by the termination and all is reflected. The reflected voltage (Vr) of 0.5 V is reduced by 6 dB and its value across the input is 0.25 V.

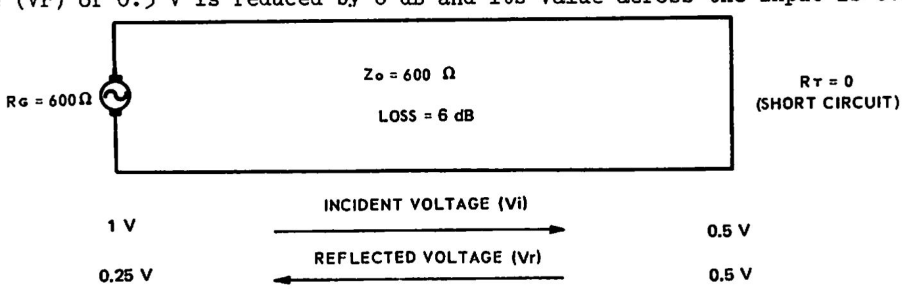


FIG. 30. LINE TERMINATED IN SHORT CIRCUIT.

Using the formula VSWR = $\frac{Vi + Vr}{Vi - Vr}$, we calculate that the VSWR along this line varies from 1.67 near the input end to infinity near the output end.

When the line loss is increased to 12 dB, the VSWR varies from 1.13 near the input end to infinity near the output end.

These calculations indicate that the VSWR is maximum near the short circuited end where the values of the incident and reflected voltage waves are similar. Near the input end, the value of reflected wave is smaller and the VSWR is relatively lower, approaching unity as the line attenuation is increased.

Other calculated values (in Fig. 30) are:

Reflection coefficient at the load, is -1.
Return Loss at the load, is 0 dB.
Reflection coefficient at the input end, is 0.25.
Return Loss at the input end, is 12 dB.

(Similar reasoning applies for a line terminated in an open circuit).

12.4 LINE TERMINATED IN R_T NOT EQUAL TO Zo. Under these conditions, some energy is absorbed by the termination and the remainder is reflected. Standing waves are produced on the line. The general behaviour is indicated by the following example.

EXAMPLE NO. 3. An R.F. generator with an internal resistance of 600 ohms is connected to a 600 ohm transmission line which is terminated in a resistance of 900 ohms. Assuming the transmission line has a loss of 6 dB when feeding a matched load, calculate:

(a) reflection coefficient at the load;
(b) return loss at the load;
(c) reflection loss at the load;
(d) VSWR near the output end;
(e) reflection coefficient at the input end;
(f) return loss at the input end;
(g) VSWR near the input end.

SOLUTION.

AT THE OUTPUT END:

(a)

$$\rho = \frac{R_T - Zo}{R_T + Zo}$$

$$= \frac{900 - 600}{900 + 600} = \frac{300}{1500} = \underline{0.2}$$

(b) Return Loss

$$= 20 \log \frac{1}{\rho}$$

$$= 20 \log \frac{1}{0.2} = 20 \log 5 = \underline{14 \text{ dB}}$$

(c) Reflection Loss

$$= 10 \log \frac{1}{1 - \rho^2}$$

$$= 10 \log \frac{1}{1 - 0.04}$$

$$= 10 \log 1.04 = \underline{0.18 \text{ dB}}$$

(d) VSWR

$$= \frac{1 + \rho}{1 - \rho}$$

$$= \frac{1 + 0.2}{1 - 0.2} = \frac{1.2}{0.8} = \underline{1.5}$$

AT THE INPUT END (REFER FIG. 31):

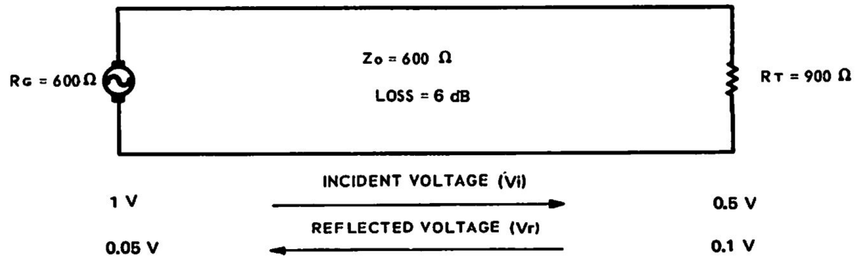


FIG. 31. LINE TERMINATED IN R_T GREATER THAN Zo.

(e) The 6 dB (2 : 1 voltage) line loss attenuates both the incident and reflected waves. Thus an incident wave of unit amplitude (for example, 1 V), is attenuated to one-half by the line loss. At the termination, one-fifth of this incident wave is reflected and before reaching the sending end, is again attenuated. The reflected wave arriving back at the sending end is therefore:

$$\frac{1}{2} \times \frac{1}{5} \times \frac{1}{2} \times \frac{1}{20} = 0.5 \text{ times the incident wave at that point.}$$

Therefore, at the input end, $\rho = \underline{0.05}$.

(f) Return Loss $= 20 \log \frac{1}{\rho}$

$$= 20 \log \frac{1}{0.05} = 20 \log 20 = \underline{26 \text{ dB}}.$$

(g) VSWR $= \frac{1 + \rho}{1 - \rho}$

$$= \frac{1 + 0.05}{1 - 0.05} = \frac{1.05}{0.95} = \underline{1.1}$$

Answers: (a) *0.2;* (b) *14 dB;* (c) *0.18 dB;* (d) *1.5;*

(e) *0.05;* (f) *26 dB;* (g) *1.1.*

(Similar reasoning applies for a line terminated in a value of R_T less than Zo).

NOTES

13. TEST QUESTIONS.

1. *What is the difference between a non-resonant and a resonant transmission line?*

2. *Explain the terms:*

   electromagnetic field, E-field, H-field.

3. *Explain the terms:*

   incident wave, reflected wave, standing wave.

4. *What is the phase relationship between the incident waves of voltage and current on a line terminated in its Zo?*

5. *Draw a graph to show how the impedance varies at points along a line which is terminated in its Zo.*

6. *Why are standing waves not present on a line terminated in its Zo?*

7. *On an open circuited line, what is the phase relationship, at the open circuit, between:*

   (a) the incident and reflected voltage waves;
   (b) the incident and reflected current waves?

8. *What are the relative values (maximum or minimum) of (a) the voltage and (b) the current at the open circuited end of a transmission line?*

9. *What causes standing waves of voltage and current to be produced on an R.F. transmission line?*

10. *Explain the terms:*

    voltage node, voltage anti-node.

11. *What is the distance (in wavelengths) between two adjacent voltage anti-nodes on an open circuited transmission line?*

12. *On a short circuited line, what is the phase relationship, at the short circuit, between:*

    (a) the incident and reflected voltage waves;
    (b) the incident and reflected current waves?

13. *What are the relative values (maximum or minimum) of (a) the voltage and (b) the current at the short circuited end of a transmission line?*

14. *Draw graphs to show the conventional representation of voltage and current standing waves produced on a transmission line* $\frac{3}{4}\lambda$ *long by:*

    (a) an open circuit termination;
    (b) a short circuit termination.

15. *Draw graphs showing how the reactance varies at points along a transmission line* $1\frac{1}{2}\lambda$ *long and terminated in:*

    (a) an open circuit;
    (b) a short circuit.

16. *An open wire transmission line is short circuited at the load end. What is the nature of the input impedance when the line has a length of:*

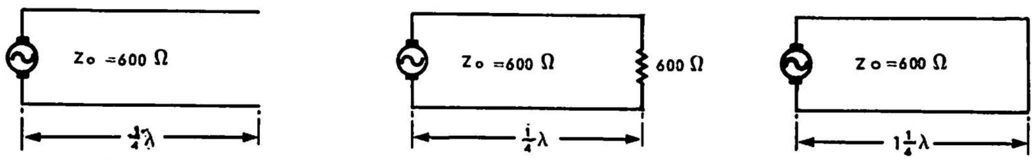
    (a) $\frac{1}{8}\lambda$; *(b)* $\frac{1}{4}\lambda$; *(c)* $\frac{3}{8}\lambda$; *(d)* $\frac{1}{2}\lambda$.

17. *Under what conditions does a resonant transmission line look like:*

    (a) a series resonant circuit;
    (b) a parallel resonant circuit?

18. *Explain why the input impedance of a transmission line with high attenuation, is approximately equal to the Zo of the line.*

19. *What will be the load impedance for each of the generators?*



20. *What impedance condition exists* $\frac{1}{2}\lambda$ *back from the end of an open circuit coaxial transmission line?*

21. *An open circuit transmission line* 0.15λ *long will have (zero, maximum, minimum, inductive, capacitive) reactance.*

22. *Draw graphs to show typical standing wave patterns (both voltage and current) when a sinusoidal R.F. voltage is applied to a line terminated in:*

    (a) a resistance greater than Zo;
    (b) a resistance less than Zo.

23. *What is the input resistance of a* $\frac{1}{4}\lambda$ *section of 600 ohm open wire transmission line which is terminated in a resistance of:*

    (a) 1200 ohms;
    (b) 300 ohms?

24. *What is the input resistance of a* $\frac{1}{2}\lambda$ *section of 50 ohm coaxial cable which is terminated in a resistance of:*

    (a) 250 ohms;
    (b) 20 ohms?

25. *What is the nature of the input impedance for the following transmission lines:*

    (a) a $\frac{1}{4}\lambda$ *section terminated in a pure inductance;*
    (b) a $\frac{1}{2}\lambda$ *section terminated in a pure inductance;*
    (c) a $\frac{1}{4}\lambda$ *section terminated in a pure capacitance;*
    (d) a $\frac{1}{4}\lambda$ *section terminated in an impedance* $(R - jX)$;
    (e) a $\frac{1}{2}\lambda$ *section terminated in an impedance* $(R - jX)$?

26. *What is meant by the term - Voltage Standing Wave Ratio (VSWR)?*

27. *Briefly explain how you would measure the VSWR on:*

    (a) an open wire transmission line;
    (b) a coaxial transmission line.

28. *State a formula for determining the VSWR of a transmission line.*

29. *The VSWR on a line is 2.5 : 1. If the measurement at a voltage node is 10 volts, what is the voltage at an anti-node?*

30. *What is the theoretical value of VSWR on a 200 ohm line which is terminated in:*

    (a) an open circuit;
    (b) a short circuit?

31. *What is the value of VSWR on a 300 ohm line with negligible attenuation, when it is terminated in a resistance of:*

    (a) 300 ohms;
    (b) 250 ohms;
    (c) 750 ohms?

32. *What is the value of the terminating resistance for a 600 ohm transmission line when the voltage standing wave is 10 volts measured across the load and 4 volts measured at a point ¼λ back from the load?*

33. *A 600 ohm transmission line is terminated in a pure resistance and found to have a VSWR of 1.5. State the value of the terminating resistor when:*

    (a) a current node occurs at the load;
    (b) a voltage node occurs at the load?

34. *Explain the terms:*

    reflection coefficient; return loss; reflection loss.

35. *What is the value of reflection coefficient for a 50 ohm line which is terminated in:*

    (a) an open circuit;
    (b) a short circuit;
    (c) its Zo?

36. *An R.F. generator with an internal resistance of 300 ohms is connected to a 300 ohm transmission line terminated in a resistance of 600 ohms. Assuming the transmission line has negligible attenuation, calculate:*

    (a) VSWR on the line;
    (b) voltage reflection coefficient at the load;
    (c) return loss in dB at the load;
    (d) reflection loss in dB at the load.

37. *A coaxial cable, which has a loss of 6 dB when feeding a matched load, is connected to an aerial having a reflection coefficient of 0.1, that is, 10%, with respect to the characteristic impedance of the cable. Calculate:*

    (a) reflection loss at the input to the aerial;
    (b) return loss at the input to the aerial;
    (c) return loss at the input to the cable (sending end);
    (d) VSWR in the cable near the output end;
    (e) VSWR in the cable near the input end.

ANSWERS TO PROBLEMS.

23. (a) 300 ohms (b) 1,200 ohms 24. (a) 250 ohms 20 ohms 29. 25 volts 31. (a) 1.0 (b) 1.2 (c) 2.5 32. 1,500 ohms 33. (a) 900 ohms (b) 400 ohms	35. (a) +1 (b) -1 (c) 0 36. (a) 2.0 (b) 0.33 (c) 9.5 dB (d) 0.5 dB 37. (a) 0.04 dB (b) 20 dB (c) 32 dB (d) 1.22 (e) 1.05

END OF PAPER.

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