ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION
GUNNERY STAFF/CAREER COURSES

TRANSMISSION LINES

INTRODUCTION

1. In order to convey energy from a transmitter to its aerial system or from an aerial to its associated receiver, as in radio, radar and TV systems, it is necessary to provide a means of carrying the electromagnetic energy that comprises the signal in question. Two main mechanisms are made available for this purpose, namely **transmission lines** and **waveguides**, both of which are employed within current Royal Artillery radar systems. The purpose of this handout is to consider the structure and properties of transmission lines.

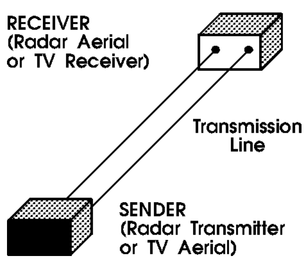


Fig.1. The basic transmission line

CONSTRUCTION

2. All transmission lines consist of a conducting medium (the two conductors) and a dielectric medium (the space between the conductors), also there will be electric and magnetic fields in both media. A simple structure for such a system is illustrated by Fig.1. At zero frequency (DC) the currents in the two conductors will be equal and opposite, since there can be no accumulation of charge in the conducting system.

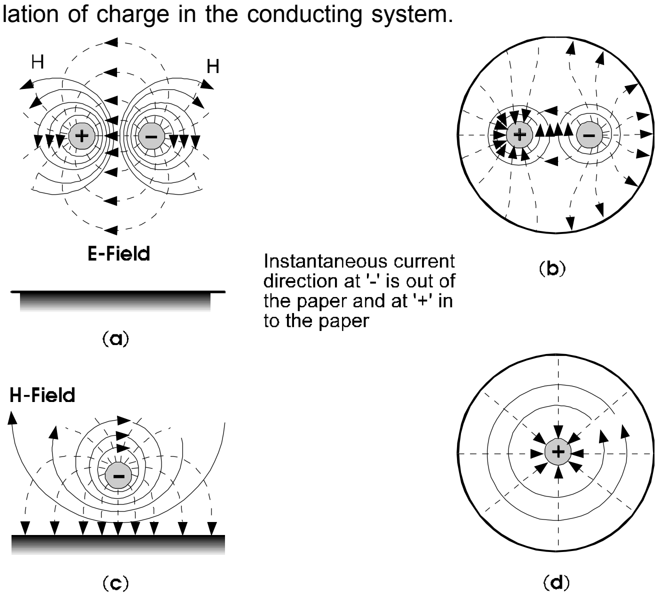


Fig.2. Types of Transmission Line

3. A similar condition exists for AC transmission, the currents in the two conductors being equal and opposite in direction at every instant at any cross-section. If the fields in a plane perpendicular (transverse) to the direction of the line are examined, the electric and magnetic fields in the dielectric will be found to lie almost entirely in that plane. In fact, as will be seen later, the energy is transmitted along the line mainly by the fields in the dielectric, the conductors merely acting as guides.

4. The layout of the conductors may take on several forms, which are broadly divided into **balanced** and **unbalanced** lines. Two identical wires symmetrically placed with respect to earth or the inside of a tubular conducting screen are representative of balanced lines, while one wire with earth return or at the centre of a conducting tube (concentric or coaxial cable) are representative of unbalanced lines. Cross sections of these configurations are shown at Fig.2, where the full lines represent the magnetic field (H) and the dashed lines the electric field (E). Configuration (c) is now very rarely used.

FIELD DISTRIBUTION

5. The type of line which is most instructive for the purposes of this handout is shown at Fig.2a, however, the unbalanced form at Fig.2d will be found more frequently in radio, TV and some low frequency radar systems. It is important to have a clear view of field distribution along the length of a parallel line and this is illustrated at Fig.3.

6. If it is assumed that the line of Fig.3 has infinite length and is fed from its left hand end by an alternating signal of wavelength, λ, then every half wavelength, $\lambda/2$, the polarity of the connections to the source will reverse as shown by the '+' and '–' signs. The changes will propagate down the line at high velocity towards the termination producing the field distribution pattern shown. Only the field maxima have been shown to avoid clutter on the diagram.

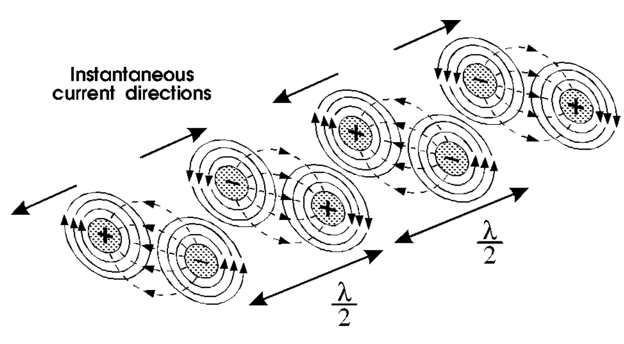


Fig.3. Field distribution along a transmission line

DISTRIBUTED CONSTANTS

7. A transmission line has resistance and reactance distributed along its length as indicated by Fig.4. The appropriate symbol for each component, usually called a constant, is drawn once only to avoid duplication. Clearly there would be resistance and inductance on both sides of the line, however, this layout is convenient. The primary characteristics of the line are:-

R = The **resistance** per unit length (Ohm).
L = The **inductance** per unit length (Henry).
C = The **capacitance** per unit length (Farad).
G = The **leakage resistance** per unit length (Ohm).

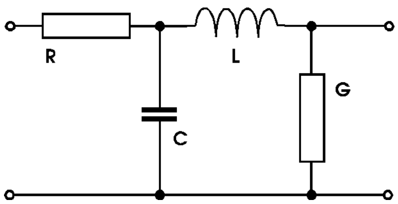


Fig.4. Transmission line distributed constants

8. Each of the components, or constants, illustrated by Fig.4 produce opposition to alternating current that will change with frequency. Since all of the component values are affected by conductor dimensions and spacing, different line constructions exhibit different characteristic values for each component. When all of the values are taken into account, it is possible to produce a figure that is know as the **Characteristic Impedance** for each section of the line.

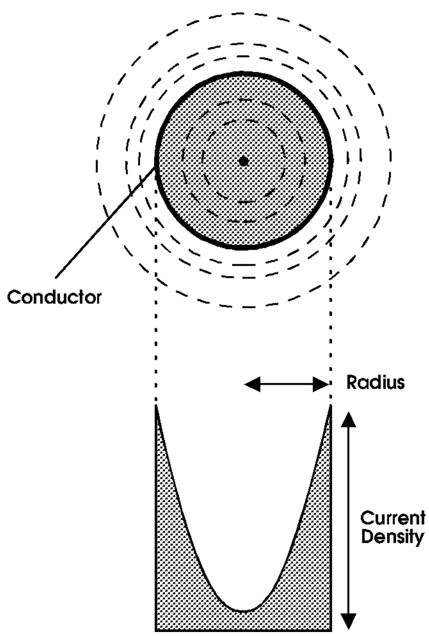


Fig.5. Skin Effect in high frequency conductors

9. It may seem odd at first sight to imply that line resistance changes with frequency. It is, however, true. The reason for the change is shown in graphic form by Fig.5. As current flows through the line, a magnetic field builds up within, and around the outside of the conductor, which is dependent upon the magnitude of the current.

10. Should the line current change, as would be expected when delivering alternating signals along it, the change of field is felt more within the conductor, being at its most intense on the centre line. The flux change induces a back EMF, greater in the centre of the conductor than at the outside, which opposes the current change producing it. As a result, the charge carriers that form the current, flow more at the edges of the conductor than in the centre, referred to as **skin effect**. This causes a thinner conducting area and a raising of overall resistance, an effect that increases with frequency.

11. The leakage resistance, often called the **leakance**, occurs because the line must be supported in some way, and however well insulated the supporting structure is made, there will always be some value of resistance, however large, across the line through which a tiny current can leak. Naturally, where a dielectric, including air, is placed between two conductors which have a potential difference applied across them, a capacitance will also be formed.

CHARACTERISTIC IMPEDANCE

12. Any transmission line, whatever its length, may be seen as a number of sections similar to Fig.4, connected together in a chain. At a given frequency, the opposition offered by each of the distributed constants, whether resistance or reactance, can be shown as a series of resistances of appropriate value. An example of this for one line section is indicated at Fig.6.

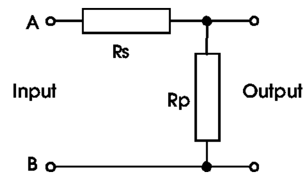


Fig.6. Transmission line resistances

13. When a number of sections of line are concatenated to form the link between say, a transmitter and an aerial, the line resistance, or impedance, is dependent upon the number of sections of line used. This impedance is important because energy from the transmitter must be coupled onto the line with minimum loss, and energy must be coupled from the other end of the line to the aerial, also with minimum loss. This means that both the output impedance of the transmitter and the impedance load of the aerial must match the line impedance, in order to obtain maximum power transfer.

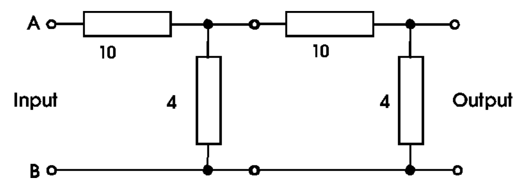


Fig.7. Two line sections in series

14. If it is assumed that the series resistance, Rs = 10Ω and the parallel resistance, Rp = 4Ω, an overall value for the line impedance builds up as more and more sections are added. In the case of Fig.6, the line impedance, i.e., the resistance between terminals A and B, is 14Ω. Chaining a second section to the first produces the structure of Fig.7, where the new line is formed by the 14Ω of the second section in parallel with the 4Ω that forms Rp of the first section, and these are in series with 10Ω. This now gives 10 + (4 in parallel with 14) = 13.111Ω.

15. Adding yet another section puts the two in Fig.7, in parallel with the one of Fig.6, to form the triple section of Fig.8. In which case the line impedance becomes 10 + (4 in parallel with 13.11) = 13.065Ω. Carrying out the same process with the addition of a fourth section gives the layout of Fig.9, and since it is formed by adding Fig.6, to Fig.8, the line impedance becomes 10 + (4 in parallel with 13.065) = 13.062Ω.

16. It can be seen from this last result that the impedance seen between terminals A and B is falling, however, the increment falls less each time another section is added. This implies that adding a few more sections will make little difference to the impedance seen between terminals A and B, and that the impedance will eventually stabilize at some specific value.

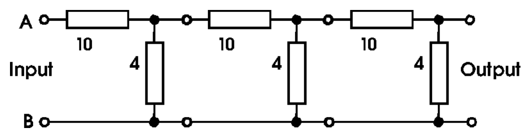


Fig.8. Three line sections in series

17. For an infinite number of line sections, the input impedance reaches a value called the **characteristic impedance (Zo)** of the line. A figure dependent upon the distributed constants, which in turn depend upon the dimensions and materials used to make the line, and the frequency of the input. In practice, transmission lines have a range of frequencies over which the characteristic impedance remains almost constant, referred to as the **bandwidth** of the line.

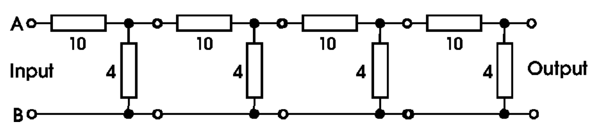


Fig.9. Four line sections in series

18. Any length of line, **correctly terminated** with a resistance equal to its characteristic impedance, will always appear, to the stage delivering a signal onto it, as if it has an impedance equal to the characteristic impedance. This is fairly obvious when given a little thought. Fig.10, illustrates the situation. The short section of line is terminated with its characteristic impedance, this actually means that an infinite length of line is attached to the end of the short section of line. In which case the line is effectively lengthened and the impedance does not change.

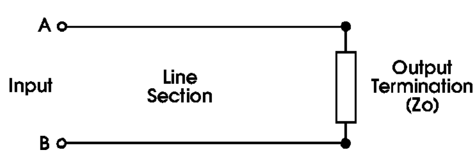


Fig.10. Perfect line termination

19. In practice it would be unusual for a length of line to be terminated by a resistor. The output termination is more likely to be the input impedance of an amplifier and the input termination is more likely to be the output impedance of yet another amplifier. A very common termination is met in the use of TV aerials, where the line input termination is the output impedance of the aerial and the line output termination is the input impedance of the first amplifying stage of the receiver.

SIGNAL PROPAGATION

20. When a radio frequency signal is delivered onto a transmission line the wave propagates along it by using the magnetic and electric fields surrounding the line and formed between the conductors. Each section of conductor forms an inductive element, around which the magnetic field must be allowed to grow, and at the same time a capacitor is formed between the lines which must be charged, both are shown by Fig.4.

21. In each case time will be taken for the fields to form and reach their maximum value. This has the effect of reducing signal velocity along the line. A finite time can always be specified for a signal to pass from one end of a transmission line to the other. In some cases the inductive and capacitive characteristics are enhanced in order to increase the time taken. In these cases the device is referred to as a **delay line**. One of the applications in which this effect is used will be met later in the course.

22. When currents flow in the resistance of the line and leakage takes place between the conductors that form it, energy is dissipated in the form of heat. It is also possible for the fields to lose energy by propagation into the surrounding space. The sum of these losses, from whichever form, is referred to as a **propagation loss** and the designer must take it into account when deciding how to deliver signals from place to place.

EFFECTS OF TERMINATION

23. The previous text has indicated how a transmission line can be terminated in order to transfer maximum power to and from an attached circuit. There are , however, certain cases in which this type of termination is not used. The two particular ones of interest are the **short circuit termination** and the **open circuit termination**. Both of these terminations are now considered.

Short Circuit Termination

24. A length of transmission line terminated by a short circuit is illustrated at Fig.11. Since the termination is a short circuit and without resistance, it is not possible for energy to be dissipated at the termination. This is, of course, a theoretical concept. In practice the line termination will dissipate a tiny amount of energy but so little as to be of no consequence. Hence, all of the energy must be reflected back along the line in the same basic form as it arrived.

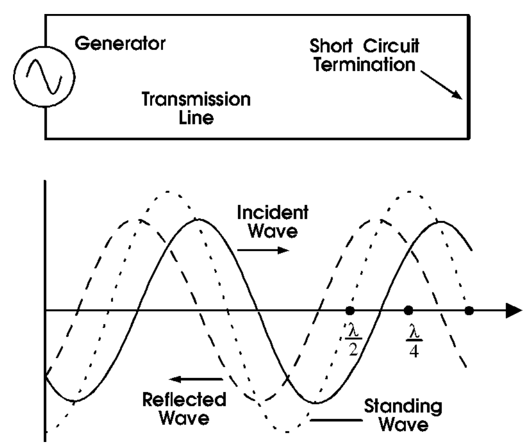


Fig.11. Voltage Waveform for Short Circuit Termination

25. The effect at the termination is shown by the waveforms drawn below the transmission line of Fig.11. The **incident voltage wave** has travelled from the line source, or generator, and reaches the termination. It is in continuous motion, rising and falling when viewed at any point on the line. At the termination, the potential difference across the line must be zero because it is a short circuit. In order to achieve this zero potential the **reflected voltage wave** undergoes phase inversion at the termination. If the incident waveform is imagined to be a series of very narrow pulses, the tops of which vary in amplitude with the incident waveform, then phase inversion merely inverts each one as it arrives and sends it back along the line. Thus the reflected waveform is comprised of all the inverted pulses travelling back towards the generator.

26. At all points on the line the incident and reflected waves add together and form what is called a **standing wave**. This standing wave is such that it has a voltage zero, also called a **node**, at the end of the line and at even numbers of quarter wavelength back from the termination. Also, the standing wave has a voltage maximum, called an **anti-node**, one quarter wavelength from the end of the line, which is repeated every odd quarter wavelength back from the termination.

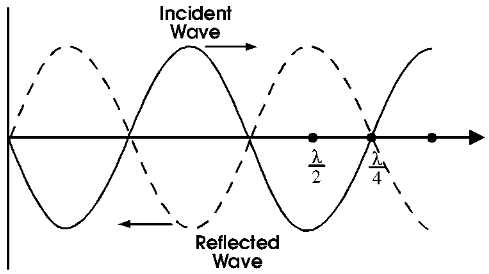


Fig.12. Line state one eighth of a wavelength later than Fig.11

27. If the incident wave is allowed to advance towards the termination by one eighth of a cycle more than its position of Fig.11, the situation would now be as shown at Fig.12. Here the reflected wave must also move one eighth of a cycle further away from the termination as illustrated. The condition at the termination must still hold, i.e., no power to be dissipated, hence, the voltage wave is reflected in antiphase, creating 0V at the end of the line. On this particular occasion the incident and reflected waves are in antiphase. This causes them to cancel at all points on the line, as a result of which the standing wave falls to zero.

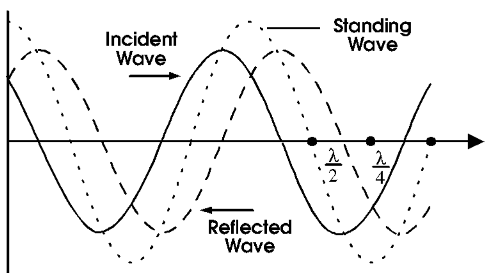


Fig.13. Line state one eighth of a wavelength later than Fig.12

28. Fig.13 shows the next one eighth of a cycle step of the incident wave towards the termination and the reflected wave away from it. Once again a standing wave is formed albeit inverted, however, that apart it has identical features to the standing wave in Fig.11. The reader will now realise that the zero standing wave of Fig.12 will only occur on the two occasions during the cycle when incident and reflected waves are in antiphase. At all other times a standing wave is formed that will have a magnitude dependent upon the positions of the two travelling waves. The standing wave has zero points, nodes, at the termination and every even quarter wavelength back along the line, it also has points of maximum, antinodes, at every odd number of quarter wavelengths.

29. The current waveform on the line has different characteristics to the voltage waveform. At the short circuit termination, the current is effectively flowing through a conductor of zero resistance, so there is no restriction upon its value. In this case the current waveform is reflected in-phase, which is opposite in sense to that which happens to the voltage waveform.

30. The current waveforms are illustrated at Fig.14. The essential features are identical to the voltage waveform diagrams apart from the fact that, since the incident waveform is reflected in-phase, the waveform does not invert at the termination but merely bounces off and returns towards the source. The main points to observe in this waveform are that, yet again a standing wave is formed, however, this time the maximum, anti-node, occurs at the termination and every even number of quarter wavelengths back from it. Also the zero, node, occurs at one quarter wavelength back along the line and every odd number of quarter wavelengths thereafter.

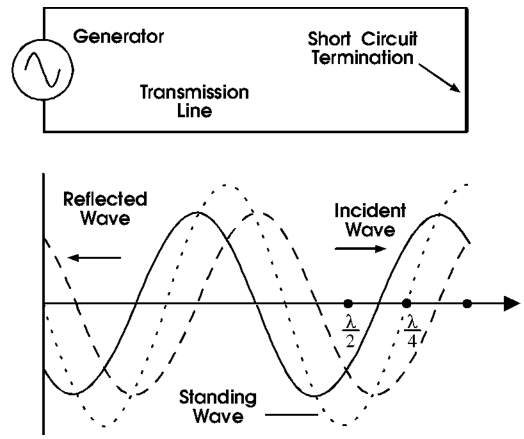


Fig.14. Current Waveform for Short Circuit Termination

31. There is no need to draw further current waveforms because the reader will know from studying the voltage waveforms that the features displayed in Fig.14, with regard to the standing wave, will be consistent. The main point to be aware of is that, whenever distribution of waves occurs, if the termination is not able to dissipate all of the energy contained within the wave, then that element which is reflected will travel back along the line and produce standing waves.

32. It is possible for these standing waves to produce dramatic heating effects because the energy is not released in any other way. This is one of the reasons for using impedance matching systems with radio aerial tuning units. If a mismatch occurs, the heat generated can cause damage to the line and to the transmitter involved, resulting in catastrophic failure of the radio. There are some cases in radar where the deliberate generation of standing wave patterns is used to control equipment operation, it is to these systems that the remainder of the text is addressed.

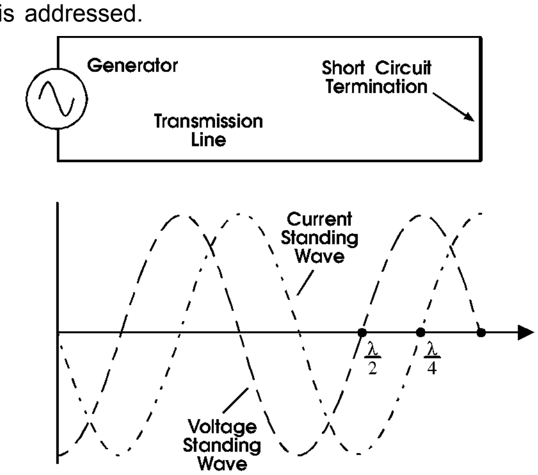


Fig.15. Short circuit termination Current and Voltage Standing Waves

Short Circuit Line Impedances

33. Current and voltage standing waves set up on a short circuit transmission line are illustrated at Fig.15. They produce impedance effects at a point on the line depending upon the values of voltage and current. Impedance **Z = V/I**, therefore, where the voltage is zero and the current is maximum, a low impedance is produced. On the other hand, where zero current and maximum voltage occurs, then a high impedance must be present.

34. At points in between these highs and lows the line will have an impedance depending upon the exact distance from the termination. A point of low impedance represents a series tuned circuit and a point of high impedance represents a parallel tuned circuit. In between these points the line will be either inductive or capacitive depending upon the distance from the termination. For a line with short circuit termination the important features are that:-

a. At the termination and points an **even number of quarter wavelengths** back a **low impedance**, zero, is produced.
b. One quarter wavelength from the termination and then **odd numbers of quarter wavelengths** back a **high impedance**, maximum, is produced.

Open Circuit Line

35. The alternative extreme connection to a short circuit is an open circuit. For this case the current at the termination must be zero and the voltage can be a maximum. A little thought on this will show that the current must now be reflected in anti-phase and the voltage in-phase. As a result, the waveforms drawn for the open circuit termination will be the reverse of those drawn for the short circuit termination. The resulting standing waves are illustrated at Fig.16.

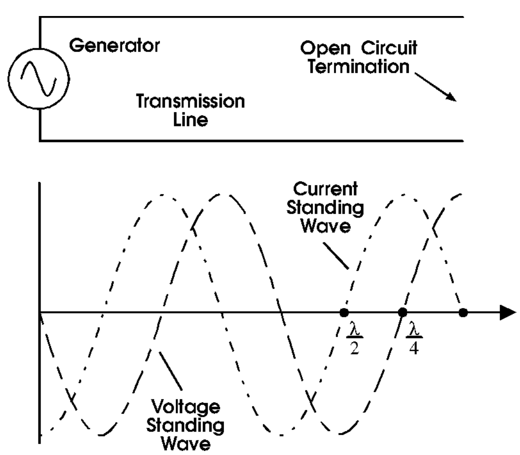


Fig.16. Open Circuit Line and its Standing Waves

36. All of the considerations and conclusions reached for this diagram are exactly the same as for the short circuit line. Impedance, **Z = V/I**, and again it will vary from point to point on the line. Thus for a line with open circuit termination the important features are that:-

a. At the termination and points an **even number of quarter wavelengths** back a **high impedance**, maxi mum, is produced.
b. One quarter wavelength from the termination and then **odd numbers of quarter wavelengths** back a **low impedance**, zero, is produced.

Employment of Short & Open Circuit Terminations

37. The two extreme types of termination are employed in various ways within radio and radar systems, some of which will be discussed in later material. A typical example is shown at Fig.17, where a length of transmission line is supported by what is usually called a **quarter wave, λ/4, stub**. The stub is formed from a section of transmission line that is cut to be exactly one quarter of a wavelength, λ/4, long at the frequency being propagated.

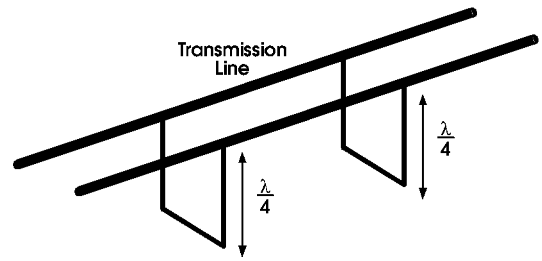


Fig.17. Transmission line with supporting λ/4 stubs

38. The section of line that forms the stub now acts as a junction at which the energy travelling along the line can split, some going along the line and some going down the stub. However, when the energy arrives at the bottom of the stub it encounters a **short circuit**. The stub section, with its short circuit, now sets up a standing wave that creates a high impedance at the line junction.

39. As a result, the high impedance discourages energy from leaving the line and travelling into the stub, however, a small amount of energy is extracted from the line in order to maintain the standing wave. The loss due to this cause is much lower than losses that would occur using other methods, including insulators, and it is certainly a lot cheaper because the stub can be made of exactly the same material as the line.

Transmission Lines at High Frequencies

40. When a pair of parallel lines is used to convey energy from point to point they will do so with little loss up to frequencies of about 30MHz. At higher frequencies the distance between the lines begins to exceed one half of a wavelength, λ/2, at the frequency in use. As this occurs the energy in the fields around the line begins to radiate and the losses increase sharply.

41. For frequencies above 30MHz and up to about 600MHz the pair of lines is enclosed in a conducting sheath, which reduces the losses. At frequencies above this the resistance of the wire increases significantly due to skin effect. This can be overcome to a large extent by using co-axial line in which the energy is very much carried by electric and magnetic fields within the surrounding sheath.

42. One technique used at these high frequencies is to employ a co-axial line with a central conductor formed from a hollow tube. This has the effect of reducing loss from skin effect. However, eventually a frequency is reached at about 2-3GHz for which even this will not overcome the losses involved. At this point a switch is made to waveguide. The main features of co-axial cable are:-

a. Easy to fit.
b. Relatively cheap against waveguide.
c. Flexible and robust.
d. Can operate over a wide frequency range.
e. Losses are unacceptable at GHz frequencies.

SELF TEST QUESTIONS

Read each question carefully and then select the single answer that you believe to be fully correct.

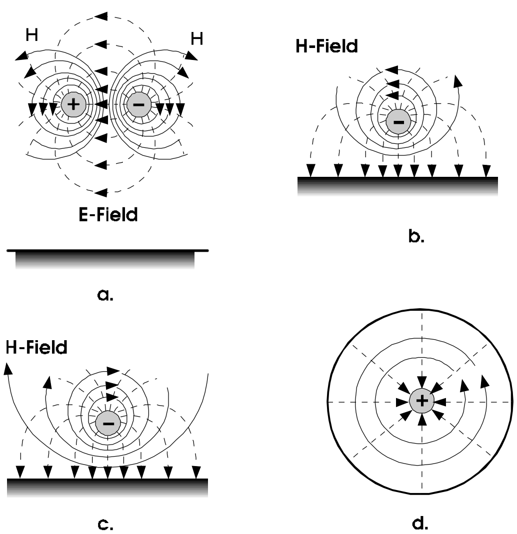
1. One purpose of a transmission line or waveguide system is to:-

   a. transport the transmitter nearer to the receiver
   b. convey signal energy from transmitter to antenna
   c. convey signal energy from receiver to antenna
   d. do all of the above

2. A transmission line employed to convey Radio Frequency energy between two points in a radar system will contain:-

   a. two conductors with a dielectric medium between them
   b. electric fields directed parallel to the line
   c. magnetic fields directed parallel to the line
   d. all three of a, b and c above

3. Among the following diagrams, the one that indicates the field pattern for a balanced line is:-



4. When Radio Frequency energy is conveyed by a transmission line the field pattern produced adjacent to it reverses polarity every:-

   a. half wavelength ($\lambda/2$) along the line
   b. quarter wavelength ($\lambda/4$) along the line
   c. half wavelength ($\lambda/2$) across the line
   d. quarter wavelength ($\lambda/4$) across the line

5. The feature known as a 'distributed constant' associated with transmission line, indicates:-

   a. the maximum length of line that can be used for a particular application
   b. the signal loss per unit length of line
   c. the magnitude of one of the primary characteristics associated with the line
   d. all of a, b, and c above

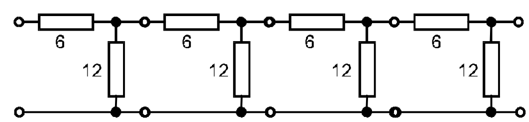
6. When a transmission line suffers from 'skin effect' it can be said that:-

   a. the frequency at which energy is being conveyed is low enough to allow the resistance of the conductors to have a significant effect
   b. the current flowing in the line is conveyed mainly in the centre of the line
   c. a large back EMF is being produced in the centre of each conductor, reducing the current flow in that region
   d. the effect falls as the wavelength carried gets longer

7. The characteristic impedance (Zo) of a transmission line is that value of resistance which must be:-

   a. connected across the line at regular intervals to balance the current flow
   b. connected in series with the line to balance the current flow
   c. used to terminate the line if all the energy being conveyed along it is to emerge at the other end
   d. used to terminate the line if all the energy being conveyed along it is to be correctly reflected

8. The following diagram illustrates the main characteristics of four sections of a transmission line. The likely characteristic impedance (Zo) for this line is:-



   a. 11.4Ω
   b. 11.8 Ω
   c. 12.1Ω
   d. 12.4Ω

9. When a transmission line is terminated by a short circuit, reflection of the incident waves is such that the:-

   a. volatge wave is reflected in-phase and the current wave is reflected in antiphase
   b. volatge wave is reflected in-phase and the current wave is reflected in-phase
   c. volatge wave is reflected in antiphase and the current wave is reflected in in-phase
   d. volatge wave is reflected in antiphase and the current wave is reflected in antiphase

10. A transmission line is accidentally cut in two. This means that, in the section which remains connected to the source:-

    a. a high impedance occurs $\lambda/2$ back from the termination
    b. a low impedance occurs $\lambda/2$ back from the termination
    c. a high impedance occurs $\lambda/4$ back from the termination
    d. a high impedance occurs $3\lambda/4$ back from the termination

11. When transmission lines are used at high frequencies:-

    a. losses are relatively small above 30MHz
    b. skin effect reduces with increasing frequency
    c. losses can be reduced by enclosing the lines within an outer sheath
    d. a changeover to waveguide becomes necessary at frequencies above about 5GHz