GENERAL DISCUSSION

INSTRUCTIONS

POWER LINE CARRIER

INTRODUCTION

Power Line Carrier is a term applied to 20 to 300 kilocycle frequency energy superimposed on power transmission circuits. Here the energy is confined almost entirely to the wire lines and not radiated into space as is common in radio broadcasting (550 to 1500 kc). This results in greater efficiency and makes it possible to transmit greater distance with less high frequency energy.

The carrier channel is an extremely reliable one over which intelligence for relaying, remote tripping, telemetering, load control, voice communication, and supervisory control can be transmitted between various points on the power system. In many applications, combinations of these functions utilize the same carrier channel. Several functions can be carried on sinultaneously over a single carrier channel by using audio frequency tones modulated on the carrier wave.

A comparison of carrier and power transmission and application principles of carrier are discussed briefly in the following paragraph.

POWER VS. CARRIER FREQUENCIES

An important difference between electric power and carrier transmission is the frequency. Although the fundamental principles of both are the same, many of the factors of primary importance at carrier frequencies are negligible at power frequencies and vice versa. For example, the power circuits are electrically short, and therefore, susceptible to approximate empirical solution, while the carrier circuits are concerned with electrically long circuits, in most cases. The relatively greater electrical length of carrier circuits results from the higher frequencies involved and not because of their mechanical length.

As an example of the wide difference in electrical lengths between the two types of circuits, consider a typical 220 kilovolt line of 750,000 circular mil conductors and 19 foot spacing. The wave length of such a line at 60 cycles is about 3100 miles. This means that the voltage at the receiving end of a full wave length line is 360° out of phase with that at the generating end. But the maximum power that can be transmitted over any given line occurs when the voltage at the receiving end lags the generator voltage by about 90 degrees. Beyond the 90 degree point the maximum power decreases. In other words, the longer the line, the less power transmitted. For this particular line, the theoretical power limits would restrict transmission to not more than a quarter wave length or a maximum distance of 770 miles. Considering the abovementioned transmission line at a carrier frequency of 60,000 cycles, the wave length becomes approximately 3.1 miles. This would indicate a maximum transmission distance of 0.775 mile for maximum power but with carrier actually distances of several hundred miles are possible.

RELATIVE EFFICIENCIES

Another important difference between power transmission and carrier transmission is the relative efficiencies. The losses in any transmission circuit may be considered to be made up of resistance and leakage losses, or as they are sometimes defined, series and shunt losses, respectively. The former are equal to I^2R and the latter to V^2G where R is the resistance of the line, V is the voltage and G is the leakage conductance. In most

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EFFECTIVE SEPTEMBER 1957

power transmission lines, the leakage losses in the absence of corona are small, hence, the solution of the problem of efficient transmission is to raise the voltage, thus decreasing the current. This is readily accomplished since most lines are electrically so short that the impedance is governed entirely by the step-up and step-down transformers and the associated load at the receiving end.

In the case of carrier transmission, the receiving equipment has little effect on the transmitting end impedance because the lines are electrically so long that most of the power is absorbed in the line. While the transmission efficiency at carrier frequencies may be quite easily calculated for uniformly constructed two-wire lines, the complexity of most transmission circuits is such that it is more practical to determine this efficiency by test. At first thought, it would seem that the very low efficiencies (in the order of 1%) which are quite common, would be entirely unsatisfactory. However, it should be remembered that the energy losses of carrier transmission do not involve large amounts of power, and, therefore, do not represent an appreciable economic loss.

ATTENUATION VS. FREQUENCY

In carrier transmission it is convenient to consider the transmission characteristic of a system in terms of attenuation or the diminuation of power along the transmission line. The ratio between the voltages, currents, or power at any two points is a measure of the attenuation of the circuit between these two points. However, it is not convenient in practice to express transmission losses or gains in terms of these ratios directly. The losses so expressed cannot be added to obtain the total loss, but must be multiplied. Consequently, this attenuation is expressed in decibels (db) which can be added directly and are defined as follows:

$$\text{db} = 10 \text{ Log}_{10} \frac{\text{Power Input}}{\text{Power Output}}$$

$$\text{db} = 20 \text{ Log}_{10} \frac{\text{Voltage Input}}{\text{Voltage Output}}$$

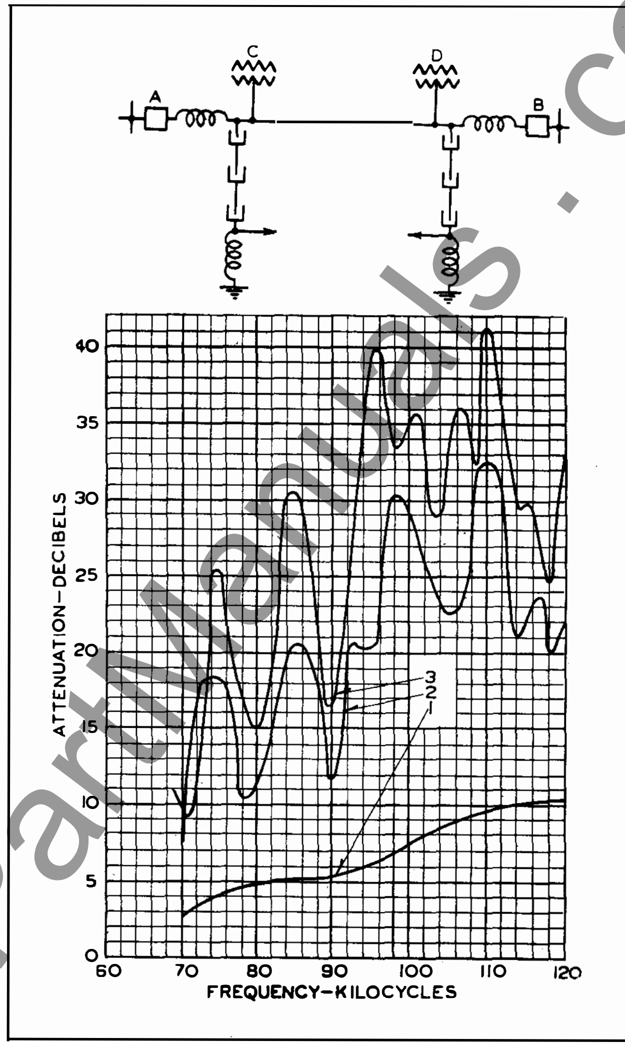


Fig. 1—Carrier Frequency—Attenuation Curve for a Typical Transmission Line.

$$\text{db} = 20 \text{ Log}_{10} \frac{\text{Current Input}}{\text{Current Output}}$$

Various power and voltage or current ratios and the corresponding decibels are shown in the following table:

TABLE I

Power Ratio	Voltage or Current Ratio	Decibels (db)	% Efficiency
1.26	1.12	1.0	79.5
1.58	1.26	2.0	63.4
2.0	1.41	3.0	50.0
2.51	1.58	4.0	39.8
3.16	1.78	5.0	31.6

Power Ratio	Voltage or Current Ratio	Decibels (db)	% Efficiency
4.00	2.00	6.0	25.1
5.01	2.24	7.0	20.0
6.31	2.51	8.0	15.8
7.94	2.82	9.0	12.6
10.0	3.16	10.0	10.0
15.85	3.98	12.0	6.3
25.12	5.01	14.0	3.98
39.81	6.31	16.0	2.51
50.12	7.08	17.0	1.99
63.10	7.94	18.0	1.58
79.4	8.91	19.0	1.26
100.0	10.	20.0	1.0
1000.0	31.6	30.0	0.1
10^5	316.2	50.0	0.001
10^8	10,000.0	80.0	0.000001
10^{10}	100,000.0	100.0	0.0000001

Standard commercial power line carrier equipment works thru 30 to 80 db attenuation. Thus it is obvious that the most practical way to consider carrier is in terms of decibels and not in terms of power ratios or efficiency. If a transmission circuit offers 15 to 20 db attenuation to the desired carrier frequency, and the desired signals are 10 db or more stronger than the unwanted signals, then a carrier set which will operate thru 30 db attenuation is ample even though its rated power output appears low.

CARRIER TRANSMISSION In Overhead Lines

The attenuation of a two-wire uniform line in decibels increases with frequency. This increase is approximately linear for untapped uniform lines but in some cases the departure from linearity is very large. If, instead of a simple two-wire line, there are one or more branch circuits, the increase in attenuation is no longer directly proportional to the frequency. In fact, a change of 5% in the frequency may easily cause an increase or decrease in attenuation of as much as 25 decibels in some circuits. If the circuit is changed by switching so that more or less branches are in use, there may be equally great changes in the attenuation. Therefore, it is desirable that the line be studied carefully in order to determine the most suitable frequency for transmission.

To determine if a suitable carrier channel is available, test data should be taken to plot an attenuation-frequency curve of the circuit. Such a curve for a typical line under various conditions is shown in Figure 1. The characteristics of line AB alone with line traps at each end is shown in Curve 1. The characteristics of the same line with tap circuit C and its associated equipment is given in Curve 2. The introduction of this circuit not only increases average attenuation of the line AB, but also introduces irregularities caused by reflection and absorption effects. Thus, between points 5000 cycles apart, there is as much as 10 db attenuation difference.

The characteristics of the same line section AB with both tap lines C and D is shown in Curve 3. This curve not only shows an increase in the average attenuation but also reflection effects that are so pronounced as to give a 20 db variation in attenuation over a 5000 cycle interval. Furthermore, there may be no similarity between the last two conditions. That is, the peaks and troughs in attenuation may not occur at the same frequencies. This frequency attenuation curve may be obtained by using the carrier transmitter-receiver set-up for regular operation, or a test oscillator and vacuum tube voltmeter may be used. The tests should include as many normal and abnormal conditions as can be set up.

It is desirable to discuss characteristic or surge impedance. Characteristic impedance* is defined as the input impedance of an infinite length line. It will have a finite value due to shunt capacitance and conductance. For finite length lines, surge impedance is the value of terminating impedance which will make the input impedance equal to it, regardless of the line length. There is no reflection from the terminating end when the line is terminated in its characteristic impedance. The characteristic impedance is determined by configuration, insulation, and other line constants, and is independent of line length.

Returning to the discussion of reflection and absorption, consider a line having an

TABLE II

Line Voltage kv	Approximate Attenuation db per Mile									
	Phase to Phase Coupling					+Phase to Ground Coupling				
	20kc	50kc	100kc	150kc	300kc	20kc	50kc	100kc	150kc	300kc
230	.03	.05	0.75	.107	.20	.040	.062	.094	.13	.25
138	.041	.065	.09	.12	.215	.051	.081	.113	.15	.27
115	.05	.075	.102	.135	.27	.062	.094	.130	.16	.34
69	.055	.08	.11	.145	.29	.069	.100	.137	.18	.36
34.5	.073	.10	.13	.18	.38	.094	.125	.160	.22	.47
13.8	.12	.15	.18	.215	.45	.150	.190	.220	.27	.56

+Phase to ground losses vary with length of circuit, ground return impedance, and the presence of other conductors in the vicinity. These values given are approximately 1.25 times the phase to phase values.

electrical length of 90° of 1/4 wave length for a particular frequency. If the remote end of this line is open, the input impedance is lower than the surge impedance. If the line were 270° (3/4 wave length) long, the input impedance would also be low, but not quite so low as for 1/4 wave length. However, at 180° (2/4 wave length), the impedance is higher than the surge impedance, and at 360° (4/4 wave length), it is not quite so high.**

As the length is increased, it is usually possible to distinguish between the odd and even quarter wave lengths, up to about 50 quarters or 4500°. However, the maximum and minimum peaks approach the surge impedance and are not easily recognizable on long lines. The units of length, (electrical degrees or quarter wave lengths) are dependent as much on frequency as upon mechanical length. Based on previous assumptions, a 15.5 mile line would be 20-quarter wave length at 60 kc. Its input impedance would be higher than the surge impedance of the line, since, as was pointed out above, even quarter-wave-length lines have relative high input impedance. If the frequency were changed to 63 kc., the 15.5-mile line would be 21-quarter wave lengths, and the input impedance would be below the surge impedance corresponding to an odd quarter wave-length line. In other words, the maximum and minimum would be separated by 3 kc. or one-fourth the frequency which corresponds to the wave length of the line. Also, for a 15.5 mile, 20-quarter wave-length line, there will be approximately 16 maximum and 16 minimum (impedance peaks) in the carrier frequency band of 50 to 150 kc. These variations in impedance may have considerable effect on the proper adjustment of the carrier transmitter.

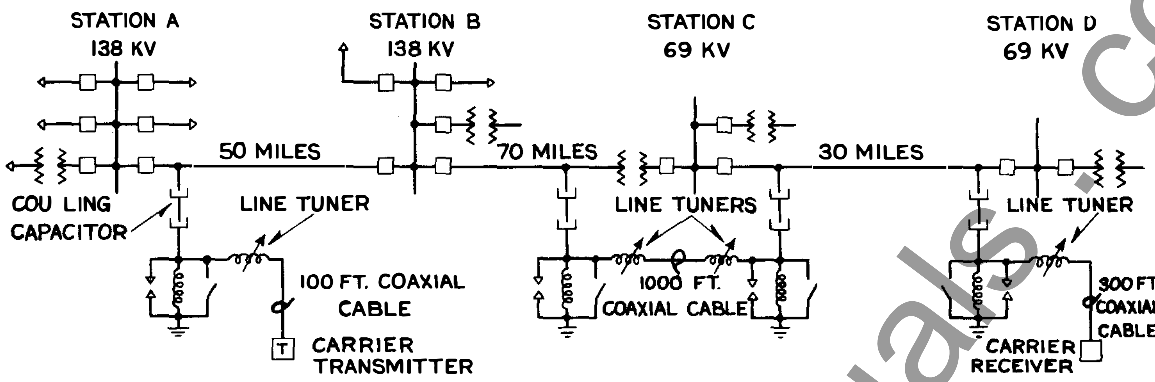
In the case of branch circuits, the impedance minimum usually represents absorption which causes high attenuation. Therefore, short lines and branch circuits should be carefully studied.

ATTENUATION ESTIMATING DATA

Where specific tests or information on the carrier losses are not available, the follow-

*For a more complete definition and discussion of characteristics impedance see chapter on "The Infinite Line" in Communication Engineering, by Everitt. (See Bibliography).

**The large difference in input impedance at the odd and even quarter wave lengths is due to reflection. A complete discussion of this phenomenon is beyond the scope of this leaflet, and reference is made to a very excellent discussion in the chapter on "Reflection" in Communication Engineering, by Everitt. (See Bibliography).



ESTIMATION OF CARRIER CHANNEL ATTENUATION AT 100 KC

1. COUPLING LOSS AT STATION A	5.0 db
2. BRANCH CIRCUIT LOSS AT STATION A (4 BRANCHES)	7.0 db
3. 50 MILES OF 138 KV LINE	5.7 db
4. BRANCH CIRCUIT LOSS AT STATION B (4 BRANCHES)	6.0 db
5. 70 MILES OF 138 KV LINE	7.9 db
6. BY PASS COUPLING LOSS AT STATION C	2.0 db
7. BY PASS COAXIAL CABLE LOSS AT STATION C	0.5 db
8. 30 MILES OF 69 KV LINE	4.1 db
9. COUPLING LOSS AT STATION D	1.2 db
TOTAL	39.4 db

Fig. 2—Typical Example of Estimating Attenuation of a Carrier Channel at 100 KC Using Phase-To-Ground Coupling.

ing general data can be used to estimate the attenuation through which it will be necessary to operate. These values are approximate and average values and the actual losses on a specific circuit may vary either way. However, the carrier equipment will provide sufficient margin in most cases to permit relatively large deviations from the stated values.

In addition to the line attenuation losses shown, coupling or terminal losses also will occur. These vary slightly with the terminal equipment employed, depending on the carrier frequency. When the line tuner is mounted at the coupling capacitor, the loss is quite small, and for estimating, a value of one decibel is used generally. If the carrier set is mounted indoors and connected thru coaxial cable to the line tuner, and additional loss is introduced, which for estimating purposes, is as follows:

TABLE III

Approximate Attenuation in Coaxial Cable

Frequency in kc	Loss in db per 1000 Ft.
20	.20
50	.32
100	.50
150	.60
300	.90

If the line tuner is mounted remote from the coupling capacitor and connected thru coaxial cable, the terminal loss will increase considerably. In this case an impedance matching transformer should be used at the coupling capacitor. The attenuation introduced increases with frequency and decreases with increasing capacity of the coupling capacitor. Coaxial cable lengths up to about 500 ft. introduce an additional attenuation of ap-

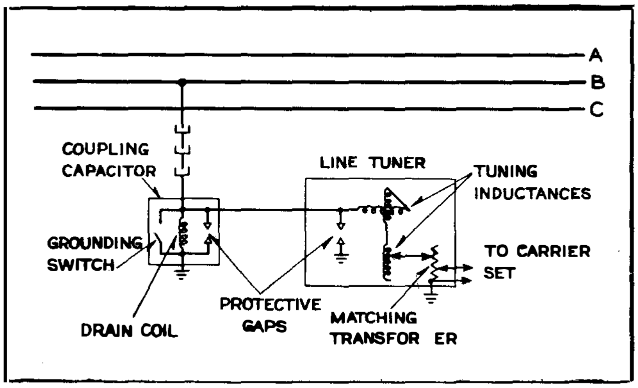


Fig. 3—Line-to-Ground Carrier Coupling and Tuning Circuits.

proximately two db.

On circuits where branch lines provide one or more paths for carrier energy loss, additional attenuation is introduced. When the carrier equipment is connected at a point in the system from which other untrapped circuits radiate, the calculated maximum loss in decibels at any frequency is:

One additional circuit	3.0 db
Two additional circuits	4.8 db
Three additional circuits	6.0 db
X additional circuits	$10 \log_{10} (X+1)$ db

The coupling losses are increased also when untrapped branch lines extend from the point where the carrier transmitter or receiver is coupled. For estimating purposes one db per branch circuit can be added.

When untrapped branch circuits are encountered at any intermediate point in the carrier channel, the calculated maximum loss in decibels at any frequency is:

One additional circuit (equivalent to three paths for the carrier energy)	4.8 db
Two additional circuits	6.0 db
Three additional circuits	7.0 db
X additional circuits	$10 \log_{10} (X+2)$ db

The above figures are all based on branch circuits which do not introduce serious reflection losses by being of a length equal to

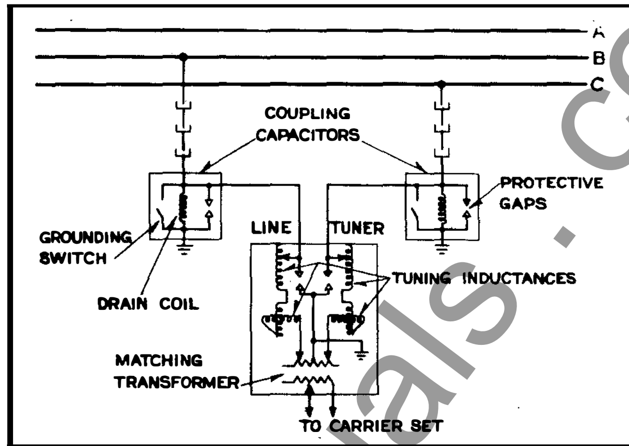


Fig. 4—Phase-to-Phase Carrier Coupling and Tuning Circuits.

odd quarter wave lengths of the selected frequency. Only stud end taps having an attenuation of 5 db or less (based on Table 2) and particularly those with an attenuation of 1 db or less, need be considered as possibilities of introducing serious reflection losses. Note also that the termination of the tap is important, since any connected equipment, even if only a potential transformer, will increase the attenuation of the tap circuit, and consequently reduce the possibility of large reflection losses.

The values given for branch circuit losses are calculated maximum values based on pessimistic conditions, and serve as an application guide. These losses will be considerably less than shown at certain frequencies, and if the choice of frequency is not limited, one should be chosen which gives the lowest attenuation. (The most satisfactory frequency can be obtained from a frequency-attenuation curve of the circuit).

A typical example of estimating the attenuation of a carrier channel is illustrated in Fig. 2. In this case it is desired to establish a phase to ground, 100 KC channel between stations A and D. At station A there are four additional branch circuits which introduce a loss of 7 db. The transformer bank on the bus is assumed to have a high impedance to the carrier frequency thus introducing negligible losses. This with a 5 db coupling loss, makes the total attenuation at station A 12 db. From Table 2, the line from A to B

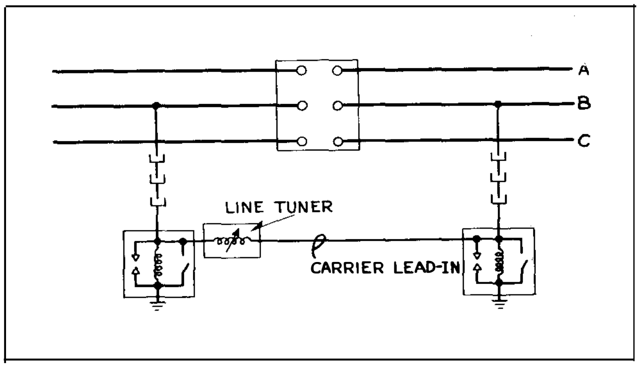


Fig. 5—Schematic of A Short Carrier Frequency By-Pass.

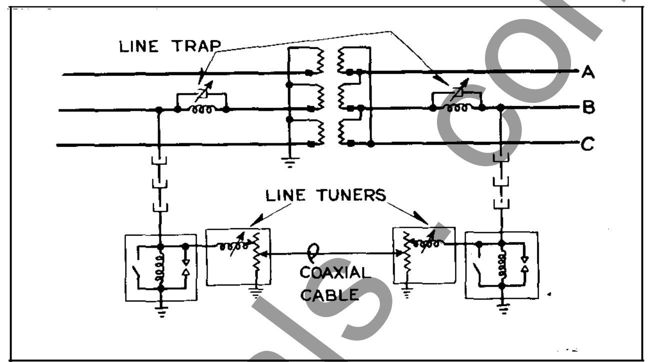


Fig. 6—Schematic of A Long Carrier Frequency By-Pass.

using phase to ground coupling at 100 KC introduces an attenuation of 5.7 db. At station B there are 2 additional branch circuits (the through carrier circuit is considered a single circuit in this case) which add 6 db to the total attenuation. The 70 mile line section from B to C adds 7.9 db. At station C there are two coupling losses of 1 db each, plus a coaxial cable loss of 0.5 db from Table 3. The line from C to D adds 4.1 db and the coupling at D adds 1.2 db. Thus the total estimated attenuation of this circuit is approximately 39.4 db.

The important consideration in any application is the overall circuit attenuation from transmitter to receiver. If the line attenuation is low, the coupling, terminal and branch circuit losses can be correspondingly high. On the other hand if a large portion of the available attenuation is used up in the line, then the other losses become more important and must be given careful consideration.

Carrier Transmission In Power Cables

Carrier transmission over a power cable is much more difficult because of the characteristics of the cable. The inductance of cables is small, while in comparison the resistance and capacitance are large. This means high losses and attenuation, and gives a value of surge impedance which may be as low as 1/10 of that for open lines. Hence, cables offer considerably greater attenuation to the carrier frequencies and often make carrier transmission quite difficult, particularly where the cable sheath is not continuous. Carrier transmission over cables should be given special attention.

The Carrier Circuit

The carrier frequency energy normally is impressed on the power circuit between one conductor and ground or between any two phase conductors. The former is termed phase to ground coupling, and the latter is termed phase to phase or interphase coupling.

The carrier energy is introduced onto the transmission lines thru a coupling capacitor and line tuning unit. One capacitor unit is required for phase to ground coupling as shown in Figure 3, and two are required for phase to phase coupling as shown in Figure 4. The capacitive reactance of the coupling capacitor is neutralized by the inductive reactance of the line tuning unit at carrier frequencies. This provides a low loss series resonant circuit between the carrier transmitter-receiver and the power transmission circuit. The drain coil mounted in the base of the coupling capacitor has a high impedance to carrier frequencies but a low impedance to 60 cycle current. This provides a path to ground for the 60 cycle charging current of the coupling capacitor without appreciable loss of the carrier energy. The protective gap across the drain coil protects the carrier equipment from any high surge voltages which may occur. The grounding switch permits the carrier lead to be grounded directly for maintenance of the carrier equipment.

With phase-to-ground coupling, the other two phase conductors, together with the earth, act as the return path for the carrier signal. Very approximately, half of the signal returns in the ground path and the other half is divided between the two phase wires. The resistance of the phase wires to the carrier frequencies is roughly one ohm per mile, as compared with average earth resistance of 20 ohms per mile. Thus the attenuation in phase-to-ground coupling is reduced by the presence of the other two phases. When a two-phase or three-phase-to-ground coupling is used, the attenuation is increased, since more of the return current is forced to flow in the earth.

The type of coupling employed with any particular application is determined by the individual requirements of that application. Relaying and supervisory control usually will employ a phase-to-ground carrier channel. For other types of transmission, especially communication, the interphase circuit is more often used.

While the transmission line offers an excellent carrier circuit medium, it is well to re-emphasize that proper consideration must be given to the following: the presence of branch lines, taps, or spurs of such a length as to offer interference from reflection, or absorption of certain carrier frequencies; power factor correction capacitor banks which may offer a series shunt; the presence of power transformers in the transmission circuit, which may completely or partially block the passage of carrier.

The high attenuation introduced by branches or taps at certain frequencies usually can be overcome by choosing a frequency in which the transmission characteristics are good over the circuit used for any switching condition on the system. An alternate method is to use line traps at the tap or connecting point of the offending circuit. These traps are adjusted to offer a high impedance to the carrier.

By-pass equipment is used to transmit the carrier energy around a transformer bank, a bus or breaker, and for other circuits where a continuous carrier channel is desired independent of switching. Two forms of the by-pass are used - the short by-pass of figure 5 and the long by-pass of figure 6. Both consist of capacitors and inductances which form a tuned circuit of low impedance around the open breaker, bus, or transformer bank for the particular carrier frequency, and a high impedance for the power frequency currents.

The short by-pass requires only one line tuner and can be used where the distance between the coupling capacitor does not exceed roughly 100 feet and where the total circuit attenuation is not too high. The cable connection between the capacitors should approximate the characteristics of an open line and be well insulated to reduce the leakage to ground particularly during rain and sleet.

Line traps, as shown in Figure 6, may be necessary if the by-pass equipment has a low impedance to ground at the carrier frequency being used. Line traps are used at each end of a relaying carrier channel to prevent short circuiting of the carrier output for an external ground fault on the same phase wire to which the carrier is coupled. They usually are not necessary to reduce losses. If the line traps are connected on the line side of the grounding switches, the line may be taken out of service and grounded without interrupting the carrier channel.

Frequency Allocations

The selection of frequencies for carrier functions on a transmission system should be given careful consideration. The rapidly expanding use of carrier makes it imperative that the most efficient use be made of the spectrum, so that future additions can be made without interfering with existing channels. This is particularly important in these days of interconnected systems where many or all of the companies involved in the interconnection are using carrier and are planning additional channels.

The spectrum normally used for power line carrier work is from 50 to 150 kc and it is expected that the bulk of the applications will fall in this range. However, specturm crowding on some systems requires that this range be extended so as to accomodate the desired number of carrier services, and to meet such requirements equipment is available for a frequency band from 20 to 300 KC. This band is covered in three steps by 20-50, 50-150, 150-300 kc equipment.

The single sideband modulation system approximately doubles the number of modulated carrier channels which can be accommodated in a given frequency spectrum by requiring only half the band width formerly necessary with other systems of modulation. The single sideband system consists of converter units which are added to double sideband (A.M.) equipments to make the conversion. In this way, a carrier system can be planned using double sideband equipment initially and later converting it to single sideband when the frequency spectrum becomes crowded.

Several factors must be considered in allocating a frequency for a new channel or in selecting carrier frequencies for several services. The first consideration is that the new frequency, or frequencies, not interfere with existing channels. This directly affects the separation required between channels, and this separation is largely a function of the type of service which the channel performs. For example, a relay carrier channel is usually narrow band and would require the minimum separation between channels for no interferance while a tone-modulated telemetering channel is broad, (usually 6 kc) and would require the maximum separation between channels. The selectivity characteristics of the receivers as well as the power levels of the transmitters have a direct bearing on the minimum separation permissible.

Noise and Interference

Noise is a random phenomenon covering a wide frequency band and contains components of all frequencies in the band. Very little is known concerning the actual magnitude of noise present on power systems. However, enough is known of the nature of noise so that steps can be taken in the design of equipment to minimize its effects. When noise produces unwanted signals which prevent proper functioning of the carrier system, it is called interference and action must be taken to minimize its effect.

Interference can be reduced by various expedients, all of which attempt to distinguish between wanted signal and interference. For example, the band width of the receiver may be narrowed, and since noise power is proportional to band width, narrowing the band to one quarter reduces the noise power to one quarter and the noise voltage to one half, or doubles the signal-to-noise ratio.

The use of audio tones to modulate the carrier wave further reduces the interference effect. For example, if the audio tone receiver band width is one-tenth the carrier receiver band width, then the noise accepted by the tone receiver will be one-tenth that of the carrier receiver. The use of the single sideband system of tone or voice modulation increases the signal-to-noise ratio over a double sideband system by 8 times or 9 db. The use of a biased detector properly adjusted gives a further possibility of increasing signal-to-noise ratio by approximately two to one, or 3 db.

The signal-to-noise ratio will vary with the attenuation through which the equipment must work. The higher the attenuation, the more sensitive the receiver (assuming constant transmitter output), and the lower the signal-to-noise ratio. For low attenuation circuits (below 33db), adjustment of receiver band width and sensitivity is usually all that is necessary to prevent interference with the proper functioning of the equipment. Carrier relaying falls within this range of attenuation, and the simple expedient of operating the equipment at a signal level well above noise level provides adequate margin of safety. In hundreds of carrier relaying installations, no case has been encountered where noise has resulted in improper operation of the equipment.

In relaying applications of carrier, it is extremely important that random noise does not interfere with the carrier signal, either by producing an unwanted signal which would block tripping, or cancellation of a wanted signal, which would cause incorrect tripping. However, the requirements of other services which utilize the carrier, such as supervisory control, telemetering, or emergency communication are not so severe, and some interference with the wanted signal usually can be tolerated, if the interference is random in nature.

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WESTINGHOUSE ELECTRIC CORPORATION

METER DIVISION • **NEWARK, N.J.**

Printed in U.S.A.