IMPULSE NOISE ON POWER LINE CARRIER WITH REGARD TO PROTECTIVE RELAYING

A Thesis

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by

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ABSTRACT

There is a great demand for reliable, high-speed communication systems for use as protection links between individual line sections in power system networks. Protection signals are generally transmitted to selectively disconnect faulted line sections from the system. The transmission medium considered is the high-voltage line itself. This thesis investigates solutions to difficulties encountered during transients caused by switching operations, lightning discharges and malfunctions on the line. The total system concept is presented and limitations on present facilities utilized are given. The underlying criterium for any system modification considered is that neither the reliability nor the security parameters of the communications link, which normally are at opposite ends of a balance, be sacrificed in order to improve either one.

Electrical impulse noise induced into the receiving system of a protection link by the operation of line disconnect switches was recorded. The amplitude and duration of each individual impulse combined with the impulse rate observed indicate that communication need not be interrupted during such noise occurrence. Yet high signal energy and receivers with wide bandwidths are preferred. Efficient methods of power and bandwidth utilization are pointed out. Improvement possible in a commonly used FSK subcarrier signalling system is experimentally verified. The use of clipping and blanking techniques were analyzed to be desirable, however, tests on an existing power line carrier system were unsuccessful.

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PRINCIPAL SYMBOLS AND TERMS

AVC - automatic level or volume control

C - channel capacity

dB - decibel

dBm - power expressed in dB with reference of 1 milliwatt

DSB - double sideband modulation

false trip - undesired receiver output caused by noise being mistaken to be a tripping command

f_g - guard frequency

f_s - suppressed carrier

f_t - trip frequency

FM - frequency modulation

FSK - frequency shift keying

IF - intermediate frequency amplifier

kHz - 1000 hertz

kV - 1000 volts

ms - millisecond

n - noise power density

Ω - ohm

reliability - property of communications channel to operate when required

RF - radio frequency

security - freedom of false trips due to noise

S/N - signal to noise

SSB - single sideband modulation

w - power

W - bandwidth

1. INTRODUCTION

In the operation of high voltage networks for the transmission of electric power, continuity and reliability of service is of paramount importance. To this purpose and also to prevent damage to equipment in the event of a fault, usually a short circuit or circuit to ground, it is frequently necessary to disconnect affected line segments. High reliability of the disconnection procedure is required. Yet unnecessary disconnection should be avoided to alleviate consequences such as loss of production and inconveniences.

Numerous methods are utilized for the protection of lines and equipment. A very important method, upon which our attention will be focused here relies on the transmission of a switching or control signal, as required, over carrier links using the rugged power transmission line itself (Alsleben et al, 1967; Brown et al, 1960) as the communication medium. At the remote end of the line the received signals permit extremely rapid co-ordination in the operation of the switching equipment. However, as any technical method, it poses some problems of its own, mainly concerned with the reliability and security of the protection provided. This study is devoted to an analysis of the factors affecting these parameters and submits some proposals for their improvement.

The two types of line fault detection methods commonly utilized are the monitoring of line impedance or the comparison of the relative phase angle between opposite ends of line segments. The former method as well as transformer protection are considered here. Consequently, the requirements of the communication link are simply to rapidly close, upon command, a contact at the other end of the power line.

The difficulties experienced are not so much in equipment failure, but in electrical noise on the power line. Such noise frequently masks the signal, rendering the receiver inoperative, or causes the occasional contact closure. Among the chief causes of error are arcs generated by faults, operation of disconnect switches and circuit breakers, and lightning impulses (Bozoki, 1968; Imaide et al, 1964; Sakic, 1968).

The ideal situation, in which there is total reliability of having a contact close when desired as well as absolute security of having no false contact closures, however, is generally not required. The necessary compromise made between these two parameters is dependent on system configuration. In "transfer tripping", for instance, as used in impedance and distance protection (Alsleben et al, 1967; Quervaind et al, 1960), a local fault detection relay must also operate to key or accept a carrier signal. A spurious contact closure caused by the receiver would in this case have no adverse effects; however, high reliability is desired since a legitimate tripping signal may be required to pass through a faulted line. To directly control network circuit breakers by means of a carrier signal, on the other hand, requires high security. For instance, on very long transmission lines, a carrier signal is sent during normal switching to provide for simultaneous operation of circuit breakers at both ends. This prevents the unloaded end voltage from rising to a level at which arcing may occur. Distribution transformers in remote locations occasionally have circuit breakers only at the low-voltage side. To prevent minor transformer faults from destroying the whole unit also requires then that a carrier signal directly trip breakers at the network tiepoint. Fortunately, in these latter two cases, signal propagation conditions are generally expected to be good and therefore, it is conceivable to sacrifice some reliability for a gain in security.

A fundamental drawback is that the 50-400 kHz frequency band, usually reserved for power line carrier use, is generally congested with numerous other telemetering and voice channels so that modulation methods requiring little frequency spectrum have been adopted. Furthermore, government licensing authorities provide restrictions on signal energies utilized.

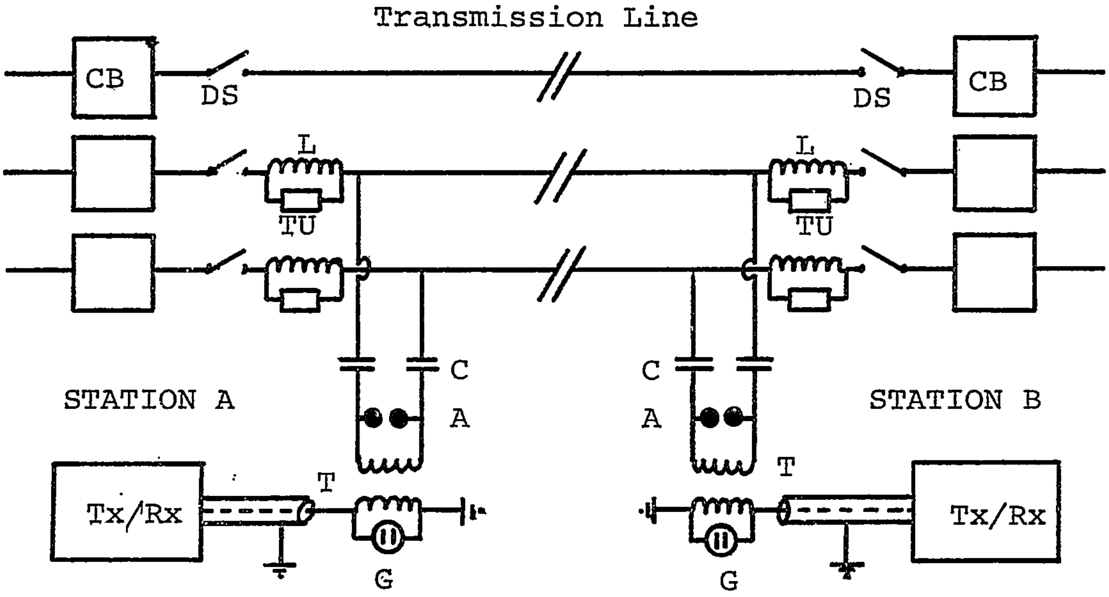
The thesis is divided into four main parts. The first deals with the attenuation and interference existing on the power line; the second, with methods and systems in use; the third, with impulse noise measurements during disconnect switch operation on a 138 kV and a 230 kV transmission line; and the fourth, with the actual investigation into methods by which communication may be improved.

2. COMMUNICATION DIFFICULTIES

A typical communications link including the terminal equipment and transmission medium is given on Figure 2.1. Phase to phase coupling is illustrated and is generally used where attenuation due to a faulted line is to be kept low. Besides having limited frequency spectrum on power line carrier the major problems are attenuation and interference. An air-gap and a gas discharge tube protect the carrier equipment from high-level transients. The high-speed air-gap A is adjusted for flashover at several kV while the slower acting gas-filled discharger G is generally chosen to conduct in the vicinity of 200 volts.

2.1 Attenuation

Attenuation of the signal is somewhat dependent on line configuration and increases with the square root of the frequency in the region of interest. For a 50-mile-long communications link operated at 100 kHz a typical signal attenuation is in the order of 16 dB under favorable conditions. In addition hoar frost and a single line fault may increase the attenuation by another 38 dB. Values for the various types of attenuation are given in Table 2.1. (Alsleben et al, 1967; Jones, 1959).



Symbol Designations:
A - Air spark gap
C - Coupling capacitor
CB - Circuit breaker
DS - Disconnect switch
G - Gas-filled arc gap
L - Wave trap
T - Line matching transformer
TU - Tuning unit
Tx/Rx - Transmitter/Receiver

FIGURE 2.1 TYPICAL POWERLINE CARRIER COMMUNICATIONS LINK

Table 2.1 Typical Signal Attenuations (for a 50-mile power line)

CAUSE	ATTENUATION
Coupling Equipment	6 dB typical (phase to phase, sum of both ends)
Line Loss	0.2 dB/mile at 100 kHz
Hoar Frost	up to 18 dB
During Line Faults	up to 20 dB (dependent on fault type and location)

During a line fault a 10w transmitted signal could therefore be received at +4 dBm with no hoar frost present.

2.2 Interference

Noise power originating from circuit breaker and disconnect switch operations, lightning impulses and corona as measured at a 3 kHz bandwidth across the coaxial communications cable are tabulated in Table 2.2.

Table 2.2 Noise Power at Receiving End

Spectrum: 40-400 kHz.
Bandwidth: 3 kHz.

TYPE	POWER (dBm)	DURATION	IMPULSES/s
Corona	-40 to -10	Continuous	180 Hz modulation
Disconnect Switch	20-30	0.2-1.5 s	to 800
Circuit Breaker	20	5-20 ms	1000-2000
Line Fault	-20 to +30	--	100-300
Lightning	30	to 1 s	1-40

These are typical values in the 40-400 kHz frequency range. Corona noise is continuous with a 180 Hz modulation (at 60 Hz power line frequency) and increases with line voltage. The other noises are impulsive in nature. During line faults the noise amplitude is very dependent on the fault current. Faults of several amperes produce high noise levels as during disconnect switch operation while established arcs of several hundred amperes produce little noise. (Alsleben et al, 1967; Bozoki, 1968; Imaide et al, 1964; Moynihan et al, 1951, 1955; Sakic, 1968; Udo et al, 1967).

The construction of line disconnects buswork, and circuit breakers affect noise amplitude or duration under normal switching conditions. Noise voltage decreases with increase in frequency. It is seen that the S/N ratio can become prohibitively low during impulse noise occurrence. For example, using a 10W transmitted signal at 100 kHz over a 50-mile line, even under favorable signal propagation conditions, can result in an instantaneous S/N ratio of -6 dB (at 3 kHz bandwidth) during the operation of a line disconnect switch.

3. METHODS AND SYSTEMS IN USE

The three main types of carrier terminals are:

(a) Type I: Single-purpose for transmission of protection signals only.

(b) Type II: Multi-purpose for simultaneous transmission of speech, telemetering, and protection signals.

(c) Type III: Multi-purpose for alternate transmission of speech and telemetering, or protection signals.

FSK, FM, DSB, and SSB systems with or without frequency-multiplexed amplitude or frequency-modulated subcarriers are conventionally used for protection purposes. Bartsch (Bartsch et al, 1961) has compiled pertinent information on power and bandwidth of typical systems.

In order to conserve precious frequency spectrum, SSB transmission, with the transmitted power normally being shared between voice, several telemetering channels, protection channel and the suppressed carrier is almost exclusively used in Saskatchewan. The protection subcarrier channel operates in the frequency-shift mode and utilizes the full carrier power when a trip or blocking signal is transmitted; during this short time the lower priority voice and telemetering signals are removed at the transmitter. This system corresponds to a combination of system Types II and III.

A block diagram of such a receiving system is illustrated in Figure 3.1. The suppressed carrier f_s is received at a

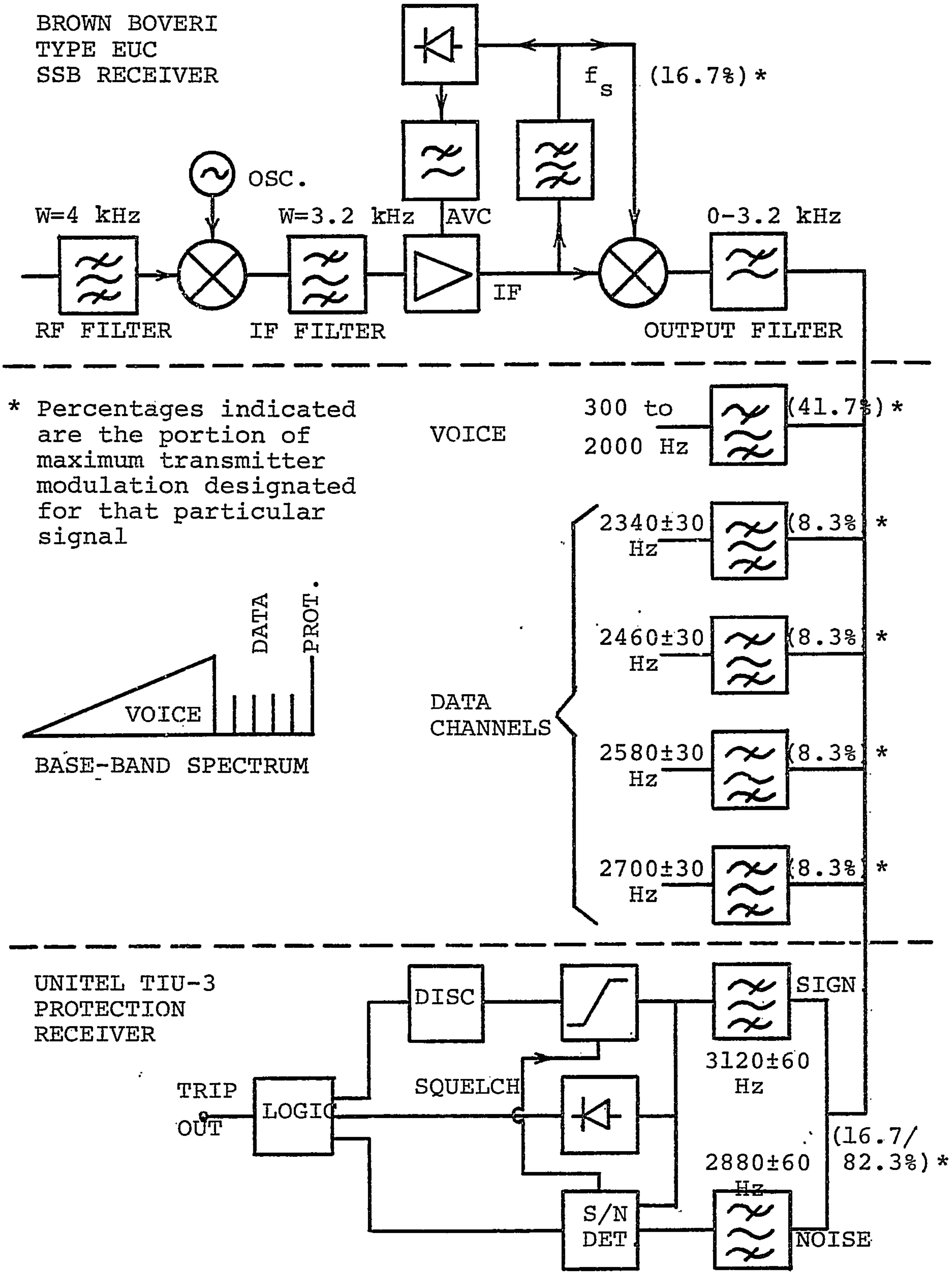


FIGURE 3.1 TYPICAL MULTI-PURPOSE SSB RECEIVING SYSTEM

level of 17% of maximum transmitter voltage modulation; the operation of the SSB receiving unit is self-explanatory. The protection receiver block diagram is of a Uni-tel TIU-3 unit and is representative of the basic operating principles used by various manufacturers. Its detailed operation is described in Appendix A.

Numerous utilities including the Saskatchewan Power Corporation receive occasional false trips on this type of receiving arrangement. Therefore such systems, at least in Saskatchewan, are restricted to protection schemes using fault detection relays at the receiving end also. To obtain additional security two TIU-3 receivers operating at different frequencies with output contacts placed in series or a similar channel with encoder/decoder attached are utilized. Since this apparently is the most popular receiver design at the present time its operation is elaborated on.

Figure 3.2 illustrates error rates (Schwartz et al, 1966, Ch. 7) for several binary systems. The curve for non-coherent FSK shows that the probability of error, which corresponds to the probability of receiving one false trip in an interval equal to the nominal transmission time, exceeds 1×10^{-1} for S/N ratios of less than 5 dB. This error rate is inadequate even for the protection schemes not requiring high security (Bozoki, 1968). The gain in security by biasing filters toward the guard frequency f_g and discriminator zero crossing frequency toward the trip frequency f_t was further supplemented by the incorporation of S/N detectors. The reason

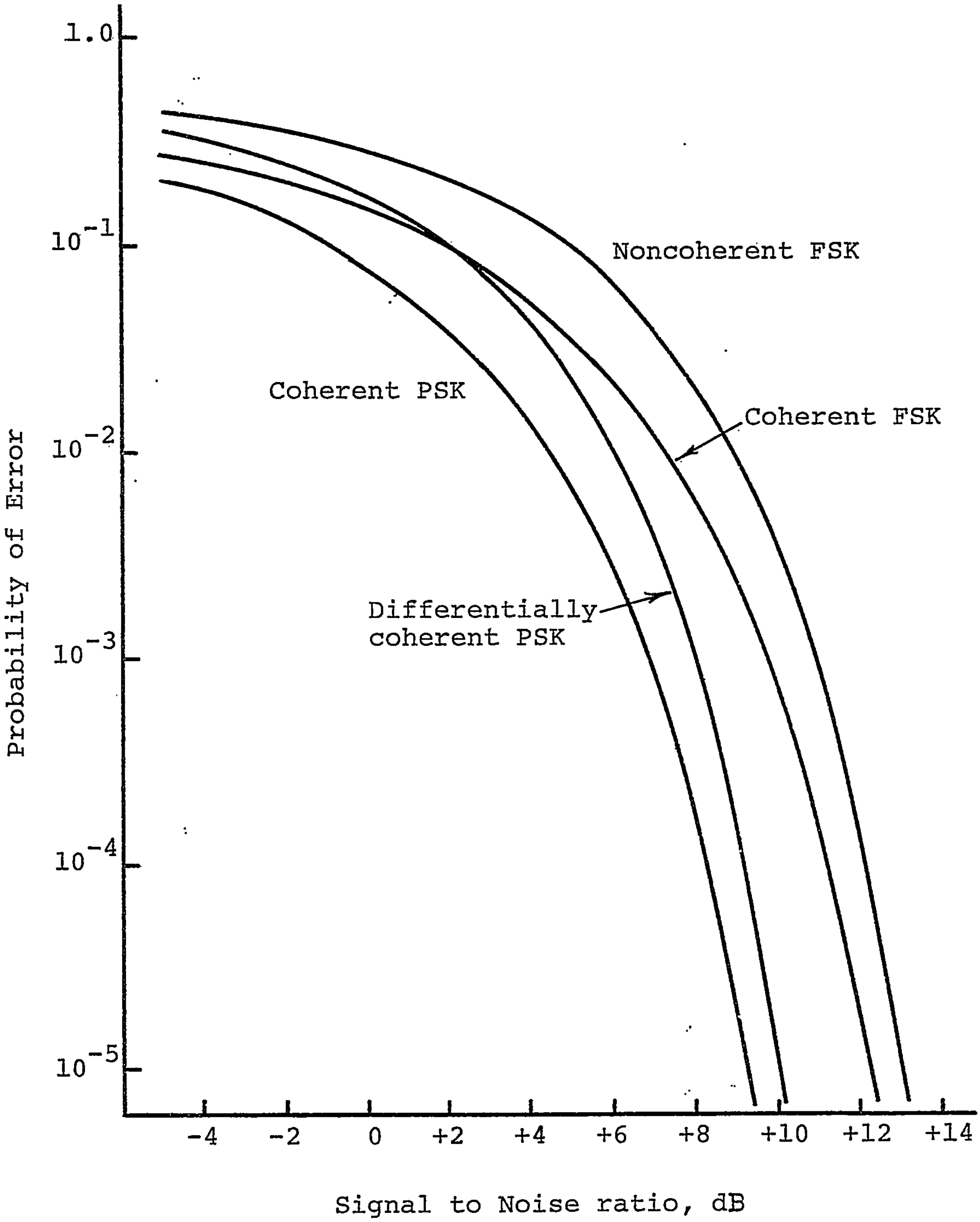


FIGURE 3.2 ERROR RATES FOR SEVERAL BINARY SYSTEMS
(Schwartz et al, 1966, Ch. 7)

for spurious outputs has been shown theoretically and experimentally, by Wacker (Wacker, 1967), to be the inability of the S/N detector to always squelch the receiver throughout the duration of a strong noise burst; the S/N detector is normally adjusted to inhibit an output when the S/N ratio in a 120 Hz frequency shift channel is less than about 12 dB. Bozoki (Bozoki, 1966) discusses ranges in security obtainable with changes in S/N settings and biasing. Optimization for a particular protection system is achieved by manipulation of these variables. However, for reliable operation these types of receiving systems demand high S/N ratios.

The Type III transmission system is especially efficient in its use of frequency spectrum and may be used in the intertripping and blocking protection schemes. In this mode of operation the protection transmitter and receiver are normally on standby. Only when station fault detection relays operate are the respective transmitters and receivers enabled (Bartsch et al, 1961). Full power and the whole bandwidth previously occupied by voice and telemetering channels is now available for the protection signal. In the standby condition the receiver's output is disabled and total security prevails.

4. IMPULSE NOISE MEASUREMENTS

In order to determine signal power requirements and investigate optimum receiver design, impulse noise originating from disconnect switches was recorded to supplement available literature. Measurements were taken on a 138 kV line and on a 230 kV double-circuit line.

Although the noise caused by line faults and lightning is of great interest there was no opportunity to record these. However "experts take the view that by far the most harmful noise voltages are those produced by the operation of isolators" (Sakic, 1968).

4.1 Beatty-Wolverine 138 kV Line

Disconnect switch noise was recorded with a Tektronix oscilloscope camera system and a Sony TC-355 magnetic tape recorder. Figure 4.1 illustrates line, coupling, and equipment arrangement used on the 138 kV Beatty-Wolverine transmission line. Records of carrier signals and noise were taken from the following appropriate test points in the operating multi-purpose SSB carrier equipment:

Test Point 1: RF output of 4 kHz bandpass filter

Test Point 2: IF waveform preceding the demodulator.

Test Point 3: Demodulated signal at 0.3-3.24 kHz bandwidth.

Test Point 4: Filtered protection signal. (approx. 180 Hz bandwidth).

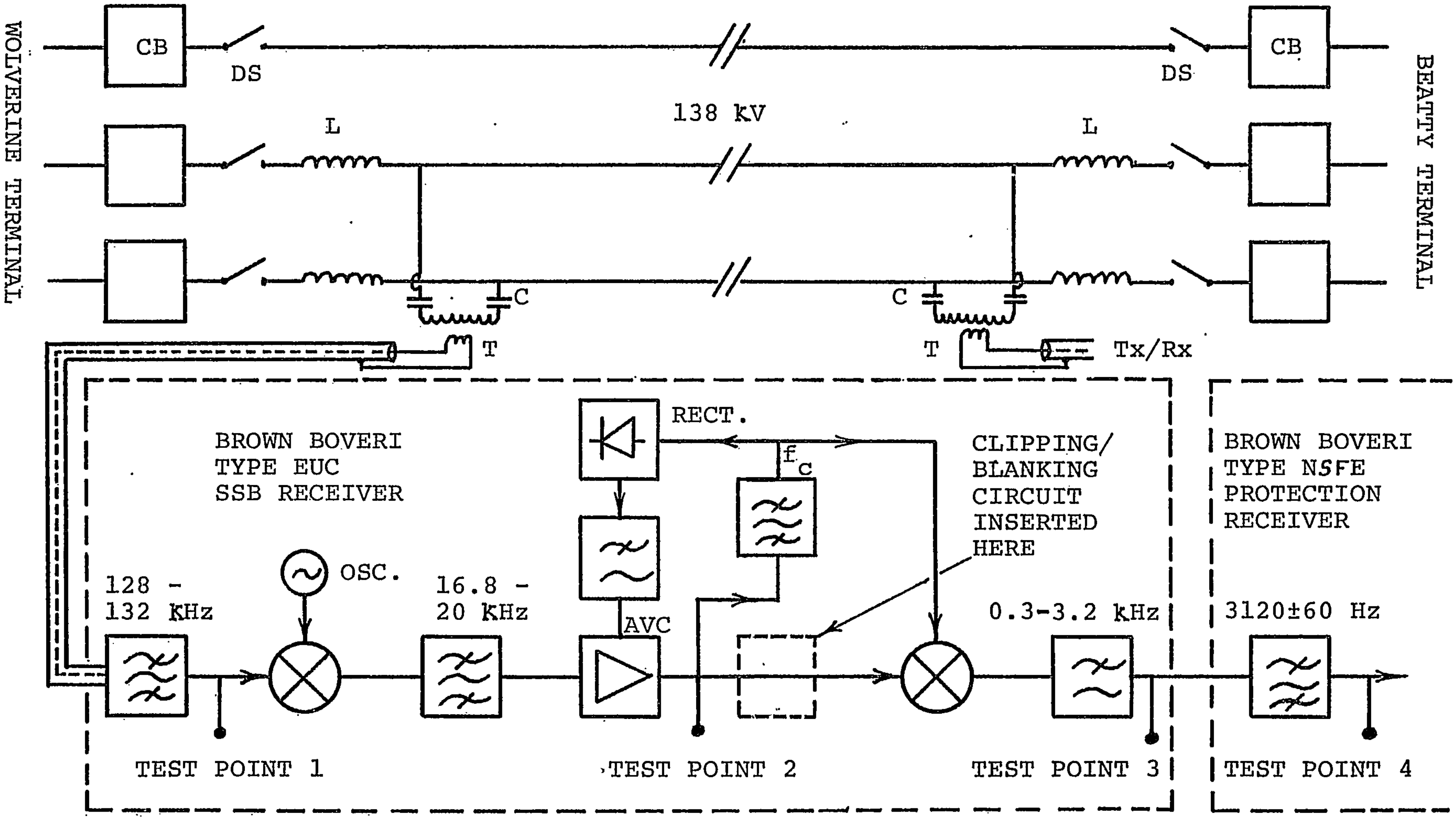


FIGURE 4.1 BEATTY-WOLVERINE LINE, COUPLING AND EQUIPMENT ARRANGEMENT

With the line energized at 138 kV from the Beatty end the motorized disconnect switches were operated at Wolverine whenever a noise burst was desired; circuit breakers at Wolverine were kept open throughout these tests. All measurements were taken at Wolverine. Tests were repeated with the line energized from the Wolverine end and disconnects operated at Beatty.

Circuit parameters:

Frequency: 128 to 132 kHz.

Coupling: phase to phase

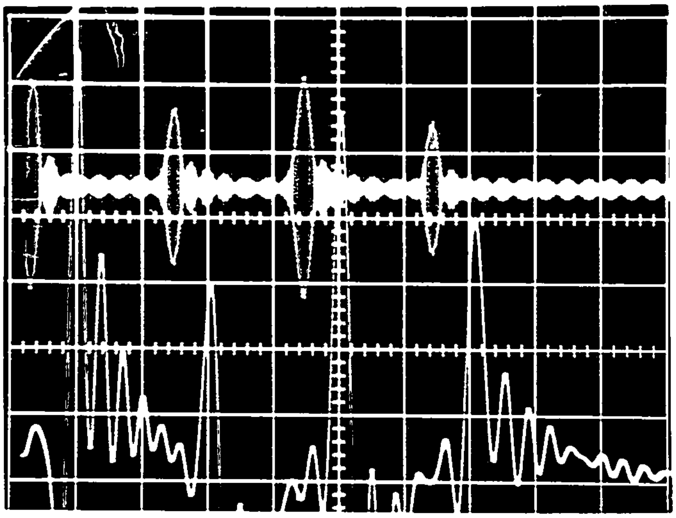
Line length: 79 miles

Transmitter output: -suppressed carrier at 0.5w
-protection guard tone at 0.5w

Figure 4.2 shows typical waveforms recorded during the operation of the disconnect switch. The top traces are RF waveforms (test point 1) and clearly show the impulsive nature of the noise. The bottom traces are corresponding demodulated AF waveforms (test point 3) and show the effect of the shock excitations. AF waveform and signal envelope after passing through the narrow-band protection filter (test point 4) are shown in Figure 4.3. Noise duration was only 200 ms. Additional oscillographs are given in Section 5.4.

4.2 Saskatoon-Beatty 230 kV Double-Circuit Line

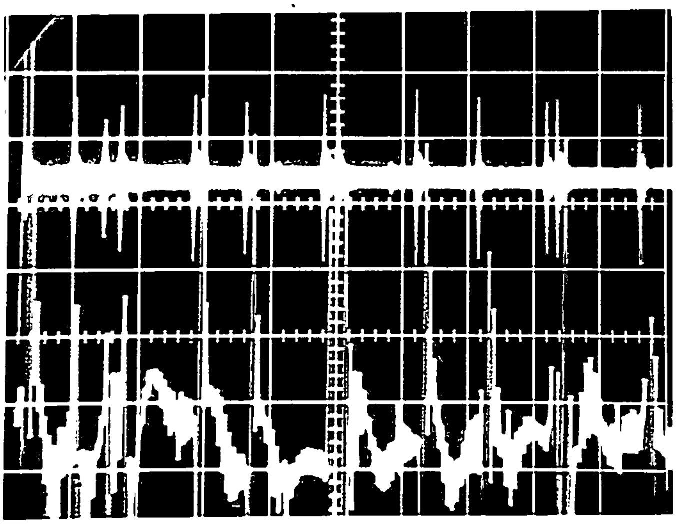
Similar measurements were made on the Saskatoon-Beatty 230 kV double-circuit line. Line configuration and coupling arrangement is given in Figure 4.4



(i) RF frequency
128-132 kHz
↑20 V/cm
→1 ms /cm

(ii)Voice frequency
0.3-3.2 kHz
↑Relative ampl.
→1 ms /cm

(a) Disconnect Switch Closing

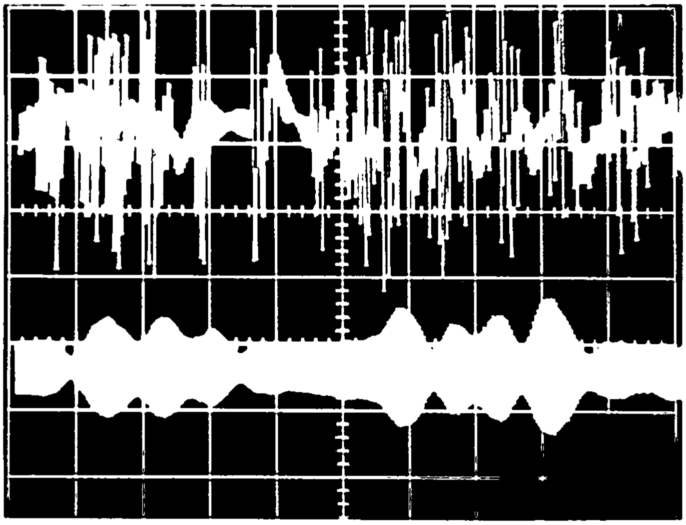


(i) RF frequency
128-132 kHz
↑20 V/cm
→5 ms /cm

(ii)Voice frequency
0.3-3.2 kHz
↑Relative ampl.
→5 ms /cm

(b) Disconnect Switch Opening

FIGURE 4.2 NOISE PLUS SIGNAL DURING DISCONNECT SWITCH OPERATION
(Switched at Beatty, observed at Wolverine)



(a) Demodulated output
0.3-3.24 kHz
↑Relative ampl.
→10 ms /cm

(b) Prot. filter output
3120±60 Hz
↑Relative ampl.
→10 ms /cm

FIGURE 4.3 SWITCHING NOISE PLUS SIGNAL DURING DISCONNECT SWITCH OPERATION. (Beatty-Wolverine line, switched and observed at Wolverine)

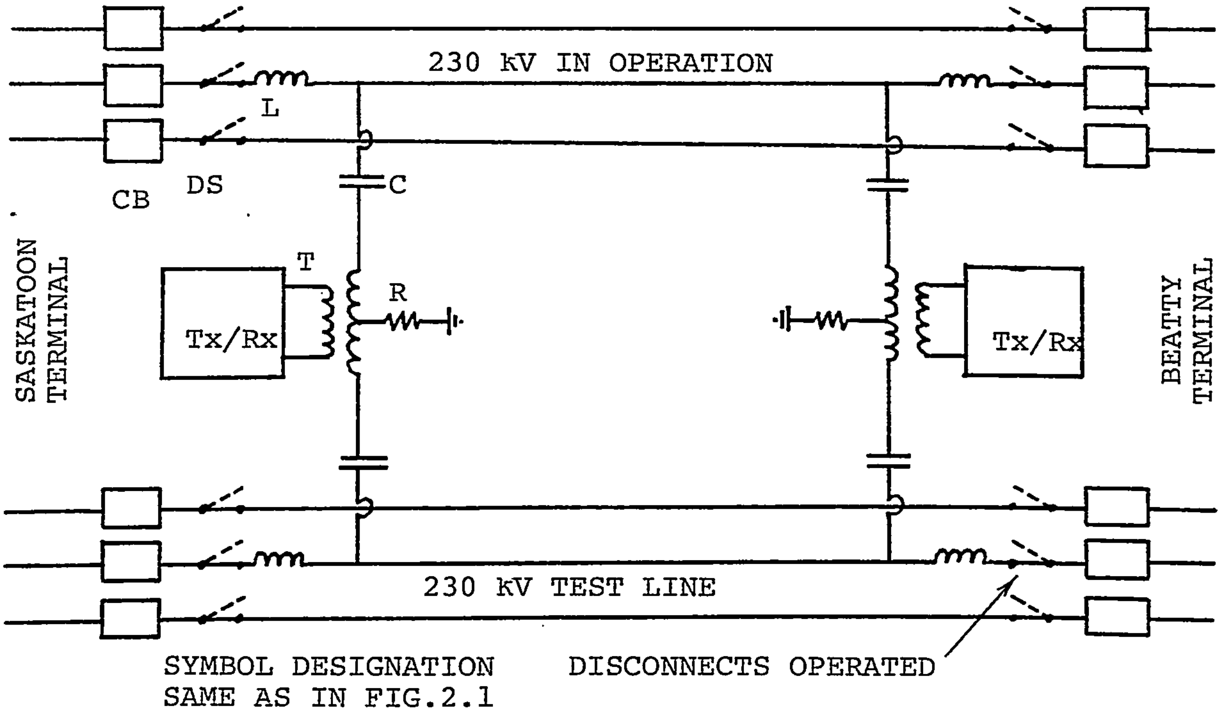


FIGURE 4.4 SASKATOON - BEATTY LINE AND COUPLING ARRANGEMENT

Circuit parameters:

Frequency: 162-166 kHz

Coupling: Special double circuit

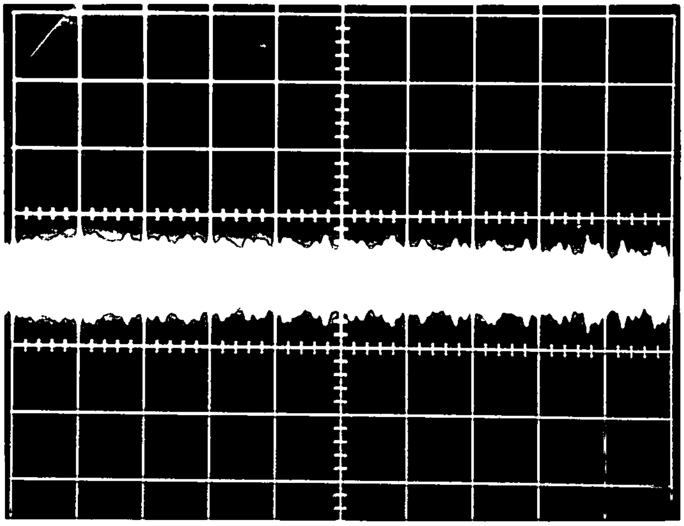
Line length: 101 miles

Transmitter output: -suppressed carrier at ≈2.5w
-3 data channels at ≈0.6w each

The RF signal comprised of the suppressed carrier and several data channel subcarriers without noise is illustrated in Figure 4.5. A typical RF signal with additive noise from the closing of a disconnect switch is given in Figure 4.6. Records of waveforms before the receiving filter were inconvenient because several local transmitters were connected to the same coaxial cable. Noise duration was 500 ms.

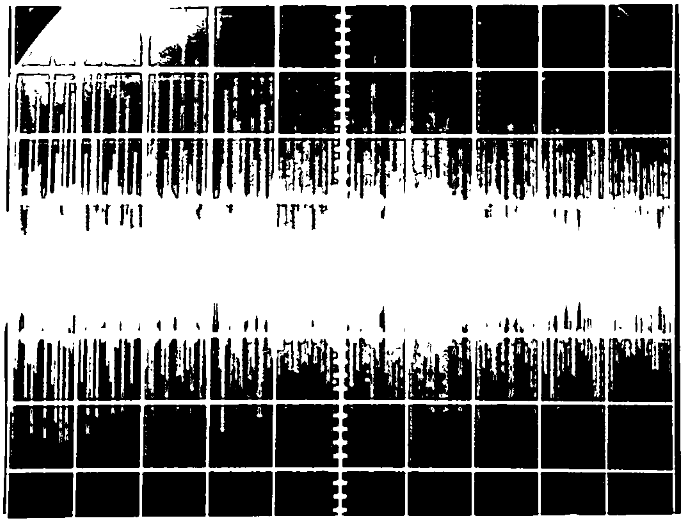
4.3 Evaluation

The peak powers received due to noise are in the order of 30 dBm at 4 kHz bandwidth and compare favorably with those of Table 2.2. The RF impulses are sharply defined with each having a duration of 0.3 to 0.4 ms. Durations correspond to approximately 1/bandwidth of the input filter and imply that impulse duration before this filter is less than or equal to this value. Of extreme interest is the space between individual impulses where the signal is essentially undistorted. Figure 4.6 shows that a maximum of about 700 impulses may be expected per second. This impulse rate corresponds to the 720 impulses/s derived from the circuit model in which the low current disconnect arc strikes and extinguishes on each of the three phases during each half-cycle. The lower trace



RF frequency
162-166 kHz
↑ 2.9 V/cm
→ 20 ms /cm

FIGURE 4.5 SIGNAL WITHOUT NOISE
(Observed at Saskatoon on Beatty-Saskatoon line)



RF frequency
162-166 kHz
↑ 2.9 V/cm
→ 20 ms /cm

FIGURE 4.6 SIGNAL PLUS NOISE DURING DISCONNECT CLOSING
(Observed at Saskatoon, switched at Beatty)

in Figure 4.3 indicates that noise in the 120 Hz bandwidth centered about the guard frequency has about the same energy as the signal itself.

It was noted that during tests some frequency shift receivers on a neighboring power line squelched during noise tests.

5. INVESTIGATIONS INTO METHODS OF IMPROVEMENT

5.1 Power

Probably the most obvious way of improving security and reliability is to increase the transmitted power. Power limits as imposed by the Department of Communications are about 100w for reasons of interference and equipment operating at such a power level is economically available. Although a power of 10w is sufficient on short and medium length lines to reliably receive a tripping signal (Quervaind et al, 1960; Jones, 1959), it is more difficult to meet security requirements.

This is especially so when multi-purpose SSB sets transmit approximately 0.5w of guard signal. Trace (b) in Figure 4.3 shows that, even after a filter of a nominal 180 Hz bandwidth extracts the guard signal, the noise power is still slightly greater than the signal power. Since in excess of 500 noise impulses/s may reach this filter the output noise may, as an approximation, be considered as narrow-band "white noise". Then the error rate curve for a binary non-coherent FSK system shown in Figure 3.2 may be applied. The output S/N ratio is about 0 dB and, without the S/N ratio detector, the probability of error without any "biasing" would be 0.3.

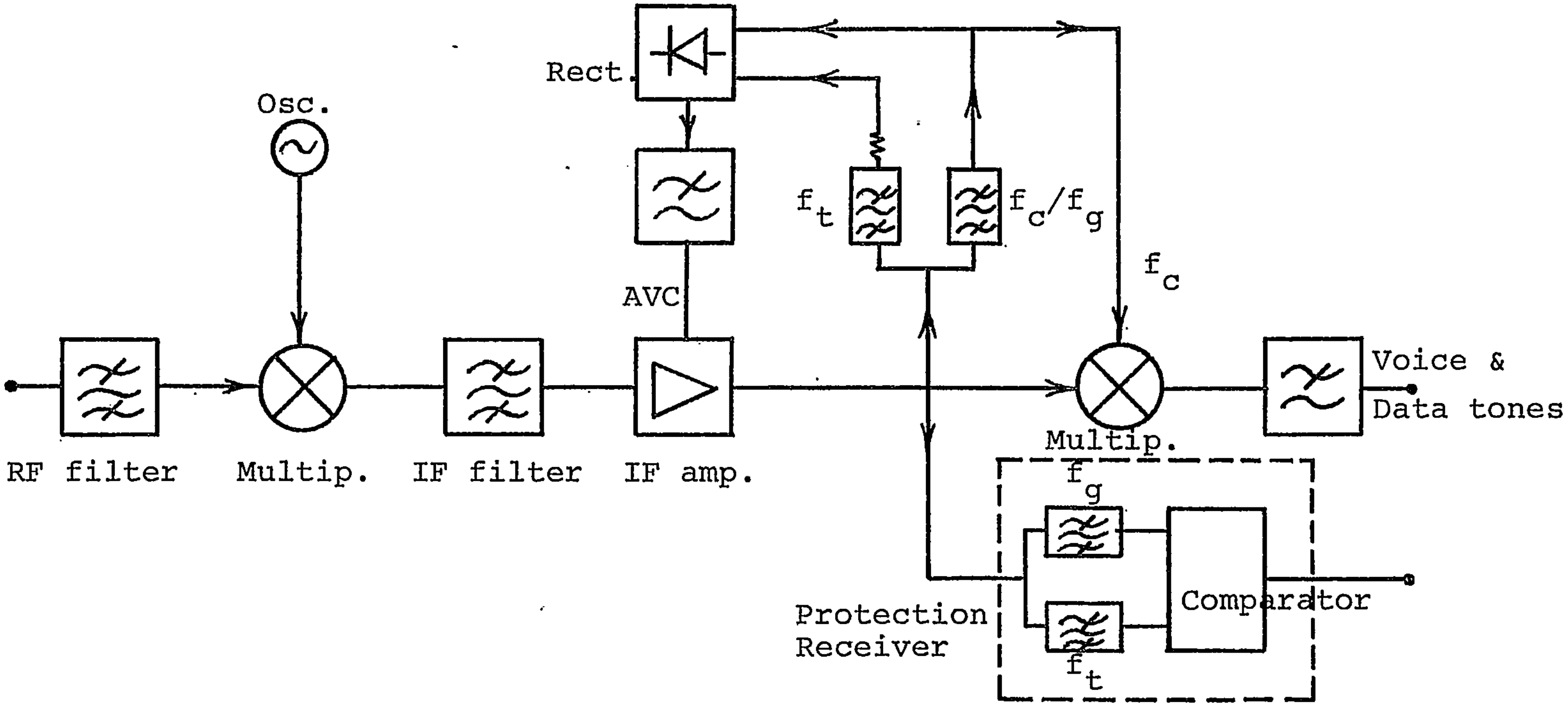


FIGURE 5.1 BLOCK DIAGRAM OF AN EFFICIENT MULTI-PURPOSE SSB RECEIVING SYSTEM

Increasing the signal power by a factor of 10 would decrease this error rate to 2×10^{-3}; a considerable improvement.

No great increase in transmitter peak power is necessary to achieve this. For example, the multi-purpose receiving system shown in Figure 3.1 transmits both the protection guard tone and suppressed carrier at 17% of maximum transmitter voltage modulation. The protection guard tone can be removed and the suppressed carrier, increased $\sqrt{10}$ times in voltage level, can serve the function of guard tone as well. Peak transmitter voltage modulation, with no change in power for voice and data channels, is now only 119% of the original value. Yet the guard signal power has been increased by a factor of 10.

Figure 5.1 illustrates a block diagram of a possible receiver circuit configuration. During normal operation the SSB receiver functions as before. A trip command uses full transmitter modulation with voice, suppressed carrier/guard, and auxiliary tones removed. The protection receiver, now operating at the IF frequency, detects the trip signal and loss of guard signal with subsequent output. SSB receiver AVC during this time is controlled by the filter centered at the trip frequency f_t and attenuator added in the AVC feedback loop.

5.2 Coding and Optimum Bandwidth-Power Exchange.

The Hartley-Shannon law states that channel capacity

$$C = B_t \log \left[1 + (S/N)_t\right] \text{ -------- } (1)$$

$$\text{Where } (S/N)_t = P_t/\eta B_t$$

It may be shown that at the output of an ideal receiver the detected S/N ratio

$$(S/N)_d = \left[1 + P_t/\eta B_t\right]^{B_t/W} -1 \text{ --- } (2)$$ (Carlson, 1968; Ch. 8.4)

Equation (2) shows the dependence of the detected S/N ratio on transmitted power P_t, basic signal bandwidth occupancy W, transmitted signal bandwidth occupancy B_t, and transmission medium noise power density η for an ideal system. Figure 5.2 shows the improvement in ideal postdetection S/N ratios possible when B_t is doubled and increased by a factor of 4 with the noise density kept constant. The improvement is exponential at the higher S/N values, but is of minor significance when these are below 5 dB, the major region of interest.

SSB is not suited for wideband noise reduction because the bandwidth ratio $B_t/W = 1$. Practical systems suitable for bandwidth/power exchange such as FM, PPM and PCM do show considerable improvement at high detected S/N values but have severe threshold limitations when these are less than 10 dB. (Carlson, 1958; pp. 347-351). SSB transmission has no such threshold limitations.

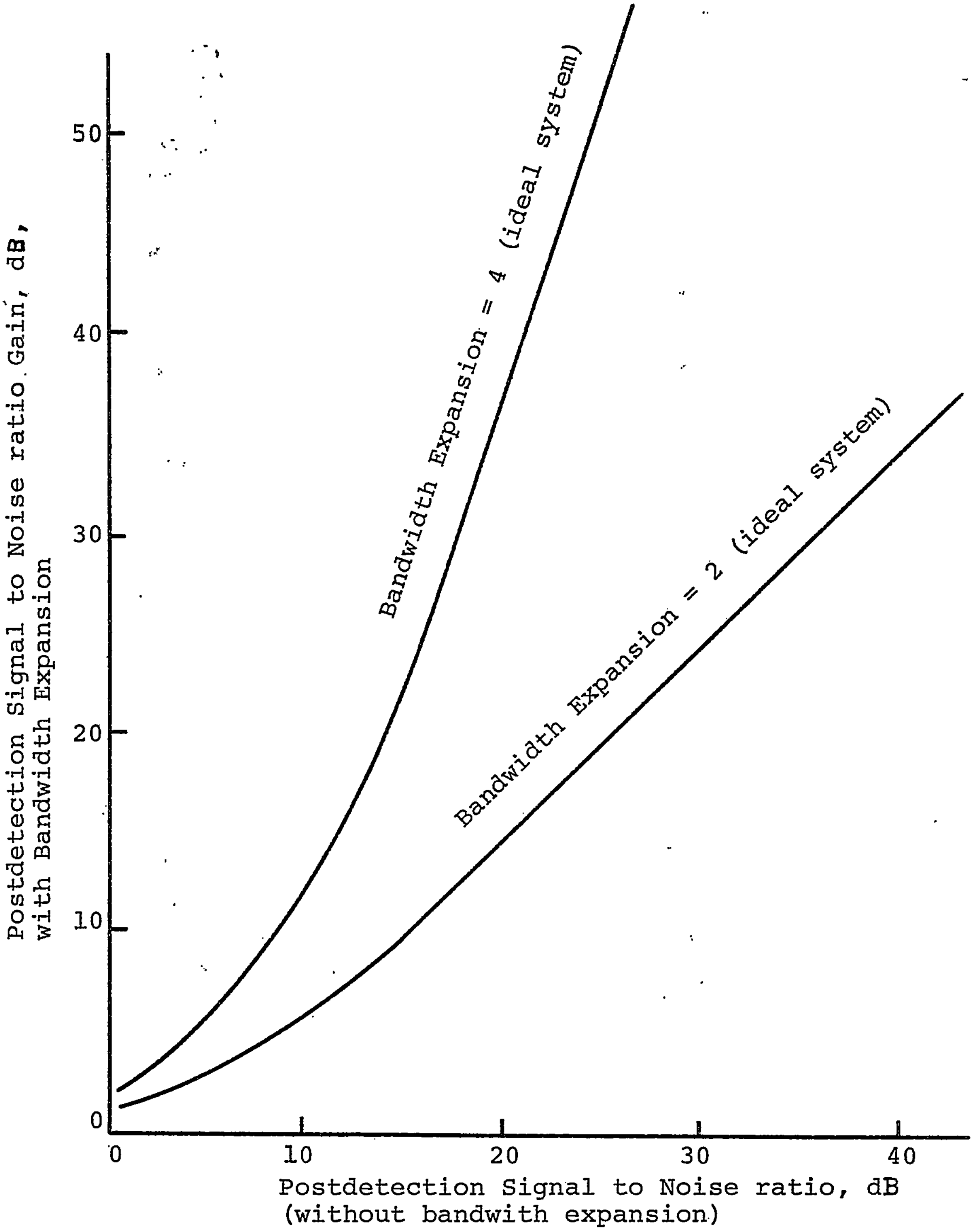


FIGURE 5.2 POSTDETECTION GAIN IN SIGNAL TO NOISE RATIO BY BANDWIDTH EXPANSION

5.3 Addition of Carrier in Noise Channel of S/N Detector.

A tone transmitted in the noise channel of a protection receiver of the type shown in Figure 3.1 can increase its security against false trips. Under such operation the S/N detector normally squelches the receiver; removal of the tone during intertripping re-enables it. No corresponding decrease in reliability results if receiver unsquelching time is negligible.

Appendix A gives equations showing the merit of this method and describes the bench-testing of a typical FSK subcarrier decoder using this additional carrier. Pulsed "white noise" as suggested by Bozoki (Bozoki, 1966) was utilized.

Figure 5.3 illustrates a set of theoretical probabilities for security and reliability as well as corresponding experimental data points, the effectiveness of this method is largely determined by the S/N detector setting. The experimental points show an order of magnitude decrease in false trip probability with no appreciable change in fail to trip probability. This is greater than the predicted security improvement. The difference is attributed to the inherent bias within the discriminator S/N detector toward guard and squelch. This, however, is incidental and does not affect the purpose of showing the relative merit of using the additional tone.

Attractiveness of this scheme is further increased by the possibility of using the noise channel for lower priority data transmission.

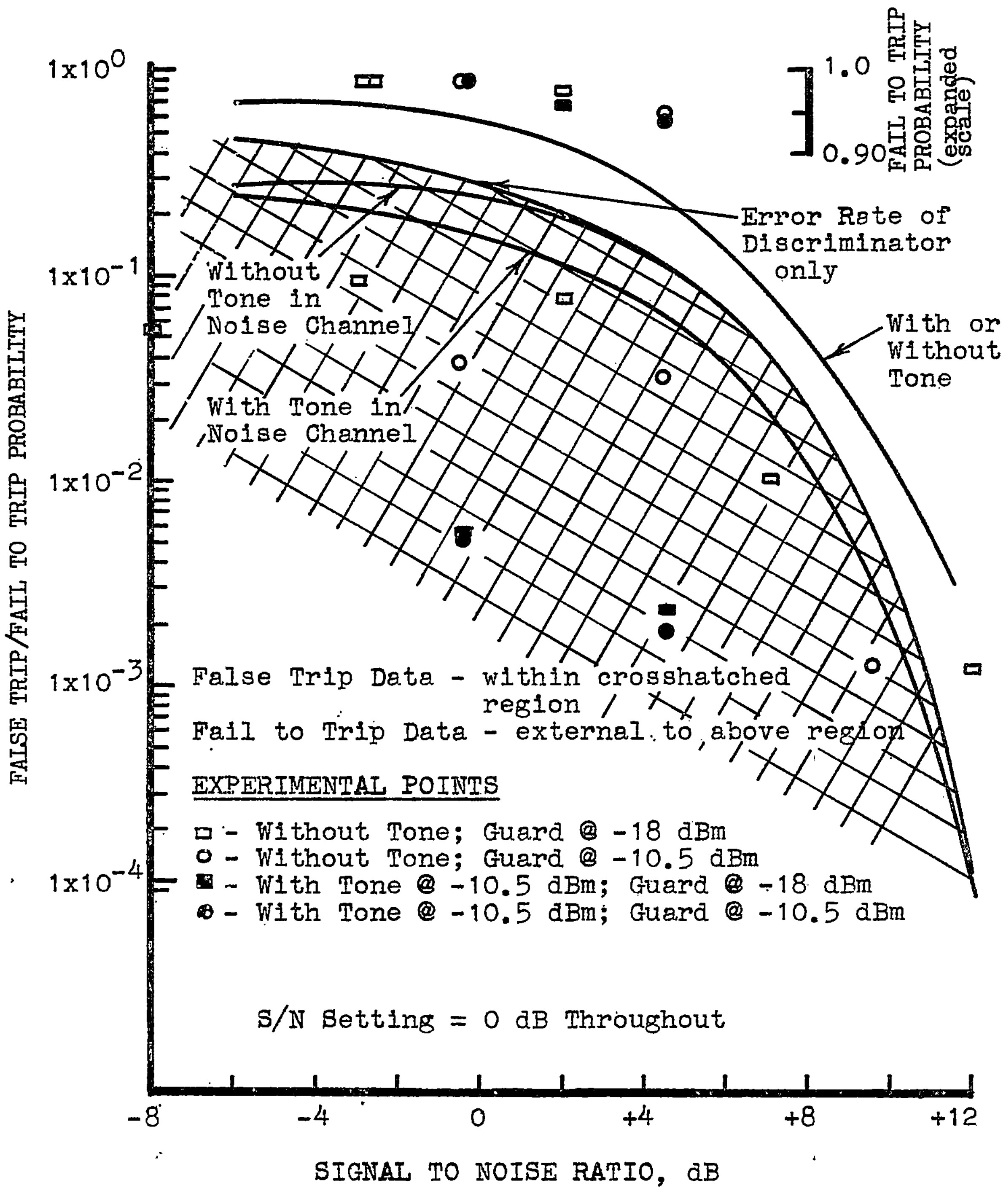


FIGURE 5.3 FALSE TRIP AND FAIL TO TRIP PROBABILITIES vs S/N RATIO WITH/WITHOUT TONE IN NOISE CHANNEL

5.4 Noise Clipping or Blanking

From the detailed noise tests it appears that even during the operation of a disconnect switch under low transmitted power there is sufficient signal information present to be decoded in the limited time allotted. The essentially undisturbed signal information is located in time between the individual high-amplitude noise bursts as seen in Figure 4.2. All that is necessary is a method of extraction.

Four multi-purpose SSB receivers were studied and none had provisions for reducing the noise passed on to the protection carrier decoder. The following narrow-band protection channel receives the full amplitude of the noise (at 3-4 kHz bandwidth) and can reduce noise amplitude only to a certain degree. Security is maintained by hopefully squelching the receiver for the full duration of a noise burst. To attain this the receiver is biased toward the guard, further reducing the reliability.

Field tests conducted by Moynihan (Moynihan et al, 1955) showed that the peak value of impulse noise on a power line is proportional to the bandwidth of the receiving system as theory predicts. It appears that in eliminating most of the noise peaks at a wide bandwidth, by either limiting their amplitudes or entirely removing them, a high enough postdetection S/N ratio can be maintained to provide both an increase in security and reliability.

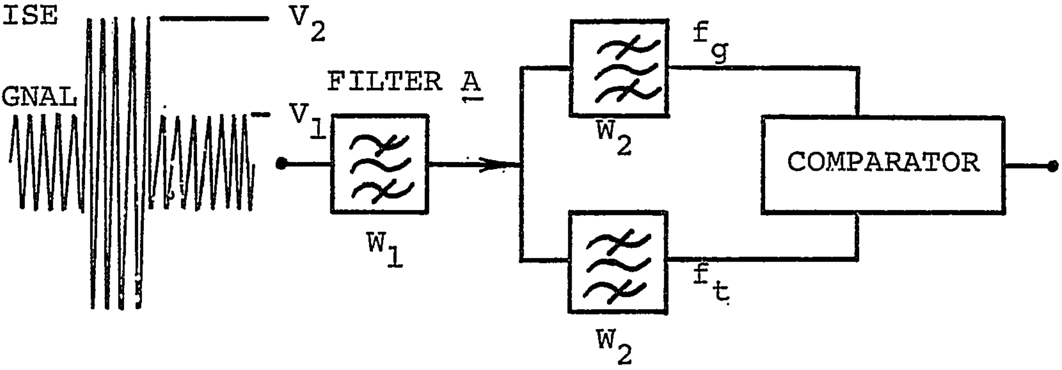


FIGURE 5.4 BLOCK DIAGRAM OF A SIMPLE FSK RECEIVING SYSTEM

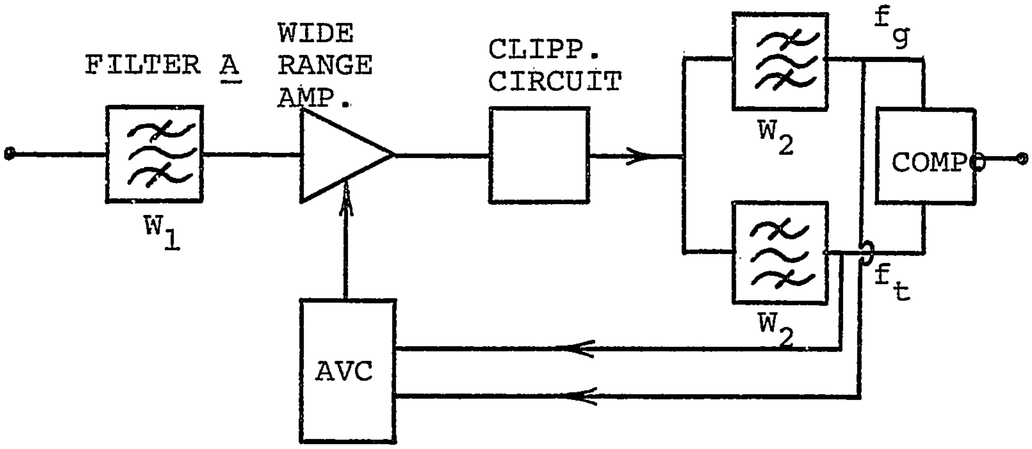


FIGURE 5.5 BLOCK DIAGRAM OF A BASIC FSK RECEIVING SYSTEM INCORPORATING CLIPPING

5.4.1 Clipping

Consider the noncoherent FSK receiving system whose block diagram is shown in Figure 5.4. Let the filters be ideal with bandwidth W_2 being less than bandwidth W_1. Also let the peak signal level be V_1 and peak noise level of impulse rate X at bandwidth W_1 be V_2; $V_2 > V_1$.

Peak signal level out of the discriminator filter is V_1 while the peak noise level is V_2W_2/W_1. Noise is reduced in the discriminator filter by the factor W_1/W_2. Disturbance duration per impulse at the output of filter A is approximately equal to the reciprocal of W_1 and at the discriminator output is approximately equal to the reciprocal of W_2.

Now let a clipping circuit be installed between the two filters with clipping level set at V_1. Signal level at the discriminator output is unchanged, but the peak noise amplitude is now V_1W_2/W_1; an additional noise reduction by the factor V_2/V_1 is realized.

For noise reduction of a system the filter bandwidth W_2 is chosen just sufficiently wide to allow the required signalling rate to be met. In practice the theoretical limiting value $W_2 = \left[1/2 \text{ x signalling rate}\right]$ cannot be achieved and W_2 = signalling rate is more realistic (Carlson, 1968; pp. 337-339). In order to conserve frequency spectrum the filter A bandwidth should be as narrow as possible. However, for reliable decoding the impulse duration, after passing through filter A, should not be greater than about 1/2X seconds. This would allow the desired signal to dominate the noise for at least 50% of the time and, in the absence of other continuous noise, assure correct decoding. Use of as wide a bandwidth as possible at the clipping point is implied. It may be noted at this time that it is desirable to clip the noise even before the first filter, but generally there are other signals including those of local transmitters on the same coaxial cable and the clipping level would necessarily have to be set high. Also, additional intermodulation products from the neighboring transmitters are not desirable (Pappenfus, 1964; pp. 301-305).

According to the preceding a receiver requiring an operating speed of 15 ms requires minimum bandwidth W_1 = 1440 Hz and W_2 = 70 Hz when the noise impulse rate X from a disconnect switch is 720/s. A value of 2-3 kHz for W_1 is advisable because reflections on the transmission line (Imaide, 1964) can increase the received impulse rate. The clipping level to peak signal level ratio can be slightly above unity and controlled automatically for signal level changes.

The block diagram of a simple single-purpose basic receiver design incorporating noise clipping is given in Figure 5.5. Similar considerations apply to multi-purpose SSB receivers. However, since the clipping level must exceed the sum of peak voice, telemetering and protection signals, improvement effected by clipping will be reduced.

For example, for a single-purpose receiver with signal and noise levels as shown in Figure 4.2, 8 is about the maximum factor by which the peak noise can be reduced. For a typical multi-purpose receiver with all channels modulated the clipping level would necessarily be increased by a factor of 3.

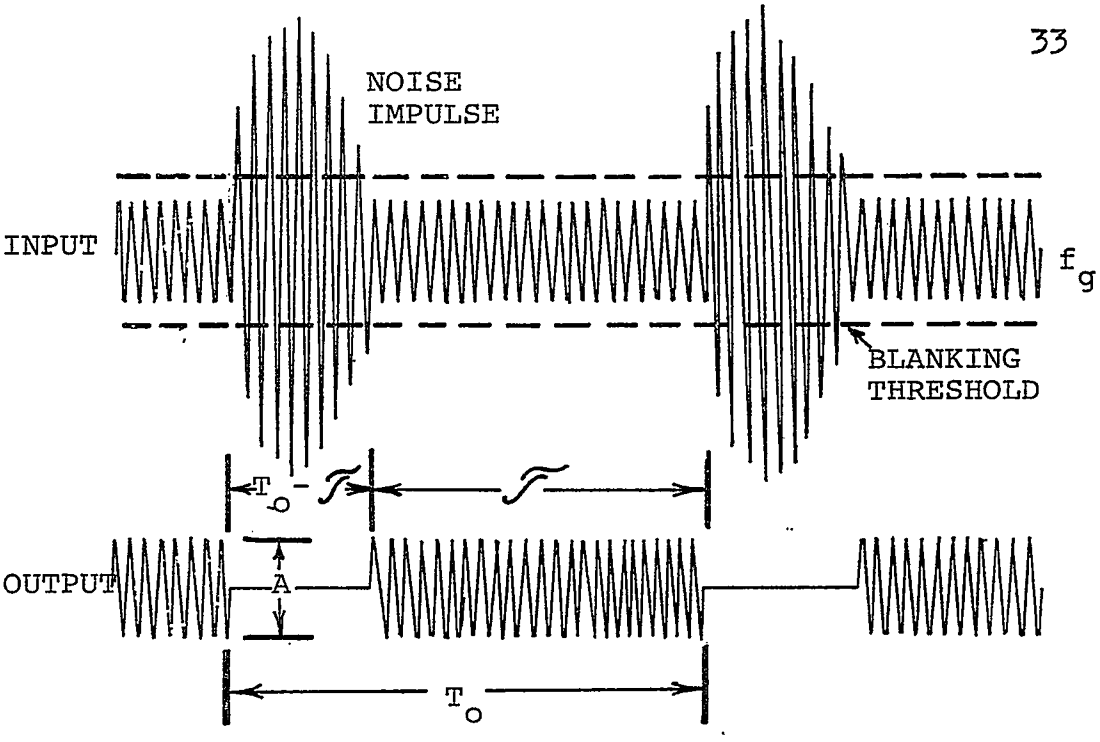
It is apparent that in a single-purpose receiver using carrier FSK the clipping circuit, amplifier with wide dynamic range, and automatic gain control feedback loop can be replaced with a simple limiting amplifier to achieve approximately the same results. As well as being economical this type of receiver would be preferred in practice because of the non-critical adjustments afforded.

5.4.2 Blanking

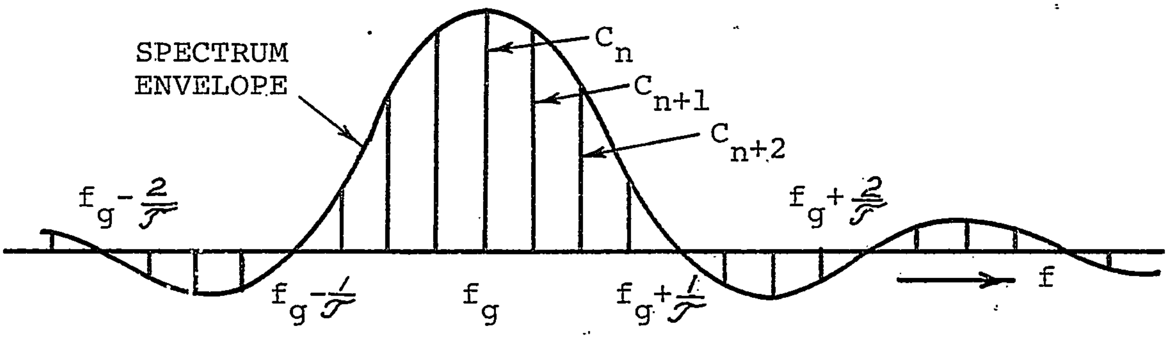
Impulse noise can also be effectively removed by blanking or silencing techniques; apparently this method has not yet been applied to power line carrier systems. The blanker opens the signal path for the duration of the noise, removing both the noise and signal during this time.

Similar considerations as for clipping apply with regard to where the noise should be blanked and receiver filter bandwidths utilized. For an AM carrier, blanking constitutes modulation with resulting sidebands while for suppressed carrier SSB it means the removal of portions of the signal.

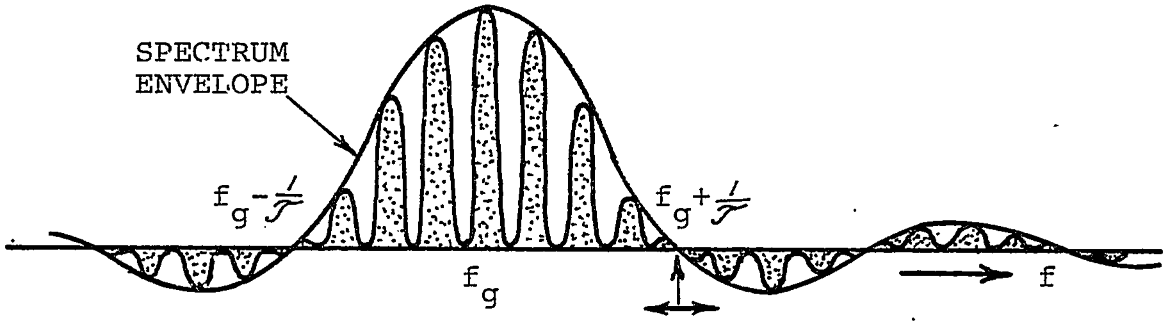
Using this method a threshold detector set somewhat above the signal level initiates blanking action. Since the disturbance duration after the receiver input is fairly well confined to the reciprocal of the input filter bandwidth, a fixed blanking duration slightly longer than this value can be utilized.



(a) Blanking Circuit Input and Output Waveforms



(b) Output Spectrum - Periodic Impulses
(negative frequency portion omitted)



(c) Output Spectrum - Non-Periodic Impulses
(negative frequency portion omitted)

FIGURE 5.6 THEORETICAL BLANKING CIRCUIT WAVEFORMS AND OUTPUT SPECTRA

Consider a receiving system such as illustrated in Figure 5.5 with a blanking circuit substituted for the clipping circuit. Figure 5.6 shows waveforms expected at the input and output of this circuit. Some complications arise as blanking introduces both distortion and interference in this circuit model. The frequency spectrum generated by sharply blanking the unmodulated carrier f_g in Figure 5.6(a) follows a sinc function envelope as illustrated in Figure 5.6(b). The blanking period is fixed at $T_o - \tau$. If T_o is constant and f_g is an integral multiple of $1/T_o$, the output spectrum may be described by a line spectrum (Carlson, 1968, pp. 26-27; Westman, 1962, Ch. 35) with individual components having an amplitude of

$$C_n = A\tau/2T_o \left[\text{sinc } (f_g - n/T_o)\tau + \text{sinc } (f_g + n/T_o)\tau \right]$$

Shaping of the blanking pulse will affect the output spectrum.

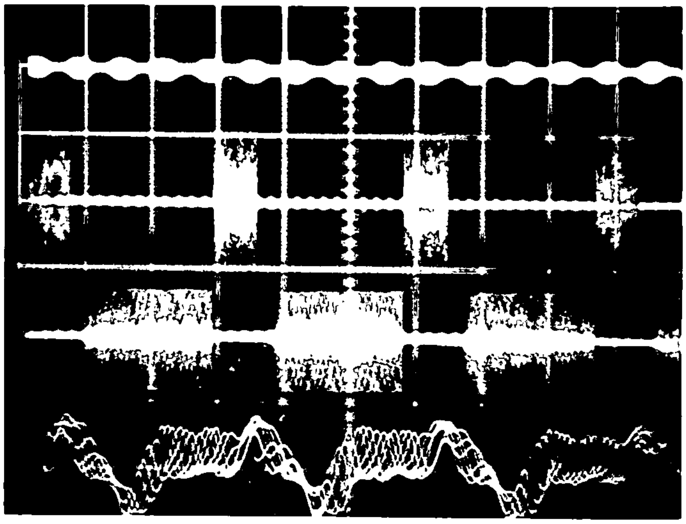
For the disconnect noise burst model described in section 4.3 the minimum $T_o = 1/720 \approx 1.4$ ms. With a blanking period of 0.4 ms, $\tau = 1.0$ ms. The frequency components in the region of interest then have the following amplitudes:

f_g	0.36 A
$f_g \pm 720$ Hz	0.12 A
$f_g \pm 1440$ Hz	-.07 A
$f_g \pm 2160$ Hz	+.02 A
$f_g \pm 2880$ Hz	+.02 A

If the impulse rate decreases the spectral components become more centered about the frequency f_g. Now, if the incoming noise pulse train becomes nonperiodic, the line spectrum changes to a spectral density with peaks centered at frequencies dependent on the prevalent impulse rate as shown in Figure 5.6(c).

It follows that the frequency separation between guard and trip channels is to be chosen with discretion. The spacing between the trip and guard frequency should be an integral multiple of $1/\tau$ where τ is the most probable RF signal train duration between impulses. This would provide a null effect for crosstalk between the two channels. Data on most probable impulse rate is not available, but designing for 720/s appears reasonable. A spacing of 2 kHz, for example, provides such a null and even an increase of impulse rate to 1250/s would keep a voltage ratio of a minimum 5:1 in the two channels.

For slow changes in signal level with time constants above several seconds the AVC will be able to maintain a proper threshold limit for blanking. A practical difficulty is maintaining a reasonable threshold level with rapid transitions in signal level. The AVC time constant is in such a case set to a low value and the filter bandwidth W_2 defines the quickest response possible. Since signal levels during a fault are expected to usually decrease due to additional attenuation, an override circuit on the threshold bias closely following the short-term average signal minima can be incorporated. Other methods of establishing threshold levels are given by Pappenfus (Pappenfus et al, 1964). This limitation makes such a receiver more useful on transformer and line protection where appreciable level changes are not expected when a trip signal is required.



(a) 100 kHz carrier modulated by 3060 Hz prot. sign.

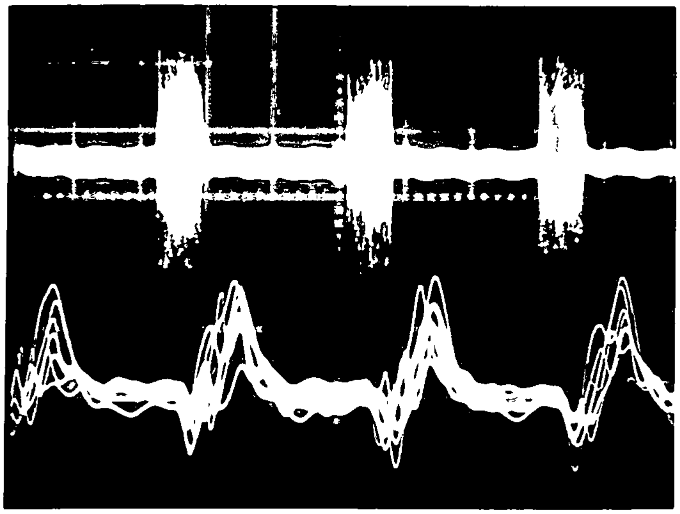
(b) Pulsed noise 5 kHz bandwidth

(c) Blanked composite signal

(d) Demodulated AM receiver output 5 kHz bandwidth

horizontal scale: 0.5 ms /cm

FIGURE 5.7 AM BLANKING TEST WAVEFORMS



(a) Relative RF and noise burst ampl.

(b) Demodulated AM receiver output 5 kHz bandwidth

horizontal scale: 0.5 ms /cm

FIGURE 5.8 AM TEST WITH NO MODIFICATION

5.4.3 Test results

a) Laboratory tests on a 100 kHz AM channel

A qualitative appreciation of improvement possible, when clipping or blanking is utilized, was obtained in the laboratory using an AM transmitter and receiver in conjunction with a TIU-3 protection Tx/Rx unit. Impulse noise was simulated. This laboratory simulation was considered necessary because no SSB equipment was readily available. Test equipment set-up and the blanking/clipping circuit description is given in Appendix B.

Figure 5.7 shows the modulated carrier, pulsed " white noise", output of the blanking circuit and the AM receiver output at a bandwidth of 5 kHz during blanking tests. Figure 5.8 shows relative signal and pulsed noise amplitudes at the input to the receiver, and corresponding demodulated signal output during tests without blanking or clipping. The ratio between demodulated peak signal and peak noise amplitude was highest when blanking was utilized.

Incorporating fixed blanking periods of 0.5 ms duration with a noise burst duration of 0.3 ms repeated every 1.5 ms, the TIU-3 decoder operated reliably when trip signals were transmitted. It was totally secure for a test period of several minutes with the S/N ratio detector disabled. During the clipping mode numerous false trips per minute were observed under the same conditions. The receiver output relay in this case was prone to momentary drop-out during reliability tests. Without blanking/clipping the security was degraded even more.

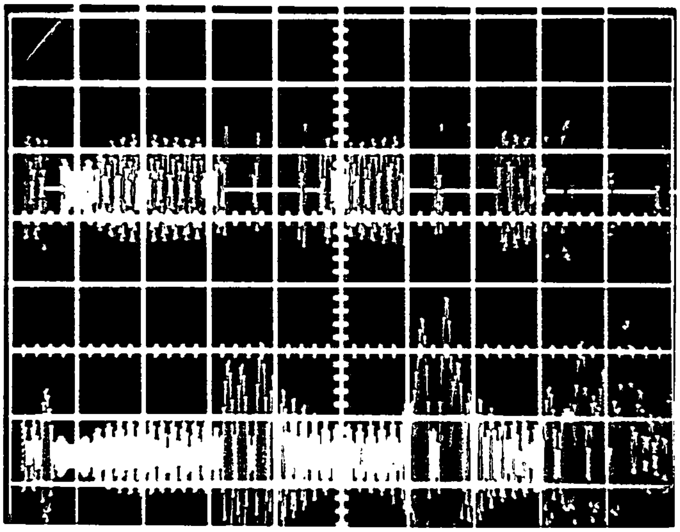
b) Clipping/blanking field trials

(i) General test method.

Field tests incorporating clipping and blanking were performed on the Beatty-Wolverine 138 kV transmission system with measurements taken at Wolverine. Line configuration, circuit parameters, and methods of noise generation were the same as in the noise tests described in Chapter 4.1. Disconnect switches were operated only at the Wolverine end of the transmission line.

The clipping/blanking circuit was modified to allow its insertion just ahead of the demodulator in the Brown Boveri type EUC SSB receiver as shown in Figure 4.1. Provisions were made for negligible loading of the previous IF amplifier stage, no insertion loss for noise-free signals, and clipping level controlled by the rectified suppressed carrier. Appendix C gives the schematic diagram of this clipping/blanking circuit, its operation, and waveforms under controlled simulated noise conditions.

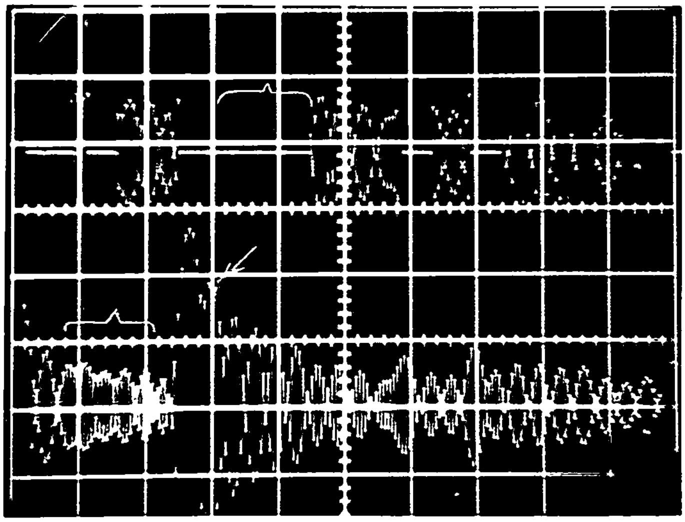
Oscillographs and magnetic tape recordings were taken. The recorded demodulated SSB output at the 3.24 kHz bandwidth was injected into a TIU-3 receiver in the laboratory to complete the evaluation. During playback the guard level was adjusted to -10.5 dBm, receiver gain was adjusted for a 30 dB fade margin, and bias favoring the guard frequency was not applied. The guard frequency received was measured with a digital counter to be 3045 Hz instead of the 3060 Hz desired. This 15 Hz offset, however, has minor significance in view of the overall input filter-limiting amplifier-dis-



(i) Blanked IF output
0.5 ms blank. time
Blanking threshold =
1.5 x signal peak
↑Amplitude relative
→2 ms /cm

(ii) IF waveform
17.76-20 kHz
↑2 V/cm
→2 ms /cm

(a) Disconnect switch closing

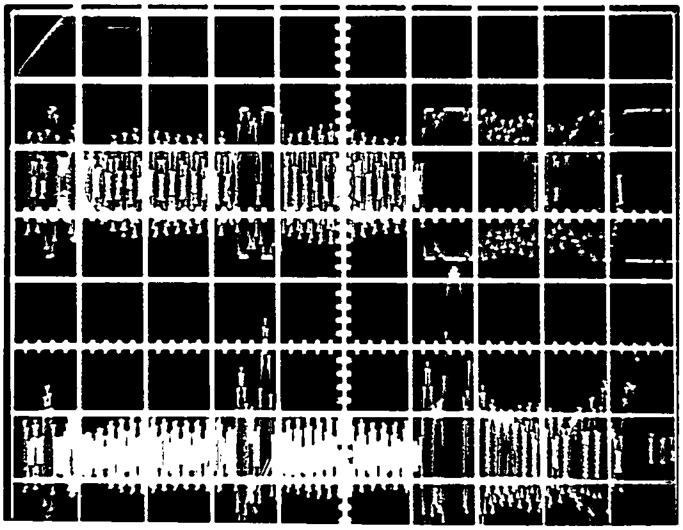


(i) Blanked IF output
0.5 ms blank time
Blanking threshold =
1.3 x signal peak
↑Amplitude relative
→1 ms /cm

(ii) IF waveform
17.76-20 kHz
↑2 V/cm
→1 ms /cm

(b) Disconnect switch opening

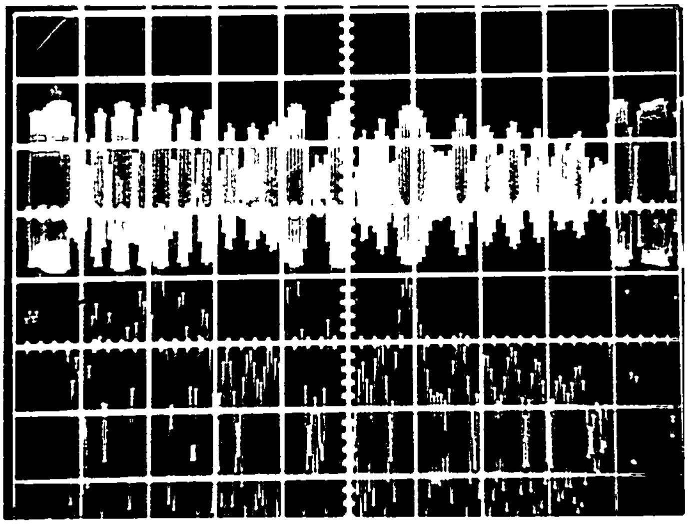
FIGURE 5.9 IF WAVEFORMS DURING BLANKING FIELD TESTS (Beatty-Wolverine line, switched and observed at Wolverine)



(i) Clipped IF output
Clipping threshold =
1.5 x signal peak
↑ Amplitude relative
→ 2 ms /cm

(ii) IF waveform
16.76-20 kHz
↑ 2 V/cm
→ 2 ms /cm

(a) Disconnect switch closing



(i) Clipped IF output
Clipping threshold =
1.5 x signal peak
↑ Amplitude relative
→ 1 ms /cm

(ii) IF waveform
16.76-20 kHz
↑ 2 V/cm
→ 1 ms /cm

(b) Disconnect switch opening

FIGURE 5.10 IF WAVEFORMS DURING CLIPPING FIELD TESTS (Beatty-Wolverine line, switched and observed at Wolverine) criminator response curve given in Appendix C, Figure C.4.

(ii) Observations.

Figure 5.9 illustrates typical input and output signals during blanking tests for a disconnect switch closing and opening at Wolverine. The blanking level was set to 1.5 and 1.3 times the peak signal level; the output traces confirm proper operation of this circuit.

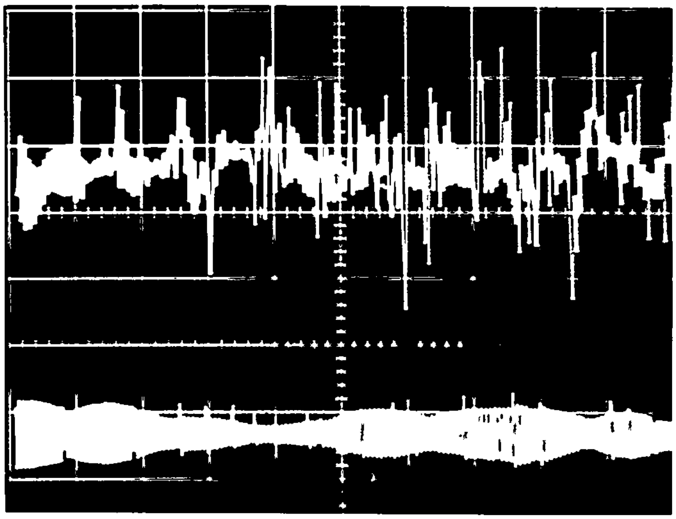
Figure 5.10 shows similar waveforms during the clipping tests.

Demodulated waveforms at the SSB receiver output and after being filtered by the protection tone filter are shown in Figures 5.11, 5.12 and 5.13. These are typical samples under blanking, clipping and normal SSB operation conditions respectively.

The final tests were made at the discriminator output of the TIU-3 receiver during playback of appropriate 0.3 - 3.24 kHz demodulated SSB waveforms. The S/N detector was disabled during these tests. Representative samples from five such sets are given in Figures 5.14, 5.15 and 5.16 and illustrate, respectively, the discriminator outputs for blanking, clipping, and no alteration conditions. The G, O, and T levels indicated represent voltage levels corresponding to outputs during guard, no signal, and trip signal being received.

(iii) Evaluation

The discriminator output waveforms summarize the improvements attained by clipping and blanking. No significant reduction in the number of possible false trips being received

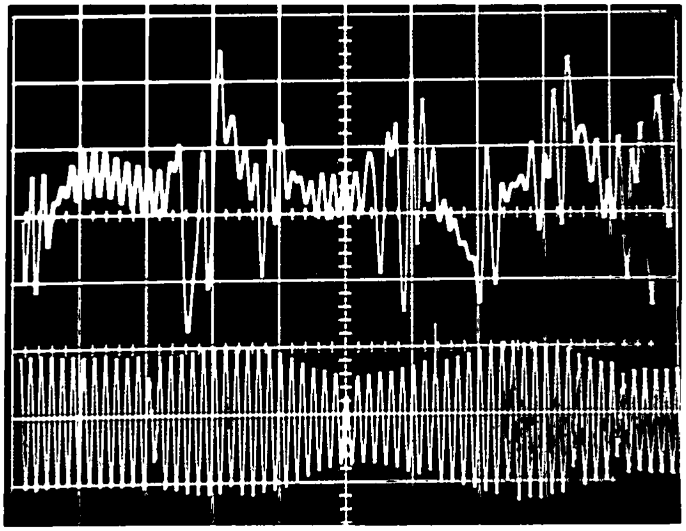


(a) SSB Rx output
0.3-3.24 kHz
0.45 ms blank. time
Blanking threshold =
2 x signal peak
↑ 1 V/cm
→ 5 ms /cm

(b) Prot. filter output
3120±60 Hz channel
↑ Relative amplitude
→ 5 ms /cm

(disconnect opening)

FIGURE 5.11 DEMODULATED WAVEFORMS DURING BLANKING FIELD TESTS (Beatty-Wolverine line, switched and observed at Wolverine)



(a) SSB Rx output
0.3-3.24 kHz
Clipping threshold =
1.25 x signal peak
↑ 2 V/cm
→ 2 ms /cm

(b) Prot. filter output
3120±60 Hz channel
↑ 0.5 V/cm
→ 2 ms /cm

(disconnect closing)

FIGURE 5.12 DEMODULATED WAVEFORMS DURING CLIPPING FIELD TESTS (Beatty-Wolverine line, switched and observed at Wolverine) is seen in either method. During blanking for the few samples taken the percentage of time, in which the discriminator output indicates a trip receive, is even greater than that for no alteration.

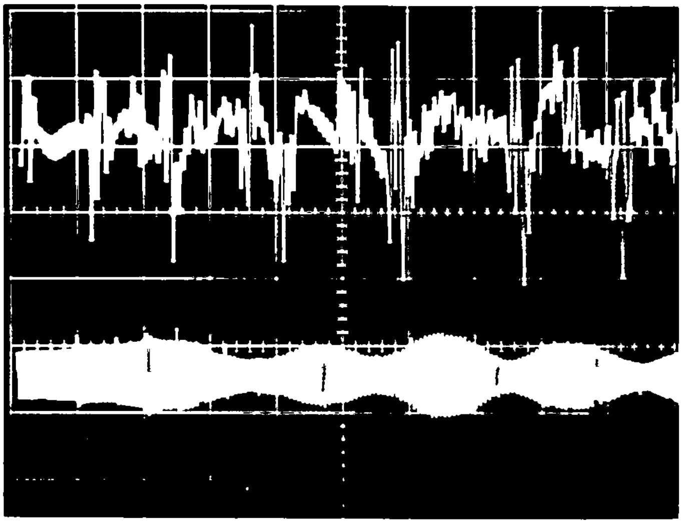
Of significance, however, is that if an integrator with a 20 ms rise time to a voltage step were placed after the discriminator, all possible false trips in the samples observed would be inhibited. This is even with no bias applied. Under no noise conditions implementation of such an integrator would delay a trip signal by approximately an additional 10 ms.

(iv) Contributing factors to negative test results.

- Modulation components:

Let all oscillograph traces start at time zero and traverse toward the right.

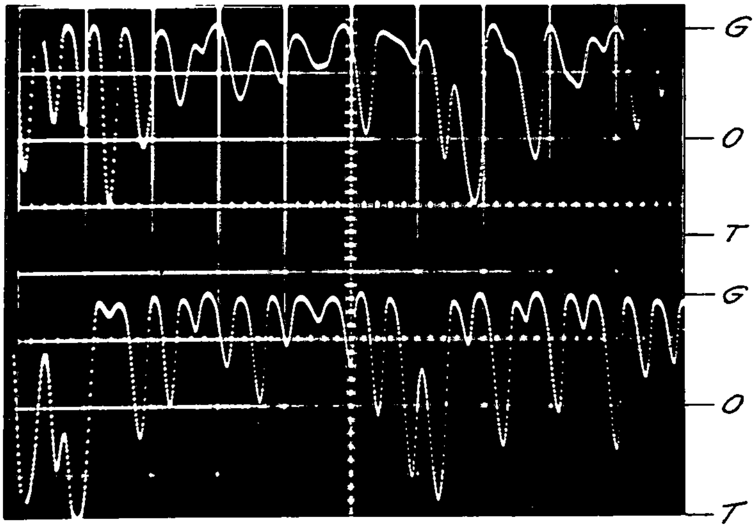
In Figure 5.9 (b), for example, the blanking circuit was triggered 4 times between times 3.0 ms and 4.5 ms. This was not expected. Close inspection reveals that immediately after the noise burst at time 2.7 ms the signal shape is undistorted; yet its amplitude is twice the normal signal amplitude and decays toward steady state value in approximately 2 ms. This type of amplitude modulation is present only during noise bursts and, as seen from Figures 5.10(a), 5.11(a), 5.12(a) and 5.13(a), has strong components at twice and three times the powerline frequency. During such modulation peaks the signal is unnecessarily blanked and an effect similar to increased impulse rate is obtained. Under modulation minima the signal is reduced; a noise appearing during this



(a) SSB Rx output
0.3-3.24 kHz.
↑ Relative ampl.
→ 5ms /cm

(b) Prot. filter output
3120±60 Hz channel
↑ Relative ampl.
→ 5 ms /cm

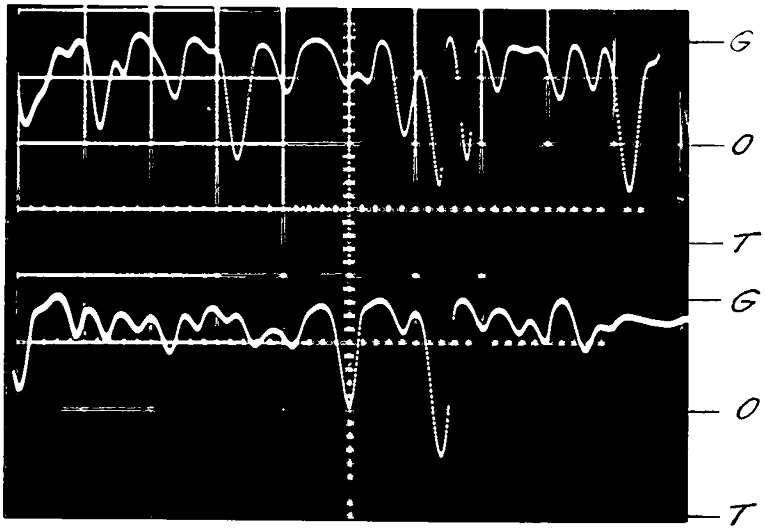
FIGURE 5.13 DEMODULATED WAVEFORMS DURING NORMAL FIELD TESTS (Beatty-Wolverine line, switched and observed at Wolverine)



Disconnect
closing
→ 20 ms./cm

Disconnect
opening
→ 20 ms /cm

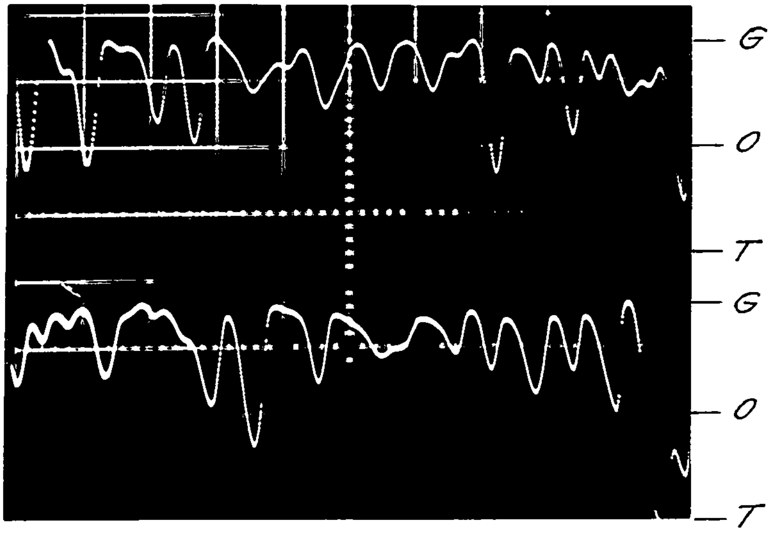
FIGURE 5.14 DISCRIMINATOR OUTPUT DURING BLANKED NOISE PLAYBACK (Beatty-Wolverine line, switched and recorded at Wolverine)



Disconnect
closing
→20 ms /cm

Disconnect
opening
→20 ms /cm

FIGURE 5.15 DISCRIMINATOR OUTPUT DURING CLIPPED NOISE PLAYBACK (Beatty-Wolverine line, switched and recorded at Wolverine)



Disconnect
closing
→20 ms /cm

Disconnect
opening
→20 ms /cm

FIGURE 5.16 DISCRIMINATOR OUTPUT DURING NORMAL NOISE PLAYBACK (Beatty-Wolverine line, switched and recorded at Wolverine) time then has a lower than average probability of being blanked.

Limited time was available in the field tests and the cause of this modulation has not yet been determined conclusively. It may originate before the receiver input or in the receiver amplifiers including the AVC circuitry. Blanking threshold levels up to twice the signal level were used during tests.

Similar considerations apply when the noise is clipped.

- Increased impulse rate:

In Figure 5.9 (b) the noise perturbs the signal throughout the time 0.8 ms to about 2.2 ms. Its amplitude is relatively low. However, this indicates an impulse rate above 720/Hz. Under this combination of impulse rate and bandwidth at the clipping/blanking point the noise behaves like a continuous "white noise", and an increase in transmitted power is wanted. It is clipped, blanked or allowed to pass to succeeding stages, dependent on its amplitude. In all three cases the S/N ratio at the output is too low to be useful. Due to the low observed amplitude the probable cause is reflections on the line.

- Threshold level for clipping and blanking:

With a clipping/blanking threshold set to 1.5 times the peak normal IF waveform, the effective threshold for the protection tone was actually 3 times its peak value. This arises from the suppressed carrier and protection tone sideband both being transmitted at the same transmitter voltage modulation. Figure C.3(a) and (b) supports this under simulated noise conditions. This then sets a limit on S/N ratio improvement possible. Elimination of suppressed carrier transmission and use of carrier insertion in the receiver would allow the threshold level to be lowered.

6. CONCLUSIONS

The noise studies have revealed vital characteristics of impulse noise, caused by the operation of disconnect switches, which can be used to advantage.

Interference-free signal regions, as shown in Figure 4.2, exist between individual noise impulses, when measured at a 3 kHz bandwidth, during a noise burst. These regions arise from the impulse rate generally being below 700 impulses per second with disturbance duration of approximately 0.3 ms per impulse at this same bandwidth. The significance of the foregoing lies in the noise not requiring to be treated as being random in nature. The possibility of extracting a signal of low energy, if the particular application warrants the expenditure of the bandwidth required to achieve this, exists.

Yet, the desirability of using high signal power cannot be overstressed; the noise energy is not so great to make any practical increase in signal power futile. The rather common use of low guard signal power such as the approximately 0.5 w utilized on the 70 mile long Beatty-Wolverine SSB link modulated by a FSK subcarrier, resulted in a signal to noise ratio in the order of 0 dB at the discriminator output. This narrow-band tone channel, of necessity, treats the noise as being random. As explained in Chapter 5.1, a power increase of 10 dB or more would not only be very beneficial, but also could be gained by circuit rearrangement.

Addition of a carrier in the noise channel of the receiver mentioned above as experimentally shown in Chapter 5.3, improves the security with no appreciable effect on reliability. Also, if an increase in transmission delay can be tolerated, Figures 5.14 to 5.16 suggest that an increase in security could be obtained by using integration time after the discriminator.

Blanking and clipping techniques can especially take advantage of the impulsive nature of the noise. These desire single-purpose receivers with bandwidths greater than necessary to just satisfy the signalling speed requirements. The improvement in output signal to noise ratio by utilizing clipping, as described in Chapter 5.4.1 for an ideal receiver, can be considerable. Probability of error is also theoretically reduced by blanking techniques, as indicated in Figure 5.6.

Field tests using blanking or clipping were not successful as no appreciable improvement in discriminator output during noise bursts was observed. Amplitude modulation of the signal itself in the IF section of the receiver, shown in Figures 5.9 and 5.10, degraded the improvement possible. The net result was that excessive as well as insufficient blanking/clipping occurred. For the case of blanking the highly desirable 2 kHz separation between guard and trip frequencies was not incorporated as this required extensive changes in both the transmitter and receiver.

The subject is not considered closed; it is hoped that some of the ideas presented will be put into use and it is recommended that the blanking method of noise reduction be further pursued.

7. REFERENCES

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8. APPENDICES

APPENDIX A. CARRIER IN NOISE CHANNEL BENCH-TESTS

Equipment set-up is illustrated in Figure A.1.

1. TIU-3 Receiver Operation

Under normal conditions a 2790 Hz guard sine wave is transmitted. To initiate a trip this signal is shifted to 2850 Hz. Either signal passes through the 2820 ± 30 Hz filter, is amplified, limited, and detected in the discriminator. The S/N detector compares envelope amplitudes at the outputs of the signal and 3300 ± 30 Hz noise sampling filters. The logic module incorporates high-speed circuitry and provides a trip output provided that the following conditions are all met:

(a) A trip signal is decoded in the discriminator.

(b) The S/N ratio is acceptable.

(c) Communications channel supervision is present.

Consider a sine wave carrier shifted in frequency from $(f_0 - B/2)$ Hz to $(f_0 + B/2)$ Hz and transmitted through a band-pass channel centered at f_0. At the receiving end, if the signal is applied to a detector with a response proportional to the instantaneous frequency deviation from f_0, the time taken (Sunde, 1969, Ch. 1.11), to detect that the input frequency was shifted, is 1/2B seconds in both of the following cases:

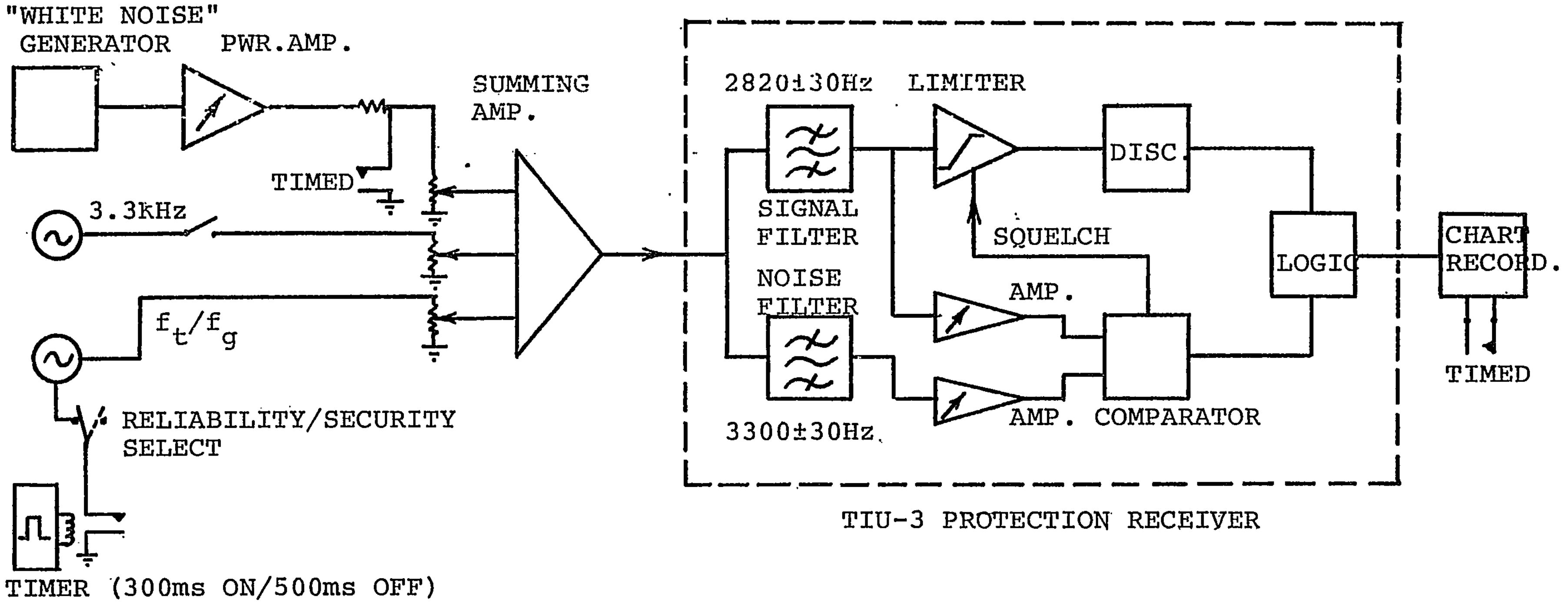

FIGURE A.1 TIU-3 PROTECTION RECEIVER RELIABILITY AND SECURITY TESTING ARRANGEMENT