# Theory and Operation of Grad

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Southern Pacific Company was confronted with the problem in the design of control circuits for automatic crossing protection of vehicular and pedestrian traffic which would be acceptable to public utilities commissions and at the same time offer a minimum of interference to movement of such traffic. This control involved the use of special timing circuits and the installation of multiple insulated joints which were expensive, both to install and to maintain. SP discussed this whole problem of modernizing railroad crossing equipment with the Stanford Research Institute.

The approach pursued by SRI was based on a proposal by Arlo Krout, principal assistant signal engineer, SP, for a system in which the grade crossing warning systems would operate at some selected prediction time and involving techniques for measuring the distance of an approaching train from the crossing and the speed of the train as well. It eliminated many of the expensive insulated joints and provided a constant warning time independent of the train's speed.

The commercial version of the SP-SRI grade crossing predictor has been developed by Marquardt Corp. The grade-crossing predictor unit developed by Marquardt is a state-of-the art solid-state device, using silicon diodes and transistors. It is designed to operate satisfactorily under the environmental conditions encountered in normal railroad operations.

### THEORY BEHIND GCP

The Grade Crossing Predictor treats the railroad track as a shorted transmission line in which the short is provided by the train. From the value of the input impedance or reactance of such a line, it is possible in this system to determine the location of the train and to obtain a value of train speed from the time derivative of this quantity. With the determination of these parameters, the train's arrival time can be calculated at the crossing. With the time of arrival known, the system can start the warning signals at a time to provide the least possible delay for vehicular and pedestrian traffic.

From a comprehensive theoretical and experimental analysis of the rails as a shorted transmission line, for the range of frequencies studied, it was determined that the capacitive susceptance is much smaller than the assigned values of shunt conductance. A straight line relationship does not exist between input impedance and track length to a short such as that imposed by the presence of a train. The relationship, however, does approach linearity as the attenuation of the transmitted signal decreases with increasing track ballast resistance.

Because of the absence of precise data on track parameters such as AC inductance and AC resistance at the GCP operating frequencies, it was decided at the outset to make an experimental determination of these quantities under conditions unaffected by track environment. A rail set-up circuit consisted of ten 132 pound rails with a total length of 386 feet. The rails were well insulated from the ground by mounting on separate ties with glass insulation between rail and supporting tie.

Measurements were obtained from this set-up concerning inductance and resistance as a function of frequency. It was noted that the inductance rises sharply at low frequencies, which is fortunate from the transmission standpoint as a higher return voltage is thereby obtained in this region. The resistance rises slightly within the operating frequency region. Empirical relationships were derived from this data, which were used in obtaining computer solutions for track impedance for various signal frequencies and values of ballast resistance.

### REACTANCE DATA

Curves were drawn showing the relationship between track reactance vs shorted transmission line length for an input frequency of 86 cps for ballast conditions ranging from a low of 2.5 to a high of 1,000 ohms per 1,000 ft. of track. Under present day operating conditions, it is doubtful if ballast conditions less than 5 ohms per 1,000 ft. are normally encountered. The 5-ohm curve begins to flatten out around 2,500 ft. and becomes tangential around 4,000 ft.

Since the predictor works on the premise that the input impedance is varying with distance to the train short, the operation of the device will not be effective on the tangential region of the curve. It will be partially effective on the curved portion and fully effective on the linear portion. The net result is a decrease in warning time from that established for the crossing.

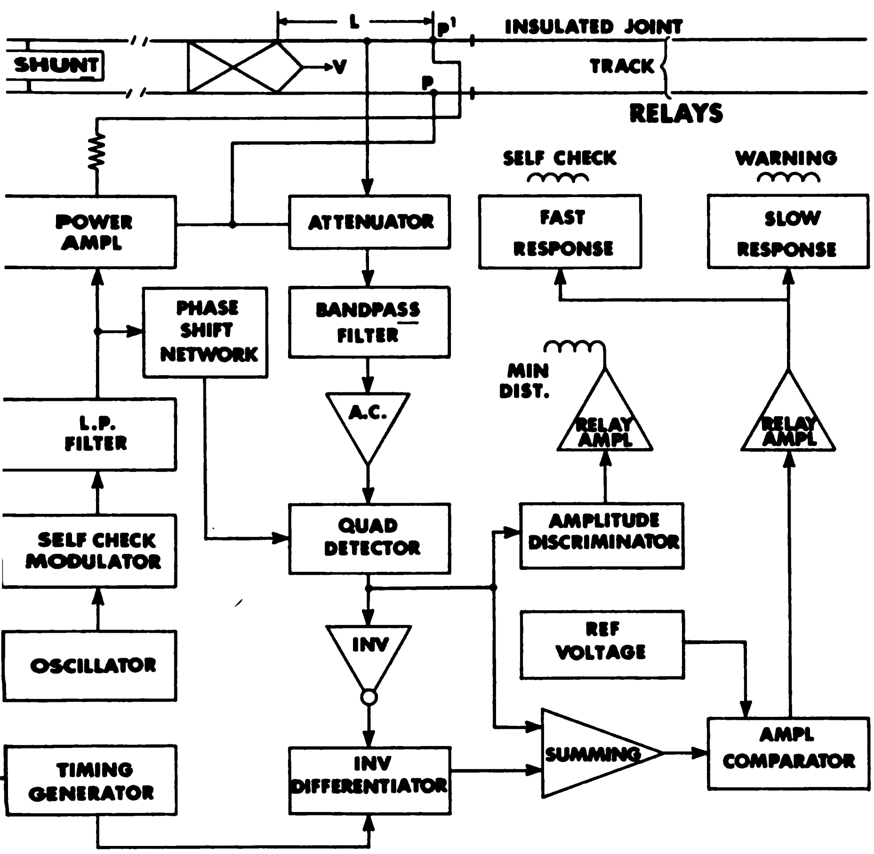
The use of a low frequency is desirable under low ballast conditions. However, since the general use of the predictor requires a multiplicity of frequencies to meet diversified operating requirements, the impedance (reactance) measurements were extended to a range of frequencies from 86 to 645 cps.

From a family of curves for a common ballast condition of 50 ohms per 1,000 ft. for the range of frequencies indicated, it was found that the impedance (reactance) increases with frequency. Since the voltage input to the predictor is directly proportional to the track impedance, the higher signal input results in improved signal-noise ratio at the output of the differentiator.

The frequencies 86, 128, 156, 285, and 645 cps were selected on the basis of minimum interference with each other and with the power line frequency and its harmonics. The 128 cps carrier will not be used extensively in the future. Also intermodulation components between higher orders of the individual carriers and power frequency components are to be avoided. For tracks with low ballast resistance, a low frequency like 86 cps is preferred because of a better reactance to track length relationship. For short distances as in yard installations, a higher frequency (645 cps) is used because of the higher voltage return from such a track. An empirical rule that no beat note between any of the components referred to above shall be closer than ± 20 cps from the carrier frequency is based on the transmission characteristics of the imput bandpass filter, in which a relatively wide bandpass is required to insure minimum phase shift within the band.

The early investigation on predictors carried out at SRI for the SP used the track impedance as the parameter to provide distance and train velocity components. Field experience indicated that this was undesirable, mainly because the resistance component of the track impedance might vary widely, possibly due to poor bonding between rails. This condition would result in an apparent increase in distance of the train from the crossing and a consequent reduction in prediction time. Since input impedance of a track is composed of a resistive and a reactive term, with a phase angle of about 70 deg., a bad bond introduces only series resistance. The high

# ossing Predictor is Explained




. 1—Functional block diagram of GCP installation.

luctive component of the input im- dance is largely due to the fact that e conducting rails have a high rmeability. Therefore, under the nditions of high ballast resistance, a d bond will only increase the sistive component. The same is true th low ballast resistance if the bad nd occurs near the predictor input nere the presence of a bad bond oduces the most serious conse- ıences.

## HEORY OF OPERATION

Operation of the Marquardt GCP epends on solution of the basic pre- ctor equation derived as follows:

Let L = the distance of the train at any time from the input to the rails

T = the warning time desired.

he voltage derived from the track put is applied to a quadrature de- ector and ideally the output from this evice is proportional to the reactance f the track. This in turn is proportion- l or representative of the distance L bove and is independent of bad re- stance up to the capability of the onstant current generator. The output of the quadrature detector is inverted and differentiated. The resulting voltage is proportional or representative of the train's velocity, $\frac{dL}{dt}$

Now if a warning time of, say, 30 seconds is desired, the output of a summing amplifier into which L and dL/dt are fed may be given by

$$L + 30 \frac{dL}{dt} = f(t)$$

At this distance L, the train will arrive at the excitation point in exactly 30 seconds, provided it continues at constant speed. The equation above represents the ideal condition where the phase of the track return voltage is exactly the same as the reference voltage fed from the oscillator through a phase shift network to the quadrature detector.

The wide ambient temperature range from −60 deg. to +160 deg. F encountered in field installations results in some degree of phase shift, especially in the input bandpass filter. This is compensated for in part by introducing an artificial phase angle delay in the reference signal input to the detector.

The actual prediction time is equal to the theoretical value for high values of ballast resistance. In practice, with low ballast resistance conditions, prediction times will generally be reduced with the greatest reduction being found for higher speed trains. From a family of curves of theoretical prediction time versus train speed for a given prediction time as set up in the predictor, it was observed that for a ballast resistance of 2.5 ohms per 1,000 ft. and a train speed of 60 mph, the prediction is reduced from 35 to 29 seconds. The situation improves with increasing ballast resistance, the error being less than 5 sec. for 5 ohms and less than 2 sec. at 10 ohms of ballast.

Curves show similar data for varying carrier frequencies and a fixed ballast resistance arbitrarily set at 10 ohms. As expected from theoretical considerations, the loss of prediction time increases with the carrier frequency. Thus at 60 mph for this ballast condition, the loss varies from 2 sec. at 86 cps to 11.5 sec. at 645 cps. This latter condition limits the use of the upper frequency to short distances requiring short warning times.

A functional block diagram of a typical GCP installation is shown in Figure 1. The basic driver of the system is an oscillator which furnishes the frequency selected for the particular crossing. This may be 86, 128, 156, 285, or 645 cps, depending on the track length required for proper prediction and ballast condition. The output is connected to a self-check modulator, the output of which is transmitted through a low pass filter to the power amplifier. The output of the modulator is connected to a phase shift network which introduces a phase shift equal to that introduced by other elements in the path between oscillator and the quadrature detector input when a pure resistance is substituted for the track impedance. The power amplifier is designed to operate as a constant current generator and this is further aided by the insertion of a large resistance between the output and the rails. The low pass filter is inserted in the line to attenuate all harmonic components above the fundamental of the carrier and thereby provide a sinusoidal waveform. This is important since the reactive nature of the track emphasizes these components, which in turn introduce unwanted noise components into the differentiator output.

The connection to the rails is made

at points P and $P^1$ and approximately 0.2 amp is fed to them. Assuming a constant current input, the voltage across the track will be proportional to the impedance and representative of the distance of the train from the crossing. A bandpass filter whose center frequency is the same as the oscillator frequency is connected across the input transformer from the track input. The voltage input is modulated by the motion of the train toward the point P, $P^1$. The output of the bandpass amplifier is applied to the signal input of a quadrature detector, the output of the oscillator being also applied to the detector as a reference in phase with the current applied to the track. The output of this detector is a voltage representative of track length L and is independent of bad bond resistance as previously noted.

The output of the quadrature detector is applied to a summing amplifier and also to an inverting differentiator and after further amplification is applied at the second input to a summing amplifier. The first input is representative of the distance L between the train and excitation points P, $P^1$, and the second input which is the derivative of this quantity represents the train's velocity. The output of the summing amplifier which inverts the inputs can be written as

$$-\left(L + T\frac{dL}{dt}\right) = f(t) \quad (A)$$

For a given warning time of, say, 30 seconds, this becomes

$$-\left(L + 30\frac{dL}{dt}\right) = f(t) \quad (B)$$

As long as f(t) remains negative, the warning signal relay remains energized, after comparison with reference voltage source and amplification by relay amplifier. If an approaching train is at a distance L greater than 30 dL/dt, f(t) will be negative and the train will take more than 30 seconds to arrive at the crossing. When f(t) becomes zero, the train will arrive in exactly 30 seconds provided it continues to travel at a constant speed. At this instant, the prediction signal relay will be de-energized and will remain in this state as long as f(t) remains positive. It will continue in this state until the train crosses the insulated joints. The warning signals remain operative for a few seconds after the last axle crosses the joints, due to the overall delay in the Predictor and associated railroad control circuits.

A block diagram with voltage waveforms for a particular quadrature detector is shown in Figure 2. The reference signal A is in phase with signal input C when a pure resistance is substituted for the track. When the reference signal A goes through zero, a Schmitt trigger followed by an RC differentiator produces a trigger pulse for the monostable multivibrator. The pulse duration of 50 micro-sec is applied through a pulse amplifier to control an electronic switch shown in waveform B. The AC signal input may be considered as having two components, the resistive component $C_R$ in phase with the reference voltage A and the inductive component $C_x$ leading the reference by 90 deg. Since $C_R$ is always zero when the sampling pulse occurs, it cannot contribute to the voltage stored by a capacitor. The latter voltage is then representative of the inductive component of the AC signal voltage from the track. This in turn is proportional to the track reactance which in turn represents L, the distance of the train from the point of excitation.

In practice, there is an inevitable drift in phase angle sampling due principally to effects of temperature (−60 to +160 deg. F) on such transmission items as the bandpass filter carrier signal. Due to careful design, including temperature compensating features, this shift has been held to a maximum of −5 deg. over the temperature range.

In Figure 1, there appears an item,

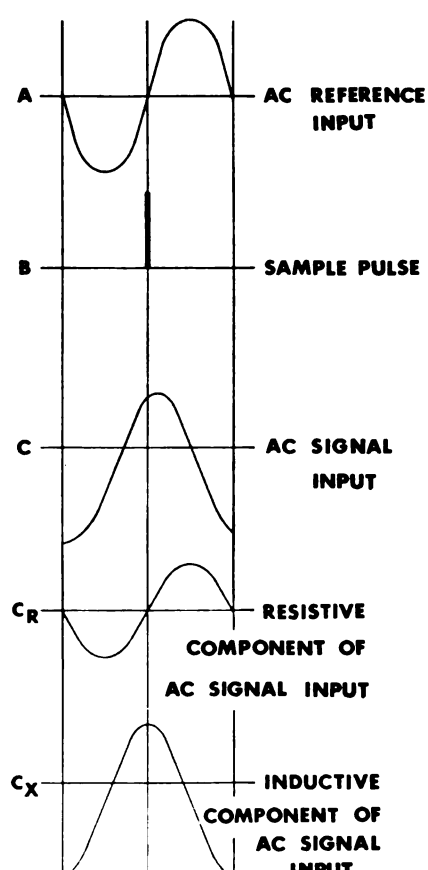


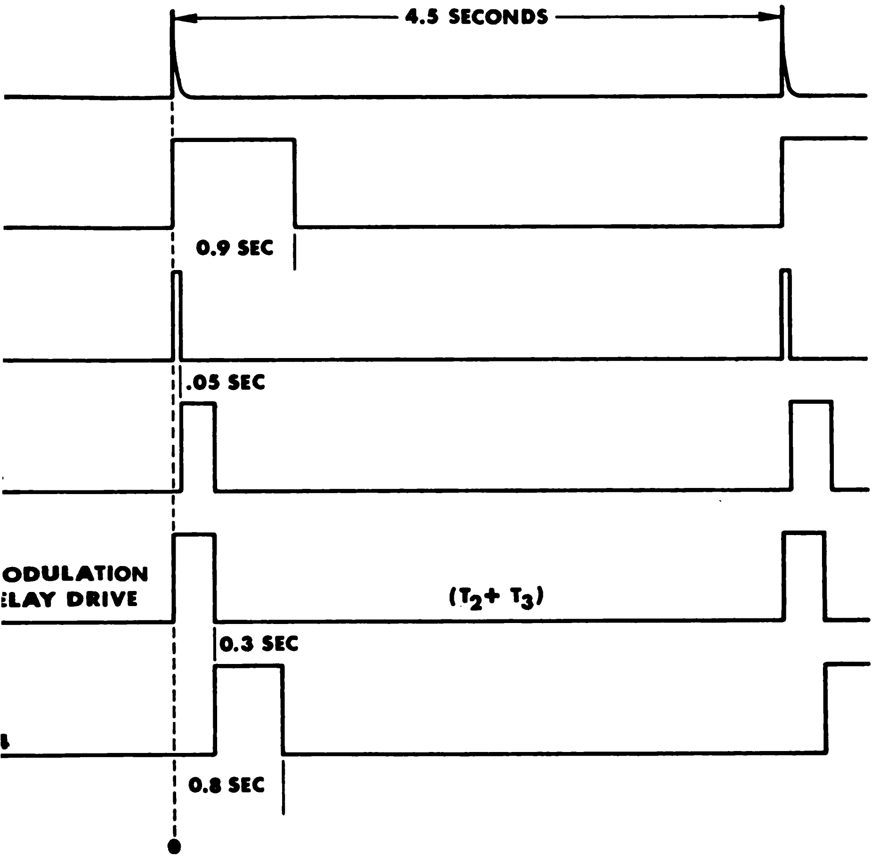

**Fig. 2**—Quadrature detector.

Relay Amplifier feeding a minimum distance override relay. This is required to operate the grade crossing signals when a train is stationary within some specified distance (40 ft.) of the crossing. Under this condition, the GCP relay contacts will be closed because the train velocity is zero and the f(t) of equation (A) is negative. The minimum distance relay becomes de-energized when the predictor voltage is less than a specified comparison voltage supplied by the amplitude discriminator.

**SELF-CHECK SYSTEM**

The substitution of an electronically controlled grade crossing predictor for the present electro-mechanical DC system makes it mandatory that a fail-safe mode of operation be provided. Since these installations are unattended and receive only periodic inspection and maintenance, a self-check subsystem has been incorporated in the GCP which detects any improper operation of the system and thereby provides fail-safe operation of the device. A timing generator shown in Figure 1 initiates self-check cycles at a rate low enough to provide adequate time between self-check cycles for prediction of train arrival time. The repetition rate is high enough to make the interval between self-check cycles sufficiently short to detect a condition which causes the warning system to malfunction. The timing generator controls a modulator, the output of which will be the carrier frequency amplitude modulated by the self-check generator output.

To simulate the shorted transmission line provided by a train, a narrow band, high Q series resonant filter is usually connected across the track at the 4,000 ft interval. The self-check modulation of the track current will give a voltage across the excitation points representative of a train moving very rapidly from $L_{max}$ to (.95 or .90) $L_{max}$ during the 3 sec self-check cycle. The pulse timing diagram of Figure 3 shows the different pulses generated during the 4.5 sec operation. Pulse t initiates the self-check cycle and recurs every 4.5 sec. Pulse $t_1$ serves to switch the offset voltage to zero for the DAV modules which will be described later. It also operates the differentiator scale factor for proper operation on self-check and prediction. Pulse $t_2$ determines the start of $t_3$. The latter time sample pulse is used in the self-check detector to check time of self-check response. $t_2$ and $t_3$ are used to drive the modulation relay. Pulse $t_4$ is employed to prevent the trailing edge of the self-check modulation (equivalent to a rapidly receding train) from causing a




g. 3—Timing diagram showing pulses generated in 4.5 seconds.

terruption of an actual prediction of approaching train.

## ARNING RELAYS

The "return" signal from the track, cluding the self-check modulated ortion is fed into the same circuit omponents as that described above r the operation of the predictor. The ormal warning and self-check compo- ents of the track signal are ultimately eparated by the slow and fast re- ponse circuits which operate respec- vely the warning relay and the self- heck relay. During the self-check ycle the differentiator scale factor ill be changed by timing generator ulse $t_1$ to a value to permit a solution f $f(t) = 0$. This will be detected by he amplitude comparator causing the ast response self-check relay to be nergized. By incorporating a slow elease, this relay will remain ener- ized during the 4.5 sec. interval be- ween self-check cycles. The slow esponse current controlling the warn- ng relay prevents the latter from re- ponding to the self-check solution. The three controlling relays associated vith the GCP are shown in Figure 4. The front contacts are in series with he standard railroad crossing (XR) elay. The GCP relays are normally energized and when any one of them drops out, the XR relay will be de- energized and the crossing warning system becomes operative. These three relays are shown as minimum distance, self-check and prediction (warning) relays. Since the system is designed fail-safe, any component or circuit failure will cause one of these relays to drop out and actuate the warning system.

The grade crossing predictor block diagram is shown in Figure 5. In this discussion each block will be treated independently and a conclusion drawn as to the effects of a failure in any of the blocks on the operation of the GCP. Any failure of the transistors in the DC-DC converter will result in loss of +32 volt supply, with the consequent drop out of the GCP self-check, minimum distance and prediction relays. Failure of the voltage regulator causes the self-check timing generator to give out $t_3$ pulses (see Figure 3) of the wrong duration and in the wrong sequence. Failure of the voltage regulator causes the scale factors in the differentiator and prediction module to be off, resulting in loss of self-check solution. In this case the self-check relay drops out.

Failure in the 6.2 volt supply results in self-check drop out caused by the biasing upset in the prediction module and the differentiator module. Failure in the driving oscillator results in loss of track drive and consequent input voltage. This results in prediction and minimum distance relay drop out. In the self-check modulator, failure of the modulation generator will result in no self-check wave-form and the self-check will drop out. Failure of any of these components or the power amplifier will result in loss of track drive, with resulting prediction and minimum distance drop out. In the return circuit, a short or open circuit in the bandpass filter will result in loss of received signal. Component failure in the AC amplifier will result in loss of signal. Loss of signal in both of these units will result in minimum distance and prediction (warning) drop out.

Failure in the quadrature detector will result in loss of distance voltage with minimum distance and prediction dropping out. The minimum distance circuit is an AC relay driver which receives its signal from a Schmitt trigger that is driven from the amplitude of the distance voltage. Short circuit or open circuit of any of these components will result in minimum distance relay drop out.

Failure in the differentiator will cause the self-check solution to appear

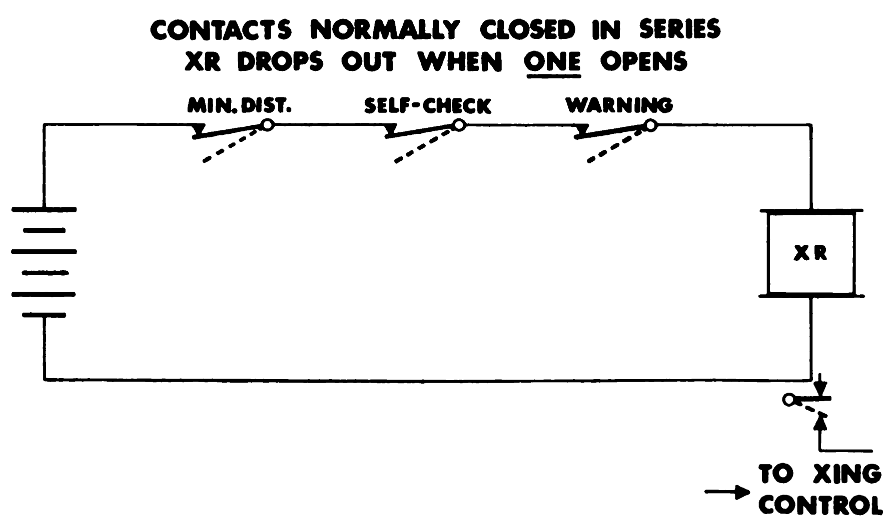



**Fig. 4**—Three controlling relays. "Warning" may be called "prediction" relay.

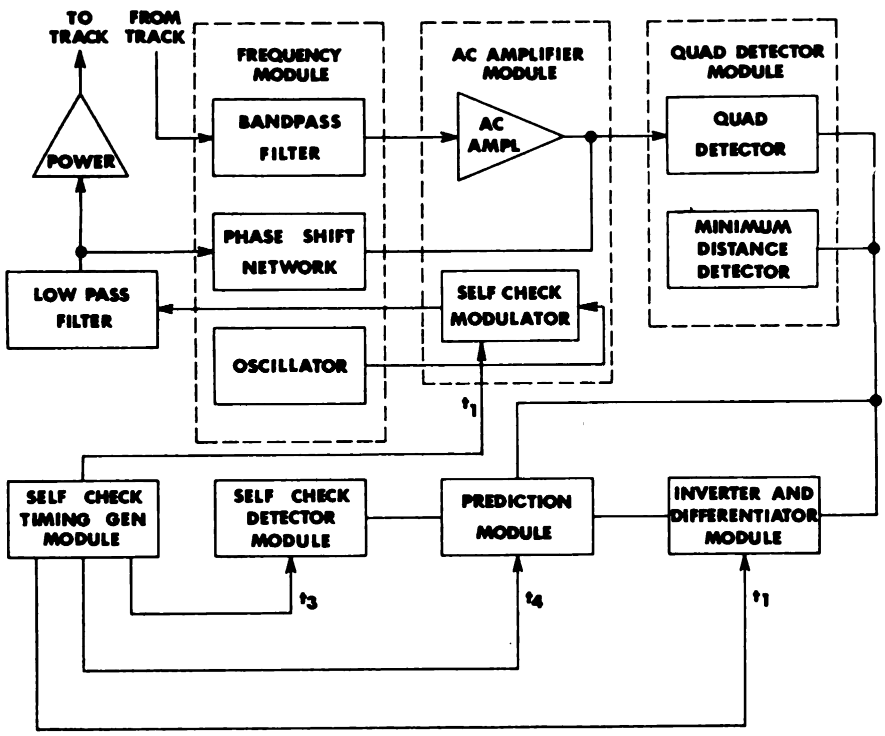



**Fig. 5**—Block diagram of the grade crossing predictor unit.

in the wrong time sequence, resulting in the self-check relay dropping out. Failure of the amplifier in the prediction module or in the prediction detector will result in no self-check getting through to the self-check detector, resulting in self-check drop out.

The self-check detector is an AND circuit in that it requires a self-check solution pulse from the prediction detector plus the $t_3$ timing pulses from the self-check timing generator and failure in this unit will result in drop out of the self-check relay. The self-check relay itself is driven by an AC relay driver. Short circuit or open circuit of any component in the relay driver results in drop-out of the relay. Loss of any transistor or component in the self-check timing generator results in loss of the timing pulses. If the timing pulse is lost, $t_3$ will not be present for summing in the self-check detector and the self-check relay will drop out.

The lightning protection afforded to the grade crossing predictor is provided by zener diodes in the transmitting circuit. Excessive voltage on the track will cause the zener diodes to short-circuit, thereby protecting the GCP equipment. Similar protection is provided on the receiving side of signal flow. Lightning protection is provided in the DC-DC converter itself in the form of zener diodes. If for any reason there is excess DC voltage input to the DC-DC converter, the circuitry will be protected by these diodes. Further lightning protection is afforded to the GCP equipment through the use of standard railroad equalizers across the tracks to protect the GCP from high voltage surge. A ¼ amp fast blow fuse is used in series with the series string of control relay contacts. The gold relay contacts are rated at 2 amp DC and normal current through these contacts is only 20 ma. The leads from the track are a twisted pair and are attached to the terminal strip in the signal cabinet. In the cabinet each lead is connected to a grounded lightning arrestor with an equalizer across the lead pair. The pole lines used to transmit the signal to the UAX relay coil use similar lightning protection, the DAX relay contacts are further protected by a 250 ma fuse.

## PREDICTOR EQUIPMENT UNIT

To facilitate ease of repair, plug-in printed circuit wiring boards are used extensively in the model 300 GCP. There are 14 plug-in type boards per system and one permanently mounted printed circuit board containing plug-in relays, switch, fuses, etc. A basic installation uses ten boards. For a situation with one downstream adjacent crossing (1 DAX), two additional boards are inserted, and for two downstream adjacent crossings, (2 DAX) another two boards are inserted.

The unit is powered from an external battery charger-rectifier system operating from 110 or 220 volts AC. An 8 to 12 volt battery is floated across the charger and supplies power to the unit in case of primary power failure. The power requirement for a single unit at 7-10 volts is 4.5 amp. A DC converter-regulator system converts the 7-10 volt input to the system to +25 volts and +32 volts. The dimensions of the unit are 33" long, 9.5" high, and 9.5" deep. The weight of the unit with a full complement of cards is approximately 48 lb.

## INSTALLATION CONSIDERATIONS

GCP installation problems are magnified by the presence of other electrical signals on the track and the proximity of other similarly protected crossings. Since the GCP is a unilaterally functioning device, a pair must be installed to cover bi-directional traffic.

A pair of insulated joints must be installed at one side of the crossing and placed as close as possible to the latter. This is a requirement since the minimum distance warning setting is 40 ft. from the joints and there is a system delay of a few seconds after the joints are passed over. Any distance between joints and crossing increases both minimum distance and the delay in returning the crossing to normal vehicular traffic flow.

It is highly desirable to install electrical rail bonds to insure reliable signal transmission. Where DC track circuits bar the use of a direct short required by the self-check system, the installation of a low impedance AC shunt across the track is required. With DC only on the track, a wideband shunt consisting of a nominal 80,000 mfd condenser may be used. Where another GCP operating on a different frequency or other audio signals are present, a narrow band tuned LC filter is installed across the track (shown in Figure 6).

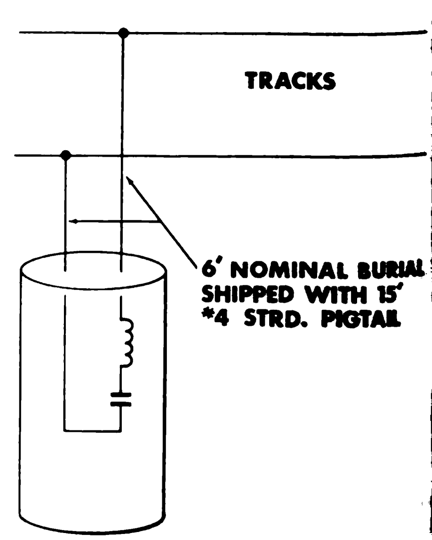
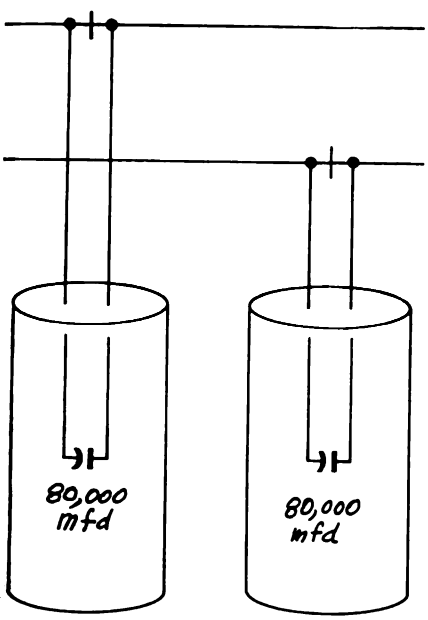



**Fig. 6**—Narrow bandpass filter.




**WIDE BAND AC SHUNT POTTED FOR BURIAL BELOW FROSTLINE**

Fig. 7—Wide bandpass filter.

DC track circuits present shunting problems, exemplified by the track relay and battery, the low impedance battery being a major difficulty. It is necessary to place a choke in series to make the battery circuit appear to have a high impedance to frequencies as low as 86 cps. Where a track rectifier is used, a wide-band shunt may be used to filter out the 120 cps ripple.

In most installations, because of the prediction distance involved, a railroad block signal will be located within it. The DC track circuit break at the block signal requires a pair of insulated joints and these are bypassed by a pair of the broad band shunts shown in Figure 7).

In the event that there is more than one crossing within a prediction distance, adjacent crossing equipment will have to be used because the GCP cannot "see through" an insulated joint. Therefore, the GCP cannot see beyond the next GCP and must use his GCP for its predictions. The nomenclature used to define the units is: Upstream Adjacent Crossing (UAX), and Downstream Adjacent Crossing (DAX). The DAX GCP which sees the train first has in its prediction computer a voltage offset equal to the distance from the DAX GCP to the UAX GCP, thus supplying a prediction equivalent to the DAX GCP being at the UAX position.

A typical adjacent crossing installation schematic is shown in Figure 8. The predictor at crossing A will have prediction modules. These are: (1)

a primary prediction module for crossing A, (2) a 1 DAX module to supply prediction for crossing B, located 1,500 ft. downstream, and a 2 DAX module for prediction at crossing C, 2,000 ft. further downstream. The GCP at B crossing will have a UAX relay to accept prediction from the 1 DAX module at A crossing. It will have its own primary prediction module and it will have a 1 DAX module with a 500 ft. offset. The UAX relay is a 7 sec. thermal delay relay to avoid loss of signal during the interval when the train has lost contact with one GCP and has not yet entered another GCP controlled area. The GCP at C crossing will have a UAX relay to accept prediction from the 2 DAX module at crossing A, and the 1 DAX module at crossing B in addition to its own primary prediction.

When a train is on the feed points, the self-check modulation is very small and this may indicate failure. This presents no problem at the primary crossing since the warning devices are in operation. To prevent improper operation of the warning system at the downstream crossing, it is necessary to bypass the self-check feature when the train is on the feed points at the primary crossing. This signal is obtained from the minimum distance relay in conjunction with the railroad track circuit relay or the GCP minimum distance relay on the opposite side of the insulated joints.

The solid-state electronic Grade Crossing Predictor will work independently of DC track signals and will result in considerable saving in installation expense since only one pair of insulated joints is required for each crossing. It operates from either 110 or 220 volts AC or from a standard railroad battery. It is capable of operating in ambient temperature from −60 deg. F to +160 deg. F, without failure of any components. To date about 100 installations have been made, and apart from some initial difficulties at time of installation, there has been a record of complete safety to vehicular and pedestrian traffic. This has been accomplished under widely varying conditions of ambient temperature and ballast condiitons. The miniature relays in some of the earlier installations have operated over 5 million times without any reported failures. **RSC**

*Editor's Note: This article on the Grade Crossing Predictor of Marquardt Corp., is essentially the full text of Dr. Frayne's paper (minus some of the mathematics) which he delivered to the Communication and Signal Section, AAR, at its annual meeting in Chicago last month. In addition to the Southern Pacific, several other railroads have ordered or installed GCP equipment at highway-railroad grade crossings: Canadian Pacific; Detroit, Toledo & Ironton; Missouri Pacific; New York Central and Seaboard Air Line. An article about one or more of these installations will be published in a forthcoming issue of Railway Signaling and Communications.*

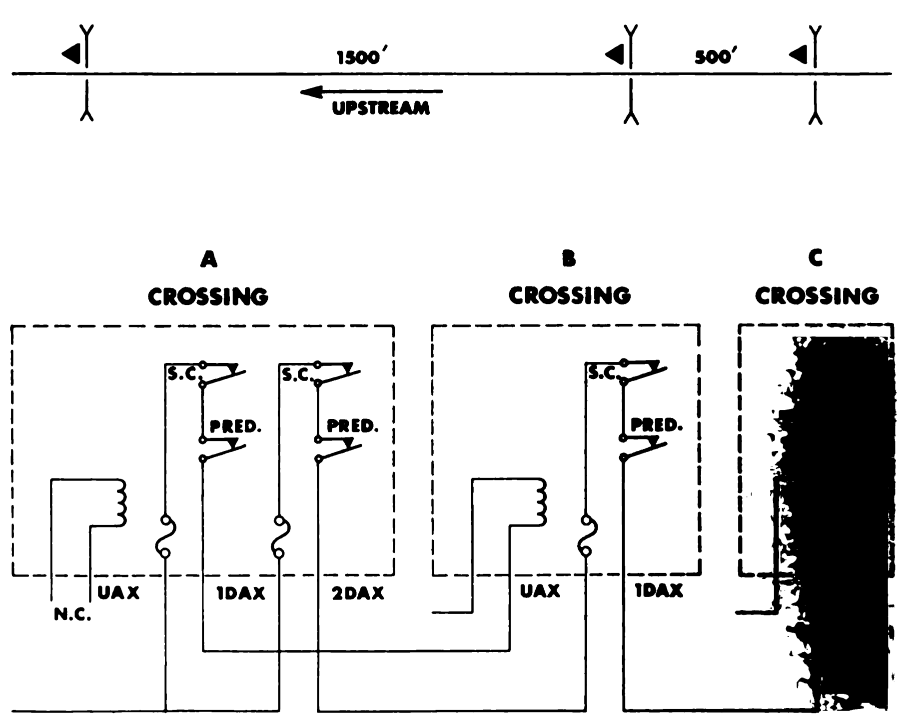



**Fig. 8**—A typical adjacent crossing installation schematic.