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Reduction of Ground Noise in the Transmitter Crowbar Instrumentation System by the Use of Baluns and Other Noise Rejection Methods

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Electrical noise interference in the transmitter crowbar monitoring instrumentation system creates false sensing of crowbar faults during a crowbar firing. One predominant source of noise interference is the conduction of currents in the instrumentation cable sheilds. Since these circulating ground noise currents produce noise that is similar to the crowbar fault sensing signals, such noise interference reduces the ability to determine true crowbar faults.

Analysis and test data are presented to show that by properly applying baluns (Balancing Units) and other noise rejection methods, the induced ground noise is reduced and proper operation of the crowbar instrumentation system is obtained.

I. Introduction

Modern day high-power transmitters use large and expensive components in the final RF amplifier stage. For example, a klystron may cost as much as $250,000. The protection of these high-cost items from destructive arcs and overloads is, therefore, of paramount importance. One of the special protection devices in a high-power transmitter is the crowbar unit. When an internal arc in the klystron is sensed, the crowbar is instantly fired and diverts the large stored energy in the power supply system, thus preventing the disaster that would result if the energy were "dumped" into the arc.

The crowbar instrumentation system that senses the faults and commands firing of the crowbar has been integrated into an overall transmitter control console. The console provides the operator with the overall status of the transmitter. The successful operation of this monitoring and protection system is unfortunately degraded due to electrical noise interference. A conductor or a circuit in a monitor and control system is always subjected to electrical influences from the surroundings. This is pronounced in crowbar systems, where high voltages and high currents arise relative to other circuits or ground. The disturbances thus caused can produce erroneous operation of the circuit, particularly if the circuit is relatively rapid and thus liable to be influenced by high frequency disturbances. Sources of these noise disturbances in monitor and control circuits include stray capacitive coupling, stray inductive coupling, circuits exposed to high voltage and high current gradients, and common impedance (all points connected to reference ground are not equivalent) [1]. Various methods of minimizing and suppressing ground noise have been used and are described in this article. Baluns were used extensively as an EMC control device (noise suppressor) and played a key role in suppressing noise in the crowbar logic and timing circuits. The noise-suppressing effects of baluns have been investigated and details are presented below.

II. Baluns as an EMC Control Device (Noise Suppressor)

Baluns, as referred to here, are basically small iron-core transformers, bi-filar wound, with an equal number of primary and secondary turns used such that the signal current passes through one winding as it goes to a load and through the other winding as it returns to the source. Although baluns have been widely used by RF designers to connect balanced transmission lines with unbalanced lines or devices, their ability to suppress noise within electronic equipment has not been as fully exploited. A balun, or common-mode choke, is a bi-filar wound, broadband transformer that allows equal and opposite currents to flow through its windings, while suppressing unequal currents, such as those due to ground noise. Because of the bi-filar windings, no net flux is generated in the balun when its two currents are balanced; therefore, balanced signals encounter no inductance when passing through the balun. For unbalanced currents, however, the device acts as an inductance and effectively breaks up the ground current path. Unlike differential amplifiers, which can also be used to suppress ground noise, baluns are not common-mode limited and do not require expensive power supplies. Other advantages over differential amplifiers are lower cost, less distortion, and vastly greater reliability.

Baluns can be applied at either the driving or receiving end of a transmission signal line. Among the driving-end applications are ground isolation, current balancing, and protection of critical analog circuitry. In receiver applications, a balun can provide isolation for digital-circuit grounds, perform noise balancing, or reduce noise associated with single-wire transmission. When used as a receiver for a single-ended line, the balun allows the line to be converted into a balanced line without picking up any ground noise.

An instrumentation system with a coaxial balun at the input of the sensor amplifier is shown in Fig. 1. As stated above, when equal and opposite currents flow through the windings, as in the case of sensor current I_L (Fig. 1), no net flux is generated, and, therefore, no inductance is encountered. If unbalanced currents flow through the windings, as in the case of I_{n1} and I_{n2}, the coaxial balun acts as an inductance. A lumped inductance in series with the sensor amplifier cable shield would not be desirable because the sensor current and noise current would be reduced, thus maintaining a constant signal-to-noise ratio.

The ground noise current, induced cable noise current, and induced cable noise voltage (I_n, I_{n2}, and V_{na}, respectively) can be derived from Kirchhoff's laws by assuming that the amplifier input voltage signal from the sensor, V_{La}, equals zero [2]:

$$I_n = \frac{V_n\,[R_S + R_L + R_a + j2\pi f\,(L_s + L_c - 2M)]}{(R_S + R_g + j2\pi f L_s)(R_L + R_a + R_g + j2\pi f L_c) - (R_g + j2\pi f M)^2}$$

$$I_{n2} = \frac{I_n\,[R_S + j2\pi f\,(L_s - M)]}{R_S + R_L + R_a + j2\pi f\,(L_s + L_c - 2M)}$$

$$= \frac{V_n\,[R_S + j2\pi f\,(L_s - M)]}{(R_S + R_g + j2\pi f L_s)(R_L + R_a + R_g + j2\pi f L_c) - (R_g + j2\pi f M)^2}$$

$$V_{na} = I_{n2} R_a$$

where

R_a is amplifier input resistance

R_L is sensor resistance

R_S is shield resistance

R_g is ground resistance

L_c is coaxial balun center conductor inductance

L_s is coaxial balun shield inductance

M is coaxial balun mutual inductance

The above equations show that the induced ground noise is minimized when $L_s \gg 0$ and $L_c \gg 0$.

III. Summary of Other Noise Rejection Methods Employed

Although baluns played a key role in reducing ground noise interference in the transmitter crowbar instrumentation system, other simple basic rules were employed to limit ground noise current to inductive and capacitive coupling. These design rules included:

(1) All circuits sensitive to disturbance of high current crowbar discharges were designed so that their outgoing and return conductors followed each other as closely as possible. The conductors were either a twisted shield pair or coaxial cable.

(2) In the crowbar cabinet, all the sensing cables (coax and twisted pair) were contained within a conductive conduit to reduce the high frequency ground noise [2].

(3) The signal grounding system was connected to the ground system at only one point.

(4) All wiring was carried out radially to prevent conductor loops.

(5) As much care and attention was given to the "disturbing" circuits as the "distrubed" ones. High voltage corona and current arcing were minimized to reduce EMI.

(6) Damping and clamping circuits (Zener diodes) were used wherever necessary.

IV. Experimental Results

The transmitter crowbar instrumentation system comprises basically the crowbar logic circuits (i.e., all circuits that monitor various transmitter critical operating parameters such as beam voltages and currents, the klystron body ("fast" body and "slow" body) and klystron magnet currents) and the crowbar timing circuit. When the klystron body currents or magnet current exceed the allowable operating range, the logic circuit senses this false operation and "fires" the crowbar, i.e., removes the beam voltage rapidly (in less than 10 microseconds). At the same time, the crowbar timing circuit measures the time it took to remove the beam voltage and verifies that the crowbar fired properly.

The data recorded in Fig. 2 was measured at DSS 13 before any attempts to apply baluns and other noise rejection methods to the crowbar cabinet and the crowbar instrumentation system were made. Note that when the crowbar was tested, the true fault should have been fast body interlock; however, due to the induced ground noise in the shields (as seen on the analog signals), the true fast body interlock was reset and false interlock signals of slow body and magnet interlocks were set.

The data recorded in Fig. 3 was measured at DSS 13 after the following modifications were made:

(1) The crowbar logic and timing circuit boards were moved from the crowbar cabinet to local control console (LCC) cabinets, about 30 feet away.

(2) All signals were carried between the crowbar cabinet and LCC by either coaxial cables or twisted-shield pairs.

(3) In the crowbar cabinet, attempts were made to reduce EMI created by voltage corona and current arcing, and all signal cables (coaxial and twisted pair) were contained in conduits. All wiring was carried out radially to prevent conductor loops.

(4) Baluns were applied to all signals arriving and leaving the logic and timing cards by wrapping each coaxial cable or twisted-shield pair around a Ferroxcube 400XT 750 3C8 core.

Due to modification (3) and primarily due to the addition of baluns, the immunity of the crowbar instrumentation system to induced ground noise was greatly increased. The system now operates without giving false indications during a crowbar firing.

V. Conclusions

By using baluns and other noise rejection methods, induced ground noise in the crowbar instrumentation system was reduced considerably, thus preventing false indications and improving reliability and the maintenance reporting feature of the system. Baluns played a key role in reducing induced ground noise without attenuating the sensor signal.

Finally, the problem of noise-rejection in monitor and control circuits in an electrically unfavorable environment, when circuits, subassemblies, or racks have to be interconnected, affects most engineers engaged in electrical design work. It is probably their biggest headache, and it is therefore necessary that noise rejection methods are applied from the start-up of the project, during the electrical and mechanical design phase.

Acknowledgment

The authors acknowledge the efforts of Keith Gwin, who performed various modifications to the crowbar instrumentation system and the crowbar cabinet.

References

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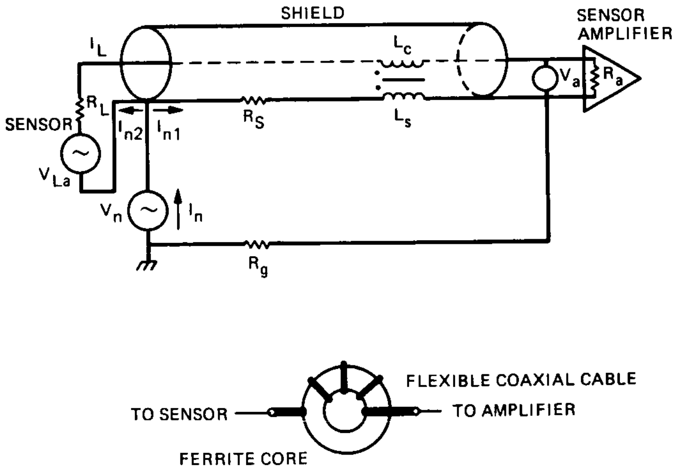

Fig. 1. Coaxial balun placed at the amplifier input

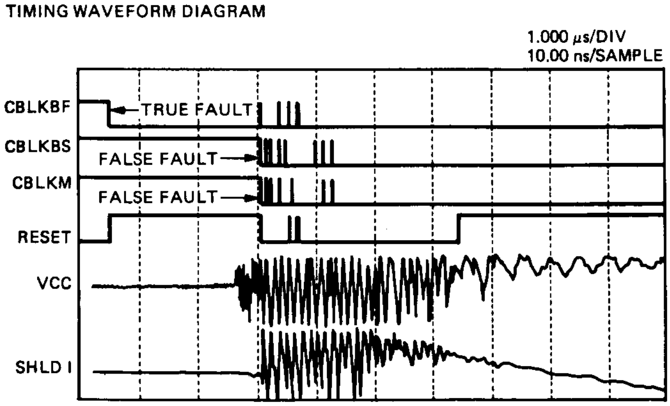

Fig. 2. Crowbar cabinet and instrumentation system noise measurements *before* improvements

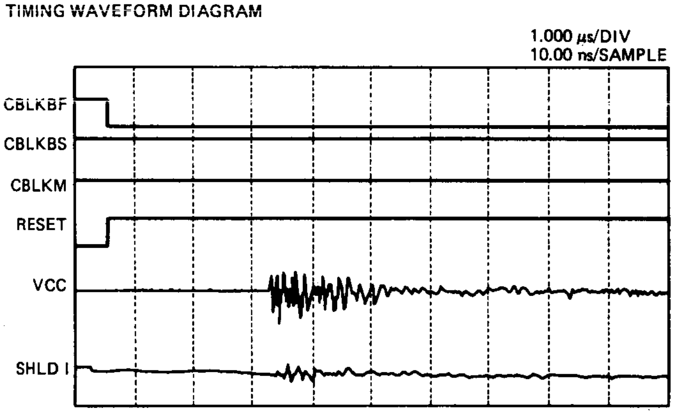

Fig. 3. Crowbar cabinet and instrumentation system noise measurement *after* improvements