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FAIL-SAFE LOGIC ELEMENTS FOR USE WITH REACTOR SAFETY SYSTEMS

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A complete fail-safe trip circuit is described which utilizes fail-safe logic elements. The logic elements¹ used are analog multipliers and active bandpass filter networks. These elements perform Boolean operations on a set of AC signals from the output of a reactor safety-channel trip comparator.

Many types of safety systems are used in the instrumentation and control channels of a nuclear reactor. Some of these systems employ electromechanical devices to perform all the necessary logic and power-switching functions, while others employ electronic components or a combination of electronic and electro-mechanical components for these tasks. In both cases the logic is a DC system with the output in one of the two possible states. These circuits are simple but they lack an important feature. A single component failure can cause the system to fail in the untripped state. Many designers have implemented the full-safe approach to trip circuit design in the attempt to solve this problem.

Many fail-safe circuits have been described in the literature^{2,3} but have had limited appeal because of their complexity.

The circuitry described in this paper may be used to replace the relatively complicated circuitry which has been used in the past, involving blocking oscillators and multi-stage amplifiers. It performs the logical AND and OR operations on the output of AC trip comparators using inexpensive integrated circuits.

The output signal from an AC trip comparator is a periodic, square-wave signal when the input is below the preset trip point and a zero level DC signal when the trip point has been exceeded. This output is used as the input to the logical AND/OR circuits.

The logical AND element is a combination of an analog multiplier and a bandpass filter as shown in Fig. 1.

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The logical OR element is a combination of a passive summer, a two-state, high-gain amplifier, and a bandpass filter as shown in Fig. 2. The logical OR element accepts two or more square signals from the AC trip comparators and will produce an output sine wave of frequency ω if any of the inputs are present.

The bandpass filter at the output of the two-state DC amplifier has a center frequency of f_1 and will reproduce the fundamental frequency component of the f_1 frequency square wave. If the DC amplifier oscillates, or if a different circuit failure produces any frequency significantly different from f_1 , the signal will be outside the passband of the filter and a zero AC voltage will be developed at the "OR" element output.

The active bandpass filter is described by the following degree-two transfer voltage ratio,

$$\frac{\frac{f}{\sigma} \cdot \frac{1}{\sigma}}{\left\{ \left[1 - \left(\frac{f}{\sigma} \right)^2 \right]^2 + \left[\frac{1}{\sigma} \cdot \frac{f}{\sigma} \right]^2 \right\}^{1/2}} \quad (1)$$

where $Q = (3 \text{ db Bandwidth})/f_0$.

The bandpass characteristic is plotted for values of $Q = 1, 10$, and 50 in Fig. 3. A bandpass filter with a Q of 10 was used to achieve a compromise between adequate center frequency bandwidth and adequate attenuation outside the passband. The fundamental sine-wave component of the incoming square wave is reproduced at the bandpass filter output while the third and fifth harmonics are attenuated by -28 db and -34 db respectively.

Fig. 3. Bandpass Filter Amplitude vs Frequency Characteristic.

The active analog multiplier is an integrated circuit whose output fulfills the equality

$$V_o = \frac{V_1 V_2}{10} \quad (2)$$

It is this equation that forms the basis for the AND circuit. For inputs

$$V_1 = V_{1M} \sin \omega_1 t \quad (3)$$

$$V_2 = V_{2M} \sin(\omega_1 t + \phi)$$

$$\text{where } \omega_1 = 2\pi f_1$$

The analytical expression for the output is

$$V_o = \frac{V_{1M} V_{2M}}{10} \sin \omega_1 t \sin \left(\omega_1 t + \frac{\phi}{2} \right) \quad (4)$$

$$\text{or} \quad V_o = \frac{V_{1M} V_{2M}}{20} [\cos \phi - \cos(\omega_1 t + \phi)]$$

The multiplier output is fed through a $Q = 10$, degree-two bandpass filter B tuned to f_1 . This filter rejects the DC component, $\frac{V_{1M} V_{2M}}{20} \cos \phi$, and passes the AC components proportional to $\cos(\omega_1 t + \phi)$.

The final component of the "AND" element is a passive high-pass filter which rejects any DC voltage that may develop at the filter B output. In the case of a failure, it can now be recognized that if either or both inputs to this logical "AND" circuit are of zero value or are not equal to the chopping frequency $f_1/2$, the "AND" output is of zero value. Bandpass filters A1 and A2 enable the multiplier to only multiply frequencies of $f_1/2$. If the inputs are different frequencies because of a circuit failure, the sum and difference frequencies at the multiplier output are likely to be outside the passband of filter B and the circuit would deliver a zero AC voltage.

Fig. 2 illustrates the logical OR element using a passive voltage summer, a two-state, high-gain DC amplifier, and a bandpass filter. This "OR" element delivers a sine wave of frequency f_1 at the output if either or both inputs are square waves of frequency f_1 , and a zero value if both inputs are zero or not f_1 -frequency square waves. With the DC amplifier the resulting square wave is of the same voltage value if either or both inputs square waves are present at the summer input.

Fig. 4 shows a typical combinational circuit, employing both logical elements.

Fig. 4. Combinational "AND" "OR" Element.

$V_1(t)$ and $V_2(t)$ are AC trip signals monitoring the same input. If either or both are in the trip state a scram output develops. $V_A(t)$ and $V_B(t)$ are two trip signals monitoring two different inputs. If both are in the trip state a scram output develops. The trip state is defined such that the AC trip voltage (i.e., V_A, V_B, V_1, V_2) is zero or not equal to the chopping frequency. With this assumption it is apparent that the logical "AND" #2 will develop a zero-voltage output for a scram condition if either or both of its inputs are zero. This will occur if either or both of the logical "AND" #1 inputs are zero, or if both of the logical "OR" inputs are zero.

Implementation and Experimental Results

The fail-safe trip concept discussed above has been implemented in an experimental reactor period meter.⁴ The block diagram of this system is shown in Fig. 5.

Fig. 5. Fail-Safe Logic Elements Used in A Reactor Period Meter.

The analog level signals from the period meter are compared using an operational amplifier to sum the chopping signal, the input signal, and the reference signal. The operational amplifier is followed by a single-ended output stage to prevent a bipolar output. Thus, when the sum of the input voltage and the reference voltage are equal in magnitude and opposite in polarity to the chopping signal, the output of the

chopper goes to 0 volts.

As previously discussed, the output of the choppers is delivered to a bandpass filter. This circuit is implemented with the Beckman 881 universal active filter. This filter is a hybrid integrated circuit essentially combining four 741 type operational amplifiers and passive components on a substrate. The 881 can be used as a low-pass, high-pass or bandpass amplifier by selecting external resistor values. The filter uses three of the internal amplifiers. The fourth amplifier is uncommitted and in this application was used to implement the chopper-comparator.

The multiplier used to perform the AND function is the Analog Devices AD532. This device is internally trimmed and requires no external adjustments or components.

Some of the experimental results for the logical "AND" element are shown in Figs. 6 and 7. The two top traces in Fig. 6, are the 10V peak-to-peak outputs of the bandpass filters for chopper-comparators 1 and 2 (5V/cm). The third trace (1V/cm) is the normal 2V peak-to-peak output of the multiplier. The fourth trace (20mV/cm) demonstrates the multiplier output with one input open and measures 15 mV peak-to-peak. The first three traces in Fig. 7 again show the normal inputs and output of the final multiplier (5V/cm, 5V/cm, 1V/cm). The lowest trace (1V/cm) is the output of the final bandpass filter which removes all traces of distortion. The output of the final filter is delivered to a scram detector, consisting of an AC coupled power amplifier with transformer-coupled output. The output wave is rectified and used to energize a relay or set of relays. Thus, any interruption of the AC signal will result in the output relay being de-energized.

TimeScale = 500 μ s/cm

Fig. 6. Typical Input and Output Voltages for First Analog Multiplier of Combinational AND-OR Element.

CONCLUSIONS

Through the use of analog multipliers and bandpass filters relatively simple and effective fail-safe logic circuits can be implemented for AC signals. The logic "AND" element, consisting of three bandpass filters and one analog multiplier, will develop a false output if either input is zero or not equal to the trip circuit chopping frequency. The logic "OR" element, consisting of a passive summer, two-state amplifier, and bandpass filter, provides a sine-wave output only if at least one input is equal to the trip circuit chopping frequency.

Timescale = 500 μ s/cm

Fig. 7. Typical Input and Output Voltages for Second Analog Multiplier of Combinational AND-OR Element.

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