The Anderson Loop: NASA's Successor to the Wheatstone Bridge

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ABSTRACT

NASA's new Anderson loop analog measurement circuit topology significantly outperforms the classic Wheatstone bridge in many measurement and control applications. Using active subtraction as the key enabling technology, the Anderson loop can provide greater accuracy with less excitation than the Wheatstone bridge and accomplish additional measurement functions. The limitations of the Wheatstone bridge are recalled and the fundamentals of Anderson loop theory are presented.

INTRODUCTION

The Wheatstone bridge has been a standard measurement circuit topology for over a century.(1) Indicators such as galvanometers and earphones did not load the bridge measurement circuit at balance conditions. Some derivative of the Wheatstone bridge could reliably estimate almost any resistive and reactive electrical quantity when the product of the opposite bridge arm impedances was adjusted to be equal.

The advent of variable resistance strain gages provided the transducer designer with a linear sensing element of essentially infinite resolution. The Wheatstone bridge was called on to operate away from balance conditions when strain gages were designed into transducers. Excellent transducers based on off-balance bridge operation became widely available at reasonable prices. DC-coupled amplifiers with good stability arrived to observe the output of bridge transducers in simple, effective signal conditioners.

Lead wire resistance variation problems that occurred when connecting high-temperature strain gages to signal conditioning equipment in the Thermostructural Laboratory of the NASA Dryden Flight Research Center led to the NASA measurement circuit topology invention(2) now called the Anderson loop,(3,4,5) A simple blending of analog subtraction with the Kelvin circuit concept,(2,6,7) the innovation proved to be a fundamental measurement circuit topology breakthrough — an enabling technology that benefits a wide variety of measurements and environments.

This paper does not suggest that the Wheatstone bridge should be abandoned in the design of new transducers. Rather, it suggests the transducer designer consider the possibility that an alternative measurement circuit topology might significantly outperform the Wheatstone bridge in some applications and, in the process, unleash the transducer designer’s creativity to accomplish previously unrealistic measurement objectives.

WHEATSTONE BRIDGE LIMITATIONS

As an electrical circuit for variable-impedance sensor element signal conditioning, the classic Wheatstone bridge provides a number of well-known advantages. They may be found presented in depth in any electrical measurement handbook.

Perhaps because there has been no alternative measurement circuit topology readily available, the disadvantages of the Wheatstone bridge are usually overlooked. In critical applications, great pains are taken to overcome them. Some of these disadvantages are:

- Half the signal from each element’s impedance change is typically consumed in adjacent bridge arms.

- The output signal is usually a nonlinear function of impedance change per individual bridge arm.

- Each individual sensing impedance variation is typically able to influence only one measurement output.

- Lead wire and connector impedance changes typically add measurement uncertainty, particularly when they occur in the inter-bridge wiring and especially when the various changes do not evolve identically.

- As many as eight lead wires may be required per bridge transducer to impose a reliable excitation level and precisely alter the output of the transducer to accomplish an end-to-end system electrical calibration.

- Multiple sensing impedances observed simultaneously provide only a single output signal that is typically a fixed function of the sensor element impedance changes.

- The transfer function, including compensation, of a bridge transducer is essentially “locked in” — typically not adjustable after manufacture and very rarely adjustable after installation when the actual operating environment becomes known.

- Thermoelectric (self-generating) outputs are difficult to separate from continuous impedance change (non-self-generating) outputs when using DC excitation.

NASA's Anderson loop measurement circuit topology deals effectively with all of these limitations by using "active" subtraction to observe the change in the output level of the variable impedance element(s) instead of the "passive" subtraction accomplished by the Wheatstone bridge circuit.

ANDERSON LOOP FUNDAMENTALS

Dual-Differential Subtraction

Consider the dual-differential subtractor, a six-terminal three-port active electronic circuit function defined in fig. 1.

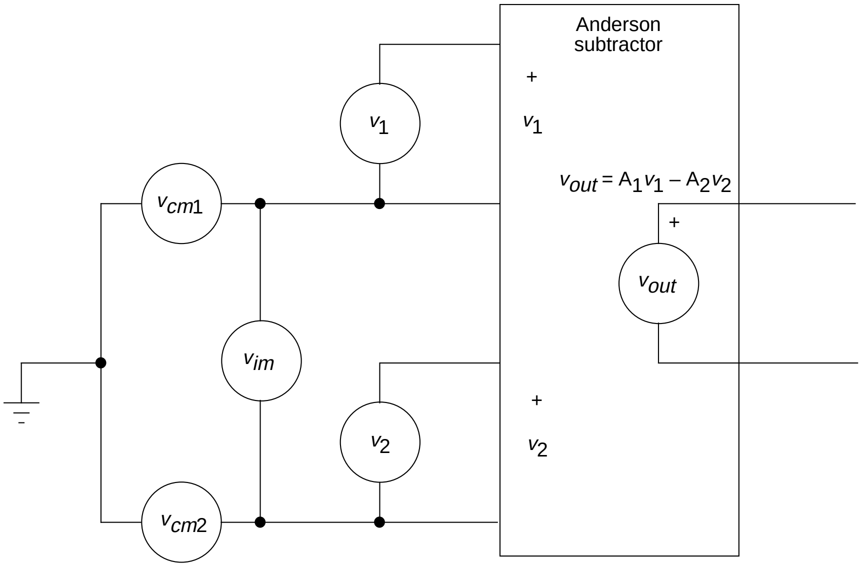

Figure 1, The dual-differential subtractor

The ideal dual-differential subtractor delivers at its output, v_{out}, the difference between two input potential differences, v_1 and v_2, amplified by gains A_1 and A_2, respectively, and is uninfluenced by any common potential difference, v_{cm1} and v_{cm2}, or interior mode potential difference from one input to the other, v_{im}.

The dual-differential subtractor is an enabling technology that has spawned a number of measurement circuit innovations, the Anderson loop among them. The active electronic circuit blocks which accomplish this function have come to be known as Anderson subtractors.(4)

Anderson Loop Measurement Circuit Topology

By using active subtractors in the Anderson loop measurement circuit topology (fig. 2), voltage drops along lead wires, R_w, are simply not included in the signals being processed.(5) Because lead wire voltage drops are not included in the potential differences observed by Anderson loop signal conditioning, the circuit equations typically have no need for wire or connector impedance terms. Lead-wire resistance becomes essentially irrelevant in the field without the cost of special electronics (such as 4 to 20 mA transmitters) near the sensing impedances.

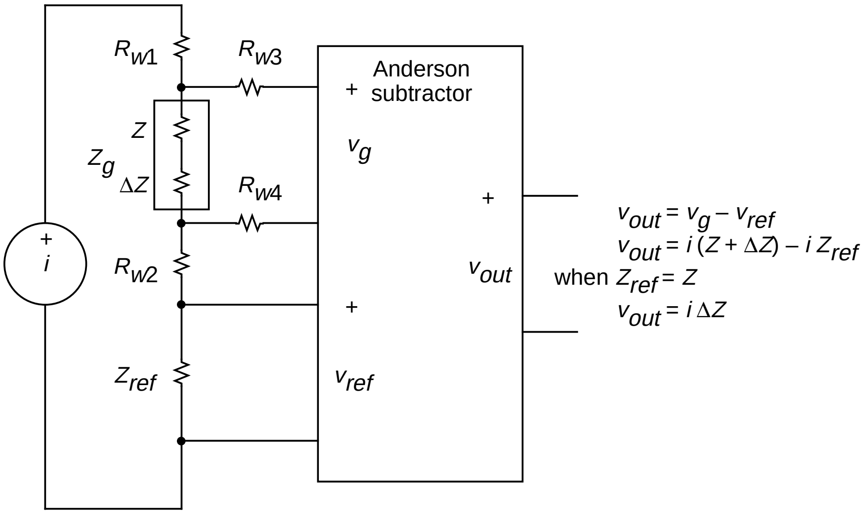

Figure 2, The Anderson loop measurement circuit topology

When the reference impedance, Z_{ref}, is chosen to be equal to the initial impedance of a sensing element, Z_g, then the exact signal conditioned output per sensing element is

$$v_{out} = i\Delta Z \tag{1}$$

for the inherently linear Anderson loop circuit while the equivalent linear approximation for Wheatstone bridge circuits is

$$v_{out} = i\Delta Z \,/\, 2 \tag{2}$$

Because voltage divider circuits are not used in Anderson loop circuits to accomplish subtraction there is not a “2” in the denominator of the equation relating output voltage to sensor current and sensor impedance change.(6) This accounts for the Anderson loop delivering double the output voltage for the same power dissipation in its sensing elements when compared to the Wheatstone bridge.

Active Subtraction

The overall quality of Anderson loop signal conditioning is primarily a function of subtractor quality. A variety of active subtractor designs are in operational use. Reasonable dual-differential subtractors can often be implemented with appropriately connected instrumentation amplifier integrated circuit components that each serve as “half-subtractors.” However, not all off-the-shelf instrumentation amplifier components are designed to have the microvolts/°C stability needed for a unity-gain subtractor applications such as strain gage signal conditioning.

An instrumentation amplifier replicates at its output the potential difference observed at its input (with gain when desired). The output is delivered with respect to the potential to which its reference terminal is tied.

Several instrumentation amplifiers, each observing the sensor and reference voltage drops across each of several sensing elements and having their reference terminals all tied to the same potential, can each act as one half of a dual-differential subtractor. The difference in the voltage drop across any pair of observed sensors (or sensor groups) is thereby made available as a differential output voltage.(7) So any sensor impedance in an Anderson loop can be used in any number of different outputs derived from a single transducer. The pairs of sensor differences available directly from the individual elements previously arranged in a Wheatstone bridge are illustrated in fig. 3.

Multiple Use Of Sensor Elements

There is no need to have any particular number of sensors in an Anderson loop (like the four essentially identical sensor arm impedances in a Wheatstone bridge). So Anderson loop transducers can be designed with any number of sensors.

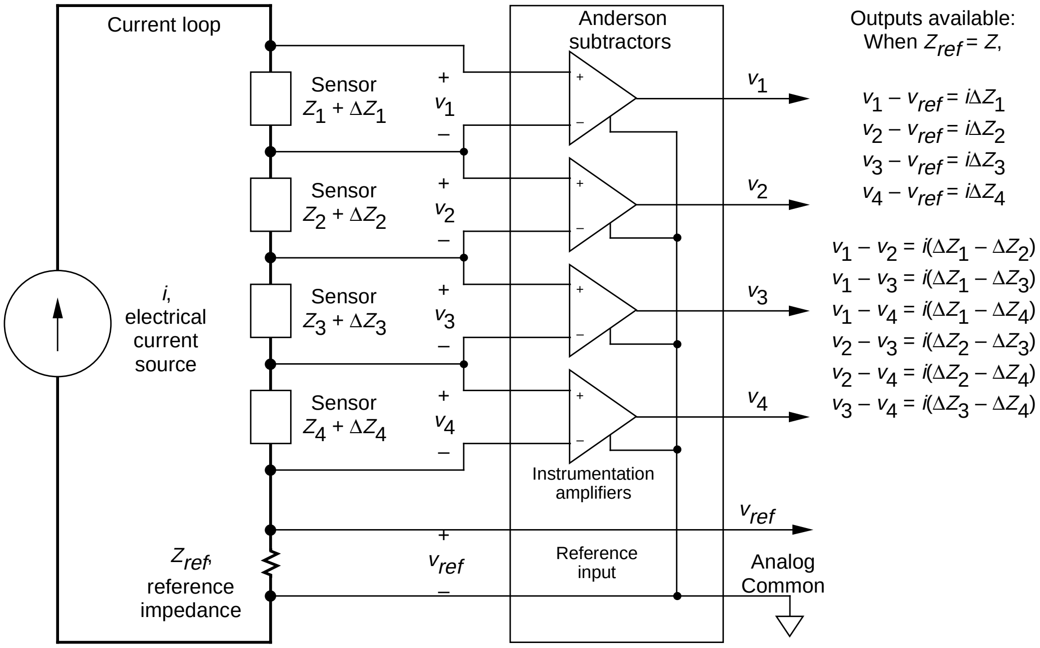

Figure 3, Instrumentation amplifiers used as Anderson loop half-subtractors

Since amplification unique to each sensor is available in the dual-differential subtractors implemented within Anderson loop signal conditioning, the same sensing impedance can appear to be any desired magnitude in each of many different outputs.(7) This allows calibration and compensation to be adjusted after installation in the field by potentiometer adjustments in the signal conditioning of Anderson loop circuits. And, the various impedances in a sensor can have conveniently different initial values.

The Distributed Sensor

The same excitation current can be routed through several dispersed sensing impedances and, with Kelvin sensing carrying their voltage drops to an Anderson loop signal conditioner, a “distributed sensor” is achieved. Precision accumulation of the sums and differences in the impedance changes of sensors, regardless of their dispersion, provides an opportunity to obtain especially accurate temperature difference measurements using RTDs in widely-separated locations. And, the desensitization and instability caused by long inter-bridge wiring can be eliminated from load cell designs.

Reduced Excitation Current

When the four gage impedances typically arranged in a Wheatstone bridge are wired in series rather than in series-parallel, the load on the excitation supply becomes $4Z$ instead of Z. Since the Anderson loop has twice the sensitivity of the Wheatstone bridge, the same output signal level can be achieved with only one-fourth of the excitation current normally applied to a bridge.(6,7)

DC Signal Separation

If one connects to a sensing impedance, such as a strain gage, with thermocouple wire then classical Wheatstone bridge signal conditioning will present the thermoelectric and impedance change signals together. With DC excitation, these signals each tend to become noise for the other.

The dual-differential subtractor circuit function can be implemented in Anderson loop signal conditioning such that impedance-based and thermoelectric signals do not experience cross-talk even with DC excitation. Without additional lead wires, both resistance change and temperature can each be continuously observed and no significant uncertainty is caused by thermoelectric levels to the resistance change output. And, the voltage drops arising from a significant DC excitation current flowing through thermocouple wire leads can be arranged to induce insignificant errors in the temperature indication.(8)

Measurement System Noise

The addition of an active element in the signal path of a measurement system can add noise to the system. This is true for the active subtractors in an Anderson loop application. However, at the signal conditioner input, the signal from a simple remote bridge sensor that does not include an internal amplifier or transmitter is likely to include a significant level of noise from the environment. The Anderson loop topology inherently provides double the usual signal when compared to the equivalent Wheatstone bridge topology.

Environmental noise tends to be much larger than subtractor noise. So, in practice, the electrical noise floor at the outputs of Anderson subtractors has been found to be essentially the same as the noise floor at the output of an equivalent Wheatstone bridge.(9) Since the output signal level from each sensor element is not attenuated by a factor of two in an Anderson loop, the signal-to-noise level in the system output for the same measured level improves by almost 6db — a major boon for measurements in a noisy environment.

System Cost

The key difference between Wheatstone bridge and Anderson loop signal conditioning is the inclusion of one or more dual-differential subtractor components. Today's parts cost in volume to implement simple Anderson subtractors is well under $1. Particularly good subtractors can be implemented today in single quantities for under $10. After the manufacturers of measurement integrated circuits perceive an emerging market, expect to see multiple sensors in an Anderson loop signal conditioned by the functions integrated on one chip.

Power supply, amplification, filtering, packaging, etc., requirements for the overall signal conditioning function remain essentially the same for both Wheatstone bridge and Anderson loop signal conditioners. However, Anderson loop excitation power requirements may be substantially lower.

IMPACT ON THE FUTURE OF MEASUREMENT AND CONTROL

The Wheatstone bridge will be around and useful for ever. But the impact of the Anderson loop measurement circuit topology on the future of measurement and control is likely to be profound. Users perceive several important benefits from the new technology.(3,5,9)

Benefits to Users

Anderson loop users immediately recognize several new benefits in their applications:

- Larger and inherently linear outputs individually available from each element in a sensor.
- Lower sensor power dissipation in portable and temperature-sensitive applications.
- Immunity to even random lead wire and connector variations without the need for expensive transmitters in hostile environments.
- Fewer, smaller and less expensive lead wires in tight installations.
- Quieter engineering unit readouts.
- Smarter sensors delivering multi-axis and multi-parameter outputs from simple sensing structures.
- Stiffer sensors having twice the frequency response for the same output level.
- Temperature compensation and calibration refinements after installation by adjustments conveniently away from the sensor — within the signal conditioner.
- Previously unheard of measurement capabilities.

- Equivalent or lower system installation and life-cycle cost.
- Measurements that just seem to be more “solid.”

The Situation Today

The clear and highly desired benefits users perceive today from their experience with Anderson loop signal conditioning is resulting in an accelerating measurement paradigm shift. New users tend to avoid Wheatstone bridge signal conditioning in future applications where they reasonably can do so. But the trend has yet to gain enough momentum to cause mainstream instrument and control system suppliers to perceive a shift in their markets.

Users having experience with Anderson loop-based measurements tend to seek out signal conditioning suppliers that already understand this new technology and buy or construct sensors to in-house designs. This approach has been far more productive (and less painful) in meeting their needs than trying to pull a new technology out of old suppliers.

SUMMARY

The Anderson loop is a simply implemented measurement circuit topology that uses active subtraction instead of the passive subtraction accomplished by the classic Wheatstone bridge. Larger, linear signals from sensing element impedance change are available with less excitation power and without the use of transmitters to achieve immunity to wire resistance variations. Sensor intelligence can be implemented within the signal conditioner, including the use of the change in a single sensing element in several simultaneous measurements and the separation of resistance variation signals from thermoelectric signals with DC excitation. Such benefits are likely to profoundly effect the future of measurement and control, fueled by users recognizing and demanding capabilities not otherwise available.

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