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Signal specific electric potential sensors for operation in noisy environments

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Abstract. Limitations on the performance of electric potential sensors are due to saturation caused by environmental electromagnetic noise. The work described involves tailoring the response of the sensors to reject the main components of the noise, thereby enhancing both the effective dynamic range and signal to noise. We show that by using real-time analogue signal processing it is possible to detect a human heartbeat at a distance of 40 cm from the front of a subject in an unshielded laboratory. This result has significant implications both for security sensing and biometric measurements in addition to the more obvious safety related applications.

1. Introduction

The Electric Potential Sensor (EPS) is a novel high impedance sensor technology invented and patented at the University of Sussex. It may be considered to operate as an almost “ideal” voltmeter and to measure spatial potential via capacitive coupling in a manner analogous to a magnetometer measuring a magnetic field via inductive coupling. In the strongly capacitively coupled limit, with the sensor physically close to or touching the source, the sensor self screens excluding the majority of external noise. In this mode of operation we have demonstrated that the EPS may be used to acquire extremely low noise high quality electrophysiological signals from the surface of the body [1,2]. To date however, the full capability of these sensors operating in a remote mode, where the sensor to source spacing may be large, up to one metre, has not been realised outside of a screened environment (Faraday cage). The work described in this paper involves modifying the response of the sensors to reject the main components of the background noise, thereby enhancing both the available dynamic range and signal to noise ratio significantly. A more traditional technique involving post processing using a hardware comb filter after the sensor has already been shown to offer significant advantages in terms of noise and dynamic range for a magnetometer [3] in situations where saturation does not occur in the sensor.

The generic EPS measurement technology is applicable to medical practice, engineering and the sciences. The input capacitance can be as small as 10 fF with an associated input resistance of $10^{15} \Omega$. The operating bandwidth depends on the particular design, coupling strength and other requirements such as noise performance, but in various versions can operate from <1 mHz to >100 MHz. This spans body electrophysiology, non-destructive testing of composite materials [4], circuit imaging [5], following the propagation of pulses in a saline environment [6] and the acquisition

of nuclear magnetic resonance signals [7] via electric field sensing. In addition the sensors are suitable for integrating into array formats for real-time imaging applications. Previously, the ability of the sensors to operate in a remote mode has been demonstrated by detecting the human heart beat from a distance of up to one metre in a screened room [8]. Other techniques capable of measuring cardiac activity remotely in a noisy environment include optical vibrocardiography [9] and microwave Doppler radar [10]. However, both are active methods and require irradiation of the subject with either laser or microwave sources. They detect the signal resulting from chest wall movement only, not electrophysiological activity directly, and for this reason only operate from the front of the body.

Current biometric technologies are focussed around fingerprint patterns [11], iris scans, facial images, and voice recognition [12]. Other techniques such as keystroke pressure and time patterns [13] are the subject of research projects. Here we demonstrate how a new sensor technology may be adapted to work in an unshielded environment and used to acquire biometric information. By comparison with other techniques the EPS is passive in the sense that no excitation signal is required in order to measure this electric field.

2. Method

The EPS uses a combination of established high impedance techniques such as guarding bootstrap and neutralisation integrated into an active sensor and measurement electrode head, along with a means of supplying the input bias current required by the amplifier for stable operation. The details of this arrangement are shown in block diagram form in figure 1 and have been published previously in some detail [14]. We will concentrate in this paper on the specific developments which have enabled the sensors to operate in the presence of large interference signals. In particular, the additional negative feedback circuits which tailor the frequency response in order to reject the main components of the background noise. In the majority of situations these correspond to the fundamental and harmonics related to the mains supply frequency which is 50 Hz in the U.K.

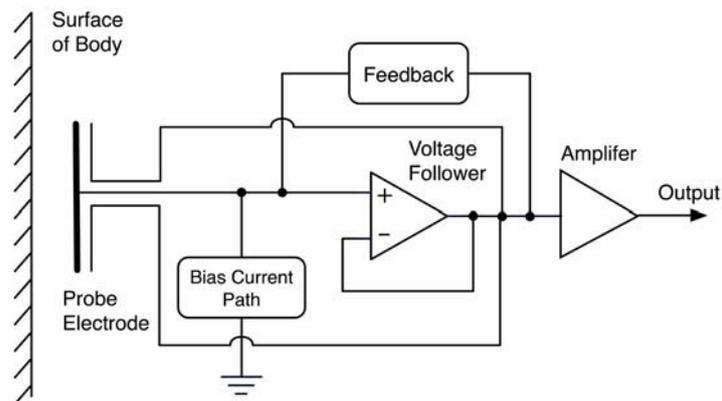


Figure 1. Block diagram showing the main subsections of the electric potential sensor which are essential for stable low noise ultra high impedance remote operation.

Typically the largest amplitudes will occur in the lowest harmonics, but the distribution between even and odd harmonics will vary depending on the particular local conditions set by the distribution system and the nature of the electrical loads.

The approach we have taken to solve this problem is to create a large rejection factor at the input of the sensor at these specific frequencies. This is preferable to post processing, since the latter cannot recover the signal if the interference is sufficiently large to cause the sensor to go into saturation and it also limits the gain which may be used in the sensor. Hence, by using front end rejection we may increase the effective dynamic range of the sensor by a factor approaching the rejection ratio. This

allows higher gain to be used in the sensor helping to improve the signal to noise ratio of the measurement. Figure 2 shows in block form the additional negative feedback path used to modify the response of the sensor. Here a bandpass filter has been implemented using a programmable switched capacitor filter IC from the LMF100 family manufactured by National Semiconductor [15]. This is configured as a second order bandpass filter with eternally adjustable quality factor (Q) and a variable centre frequency up to 100 kHz, which may be programmed by the use of an external clock frequency. The effect this filter has is to increase negative feedback at the centre frequency of the filter only, thereby reducing the sensor gain at this single frequency. The resulting response of the sensor exhibits a sharp notch, as expected, due to this increased negative feedback. Figure 3 is an example of the measured response in the region of the notch frequency for a sensor with such a feedback circuit incorporated. This shows in particular a rejection of 95 dB achieved at 50 Hz with a -3 dB bandwidth of only 4 Hz.

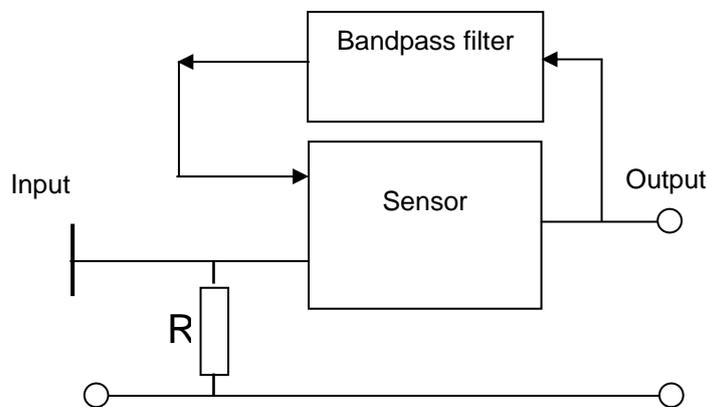


Figure 2. Block diagram showing the implementation of a bandstop function by incorporating a bandpass filter in a negative feedback configuration to modify the response of the sensor.

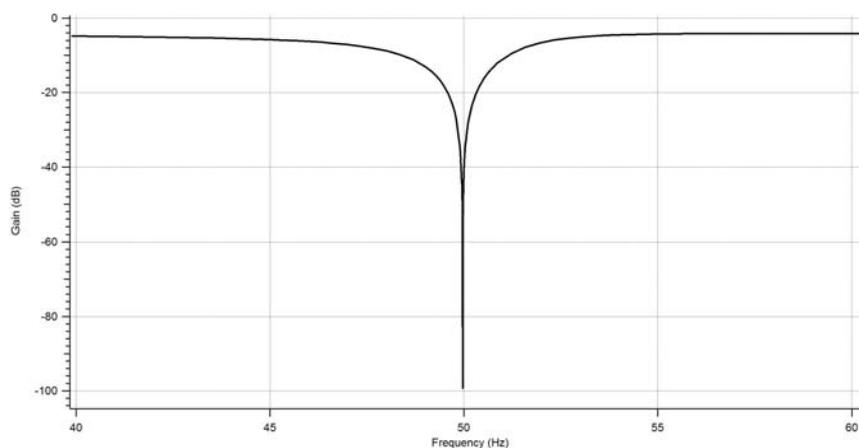


Figure 3. Measured response for a sensor configured with a bandstop function as per fig. 2, showing a sharp notch in the response at 50 Hz with >95 dB of rejection and a -3 dB bandwidth of 4 Hz.

In the implementation described here four such filters are used in a parallel arrangement in order to attenuate four separate frequencies as shown in figure 4, with the outputs of the filters being summed and fed back. The clock signals are derived synchronously, one for the each of the four bandpass

filters, allowing the notch frequencies to be individually selected. This was achieved using four AD9833 programmable waveform generator IC's from Analog Devices [16] which use direct digital synthesis techniques. They are programmed by an on board 8 bit PIC on startup to select the desired notch frequencies. A global external 3 MHz clock signal is used which provides a convenient method of fine tuning the centre frequency of all the filters simultaneously, if required.

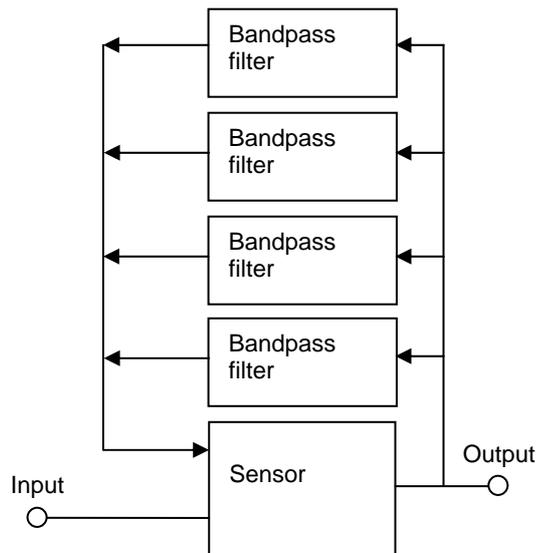


Figure 4. Block diagram showing a multiple bandstop function implemented using four bandpass filters in the same configuration as shown in figure 2.

3. Results

The net result of imposing these notch responses on the sensor is shown in figure 5. Here the overall frequency response of the sensor is measured through a weak capacitive coupling of 0.1 pF. The upper and lower roll-off frequencies set the operational bandwidth (-3 dB) of the sensor to be 1 Hz to 1 kHz. This is due to the characteristics of the particular EPS used for this measurement and the nature of the weak coupling between the sensor and the source. The four notch frequencies are set to 50, 100, 150 and 200 Hz in this example, but can easily be set to any desired combination of frequencies within the operational bandwidth of the EPS by modifying the clock frequencies in the PIC startup routine. The depth of the measured notches is apparently much reduced from that seen in the data of figure 3, however this is an artifact due to the limited frequency resolution of the analyser when spanning a large range of frequency space.

Clearly if the predicted attenuation figures of 95 dB are obtained with each of the notch filters it should be feasible to operate the sensor in an open unscreened environment in the presence of electrical noise related to the mains supply frequency and harmonics. In order to demonstrate this capability a single EPS was used to detect the electrical activity due to a human heartbeat at a distance of 40 cm from the surface of the body. Previously this measurement had only been possible using the EPS within an electrically screened room [8]. The raw data is shown in figure 6. The subject was seated and stationary during the measurement. Note that no subsequent signal averaging or processing techniques have been applied, this is raw data acquired in real-time. Despite this there is no evidence of 50 Hz or harmonically related noise components in the data presented. Without the use of this additional feedback technique the EPS is driven into saturation under these measurement conditions in an open unscreened environment, precluding the acquisition of data and therefore the use of post processing or signal recovery methods.

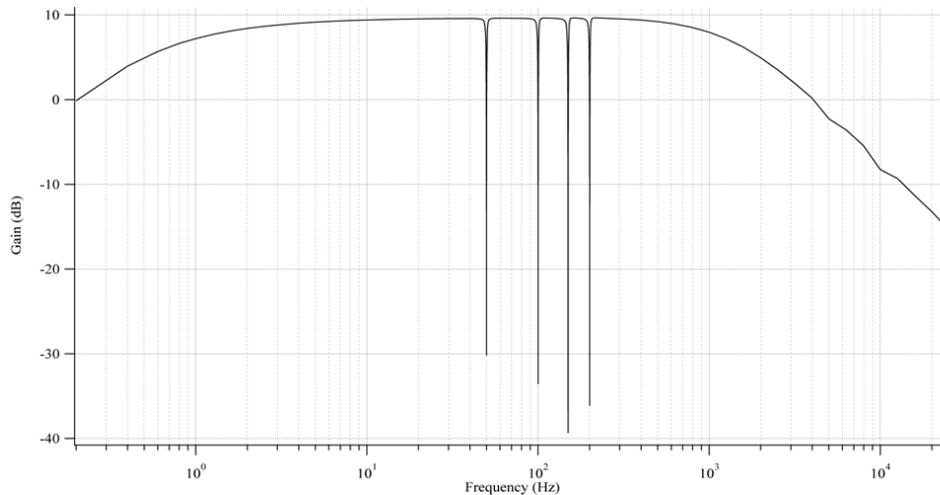


Figure 5. Frequency response data for a sensor with multiple bandstop functions and an operational bandwidth of 1 Hz to 1 kHz when coupled through a 100 fF capacitor.

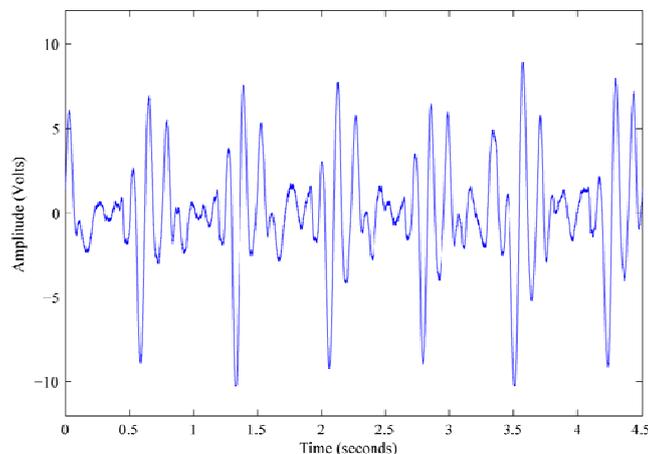


Figure 6. Human heart signal measured at a distance of 40 cm from the front of the body in a noisy unshielded environment. This is raw data with no signal averaging or digital processing applied.

4. Conclusions

The ability to operate a high impedance sensor in an open unshielded environment in the presence of electrical noise has been demonstrated. This was enabled by the use of frequency selective feedback techniques to modify the sensor response and to suppress the main components of noise at the input of the sensors. Rejection of 95 dB for up to four specific programmed noise components is reported. In contrast to other techniques such as post sensor filtering or digital post processing reconstruction the method described will operate in levels of interference which would normally drive the sensor into permanent saturation, so rendering other techniques useless. The ability of the modified EPS is demonstrated by acquiring a heart signal remotely at a distance of 40 cm in an open electrically noisy laboratory. The effectiveness of the filtering technique is manifest through the complete lack of any 50 Hz related noise on the raw data presented in this paper.

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