

# ***Improving Common-Mode Rejection Using the Right-Leg Drive Amplifier***

Venkatesh Acharya

*High-Performance Analog Products*

## **ABSTRACT**

This article discusses the need to improve common-mode rejection (CMR) in electrocardiogram (ECG) subsystem applications. Several different techniques to improve CMR while also considering both patient and operator safety are presented. This report also reviews the implementation of the right-leg drive (RLD) loop technique to improve CMR using the [ADS129x family of analog-to-digital converters](#) (including the ADS1298/96/94 and the ADS1198/96/94) and the corresponding performance results.

## **Contents**

1	Introduction .....	2
2	Common-Mode to Differential Signal Conversion .....	3
3	Techniques to Improve Common-Mode Rejection .....	4
4	Closed-Loop RLD system .....	5
5	The Effect of Lead-Off Disconnection in an RLD System .....	6
6	Improving CMR Using the RLD Amplifier with the ADS1298 .....	7
7	Conclusion .....	10
8	References .....	10

## **List of Figures**

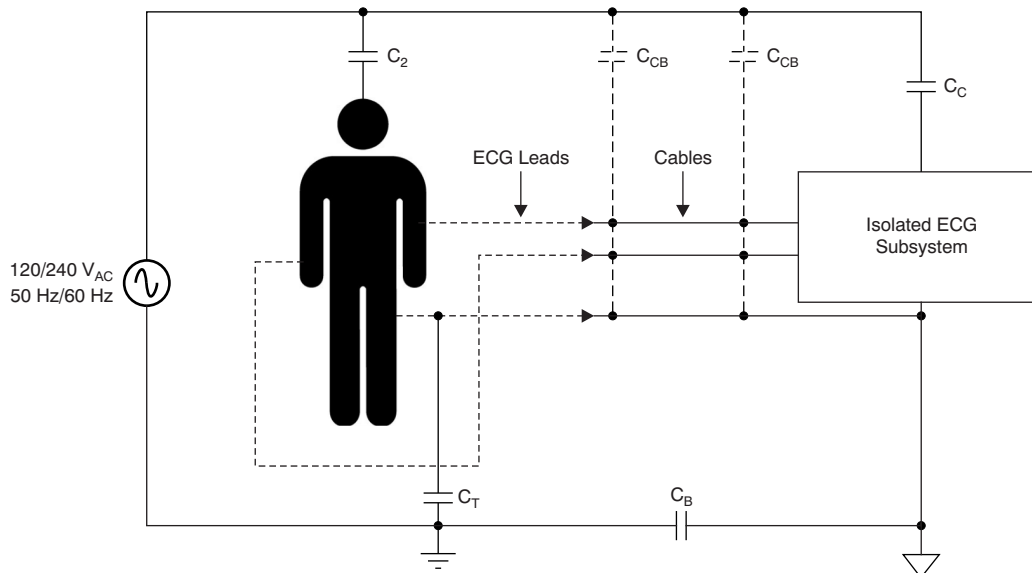
1	Typical ECG System .....	2
2	Understanding the Effect of Common-Mode Rejection Mismatch.....	3
3	Applying the Common-Mode Voltage at the Patient's Body Using $R_p$ .....	4
4	Technique to Improve CMR with a Large Protection Resistor .....	5
5	Improving CMRR by Completing RLD Feedback Loop .....	6
6	Analog Front-End of an RLD Subsystem with Lead-Off Currents to Monitor Electrode Snugness .....	6
7	Test Setup with ADS1298EVM with Protection Circuitry Elements .....	7
8	Measurement Setup Using ADS1298EVM .....	8
9	Output Spectrum Comparison.....	9

## 1 Introduction

Common-mode rejection, or CMR, is one of the most important performance parameters for ECG system applications. International standards set by organizations such as the Association for the Advancement of Medical Instrumentation (AAMI), the International Electrotechnical Commission (IEC), and various medical authorities of different countries specify the test methodology that must be followed in order to use most ECG systems.

In an ECG system, a large amount of electromagnetic interference (EMI) is coupled to the patient's body through the skin. EMI can also couple to the ECG system through coupling capacitors  $C_2$  and  $C_T$  as shown in Figure 1. Furthermore, It can be coupled to the system through a power coupling capacitor,  $C_C$ , and in some cases through the long ECG signal measuring cables and protection circuitry that are usually located in front of the ECG system. There can also be coupling from the ac power supplies through coupling capacitor  $C_{CB}$  to the cable. Capacitance  $C_B$  is coupled between ac ground and the ground of the ECG subsystem. The value of the entire system CMR depends on the capacitance value of  $C_B$ . By comparison, in the case of a perfectly isolated system where there is no coupling between the grounds, the system would exhibit very high CMR.

There are also several frequencies of interest, depending on the location and the country of operation. The primary source of interference is the ac main that generally operates at 50 Hz (Europe and Asia) or 60 Hz (US). Apart from these two frequencies, Eastern European railway traction power networks use distributed single-phase ac power at 16 $\frac{2}{3}$  Hz. A frequency of 25 Hz is used for the Austrian railway.



**Figure 1. Typical ECG System**

## 2 Common-Mode to Differential Signal Conversion

Common-mode to differential mode conversion is a result of the combination of mismatches in electrode impedances, cable impedances (distributed RC impedance), and onboard protection circuitry (typically including resistors, capacitors, and diodes) at the input of the programmable gain amplifiers. For simplicity, consider a non-isolated (that is, the ac ground and system ground are shorted) ECG subsystem with a simple RC filter in the signal path as shown in Figure 2.

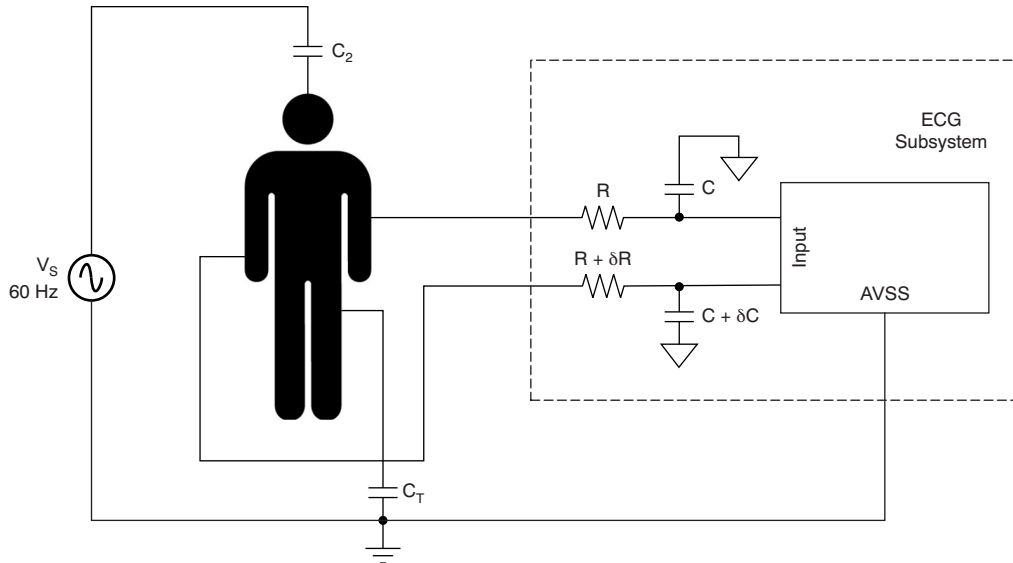


Figure 2. Understanding the Effect of Common-Mode Rejection Mismatch

For an ac signal  $V_s$ , the value of the signal that appears at the patient's body is given by Equation 1:

$$V_P = \frac{Z_G}{Z_G + \frac{1}{sC_2}} \cdot V_s \quad (1)$$

Where  $Z_G$  is the effective impedance from the patient's body to ground.  $Z_G$  is approximately equal to:

$$Z_G \approx \left[ \left( \frac{1}{sC_T} \right) \parallel \left( \frac{1 + sRC}{s2C} \right) \right]$$

This signal  $V_P$  is a common-mode signal to the system. If the values of  $R$  and  $C$  modeled in the differential signal are perfectly matched, then the system exhibits a very large CMR. If we assume the mismatch of  $\delta R$  and  $\delta C$  in resistor  $R$  and capacitor  $C$ , respectively, the CMR of the entire system can be approximated to Equation 2.

$$\text{CMR} = 20\log\left(\frac{\delta R}{R} + \frac{\delta C}{C}\right) + 20\log\left(\frac{f}{f_c}\right) \quad (2)$$

where  $f_c$  is the  $-3\text{-dB}$  frequency of the RC filter.

If 1% precision external components are used and the bandwidth of the RC filter is approximately 6 kHz, the system then has only 74 dB of CMR at 60 Hz. In the real world, the front-end of the ECG does not contain only first-order RC filters; it includes electrodes, cables, and second- or third-order RC filters. Considering all of these components, mismatch can easily accumulate, and thus contribute up to 20% or more of the signal. This degree of mismatch degrades the CMR of the system to less than 60 dB at 60 Hz. Therefore, it is necessary to consider different techniques to improve CMR.

It should be noted that there is a tradeoff when choosing the bandwidth of the antialiasing filter to be located in front of the modulator. Considering the mismatch between the discrete components, it is better to select the large bandwidth; at the same time, the upper limit of the bandwidth is determined by the sampling frequency of the modulator.



Intuitively, the resistor that drives the potential comes in parallel with  $Z_G$  (refer to [Section 2](#)), and thus a larger attenuation is achieved. When the value of the resistor used to drive the potential of the body is reduced, CMR of the entire system improves. In the case of a fault condition where the patient's body is accidentally connected to the system ground, it also provides the path for the current from the reference node  $V_{REF}$  through the resistor  $R_P$ . In accordance with IEC standards ([Ref. 2](#)), a maximum of 50  $\mu A$  *single-fault condition* current is recommended. Depending on the value of the power-supply voltage used for the system, the value of the protection resistor  $R_P$  is chosen. In a system with  $V_S = 5 V$ , the minimum value of the resistor needed is 100 k $\Omega$ ; if a 3-V power supply is used, a 60-k $\Omega$  resistor can limit the single fault current to safe current.

The system CMR can be further improved by incorporating the portion of the protection resistor  $R_{P2}$  inside the operational amplifier, as shown in [Figure 4](#). The sum of the protection resistors  $R_{P1}$  and  $R_{P2}$  is equal to the resistor  $R_P$ . In this case, only  $R_{P1}$  comes in parallel with  $Z_G$ , attenuating the common-mode signal further. But during a single fault condition, both resistors limit the fault current. This added advantage is available at the cost of reduced swing at the output of the operational amplifier because of a voltage drop across resistor  $R_{P2}$ . Usually, however, under normal operating conditions, the current at this path is less than 1  $\mu A$ , making this concern trivial.

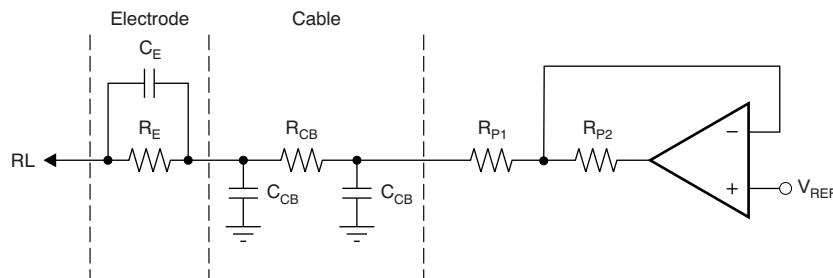


Figure 4. Technique to Improve CMR with a Large Protection Resistor

#### 4 Closed-Loop RLD system

CMR can be further improved by sensing the input common-mode voltage at the programmable gain amplifier (PGA) outputs and amplifying the difference using the right-leg drive (RLD) amplifier as [Figure 5](#) shows. This feedback loop improves CMR by an amount equal to  $(1 + A)$ , where  $A$  is the closed-loop gain of the feedback loop. The value of the closed-loop gain depends on the values of the feedback resistor  $R_F$ , feedback capacitance  $C_F$ , and PGA output common-mode sensing resistor  $R_{CM}$ .

Quantitatively, the value of the closed-loop gain  $A$  at a given frequency  $f$  is equal to [Equation 3](#):

$$A = 2 \cdot \frac{Z_F}{R_{CM}} \quad (3)$$

where:

$$Z_F = \frac{R_F}{1 + sR_FC_F}$$

Stability is the major concern in this RLD technique. Note that the protection resistor and the cable impedance form a low-pass filter. Depending on the model of the cable, this pole can be as small as 2 kHz because of the protection resistor and cable. Therefore, capacitor  $C_P$  is introduced such that it introduces the zero in the RLD path. Closed-loop bandwidth can be controlled by using capacitor  $C_F$  which is connected across feedback resistor  $R_F$ ; see [Figure 5](#).

The closed-loop bandwidth of the RLD loop is approximately equal to:

$$f_{BW} = \frac{1}{2\pi R_FC_F}$$

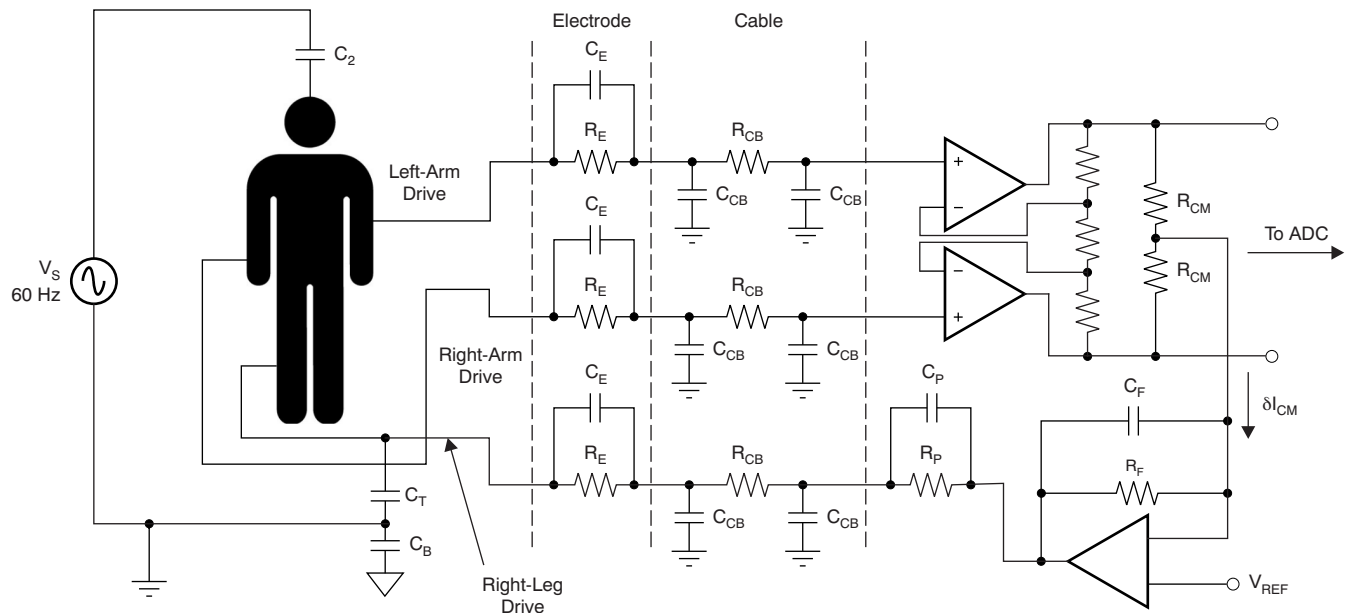


Figure 5. Improving CMRR by Completing RLD Feedback Loop

## 5 The Effect of Lead-Off Disconnection in an RLD System

ECG subsystems usually include lead-off currents as shown in Figure 6 to monitor the connectivity of the electrode with the skin. When an electrode is loose or not connected to the skin, the lead-off current drives the electrode potential to either of the rails, either ground or at supply voltage.

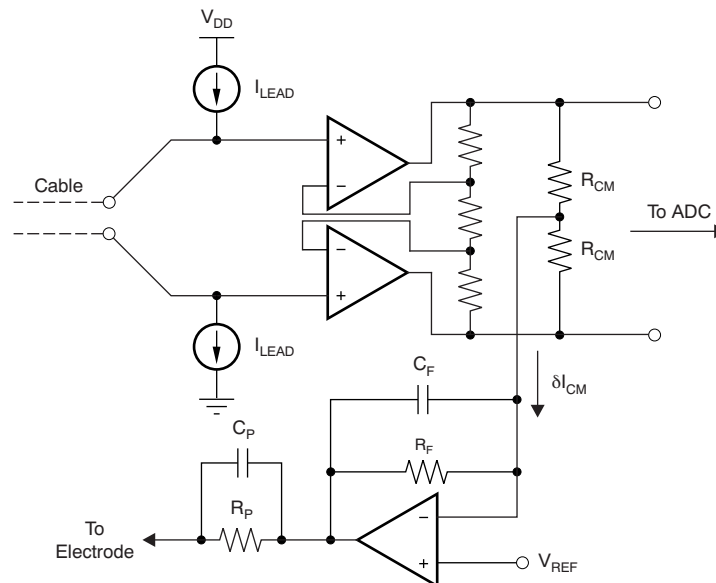


Figure 6. Analog Front-End of an RLD Subsystem with Lead-Off Currents to Monitor Electrode Snugness

Consider a situation when the right arm (RA) electrode is open and the left arm (LA) electrode is snug. In this case, the output common-mode of the PGA is driven away from the reference voltage, which causes the RLD feedback loop to fail. This situation can lead to the common-mode voltage of the patient's body being driven to either of the rails, where it could also hit the rails and subsequently stop the PGA from working altogether. Therefore, one should be very careful when using this RLD feedback technique in cases where there is a high chance of having an electrode lose contact or become disconnected from the patient. Whenever this technique is used, one should continuously monitor the status of the electrode connection; in case of failure, the RLD closed loop should be open. This configuration can be achieved by placing the switch in the path between the PGA output common-mode averaging point and the inverting input terminal of the RLD amplifier. In cases where the RLD feedback technique cannot be used at all as a result of practical limitations, CMR can be further improved by using a splitting resistor technique.

## 6 Improving CMR Using the RLD Amplifier with the ADS1298

The test setup used to measure the CMR of the ADS1298-based ECG subsystem discussed in the [ADS1298ECGFE-PDK User's Guide](#) (see [Ref. 3](#)) is shown in [Figure 7](#). A snapshot of the measurement setup is also provided; see [Figure 8](#). A 20-V peak-to-peak sine wave was used as the excitation signal. The value of coupling capacitors  $C_2$  and  $C_T$  (from the ac main) are equal to 100 pF. 220 pF is value of capacitor  $C_B$  that connects the ac ground and the EVM board ground. Electrodes are modeled using resistor  $R$  and capacitor  $C$  connected in parallel as illustrated. Values of  $R$  and  $C$  are 51 k $\Omega$  and 47 nF, respectively.

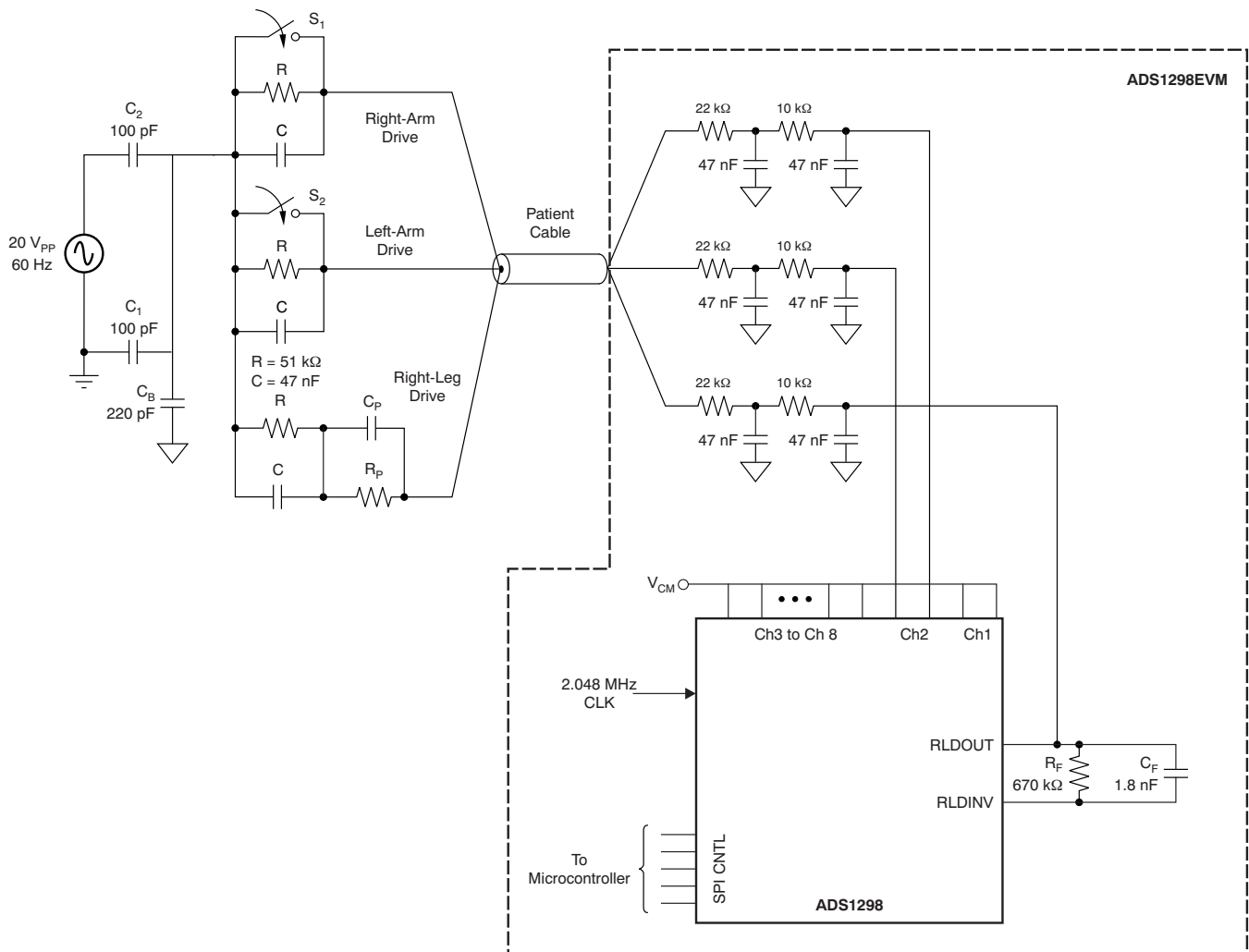


Figure 7. Test Setup with ADS1298EVM with Protection Circuitry Elements

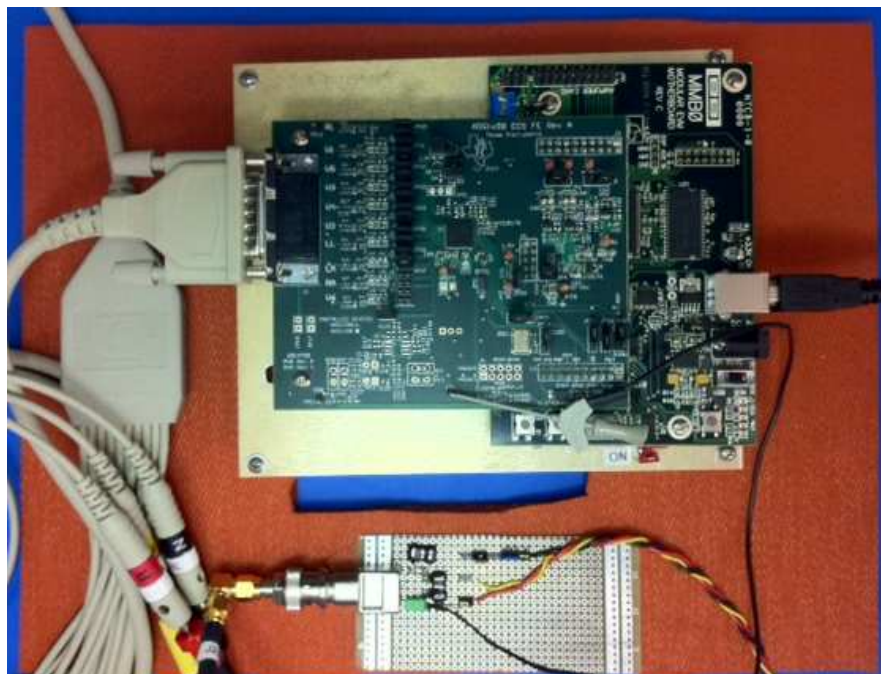


The standard ECG cable is used in this experiment. This cable includes a 10-k $\Omega$  protective resistance. The cable is followed by the onboard protection RC filter. The values of the components used to implement the filter are presented. All measurement results are noted with  $S_1$  = open and  $S_2$  = closed. This configuration corresponds to complete mismatch in the signal differential path. In accordance with the AAMI and IEC standards (see [Ref. 4](#) and [Ref. 5](#)), the system CMR in this complete mismatch condition should be at least 92 dB.

[Table 1](#) compares the expected and measured CMR values for different values of the protection resistor  $R_P$  with and without the RLD feedback loop. The value of  $C_P$  is chosen such that zero as a result of  $R_P$  and  $C_P$  is approximately 60 Hz. Expected values are obtained by TINA SPICE using Spice modeling of the PGA and RLD amplifier in the ADS1298.

**Table 1. Summary of Measurement Results**

No RLD Feedback		
$R_P$	Measured $V_{PP}$	Measured CMR
1 M $\Omega$	5.9 mV $_{PP}$	70.6
100 k $\Omega$	1.7 mV $_{PP}$	81.1
75 k $\Omega$	1.6 mV $_{PP}$	82.0
50 k $\Omega$	1.36 mV $_{PP}$	83.3
With RLD Feedback (1 M $\Omega$    1.5 nF)		
1 M $\Omega$	N/A	N/A
100 k $\Omega$	0.43 mV $_{PP}$	93.3
75 k $\Omega$	0.35 mV $_{PP}$	94.9
50 k $\Omega$	0.316 mV $_{PP}$	96.0

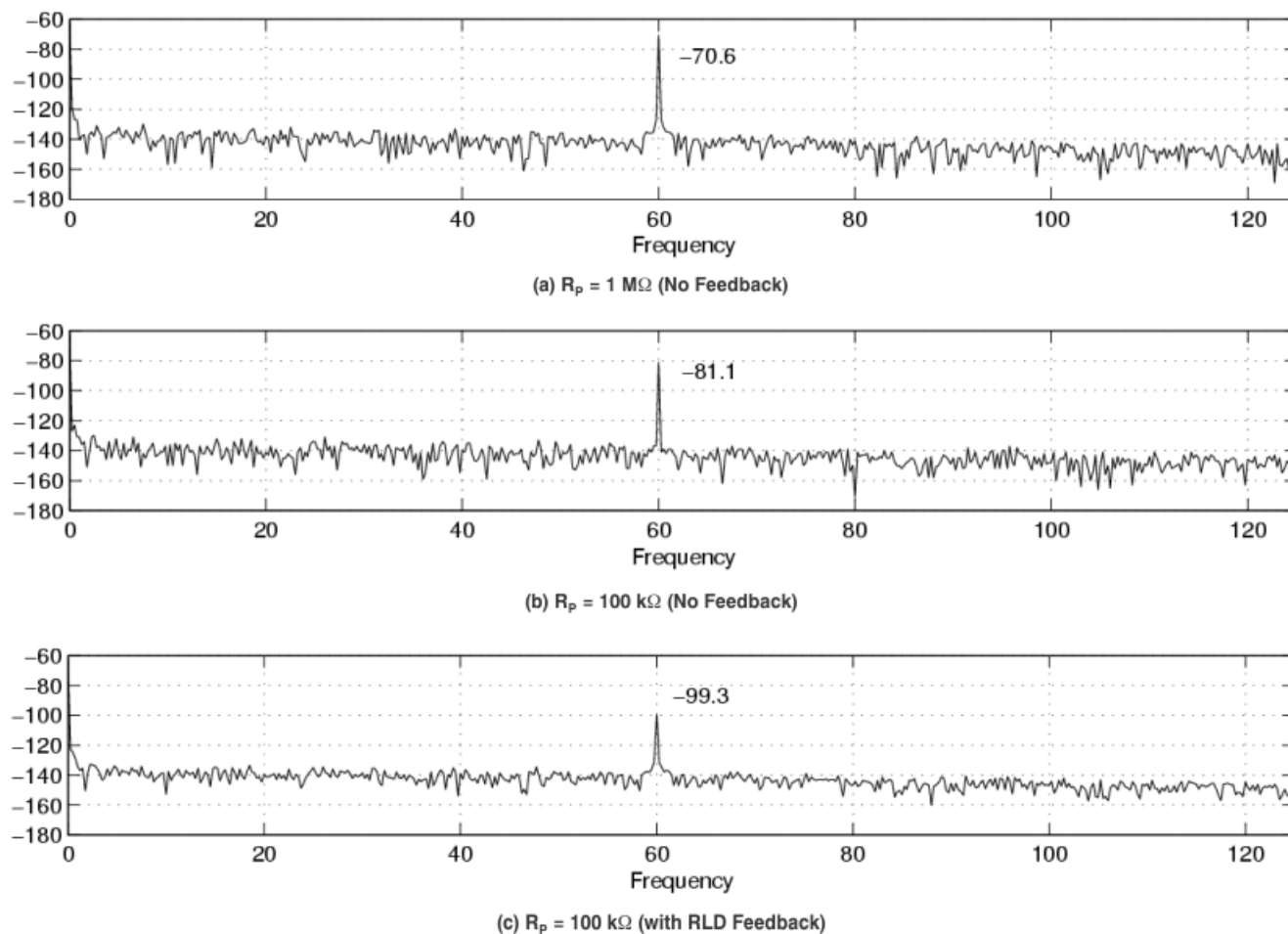


**Figure 8. Measurement Setup Using ADS1298EVM**



Figure 9 presents the CMR of the ECG subsystem at three different conditions:

- (a)  $R_p = 1\text{ M}\Omega$
- (b)  $R_p = 100\text{ k}\Omega$
- (c)  $R_p = 100\text{ k}\Omega$  with RLD feedback



**Figure 9. Output Spectrum Comparison**

An inverting gain configuration is achieved using the RLD amplifier available in the ADS1298. In this experiment, the values of  $R_F$  and  $C_F$  used are  $1\text{ M}\Omega$  and  $1.5\text{ nF}$ , respectively. The closed-loop gain of the RLD loop depends on the number of channels that are used to detect the common-mode voltage. In this experiment, only one channel is used to sense the common potential of the input. For the given feedback resistor, as the number of channels used to measure the common-mode potential increases, the gain also increases accordingly. The nominal value of  $R_{CM}$  used in the ADS1298 is equal to  $220\text{ k}\Omega$ . The closed-loop bandwidth is approximately  $106\text{ Hz}$ .

The ADS1298 provides the option to monitor the value of electrode potential through the lead-off feature. It also supports digital control, which can be used to turn on or turn off averaging of the PGA outputs. These two options can be used efficiently to ensure that whenever there is a loose contact or disconnection of the electrode, the RLD feedback is opened to avoid the railing of the bias potential at the patient's body.

## 7 Conclusion

This application report explains in detail several techniques to improve the common-mode rejection of an ECG system using a RLD amplifier. Measurement results using the ADS1298EVM board were also presented.

## 8 References

1. Winter, B.B. and Webster, J.G. (1983). *Driven-right-leg circuit design*. IEEE Transactions on Biomedical Engineering, Vol 30, No 1. Pp. 62 - 66.
2. Safe current limits for electromedical apparatus. ANSI/AAMI ES1-1993.
3. [ADS1298ECG-FE Demonstration Kit](#) user guide. Literature number [SBAU171A](#).
4. American National Standard ANSI/AAMI EC11:1991/(R)2001/(R)2007.
5. International Standard IEC 60601-2-27.

## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications, notwithstanding any applications-related information or support that may be provided by TI. Further, Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

### Products

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DLP® Products	<a href="http://www.dlp.com">www.dlp.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Clocks and Timers	<a href="http://www.ti.com/clocks">www.ti.com/clocks</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Mgmt	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>
RFID	<a href="http://www.ti-rfid.com">www.ti-rfid.com</a>
RF/IF and ZigBee® Solutions	<a href="http://www.ti.com/lprf">www.ti.com/lprf</a>

### Applications

Communications and Telecom	<a href="http://www.ti.com/communications">www.ti.com/communications</a>
Computers and Peripherals	<a href="http://www.ti.com/computers">www.ti.com/computers</a>
Consumer Electronics	<a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>
Energy and Lighting	<a href="http://www.ti.com/energy">www.ti.com/energy</a>
Industrial	<a href="http://www.ti.com/industrial">www.ti.com/industrial</a>
Medical	<a href="http://www.ti.com/medical">www.ti.com/medical</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Space, Avionics and Defense	<a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a>
Transportation and Automotive	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Video and Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>
Wireless	<a href="http://www.ti.com/wireless-apps">www.ti.com/wireless-apps</a>

TI E2E Community Home Page

[e2e.ti.com](http://e2e.ti.com)

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2011, Texas Instruments Incorporated