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Wide input range, fully-differential indirect current feedback instrumentation amplifier for self-x sensory systems

Symmetrischer Instrumentierungsverstärker mit indirekter Stromgegenkopplung und hoher Eingangsspanne für integrierte Sensorsysteme mit Self-x-Eigenschaften

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Abstract: This paper research presents the design of wide input range indirect current feedback-instrumentation amplifier (CFIA). In order to extend the input range without sacrificing the amplifier performance, the negative feedback is applied to the source coupled differential pairs inputs. The feedback network and the biasing current can be programmed to work at different values to meet different signal conditions or to self-correct the drift in the amplifier properties. The simulated input range V_{in} ; $P-P=1.6$ V with total harmonic distortion of 0.93 % at 5 MHz frequency. Thus the proposed CFIA is very suitable to read the high speed and high common mode range TMR differential voltage sensor signal. The circuit is implemented using the CMOS 0.35 μ m technology from Austriamicrosystems (AMS) and by using Cadence Virtuoso design tools.

Keywords: Instrumentation amplifier, indirect current feedback instrumentation amplifier, differential-difference amplifier, fully balanced differential- difference amplifier, tunnel magnetoresistance sensor.

Zusammenfassung: Dieser Beitrag stellt den Entwurf eines Instrumentierungsverstärkers mit indirekter Stromgegenkopplung (CFIA) vor, der u.a. einen hohen einseitigen Signalspanne bietet. Um dies ohne Einbußen anderer Leistungsparameter des Verstärkers zu erreichen, wurde ein Gegenkopplungsmechanismus bei den Sourcegekoppelten Paaren in den Differenzverstärkereingangsstufen zum Einsatz gebracht. Das Gegenkopplungsnetzwerk und der Bias-Strom können angepasst werden, um verschiedene Eingangssignale verarbeiten und Drifteffekte kompensieren zu können. Simulationen zeigen eine mögli-

che Eingangsspanne von V_{in} ; $P-P=1.6$ V mit einer Verzerrung (THD) von 0.93 % bei 5 MHz. Mit dieser und weiteren im Beitrag vorgestellten Eigenschaften erweist sich der vorgeschlagene CFIA als sehr gut geeignet sowohl mit hoher Messrate und auch mit hoher Eingangsspanne Sensorsignale, wie die von TMR-Sensoren, zu erfassen. Die Schaltung ist zur Zeit in der 0.35 μ m CMOS-Technologie von Austriamicrosystems (AMS) mit Cadence Virtuoso umgesetzt und validiert worden.

Schlüsselwörter: Instrumentierungsverstärker, Instrumentierungsverstärker mit indirekter Stromgegenkopplung, symmetrischer Instrumentierungsverstärker mit Gegentaktausgang, Tunnel-Magneto-Resistiver (TMR) Sensor.

1 Introduction

An Instrumentation amplifier (in-amp) is an essential part in measurement systems and sensor applications, especially for bridge sensors [9, 22, 23]. In-amp gain importance in sensor electronics read-out circuits with self-x capability (self-maintaining, self-diagnosing/monitoring, self-healing/repairing, self-calibrating, self-adaptation) for industry 4.0 and internet of things (IoT) [8] where smart sensors represent prerequisites of the system [19]. There are few topologies to implement the in-amp circuit, among them are the conventional three based op-amps and the indirect current feedback in-amp (CFIA) [23]. The conventional in-amp employs three operational amplifiers and seven resistors. This type of in-amp suffers from several issues. Firstly, it has limited input common-mode range (ICMR), which is becoming a problem for single supply CMOS application [9, 10]. Secondly, the amplifier common mode rejection ratio (CMRR) is susceptible to the matching between the feedback resistors [21]. A small mismatch between these resistors could severely degrade the CMRR. Hence, an expensive trimming process may be required to precisely match these resistors, which are

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almost not available by standard CMOS technology [17]. Thirdly the power consumption is not low due to the use of three individual op-amps. In comparing with the CFIA counterpart, the latter one does not suffer from CMRR sensitivity to the feedback resistors matching. The mismatching in the feedback resistors leads only to affect the voltage gain value, while the CMRR is subject to the matching between the two input ports transconductances [5, 18]. The CFIA can achieve high CMRR because the input transconductance stage converts the differential input voltage to a differential current, making this topology very suitable for bridge read-out circuit [23]. Unlike the three op-amp in-amp, the indirect CFIA can work with different common mode voltage (V_{CM}) from the sensors, and can read differential signal with a common mode voltage level that may include either of the supply rails [9, 21]. The input and the feedback transconductors of the indirect CFIA share the same output stage, thus consume less static power [23]. The simplified block diagram of the fully differential indirect CFIA is presented in figure 1 [3, 4, 7, 21].

Fig. 1: Simplified block diagram of the indirect CFIA.

The main active part of the indirect CFIA is the differential-difference amplifier (DDA) [18]. The input and feedback transconductors (G_{m1} and G_{m2}) convert the input and feedback voltages to differential output currents. The next stages amplify the difference between the two currents, convert them back to voltage signals and drive both the output load and the feedback network. The first indirect CFIA circuit based on DDA architecture was reported in [13] while the first concept of indirect current feedback was introduced in [15]. The in-amp closed loop differential DC gain (A_{CL}) can be approximated as [12, 18, 23]:

$$A_{CL} = \frac{(V_{out+} - V_{out-})}{(V_{in+} - V_{in-})} = \frac{G_{m1}}{G_{m2}} \cdot \frac{R_{21} + R_1 + R_{22}}{R_1} \quad (1)$$

It follows from (1) that if the input and feedback transconductors are perfectly matched, it will result in a voltage gain that is well defined and controlled by the feedback resistors ratio only. The transconductance values (G_{m1} and G_{m2}) depend on several design variables like the biasing current, transistor's size, transistor's type, and the common mode voltage level. To achieve good matching and high gain accuracy, these parameters must be carefully considered in the design and layout process, which still considered as a design challenging of indirect CFIA [10]. The indirect CFIA suffers from an important issue related to the DDF core. The differential sensed and feedback signals are applied directly to the floating inputs of G_{m1} and G_{m2} stages respectively. Although this scheme provides a very high input impedance to the CFIA, but the linear range of operation is limited to the available linear range of G_{m1} and G_{m2} that must handle this difference, which is practically not enough for the applications that requires to read a large differential sensor signals [23]. Several linearization strategies can be followed to extend the input range. Mostly, these techniques are based on reducing the effective transconductance of the input and feedback differential transistors by decreasing transistors width to length ratio, increasing biasing current, and or employing source degeneration solutions [16, 18, 20, 21]. However, these approaches trades some of the important circuit aspects like AC performance, noise, ICMR, and power consumption for the sake of linearity. One of the best innovative solutions was introduced in [6] and [2]. The solution is based on applying the negative feedback on both of the differential pairs inputs of the DDA. By this method, the inputs of each pair are virtually shorted together in similar fashion of the op-amp and hence will not experience the applied voltage difference. Therefore, the design with high linear range and high G_m is possible without trading other circuit properties. The authors in [2] refer to the circuit as fully balanced DDA (FB-DDA).

The primary objective of this research is to design a wide input range fully-differential CFIA with self-x enhanced capability. The proposed CFIA circuit would be able to cover the tunnel-magnetoresistive (TMR) sensor output signal range at high sample rate required for impedance spectroscopy. A universal sensor interface chip (USIX) with self-x properties was already designed for this purpose in [8] and updated to the next improved version USIX 2.0 in [14]. Both chips are based on single ended CFIA. A later CFIA improvement was achieved by the authors in [1] to extend the input range by using source degeneration technique. The present work would enhance the chip with fully differential CFIA to take the advantages of the fully differential signal properties and

to make useful adoption of the FB-DDA technique. That will add flavour to the USIX chip concept, as a measurement method and sensor diagnosis method, and it will be applicable for industry 4.0 applications.

2 Proposed indirect CFIA

In the FBDDF circuit from [2], two identical resistors are fed back to the input. Therefore, a mismatch between the feedback resistors degrades the CMRR properties of the in-amp in a similar way of the conventional counterpart. To overcome this problem, we propose a CFIA circuit based on the same FB-DDA principle, but it is insensitive to the feedback mismatch problem to the CMRR. Hence, the feedback network can be freely programmed to meet different gain requirements or to compensate for the gain drift. The proposed CFIA circuit block diagram is depicted in figure 2.

Fig. 2: Simplified block diagram of the proposed indirect CFIA.

3 Circuit level implementation and simulation results

The CMOS realization circuit of the fully-differential CFIA core (FD-DDA) is depicted in figure 3. The amplifier core is based on the robust power efficient class AB folded cascode op-amp introduced by [11]. The input and feedback transconductors are implemented using identical PMOS and NMOS transistors to have matched transconductors with an extended ICMR to the supply rails. As a result, the sensor and the in-amp circuits can work at different high or low common mode voltages. To complete the transconductors matching condition for the entire region of operation with improved CMRR properties, both stages

are biased with identical currents from high impedance current sources built by the wide swing mirrors as depicted in figure 4.

Fig. 4: Wide swing biasing circuit of the CFIA.

Cascode Miller compensation capacitors ($C_{C1} - C_{C4}$) are used to stabilize the circuit with higher gain bandwidth as comparing to the normal Miller compensation connection without using an additional resistor to shift or cancel the right-half plane (RHP) zero [10, 11]. The CFIA circuit is supported with power-down scheme transistors (blue-colored) that lower down the power to zero at the standby condition, this is especially important when the circuit is powered by a battery. The common mode feedback circuit (CMFB) is shown in figure 5.

Fig. 5: CMFB circuit.

Fig. 3: Fully-differential CFIA circuit.

The average resistors are implemented by a very high pseudoresistor constructed by the MOS-Bipolar connected transistors (MC7-MC10) [23]. Hence, eliminating the need of large poly resistors or using additional buffer amplifier to drive small poly resistors. Elements size of the designed CFIA are summarized in table 1. Common centroid layout procedure is extensively followed in the circuit layout design to reach a high degree of matching and minimum offset error. The circuit layout is presented in figure 6. The main nominal post layout CFIA performance parameters are summarized in table 2 while the design is being approved by running the Monte-Carlo simulation under the standard industrial temperature range (-40°C to 85°C). Simulation is performed with a connected load of $100\text{ k}\Omega$, feedback resistors of $100\text{ k}\Omega$ and capacitor load of 5 pF .

Table 1: CFIA circuit elements size.

Element	(W in μm /L in μm)
M1-M4, MB7-MB10, M17, M18, MC5, MC6	10/1
M5-M16, M19, M20, MB1-MB6, MB11, MB12	20/1
M23-M26, MB13-MB16, M35, M36	30/1
M27-M30, M33, M34, M21, M22, M37, M38, MC1, MC2, MB17, MB22	60/1
M31, M32	120/1
MD1, MD3	210/0.55
MD2, MD4	70/0.55
MP1-MP9, MPB2, MPB3	2/0.35
MPB1	10/0.35
MC3, MC4	90/1
MC7-MC10	4/4
Poly Capacitors ($C_{C1} - C_{C4}$) = 0.8 pF	42/43.5
Poly Capacitors ($C_{M1} - C_{M2}$) = 0.2 pF	14.65/15.45

Fig. 6: CFIA layout view.

Table 2: CFIA post layout nominal simulation results, fully differential configuration, $V_{DD} = 3.3\text{ V}$, $V_{CM} = 1.65\text{ V}$, $T = 27^{\circ}\text{C}$.

CFIA design parameter	Value
Differential DC gain (A_{VD})	103.8 dB
Gain bandwidth product (GBW)	49.5 MHz
Phase margin (PM)	52.5°
Slew rate (SR)	92 V/ μs
Differential input linear range (V_{ID})	1.6 V _{P-P}
Input offset voltage (V_{OS})	8.8 μV
Common mode rejection ratio (CMRR)	80 dB
Power supply rejection ration (PSRR)	250 dB
Settling time (τ_s) @ 0.1 % error accuracy	67 ns
Equivalent input noise voltage (V_n)	1.4 $\mu\text{V}_{rms}/\sqrt{\text{Hz}}$ @10 kHz 142 nV _{rms} / $\sqrt{\text{Hz}}$ @1 kHz
Total harmonic distortion (THD) @ $V_{ID} = 1.6\text{ V}_{P-P}$ and unity gain	0.567 %@1 kHz 0.943 %@5 MHz
Static power dissipation (P_D)	2.552 mW
Standby power dissipation	0.0 mW

4 Conclusions

In this paper, a wide input linear range V_{in} ; $P-P=1.6$ V CFIA has been designed. The obtained high AC and dynamic performance make the presented work very suitable to deal with high speed and large common mode range TMR sensor signal required for impedance spectroscopy measurements at high sample rate. The proposed CFIA made a successful application of the FB-DDA principle but it is insensitive to the feedback resistors matching. Further improvements are also possible for the future work. These includes improving the noise performance and enhancing the DC gain to approach better linearity. Based in our proposed CFIA and the FB-DDA principle, these improvements can be achieved without trading the input linear range. Self reconfiguration/trimming, in particular for tracking offset compensation, is not yet done, and is needed, along with other advanced circuits for the overall USIX 3.0 chip goal.

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