

A High Isolation Analogue Switch and its Application in Digital Sampling Bridge

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Abstract – This paper describes a high-isolation analogue switching device to replace the mechanical reed switches used in precision digital sampling bridges. The switching speed of the designed analogue switch is much higher than that of the mechanical switches, and the Off-Isolation is good enough at frequencies between 1 kHz and 100 kHz. A method of applying the designed analogue switch to an automatic source balanced single digital sampling bridge is given, the theoretical measurement accuracy of the given bridge can reach ppm level with faster measurement speed. Finally, the actual Off-Isolation of the designed switch is verified by the method of detecting the small signal by the lock-in amplifier. The designed switch has a simple structure, is convenient and practical, and simplifies the design of the impedance bridge, it has been successfully applied to a digital sampling bridge developed at NIM.

Keywords – Analog switch, Off-Isolation, Impedance bridge, Sampling method

I. INTRODUCTION

With the increasing demand for impedance calibration services, traditional high-precision coaxial AC bridges or orthogonal bridges are no longer suitable for the needs of contemporary society because of their long time-consuming^[1]. The commercial fast impedance measuring instrument has a faster measuring speed, but its measuring accuracy is normally less than 0.02%, which is hard to meet higher precision calibration services.

In order to balance the contradiction between time consumption and measurement accuracy, digital auxiliary bridges have been developed by many laboratories. The basic principle of digital auxiliary bridge is to replace the inductive voltage divider (or inductive shunt) in a conventional coaxial AC bridge with two signal sources.

As high-precision arbitrary signal sources are difficult to obtain, a type of impedance measurement method based on two channel digital sampling is designed^[2]. Since there are no two ADCs with identical performance, ADCs will introduce errors. Single channel

sampling is a good way to reduce the inconsistency of the ADCs^[3], but requires signal switching devices.

At present, coaxial switching or home-made reed switches are generally used for signal switching to meet the isolation requirements during measurement, but its setting time is too long, and the life of the mechanical switch is very limited. The paper^[4] proposes an AD synchronous sampling method by using self-designed reed switches as signal switching devices. However, the reed switch has a complicated structure and the setting time is about 20ms.

Since the introduction of the analog switch in the 1960s, it has been widely used in various designs of electronic systems because of its fast switching speed and long life, but its on-resistance and off-isolation have always been difficult points in analog switch design.

In the paper^[5], a method for designing high-isolation analog switches is introduced, the advanced π -type structure can greatly limit the input signal to the output, but its isolation is only -63 dB in the audio range. In order to achieve measurement accuracy of the order of 10^{-6} in the digital sampling bridge, it is generally required that the signal isolation device has an Off-Isolation better than -120 dB.

To meet the needs of impedance measurement, a high-isolation high-frequency analogue switch is designed. The analogue switch has been successfully applied to a digital sampling bridge with automatic source balance developed at NIM.

II. DESCRIPTION OF THE METHOD

A. Analog Switch Working Principle

The analogue switch is a tri-stable circuit that determines the connection state of the input and output depending on the level of the gate control. When the strobe control is in the enable state, the output terminal and the input terminal are in the on state. When the strobe control is in the non-enabled state, the output and the input are in the blocking state, no matter how the input signal changes, the output of an analogue switch is in a high resistance state. Fig.1 illustrates a schematic diagram

of an analogue switch based on MOFET.

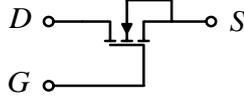


Fig. 1. MOSFET switch diagram

When $V_{GS} > V_{GS(ON)}$, the switch is in the on state, and there will be an on-resistance $R_{DS(ON)}$ between the source and the drain. When $V_{GS} < V_{GS(ON)}$, the switch will be in high-impedance state, which means an off state under ideal conditions, however, there will be leakage current I_{DS} in practice.

B. Analog Switch AC Characteristics

If there is an AC signal in the transmitted signal, the performance of the analogue switch will change. The AC coupling capacitance between the source and the drain and the leakage capacitances of the source and the drain to the ground will make the transmitted signal to be distorted. Fig.2 depicts the equivalent diagram of the analogue switch at high frequencies.

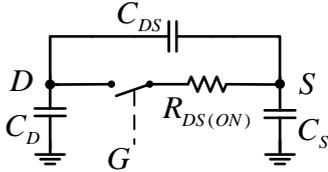


Fig. 2. AC MOSFET switch equivalent diagram

In Fig.2, C_{DS} is the coupling capacitance between source and drain, C_S is the source-to-ground leakage capacitance, C_D is the drain-to-ground leakage capacitance, and $R_{DS(ON)}$ is the on-resistance between source and drain.

At high frequencies, even if the analogue switch is at the off state, there are some signals coupled to the output through the C_{DS} . The degree of coupling is generally measured in terms of Off-Isolation. When using a multiplexer, the degree of Off-Isolation will also be affected by the crosstalks between adjacent signal channels.

If the D terminal is regarded as the signal input terminal and the S terminal is regarded as the output terminal, then the transfer function of the analog switch is as shown in Equation.1.

$$A(s) = \frac{s \cdot R_L \cdot C_{DS}}{s \cdot R_L \cdot (C_{DS} + C_S) + 1} \quad (1)$$

R_L is the load resistance of the latter stage, C_D is ignored.

When $V_{GS} > V_{GS(ON)}$, since the impedances of C_{DS} and C_S is much larger than $R_{DS(ON)}$, the branch where the C_{DS} locates can be regarded as an open circuit. The key parameter of the analogue switch is only $R_{DS(ON)}$ at the on

state.

C. Design of High Isolation Analog Switch Circuit

In the audio frequency range, the Off-Isolation of a single analog switch chip is usually not lower than -85 dB. In the traditional circuit design, in order to obtain higher isolation, two analog switch chips are adopted to compose a T-connection. The key point of the T-connection is the use of two sets of single-pole double-throw switches, as shown in Fig.3.

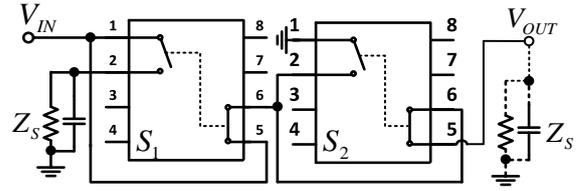


Fig. 3. T-connection analog switch circuit

In Fig.3, the V_{IN} is normally connected to an impedance Z_S at the off state of the switch. The output is also connected to a same impedance Z_S , which is the input impedance of the following stage. No matter whether the T-connection switch is at the on state or the off state, the input stage will have a stable impedance load.

When the T-connection switch is at the on state, the on-resistance of the T-connection switch will be doubled than single stage analogue switch.

When the T-connection switch is at the off state, the pin 2 of S_2 will be connected to the ground. The signal coupled from the previous stage will flow into the ground through the switch, and the signal coupled to the output will be extremely attenuated. But if the impedance at the output is too large, the signal coupled from the input to the output will be not neglectable.

The T-connection analogue switch circuit in the off state can be equivalent to Fig.4. In Fig.4, the impedance Z_S of the input stage is omitted. C_a and C_b are the coupling capacitances between the drain and the source of the two analogue switches. $R_{DS(ON)}$ is the on-resistance of the normally open switch of S_2 .

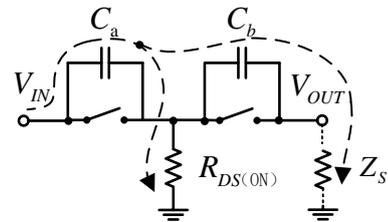


Fig. 4. T-connection switch equivalent circuit in the off state

In the application of digital sampling bridge, when measuring a large impedance, the load impedance Z_S may reach 1 M Ω , which will result in the isolation not reaching the required level -120 dB. To make the Off-

Isolation acceptable of the analogue switch, a type of double T-connection high isolation analog switch circuit is proposed, as shown in the Fig.5.

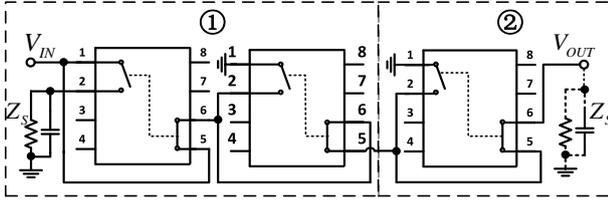


Fig. 5. Double T-connection analog switch circuit

In Fig.5, the first part adopts the traditional T-connection, the second part consists of another one single-pole double-throw switch which can form the other T-connection with the front stage, and the two parts are connected by coaxial lines.

When the double T-connection switch is at the on state, the on-resistance of the switch device is tripled compared to the single stage switch. For the on-resistance of the switch can be compensated by connecting the switch output to a voltage follower with high input impedance, the signal will not be attenuated. At the same time, the benefit is that the setting time can be drastically reduced, only 50 ns for the analog switch chip DG642, which is much higher than the reed switch which means the measurement speed will be significantly improved.

When the switch device is at the off state, its equivalent circuit is shown in Fig.6.

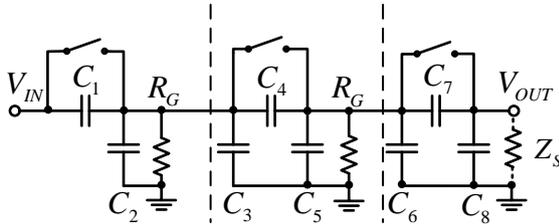


Fig. 6. Double T-connection analog switch equivalent circuit

In Fig.6, C_1 , C_4 , C_7 are analog switch source-drain coupling capacitors, C_2 , C_5 , C_8 are drain-to-ground leakage capacitors, C_3 , C_6 are source-to-ground leakage capacitors, and R_G is on-resistance between source and drain.

The transmission network is formed by cascaded three-level networks, and the transfer functions correspond to $H_1(j\omega)$, $H_2(j\omega)$, and $H_3(j\omega)$. The expression of the network transfer function is

$$H(j\omega) = H_1(j\omega) \cdot H_2(j\omega) \cdot H_3(j\omega). \quad (2)$$

Refer to Equation.1, then

$$H_1(j\omega) = \frac{j\omega R_G C_1}{j\omega R_G (C_1 + C_2 + C_3) + 1}. \quad (3)$$

$$H_2(j\omega) = \frac{j\omega R_G C_4}{j\omega R_G (C_4 + C_5 + C_6) + 1}. \quad (4)$$

$$H_3(j\omega) = \frac{j\omega Z_S C_7}{j\omega Z_S (C_7 + C_8) + 1}. \quad (5)$$

For the convenience of analysis, the capacitor C_3 in the second stage network is classified into the first stage, and the capacitor C_6 in the third-level network is classified to the second stage.

Referring to the data sheet of DG642^[6], the source and drain to ground leakage capacitance is 8~20 pF, the on-resistance R_G is 5 Ω , the source-drain coupling capacitance is 0.3 pF. When the load impedance Z_S is 1 M Ω , the Off-Isolation of the output and input remains below -180 dB up to 1 MHz according to the theoretical transmission model. Due to the influence of residual parameters, the actual analog switch does not reach the theoretical level.

When designing a PCB, the most important thing is to design the PCB of the two parts of the analog switch separately, which is physically guaranteed that there will be no line coupling capacitor. Secondly, when designing the PCB board, the principle to be followed is that the input terminal and the output terminal should be kept away as far as possible. To avoid crosstalk between different channels, all the switch chips are shielded with a grounded shielding box.

D. Application of the Switch in Digital Sampling Bridge

As shown in Fig.7, the entire sampling device consists of three parts, the first part is a digital auxiliary bridge, the second part is an analog switch switching circuit in which two double T-connection switches K_1 and K_2 are adopted, and the third part is a sampling device.

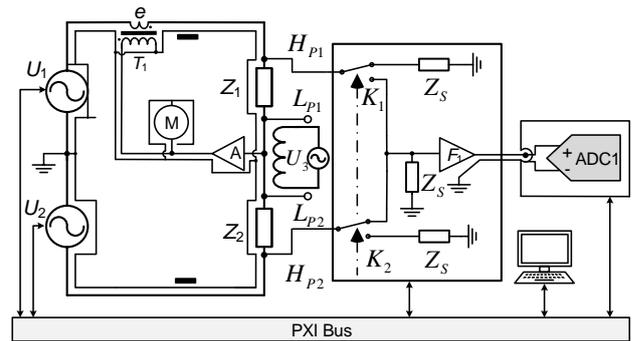


Fig. 7. Single AD channel digital sampling bridge

The bridge is a digital auxiliary bridge with automatic source balance^[2]. When the bridge is unbalanced, by transmitting a part of the voltage of the Z_1 and Z_2 connection points to the branch of signal source U_1 , the port voltage can be dynamically adjusted. Signal source U_3 is eliminated for the residual voltage between impedances Z_1 and Z_2 , and the low potentials of Z_1 and Z_2 are adjusted to zero by monitoring the voltages of

points L_{P1} and L_{P2} . At equilibrium,

$$\frac{U_1+U_e}{U_2} = \frac{Z_1}{Z_2}. \quad (6)$$

Once the bridge is in equilibrium state, no matter how the state of the analog switch changes, the load impedance Z_S loaded to the bridge will always keep same, which can prevent unbalanced fluctuations to the bridge during the switching process. The voltage follower F_1 is adopted to compensate the on-resistances of the switches K_1 and K_2 .

U_e is the voltage fed back from the impedance bridge, and is proportional to the bridge center voltage under the action of the feedback transformer T_1 . When the process of adjusting T_1 , if the voltage meter M appears to be zero, the bridge enters the equilibrium state.

Signal acquisition uses a single ADC to achieve simultaneous sampling, which shifts the limit of measurement accuracy of the source to the nonlinear error of the ADC. The selected ADC chip is the LTC2378 with a nonlinearity error of only ± 2 ppm, which will make the accuracy of the bridge can reach 10^{-6} level.

III. RESULTS AND DISCUSSIONS

The actual Off-Isolation of the analogue switch is lower than the theoretical isolation because of the other stray couplings between the input and output signals. A test circuit is constructed for Off-Isolation testing of analogue switches.

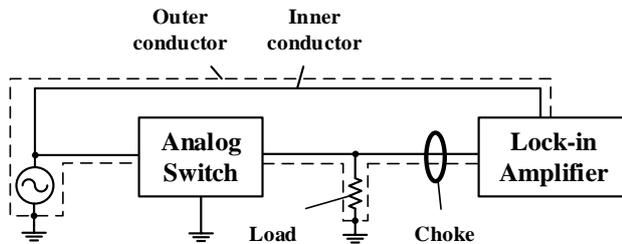


Fig. 8. Off-Isolation measurement circuit

The test method given in Fig.8 is a small-signal detection method based on lock-in amplifiers commonly used in the small signal measurement. The analogue switch should be placed in off state for Off-Isolation testing. To accommodate larger impedance measurement occasions, the load impedance is selected as $1\text{ M}\Omega$.

Fig.9 shows the comparison of the isolation of the traditional two-stage analogue switch and the designed three-stage designed switch under actual conditions.

The *Required Line* in Fig.9 is the lowest standard line to ensure that the measurement accuracy reaches ppm level in impedance measurement.

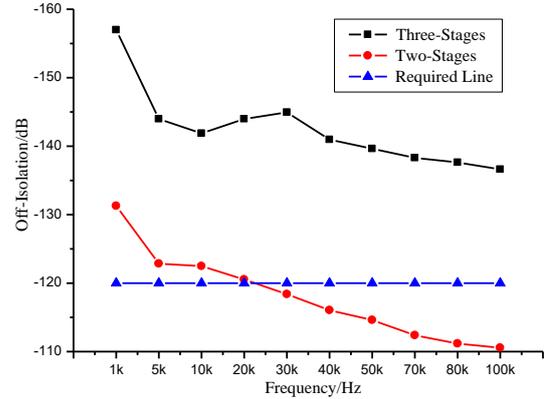


Fig. 9. Analog switch's Off-Isolation

In the frequency range of 100 kHz, the isolation of the designed analogue switch can reach a satisfactory -135 dB or better, which can satisfy the demand of impedance measurement. Compared with a commercial coaxial switch (N1810U), although the coaxial switch (N1810U) has a higher testing isolation of -160 dB in the range of 100 kHz, the isolation performance of the designed analogue switch is good enough and the switching speed is much high than the coaxial switches.

IV. CONCLUSIONS

This paper describes the design and application of a high isolation analogue switch device. The experimental comparison results show that this analogue switch can transmit signals with very low crosstalk and can replace coaxial switches.

V. ACKNOWLEDGMENT

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REFERENCES

- [1] B. Hague and T. Foord, *Alternating Current Bridge Methods*, 6th ed. London, U.K.: Pitman, 1971.
- [2] Yang Y, Lu W, Huang L, et al. *A digital impedance bridge with auto-balancing source ratio*[C]//2016 Conference on Precision Electromagnetic Measurements (CPEM 2016). IEEE, 2016: 1-2.
- [3] Overney F, Jeanneret B. *RLC bridge based on an automated synchronous sampling system*[J]. IEEE Transactions on Instrumentation and Measurement, 2011, 60(7): 2393-2398.
- [4] Mašláň S, Šíra M, Zachovalová VN, et al. *Digital sampling setup for measurement of complex voltage ratio*[J]. IEEE Transactions on Instrumentation and Measurement, 2017, 66(6): 1355-1363
- [5] Yonggui Hu, Jiabin Zhang. *A high isolation video analog switch* [J]. *Microelectronics*, 1997(5):342-345.
- [6] Vishay Siliconix, *DG642 datasheet*, www.vishay.com.