

A MODULAR COAXIAL MULTIPLEXER WITH HIGH ISOLATION BETWEEN CHANNELS

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Abstract – An universal coaxial multiplexer for switching one measurement device between several measurement points is described. The coaxial multiplexer consists of independent switch modules (channels), which are controlled via optical fibres. The off-state isolation of multiplexer was measured to be better than -185 dB at 1 kHz. Properties of the multiplexer enable to use it in automation of high precision 2-TP and 4-TP coaxial a.c. bridges or other precise measurement applications.

Keywords: multiplexer, switch, coaxial, impedance measurement, automation

1. INTRODUCTION

Electrical impedance plays a key role in many industrial measurements based on evaluation of absolute impedance values or on evaluation of impedance changes. Today increasing amount of measurements together with lowering its uncertainty places demand on automation of measurement processes. In the case of impedance ratio measurements, there is a need to achieve relative uncertainty level of 10^{-7} with automated devices below and above kHz frequency range [1]. Consequently, high quality and fast switches for precise measurements are crucial in development of such measurement circuits.

In a wide range of precision electrical impedance measurements are involved measurement circuits based on coaxial techniques. Application of coaxial techniques in measurement circuits takes advantage in acquiring of immunity to electrical interferences. When a coaxial a.c. circuit for ratio measurement of two impedances is used, several balance conditions have to be fulfilled. Typically, amount of balance is measured by means of few detection transformers implemented within the circuit and a phase sensitive null detector [2, 3]. To omit manual switching of the null detector between measurements points (e.g. outputs of detection transformers), a computer controlled coaxial multiplexer has to be used. For successful implementation of the multiplexer in a precise coaxial measurement circuit without decreasing the circuit accuracy, the multiplexer has to fulfil following requirements:

- full shielding from surrounding environment,
- negligible crosstalk between off-state input and output,
- sufficiently low straight impedance of the closed channel,
- ability to control connection of not only the signal path but also of the shielding of the coaxial circuit.

Commercial multiplexers (switches) are not usually useable because of permanent shield connection between input and output connectors, which means that they create unwanted current paths in the whole circuit. Consequently, coaxiality of the currents flowing within the circuit is violated and immunity to outer electromagnetic fields is lost. Several types of switching principles can be used for realization of precise switches, e.g. mechanical switch controlled by step motor [4], hydraulic valves [5] or relays [6]. The speed of switching process is mainly limited by actuator's properties. To increase speed of switching, a semiconductor switch can be used, but it can introduce channel crosstalk problem or significant resistance of the signal path. A coaxial multiplexer with suppressed crosstalk between channels and ability to switch channels within a few milliseconds was designed and realized. Its properties go beyond usual commercial switches and will be described in this paper.

2. DESIGN OF COAXIAL MULTIPLEXER

2.1. Coaxial multiplexer concept

Coaxial multiplexer consists of control unit and separated switch modules (channels). Each switch module is designed as an independent box with one input and one output. While each switch module is powered from own battery cells and controlled via fibre optic cable, switch modules are isolated from each other and also from the control unit. Such a modularity brings the ability to use switch modules as a multiplexer or demultiplexer theoretically with up to 508 channels. An example, where four measurement points situated within one circuit are measured by one null detector, is in Fig. 1.

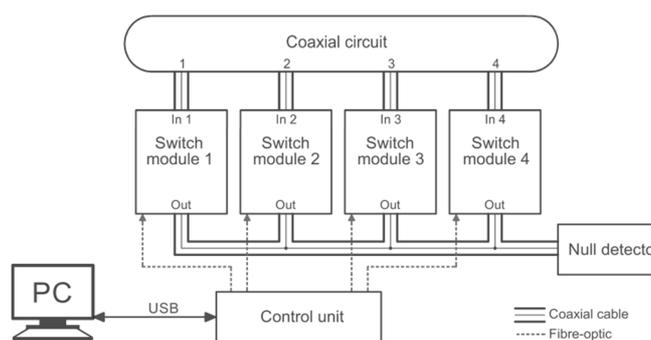


Fig. 1. Principle schematic of the coaxial multiplexer application.

2.2. Principle of the switch module isolation

The final design of each switch module consists of three relays in series placed in three screening chambers and is completed by one more relay for switching of the outer conductors of input and output ports. When the switch module is in off-state, internal wiring is formed in the following order (see Fig. 2):

- inner conductor of the input port and wire *a* is floating
- wire *b* is connected to the outer conductor of the input port via relay K2
- wire *c* is connected to the outer conductor of the output port via relay K4
- inner conductor of the output port and wire *d* is floating

When necessary, switch module can be programmed to short the input port (to connect inner and outer conductor) in off-state by means of relay K1. It is helpful for specific measurements, for example when a current detection transformer is connected to the input of the switch module and low impedance of the detection circuit has to be maintained even if switch module is in the off-state.

When the switch module is in on-state:

- inner conductor of the input port is connected with the inner conductor of the output port via wires *a*, *b*, *c* and *d* and relays K2, K4 and K5
- outer conductors of both ports are connected via relay K3

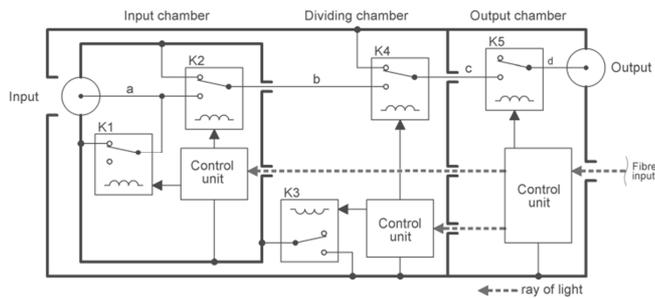


Fig. 2. Block schematic of the switch module (off-state).

A simplified schematic of parasitic capacitances in off-state resp. series resistance in on-state is shown in Fig. 3 a) resp. b). From Fig. 3 a) is clear, that effect of residual parasitic capacitances in the switch module is suppressed by connection of both sides of capacitance C_{K4} (by means of relays K2 and K4) to ground potentials, which are nearly the same. Reduction of number of relays is not applicable while it will lead to flow currents between outer conductor of the input port and inner conductor of the output port in off-state.

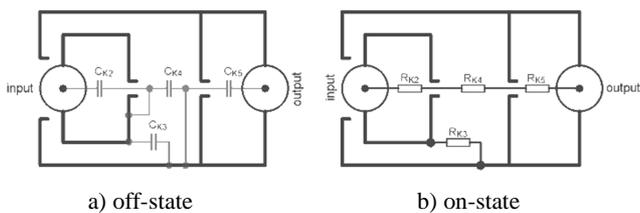


Fig. 3. Principle schematic of coaxial multiplexer application.

2.3. Switch module realization

All switch modules and each chamber in each switch module are controlled by means of infrared (IR) serial data communication. Only one fibre optic input and one direction communication is for its simplicity used. To secure system against fault of the switching due to malfunction of the IR communication, Manchester coding is used for programming of each control unit. Moreover, when corrupted data are received, switch module can be set to predefined state. Each battery in the module can be tested without need to open module by sending special command to the unit – condition of each battery is indicated by a beep signal. Standard size of each switch module is about 115x90x55 mm and can be modified by using different box cases.

The electronic circuit in the each chamber is designed for ultra-low current consumption (only few μA in sleep mode, about 60 mA during switching). While Li-SOCl₂ batteries are used, lifetime of coaxial multiplexer is not significantly limited by self-discharging of batteries and coaxial multiplexer should operate at least few years in normal working conditions without changing battery cells. Up to now, all switch modules have been used for about two years with more than 50 000 switching, one module with more than 100 000 switching without any failure.

2.4. Control unit realization

Communication between PC and switch modules is realized with a help control unit, consisting of USB input and four fibre optic outputs (see Fig. 1). While each control unit has a unique identification USB code, several units can be connected to one PC. An executable or NI Labview program can be used to control switch modules. Standard size of the control unit is about 60x50x25 mm.

2.5. Optional application: an isolated shorter

Several measurement applications based on balancing procedures or with a need to neglect effects of parts of circuits have to implement shorting circuits. For applications, where shorting between inner and outer conductor is necessary, a shorting circuit based on similar hardware like switch module was realized (Fig. 4). The shorter is miniaturized, consists of battery check circuit and is controlled with the control unit described above.

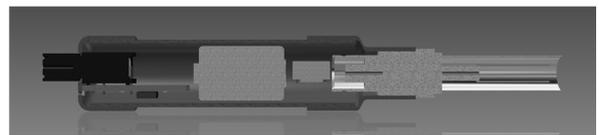


Fig. 4. Cross-section cut of the shorter. Left to right: fibre optic connector, printed circuit board, battery cell, shorting relay, coaxial BPO (MUSA) connector

3. VERIFICATION OF SWITCH MODULES

To verify properties of the coaxial multiplexer, switch modules were tested for their properties in off-state (isolation properties) and on-state mode (contact resistance).

3.1. Isolation properties

Straight capacitance and admittance of switch modules were measured with a help of precision capacitance bridge AH2700A. Due to small measured values, it was necessary to carefully test the whole measurement circuit to eliminate possible systematic errors (interferences, nonlinearities, offsets). The offset of the measuring circuit was evaluated with same geometrical cable arrangement, which was used during main measurement. Possible nonlinearities of the capacitance bridge were checked by comparison of measurements of switch module straight capacitance in parallel with and without 1 pF capacitance standard. Evaluation of measurements has shown, that the straight capacitance of the switch module is below 1 aF and is not measurable with our equipment. Results of capacitance and admittance measurements for four switch modules together with uncertainties ($k=2$) are provided in Table 1.

Table 1. Straight capacitance and admittance of four switch modules (parallel equivalent scheme).

Quantity	Switch module S/N			
	Su0001	Su0002	Su0003	Su0004
C_{OPEN} [aF]	0.0 ± 0.5	-0.1 ± 0.5	-0.1 ± 0.6	0.0 ± 0.5
G_{OPEN} [fS]	0.4 ± 3.1	0.2 ± 3.1	0.3 ± 3.4	0.1 ± 3.1

Direct measurements of the off-state isolation and crosstalk between two channels were performed at 7 V_{rms} level with a help of a.c. voltage source (CMI SWG03 type for measurements at 1 kHz and HP 3245A type at 1 MHz) and lock-in amplifier Signal Recovery 7280. The off-state isolation was measured to be better than -185 dB at 1 kHz and better than -155 dB at 1 MHz, which is on the level of the accuracy limit of the used measurement equipment. Due to the modular construction of the multiplexer, the crosstalk between two channels is on the same level as the off-state isolation of the one switch module. With such good isolation properties, the coaxial switch can be theoretically used not only for switching measurement device between several measurement points, but for switching of calibrated impedances in the coaxial measurement circuit too.

3.1. Resistance of the closed switch module

Several relays were tested for reliability of the contact resistance during lifetime of modules. Contact resistance was measured at frequency 1 kHz by means of LCR meter Agilent E4980A. When switch modules connect signal sources to a voltmeter or null detector in a real application, nearly zero currents (bellow μA or nA level) flow through contacts. It is not possible to get reliable test results with LCR meter with such a low currents. Hence, current 0.1 mA was chosen. Other resistance measurements were performed at current 10 mA to simulate behaviour of switch modules at higher current loads. LCR meter was used in 4-TP measurement mode and, thus, the results are influenced not only by relays K2, K4 and K5, but by shielding and relay K3 too (see Fig. 3 b). Two types of relays were used for testing. Finally, TQ2S- L-3 type (Panasonic Electric Works

Europe AG [7]) was chosen for future use because of better stability of contact resistance. Typical contact resistance of four relays in series was lower than 90 m Ω , see Fig. 5. The uncertainty ($k=2$) of the contact resistance measurement was lower than 20 m Ω (including repeatability of the measurement and accuracy of LCR meter). Series resistance of the closed switch module can be alternatively decreased by connection of more relays in parallel without any influence on isolation parameters of the module.

At higher frequencies, series inductance of switch module can play a significant role in total impedance of the switch module. Rough measurements at 100 kHz have shown that typical contact impedance of the switch module is still lower than 100 m Ω .

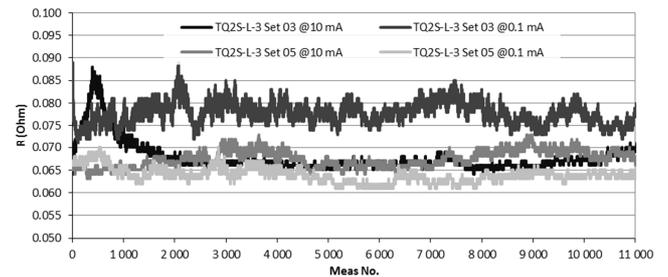


Fig. 5. Example of contact resistance measurement, relay type TQ2S-L-3. Results shown for relay set No. 03 and No. 05 at current levels 10 mA and 0.1 mA.

4. BEHAVIOUR OF THE MULTIPLEXER IN REAL APPLICATIONS

4.1. High frequency 4-TP coaxial bridge at 1 MHz

The coaxial multiplexer was tested in a real coaxial circuit, a 4-TP high frequency (HF) coaxial bridge. The bridge was configured for ratio measurement of two air filled capacitors (Agilent 16380A standard capacitor set) with nominal values 1 pF and 10 pF at frequency 1 MHz. Fig. 6 shows connection diagram of the coaxial bridge. Reference ratio arms are formed by inductive voltage divider IVD, compared ratio arms by impedances Z_1 and Z_2 (capacitors 1 pF and 10 pF). The energizing part of this bridge consists of a voltage source G1, a transformer ATR1, and an auxiliary transformer ATR2. The main balance is controlled by means of voltage source G2 and an injection transformer ITR. Variable impedances Z_{I1} , Z_{I3} and Z_{I2} and Z_{I4} assure zero currents in high potential leads. The effect of the unwanted potential drop on the impedance of the link Z_L between Z_1 and Z_2 is eliminated by means of a combining network consisting of Z_{CN1} and Z_{CN2} . A no-load condition on the output tap of the IVD is achieved by Wagner ground circuit formed by C_W and R_W . Details of the bridge construction and its operation are given in [8]. The null detector (lock-in amplifier Signal Recovery 7280) is switched to measurement points U_{D1} , ... U_{D4} by means of the coaxial multiplexer switch modules SW1 ... SW4. While detection transformer DTR3 with ratio 25:1 is used, the null detector can be used to measure voltage across the bridge too.

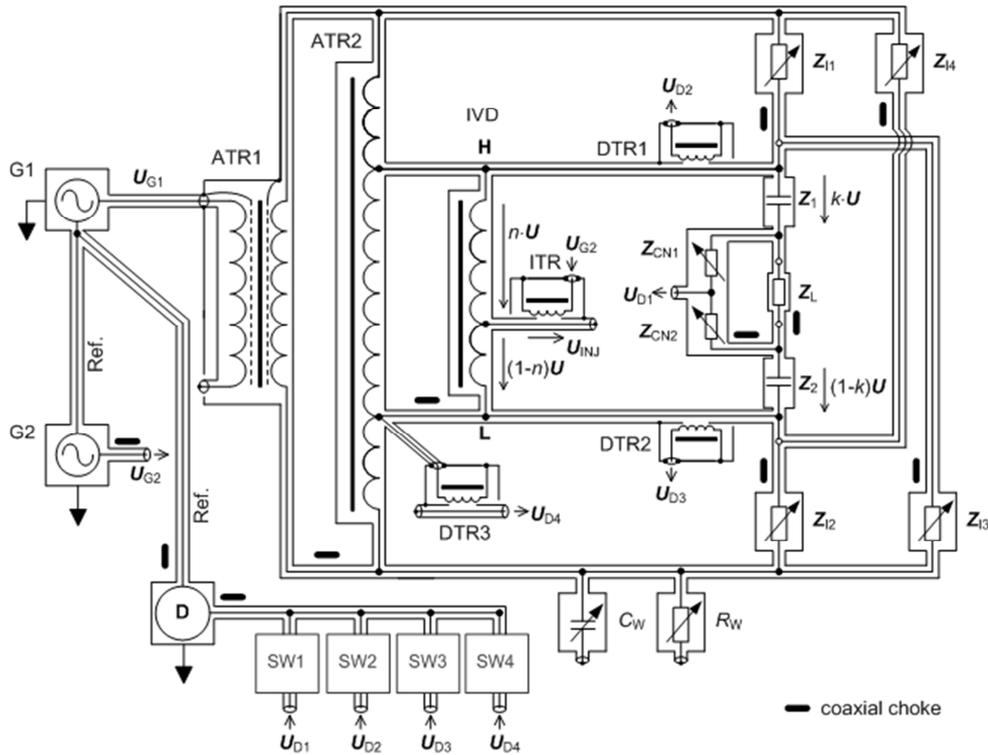


Fig. 6. HF 4-TP bridge configured for ratio measurement of two capacitors with impedances Z_1 and Z_2 and with the implemented coaxial multiplexer (modules SW1 ... SW4). Details of bridge are described in [8].

Two measurements were performed: manually operated measurement without coaxial multiplexer and with coaxial multiplexer. Both measurements were done within short time, to omit effect of non-stability of the air filled capacitors on ratio measurement. Results of the capacitance ratio measurement $K=C_2/C_1$ are provided in Table 2. Difference between measurement results is smaller than measurement uncertainty. It has to be noted, that on switch module SW1 is detected voltage on the level below 100 nV, on SW2 and SW3 are detected voltages in μV range and on SW4 in 10 mV range. Consequently, the ratio between voltages connected to coaxial multiplexer is higher than 10^5 . Details on sources of uncertainties are given in [8]. Uncertainty of calculated difference $K_2 - K_1$ between measurements is smaller than the written one due to correlation between measurements of K_2 and K_1 .

Table 2. Results of ratio measurement without and with coaxial multiplexer at 1 MHz.

Null-detector connection type	Ratio K (-)	Uncertainty (-) ($k=2$)
Manually operated K_1	10.002 54	0.000 13
With multiplexer K_2	10.002 55	0.000 13
Difference $K_2 - K_1$	0.000 01	<0.000 18

4.2. Fully automated 4-TP coaxial bridge

Low crosstalk and high lifetime of switch modules able to use coaxial multiplexer in high precision fully digital (FD) bridges, where high switching rate of switches is important. An audio-frequency version of FD bridge for

calibration of impedance standards in the whole complex impedance plane is under development within project [1] at CMI. Application of digital voltage sources instead of manually operated components (such as Z_{11} , Z_{13} , Z_{12} , Z_{14} , Z_{CN1} , Z_{CN2} , C_W and R_W , see Fig. 6) together with using coaxial multiplexer increase the efficiency of calibration procedure, while balancing algorithm implemented in control program for voltage sources and coaxial multiplexer able to perform automated calibration over wide frequency range without need of manual bridge adjustment. Simplification of the bridge topology is clear from Fig. 7, where all manually operated components are removed and main balance is performed by changing ratio of voltages of generators G1 and G2. The effect of the unwanted potential

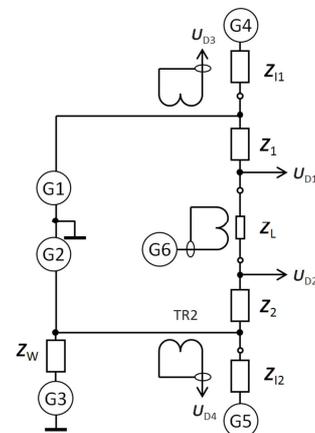


Fig. 7. FD 4-TP bridge (for simplicity, detector D and coaxial multiplexer modules SW1 ... SW4 are not shown)

drop on the impedance of the link between Z_1 and Z_2 is eliminated by nulling potential difference $U_{D1}-U_{D2}$ (by means of voltage source G6). Voltage sources G4 and G5 assure zero currents in high potential leads. The voltage sources consist of set of compact two-channel isolated digital synthesizers CMI SWG03 with clock and phase synchronization. Preliminary results show, that, short-time amplitude stability of CMI SWG03 (better than $1 \mu\text{V}/\text{V}$) together with negligible crosstalk of coaxial multiplexer able to perform automated ratio measurements of impedances with base accuracy better than 10^{-6} in kHz frequency range.

5. CONCLUSIONS

The coaxial multiplexer with wide range of usability in automated precision measurement circuits was designed. An emphasis was put on the high isolation between channels and the low power consumption together with relatively high speed of switching. To fulfil all requirements, the multiplexer was realized with signal relays as switching members in a special arrangement to achieve extremely high isolation between channels. During testing of multiplexer properties was shown, that off-state isolation is better than -185 dB at frequency 1 kHz (level of measurement uncertainty). Contact resistance of closed channel is typically lower than 100 m Ω and can be improved by parallel connection of more relays without any influence on isolation parameters of modules. Practical testing of the coaxial multiplexer in the coaxial impedance bridge has shown, that using of such a device has negligible effect on measurement results, although the ratio between voltages connected to coaxial multiplexer inputs was higher than 10^5 .

Modular design of the realized coaxial multiplexer allows easy expansion of number of channels without changing isolation properties of the multiplexer. Due to optimized control circuit and used battery type, multiplexer can be used for several years and more than hundred thousand switching without need to change battery.

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