Magnetic Resonance Imaging 56 (2019) 151–155

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.elsevier.com/locate/mri

Original contribution

# The downhole circumferential scanning magnetic resonance imaging tool

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ABSTRACT

The downhole circumferential scanning magnetic resonance logging is able to image saturation distribution and fluid properties of stratum around a borehole, thus providing relevant and abundant information for formation evaluation. The device employs a phase-controlled excitation device based on combined array structure to accomplish three dimensional data acquisition from axial, radial and circumferential directions. This paper focuses on the design principle of device and the structure of electronic control system. A mutual coupling analysis with array antenna was carried out using inductance coupling principle, and realize the decoupling and energy discharge compensation of array antennas. The circumferential scanning nuclear magnetic resonance technique has a potential of overcoming the weakness of two dimensional measurements and raising new applications that it determines the azimuth of the fluid in the borehole and realizes the imaging measurement of the pore structure and the reservoir fluid.

## 1. Introduction

With the increasing difficulty of exploration, conventional logging technology has been unable to meet the needs of accurate oil and gas evaluation, especially in the evaluation of complex oil and gas reservoirs such as low porosity, low permeability, low resistivity and unconventional reservoirs [1]. Nuclear magnetic resonance (NMR) logging as one of Imaging logging technology can provide important rock physical parameters such as porosity, bound water, permeability and pore size distribution, and can effectively identify and evaluate the fluid properties and so on. It is widely used in the comprehensive evaluation of complex oil and gas reservoirs such as complex lithology, special lithology, low porosity and low permeability and low resistivity.

The nuclear magnetic resonance imaging (MRI) logging has been developing rapidly for decades, and it is still the hot topic of oil and gas exploration technology [2]. For example, relaxation and diffusion methods from NMR logging can be used to obtain porosity, fluid properties, flow properties and saturation distribution of stratum. NMR logging mainly includes the following three parts. First is hardware which is refers to magnet structure, antennas, electronics and surface system. The second is the method which includes pulse sequences and data processing. The third is the explanation of data from which we can acquire information about fluids and pore structure in porous media.

The NMR logging signal detected in down hole NMR probe is from hydrogen nuclei of pore fluids, which are located several kilometers underground. So the logging instruments work in a harsh environment where it has the high temperature and high pressure. The size of instruments is also restricted, and the motion effect of probe complex the measurement. This means that NMR logging measurement needs high reliable and efficient instruments. At present, several obvious developing trends have been formed:

- ➢ Modularized probe magnet structure
- ➢ Array antenna structure
- ➢ Exploration space azimuth
- ➢ Multi-Parameterization of detecting object attributes

However, with the exploration objects from conventional reservoirs to deep stratum, deep water and unconventional oil and gas reservoirs, higher requirements have been put forward for downhole oil and gas exploration technology. The existing two-dimensional nuclear magnetic resonance instruments do not have the resolution of circumferential reservoir properties. At present, nuclear magnetic resonance logging technology needs to be continuously upgraded and replaced. Therefore, on the basis of the existing technology, we designed a novel circumferential scanning magnetic resonance imaging (CSMRI) logging tool, which has the feature of centric and eccentric instruments to realize the performance of both scope of 360-degree detection round the borehole and sectional region detection. The development of this technology will bring an important change for downhole oil and gas exploration technology. It truly has a potential of achieving three-dimensional magnetic resonance imaging for complex reservoirs. The main focus of this paper is on the design and the structure of the electronic control system and shows how to overcome the technical challenges of decoupling array antennas and switching the radio frequency quickly.

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https://doi.org/10.1016/j.mri.2018.09.031
Received 31 July 2018; Received in revised form 26 September 2018; Accepted 26 September 2018
0730-725X/ 

## 2. Design of CSMRI tool

An orthogonal electromagnetic field which produced by the array magnets and antennas of circumferential scanning MRI tool excites Nuclear Magnetic phenomena in the target layer. The array antennas are also used to acquire echo signals. In order to achieve the three dimensional information from circumferential, radial and axial, the tool realizes circumferential orientation by switching different combinations of array antennas, obtains radial slices information by tuning circuit changing emission frequency, and the axial information comes from the movement of the instrument. So the tool can get three dimensional information around the borehole.

The underground part of instrument structure consists of two components: probe and electronic cartridge.

### 2.1. Probe of CSMRI tool

The design of the magnet and antenna achieve the orthogonal matching of the static magnetic and radio frequency fields, enlargement of sensitive volume, overall mechanical properties of the probe, and assembly process requirements. This tubular MRI logging sensor has flexible and practical sensitive volumes (DOI, gradient, height) for different purposes by changing suitable array antennas. The probe structure and the distribution of magnetic field are shown in Fig. 1.

In this paper, the magnet is designed based on the classic "inside-out" concept for logging while drilling proposed by Jasper A. Jackson [3-5]. Traditional utilization of this structure served its purpose on its homogeneous field which had an unpractical sensitive volume. The new idea on sensitive volumes was proposed to realize circumferential scanning. The static magnetic field of this instrument is produced by multiple-unit permanent magnets array that includes two N poles opposite main magnets. The main magnets are composed of multi small magnets with axial polarization and a series of focusing magnets. The focusing magnets with Halbach structure were employed between main magnets to improve DOI for easy excitation and mud signal elimination. The array antennas of this probe have 24 copper strips that equidistantly surround the magnet. By combining antennas, we can achieve the information from different opening angles and different azimuth. With the increasing number of stripes, the opening angles increased. This tubular MRI logging sensor has flexible and practical sensitive volumes (DOI, gradient, height) for different purposes by changing suitable array antennas [6].

### 2.2. Electronic cartridge of CSMRI tool

The designed electronic system for the new MRI logging tool has to fulfill the requirement of home-built sensor with the limitation of high temperature in a harsh environment. Electronic system consists of array antenna controller, transmitter and receiver circuit, main controller, auxiliary measuring system and capacity cartridge. The functional block and signal flow diagram are shown in Figs. 2 and 3.

The main control circuit is composed of DSP and FPGA. The DSP receives measurement mode parameter and control commands of ground system, and sends the information to the control circuit FPGA, the echo acquisition circuit and the pulse processing circuit after decoding. FPGA generates all the timing and control signals that include transmit control signals, energy releasing control signals, duplexer circuit control signals, acquisition circuit control signals and array antennas control signals. The clock for all these control signals is based on the DDS generated. FPGA generates the transmit control signal that satisfies specific timing according to specific measurement mode. The full-bridge switch of transmitter is controlled by the output of amplifier driver, and chop the 600 V DC high-voltage into a high-power RF pulse with 2400 V peak value. The energy stored in the antenna is quickly released through the multi-stage bleeder circuit after the antennas emitted. The preamplifier circuit is protected by a duplexer circuit between the antenna and the preamplifier. After the energy is discharged, it is ready to receive the echo signal. At this time, the duplexer circuit allows the echo signal to enter the preamplifier circuit. The amplified echo signal is sent to the echo acquisition circuit, and the amplitude and phase information is extracted by the phase sensitive detection algorithm after sampling. During the pulse transmission, the

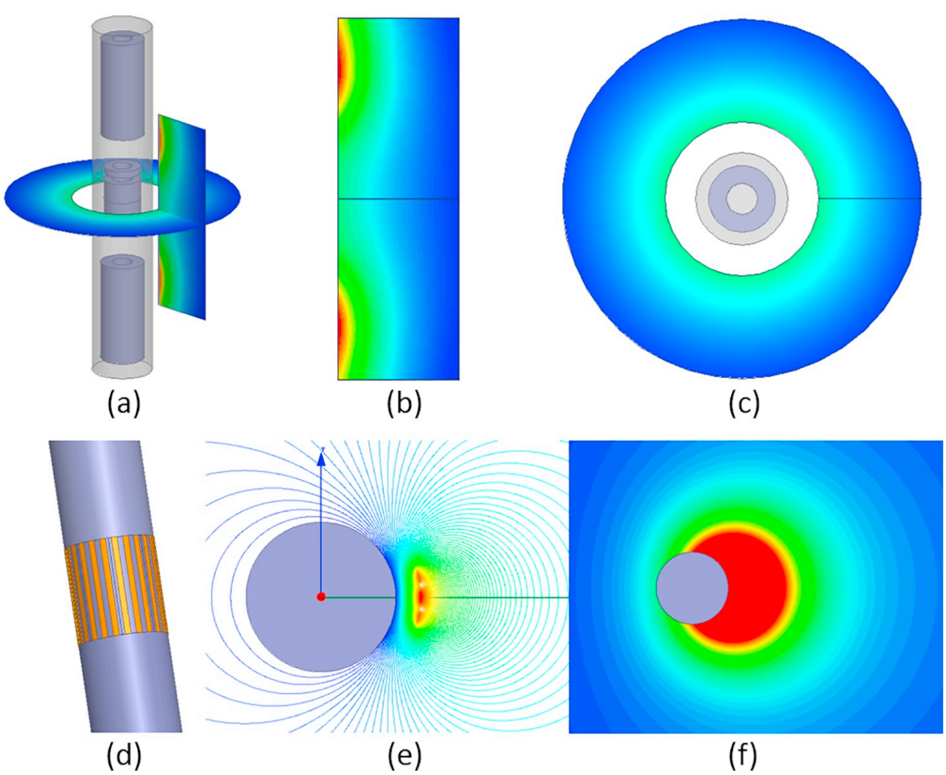


**Fig. 1.** Probe structure and the distribution of magnetic field. (a) Three-dimensional magnetic field distribution. (b) Cross section of static magnetic field strength. (c) longitudinal section of static magnetic field strength. (d) The array antennas configuration. (e) Radio frequency field magnetic lines distribution of three strap antennas. (f) Radio frequency field distribution of three strap antennas.

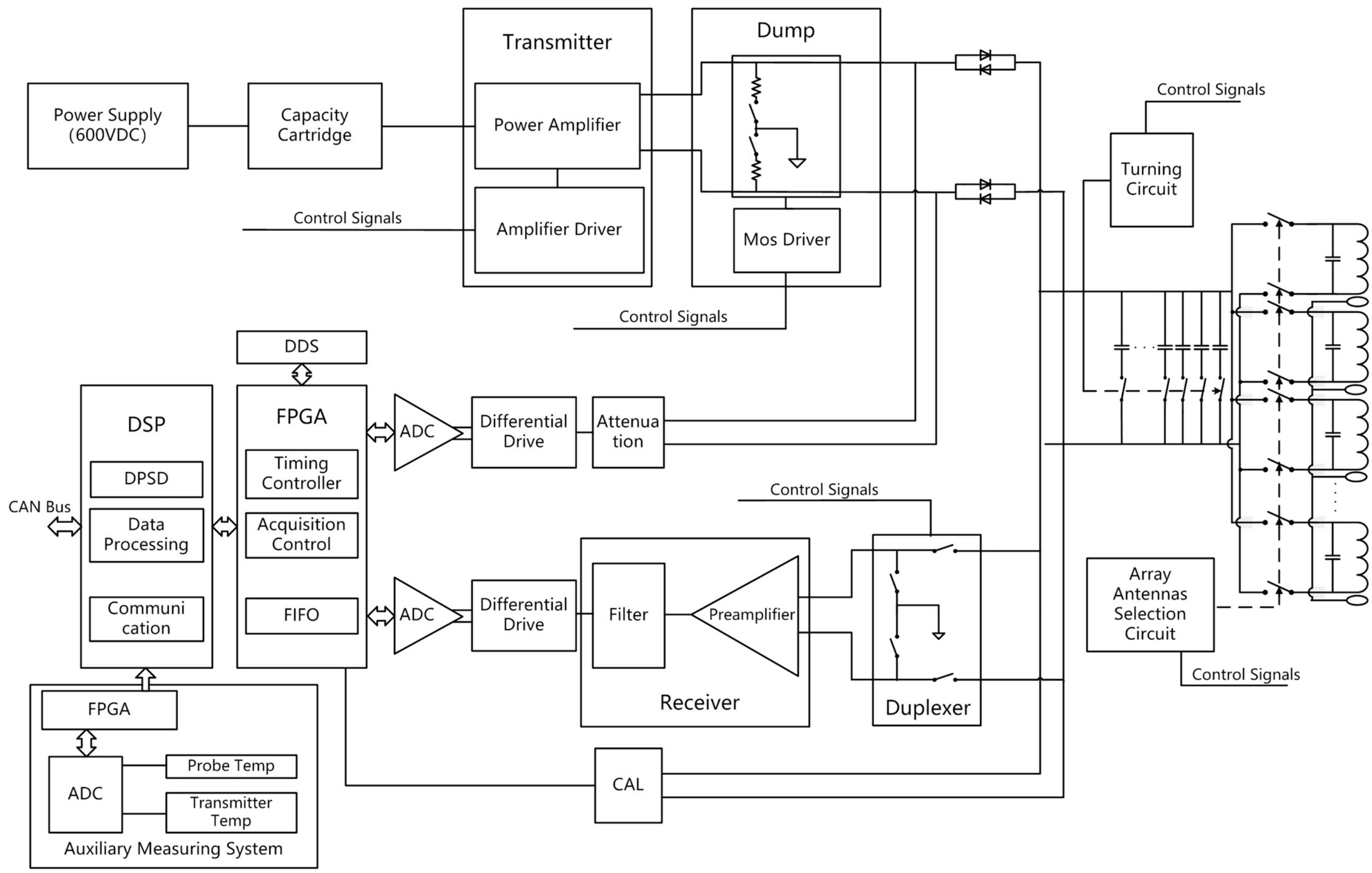


**Fig. 2.** Block diagram of electronic cartridge.

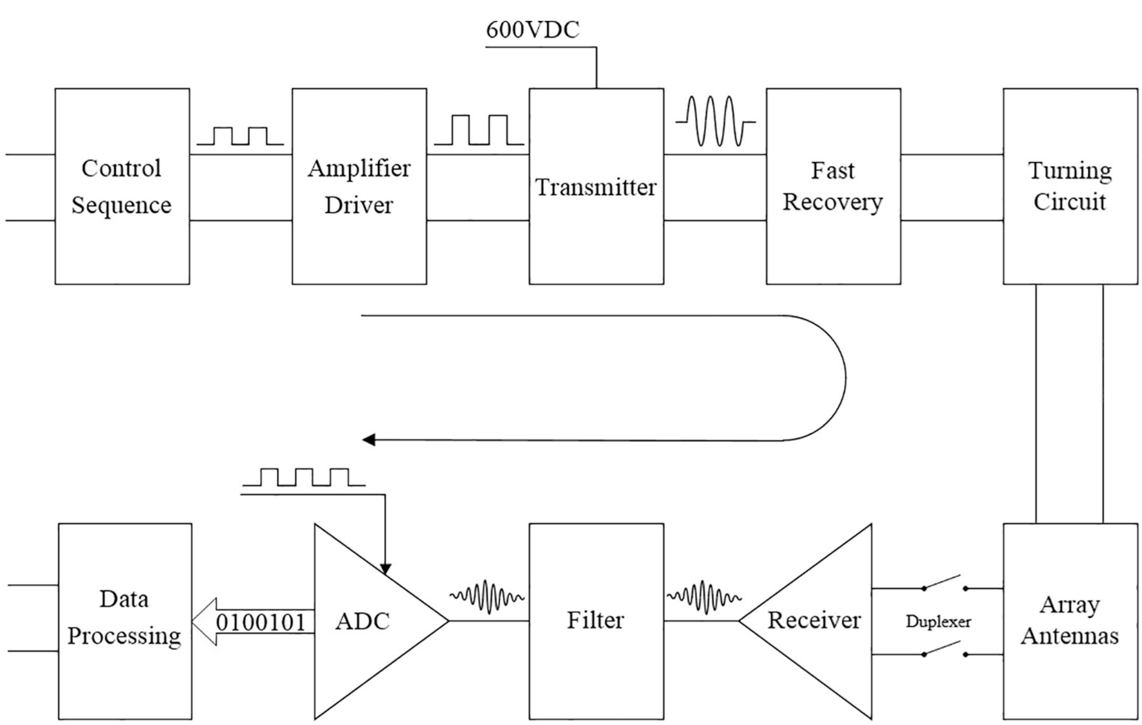


**Fig. 3.** Signal flow diagram of electronic cartridge.

transmitted pulse is monitored to correct the transmission power of the echo signal amplitude, the RF pulse is attenuated by the attenuation circuit and sent to the pulse processing circuit for processing. During the polarization time, the scale signal generated is sent to the antennas control circuit, and attenuated to measure the total gain of the device. The amplitude of the echo is scaled by gain value to obtain the true porosity information. The auxiliary measuring system mainly implements temperature measurement, high pressure monitoring, instrument

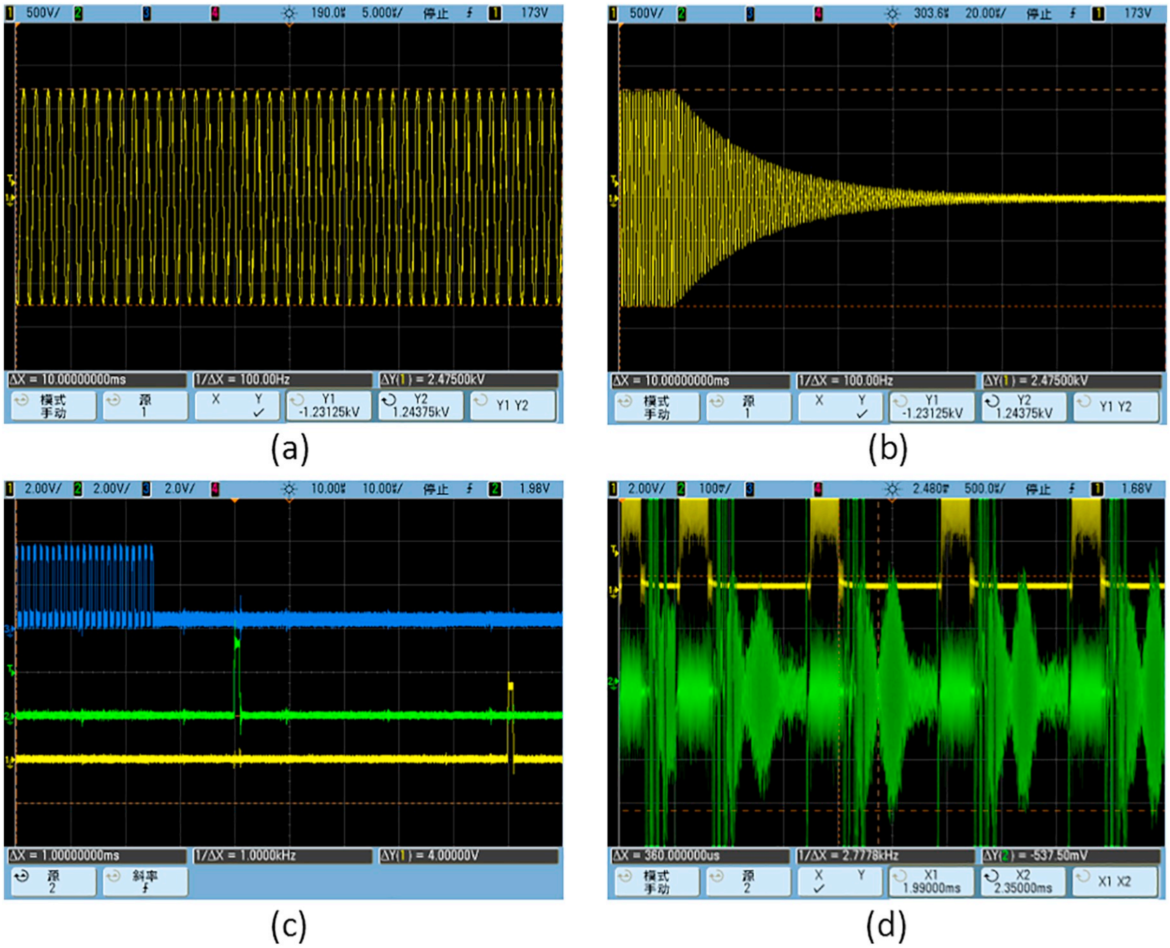


**Fig. 4.** The testing results of electronic cartridge. (a) The output signal of transmitter. (b) High power attenuation signal. (c) Array antennas control signals. (d) The acquisition echo signals of receiver.

state monitoring and so on. The capacity cartridge supplies power for the operation of high power radio frequency (RF) transmitter. Fig. 4 is the testing results of electronic system.

According to the principle of circumferential scanning MRI logging tool, the prototype mainly includes the probe, circuits, skeleton and shell. Compared with the traditional electronics of NMR logging tools, circumferential scanning MRI tool has the special design for its array antenna controller. When antennas polarize the protons, there is a large current and voltage radio frequency pulse in the coil. So, how to control array antennas to realize circumferential scanning? And another question is that the antennas remain a little power after transmitted. During this time, the antenna cannot rapidly collect the signals. How to fast release this partial energy so that timely receive echo signals?

## 3. Design of array antennas controller

The array antenna controller consists of three main parts: array antennas selection circuit, fast antennas recovery circuit and antennas turning circuit. It is used to select array antennas, eliminate the coupling phenomenon of the antennas, release the energy stored in the antennas and turning resonant frequency of antennas. The schematic diagram of array antennas controller is shown in Fig. 5.

Array antennas selection circuit relies on active switches to accomplish different opening angles and different azimuth. The active switches consist of two MOSFET switches and a coupling transformer that isolate the noise from driver circuit. Through the test of this circuit, we can prove the conversion rate of switches is less than 52 ns. At low frequency, just like the frequency of NMR logging instruments, our system allows very rapid excitation bandwidth. Because the system allows multiple slices to be detected during the execution of the same CPMG sequence, this circuit is able to meet each excitation and refocusing pulse consists of different frequencies.

The fast antennas recovery circuit controlled by radio frequency MOSFET reduces the quality factor value of antenna after pulse transmission, so it can quickly dump the energy stored and reduce the recovery time of antenna. The fast antennas recovery circuit was designed to be coupled and uncoupled, in turn, from the probe by a fast logic-controlled switch. Because of the high voltage of coil, the withstand voltage of switches is greater than 3 kV and the breakover current is larger than 12 A. Through successively turning off switch convert antenna Q value achieves high power discharge.

By switching the tuning circuit, as other NMR logging tools, the tool realizes slice observation of the probe with different radial depth. However, antennas of probe are also known as self-inductive elements. If two or more coils produce an intersecting magnetic flux, these coils have magnetic coupling or mutual inductance. Because the probe is designed with the structure of array antennas, the coupling phenomenon occurs between each antenna. This phenomenon damages the energy of RF emission and affect the quality of echo signals. In view of this effect, we put the array antennas selection circuit between capacities of turning circuit. When a group of antennas is selected, the resonance frequency of other antennas is far from the frequency of the working antennas. This method is used to eliminate the coupling between array antennas.

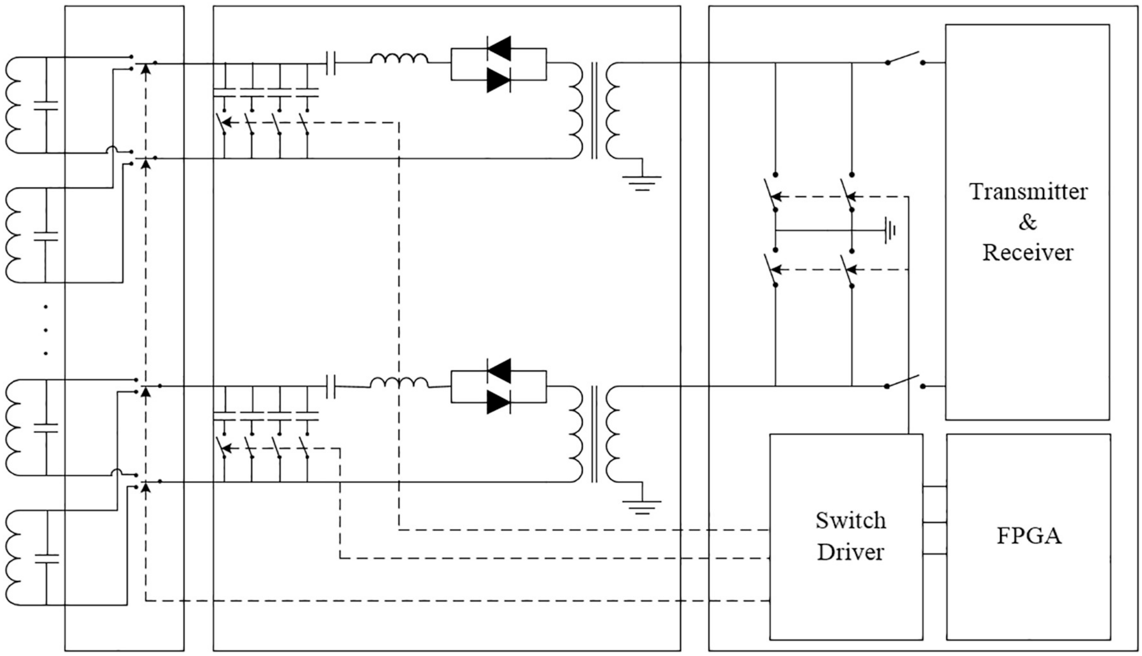


**Fig. 5.** Schematic diagram of array antennas controller.

## 4. Conclusion

This paper designs and realizes a kind of circumferential scanning magnetic resonance imaging logging tool. The designed MRI probe employs array antenna and phase-controlled transmitters to accomplish spin echo data acquisition. The numerical simulation and prototype experimental results shown the feasibility to provide three dimensional NMR signal. Future work will make the magnetic resonance imaging visible in heterogeneity stratum with continued development in hardware, software and pulse sequence and data processing technique.

## Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 21427812), National "111 Project" (B13010), and Beijing Science and Technology Project (Z161100004816004).

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