Application Note

Static Magnet Power Supply Design for Magnetic Resonance Imaging Application

Bill Xu, Donna Xu, Wendy Wang, Sanjay Pithadia, Irene Qin

ABSTRACT

Magnetic Resonance Imaging (MRI) is vital equipment in modern hospitals and an MRI helps doctors and patients to diagnose multiple diseases. In an MRI equipment, a magnet is one of the key parts which generates a constant magnetic field. There are two methods to produce a static constant magnetic field in a modern MRI system. One method uses a permanent magnet and another one uses a superconducting coil to produce the magnetic field. In modern designs, most high-end MRI equipment use superconducting coils to generate a static magnetic field. The current in superconducting coils can go up to 500 A or more. For driving a superconducting coil, MRI designers need to design a power supply with high output current capacity. This application note proposes a design to design such a power supply to drive the superconducting coil of an MRI equipment. Since there are lots of books and articles to discuss the power circuits or topology for power supplies, this application notes mainly focus on discuss the controller system design.

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

1.1 Magnet of the MRI

Figure 1-1 shows the block diagram of a typical MRI system. Magnet is the key part and also the most expensive part in such a system. There are mainly two methods to generate a constant magnetic field for an MRI system. One method uses a permanent magnet and the other one uses a superconducting coil with high current to generate a constant magnetic field. Permanent magnet-based system is mainly used for magnetic strength less than 0.5T (Tesla) application. For magnetic strength more than 1T such as 1.5T or 3T system, superconductor coils are commonly used and this type MRI is widely used in hospitals nowadays. The internal magnetic strength of an infinite length solenoid is decided by Equation 1.

$$B = \mu n I \quad (1)$$

Here, μ is permeability of air and equal $4\pi \times 10^{-7}$, n are coils of one meter, I is current flow the coils. Assume n=4000, B=3 T then I=597 A. MRI application also ask a high stable and constant magnetic. It is necessary for MRI designers to design or purchase a precise high-output current power supply which can drive the superconductor coils.

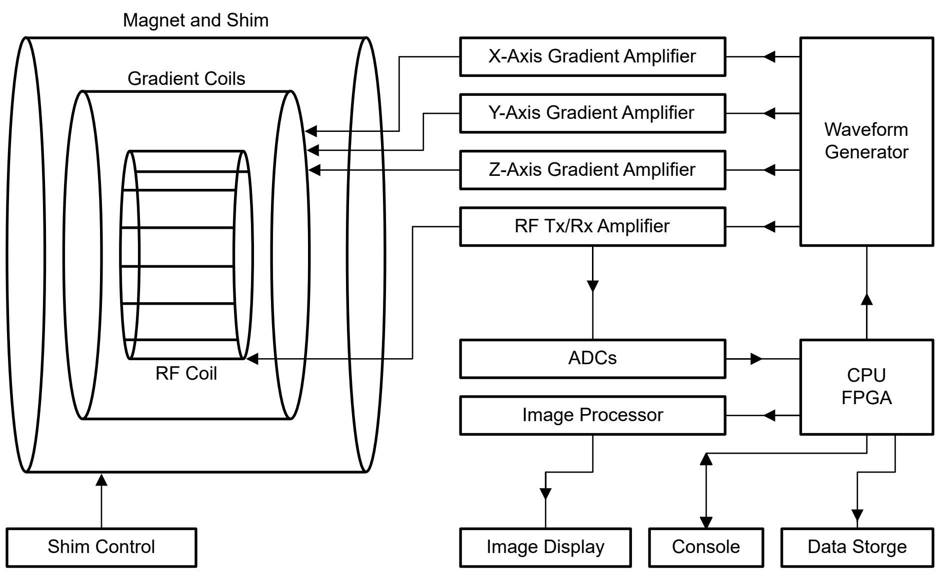

Figure 1-1. MRI System Block

1.2 Key Challenge to Design a Power Supply to Driver Superconductor

As highlighted in the introduction, to produce a high-strength magnetism for MRI systems like 1.5 T, 3 T, 5 T or 7 T, modern MRI machines use superconductor coil. The current that drives these superconductor coils can potentially be high up to 500 A or more. Here are some challenges that can arise while designing such power supply.

1. High current designs need high-capacity power MOSFETs. Not many manufacturers produce such large current capacity power electronic devices. Possibly, paralleling two or several MOSFETs can support higher current capacity. However, current sharing is common issue with such schemes and extremely difficult to solve.
2. High current capacity corresponds to high power consumption which can cause potential thermal and reliability issues.
3. MRI systems need power supply has high-stable output voltage. since high current power MOSFET can not implement high speed switching. then large buffer capacitor has to be used for stable the output voltage and this means potentially bigger capacitor for buffer which can affect the size of the design.
4. For this specific application, adopt large capacity current power MOSFET also potential means higher cost than use two small capacity MOSFET for exactly same output current.

2 Four-Phase Interleaving Phase-Shifted Full Bridge Power Supply Design

In generally, most designer potential to design the power supply to drive superconducting coils with a single PSFB circuit. but potential to meet challenges ahead said. To solve these challenges, this paper proposes a four-phase interleaving phase-shifted full bridge scheme as shown in Figure 2-1. As abstract clarify, this application notes mainly focus on controller system than power electronic topology.

Consider the basic specifications as the following:

- Input voltage: DC48V to DC60V
- Output voltage: 0 to 10V DC
- Output current: up to 500A
- Output current precision: 0.1%
- Output current temperature drift: 10ppm max
- Output current ripple and noise: less than 100mA

The benefit of 4-phase interleaving phase shifted full-bridge scheme is:

- Low-capacity power MOSFET can be used which means relatively easy sourcing of components
- Possibly reduced thermal issues because of lower current rate

Interleaving scheme reduces output buffer capacitor size and capacity because of four times increase in the switching frequency.

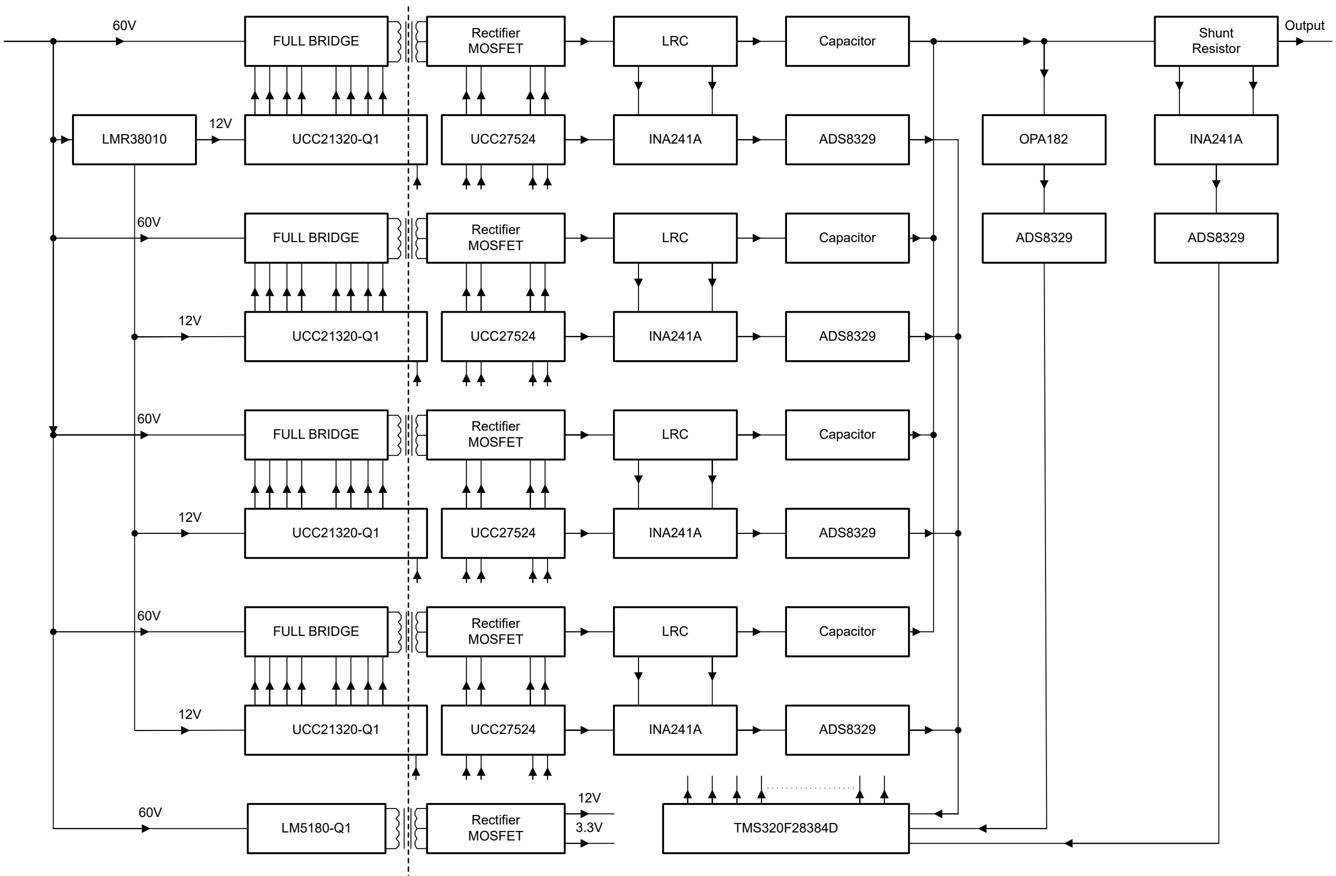

Figure 2-1. Phase Interleaving Phase Shifted Full-Bridge Power Supply Block Figure

3 Sub-System Description

3.1 Micro-Controller

In this design, TI proposes TMS320F28384D as digital micro-controller due to the powerful functionality and low cost. The main benefits as follows.

- Two TMS320C28x 32-bit CPU-core and one Arm Cortex-M4 processor can meet real-time control requirements
- Abundant interface and connectivity to ease engineer design and potential communication application
- Enough internal flash and RAM can meet most system requirements
- 32 PWM (Pulse Width Modulator) channels to meet most of the MOSFET drive requirements
- Four 16-bit,1.1 MSPS ADCs with 12 differential or 24 single-ended inputs. The ADC can also be configured to 12-bit/3.5 MSPS/24 channel. This ADC can be used to monitor current flowing through the full bridge
- Other interfaces: 4-SPI, 4 UART, 2 IIC, Ethernet, USB2.0

TI also provides digital power supply libraries or demo code to support customers to quickly develop their system. *Phase-Shifted Full Bridge DC/DC Power Converter Design Guide* discusses the digital phase shifted full bridge DC-DC power-converter design with TI DSP.

3.2 Auxiliary Power Supply

The LM5180 is a primary-side regulated (PSR) fly-back converter with high efficiency over a wide input voltage range of 4.5V to 65V. The isolated output voltage is sampled from the primary-side fly-back voltage, eliminating the need for an optocoupler, voltage reference, or third winding from the transformer for output voltage regulation. LM5180 integrates many other functions for an isolated power supply such as soft start, Input UVLO and thermal shutdown protection, Hiccup-mode overcurrent fault protection, Internal loop compensation, Soft switching avoids diode reverse recovery and low EMI.

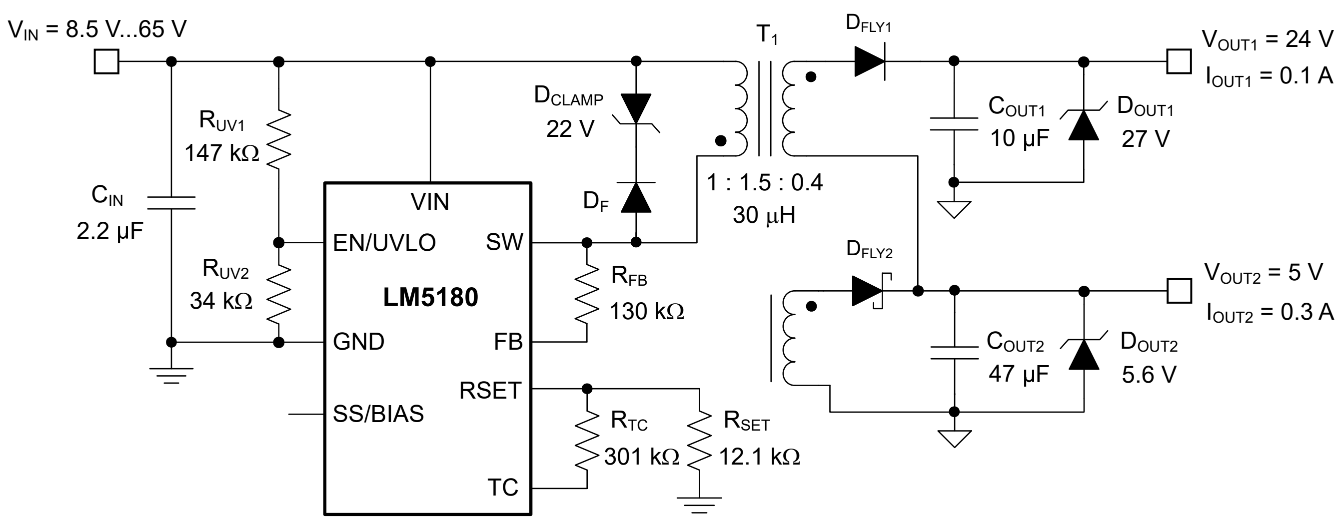

Figure 3-1. Power Supply for System

LM5180 can be used in this system for power supply TMS320C28384D and associated supporting circuits such as MOSFET driver. The output voltage can be setup by Equation 2. NPS is the turn ratio between primary side and secondary side. VD is the drop voltage of rectifier diode, VOUT is output voltage, RSET is 12.1k and VREF is 1.21V according data sheet.

$$R_{FB} = (V_{out} + V_D) \times N_{PS} \times \frac{R_{SET}}{V_{REF}} = \frac{(V_{out} + V_D) \times N_{PS}}{0.1mA} \quad (2)$$

3.3 Current Sensing

To balance the current between each phase, a high-precise current sensing amplifier INA241 can be used in this proposed design. The INA241 is an ultra-precise, bidirectional current sense amplifier that can measure voltage drops across shunt resistors over a wide common-mode range from –5 approximately 110V, independent of the supply voltage. The high-precision current measurement is achieved through a combination of low offset voltage (±10μV, maximum), ultra-low gain error (±0.01%, maximum) and a high DC CMRR (typical 166dB). The INA241 is designed for high voltage, bidirectional measurements in switching systems that see large common-mode voltage transients at the device's inputs. The enhanced PWM rejection circuitry inside the INA241 to make sure the minimal signal disturbance at the output due to the common-mode voltage transitions at the input. The INA241 is available in five gain options: 10V/V, 20V/V, 50V/V, 100V/V, and 200V/V. Multiple gain options allow for optimization between available shunt resistor values and wide output dynamic range requirements.

For reducing the cost, customers can use the resistance of the inductor to monitor the current of each phase. The ripple voltage of the inductor is a high-frequency alternative voltage and the average value equals 0V, but the direct voltage indicates the current through the inductor. So, a low pass filter can be used to filter the AC component and get DC current for the controller to monitor and adjust the phase current equally. The detailed circuit as shown in Figure 3-2. The current can easily be obtained by Equation 3.

$$I = \frac{V_{CS}}{R_{DCR}} \tag{3}$$

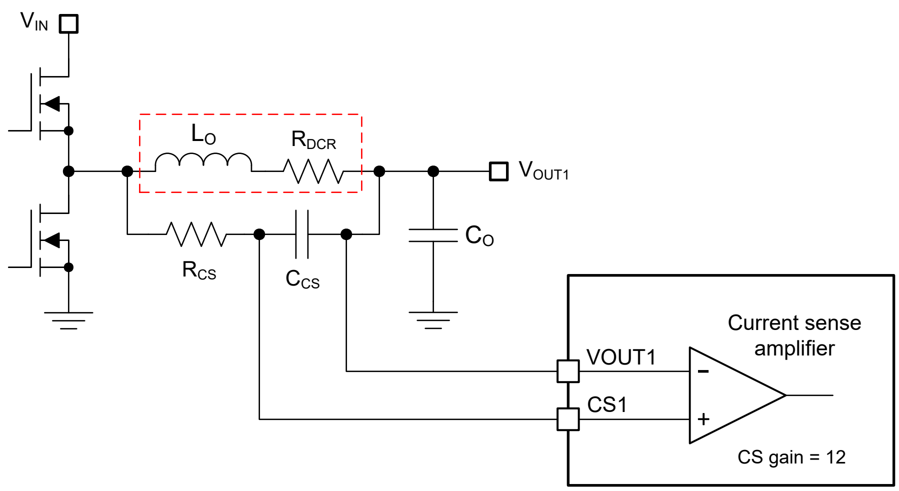

Figure 3-2. Phase Current Monitor Circuit

3.4 ADC Interface

The output voltage to drive superconductor coils generally in range of 0 approximately 10V. for get 0.1% precision, the resolution of ADC can be better than 5mV in worst case for a 5V full range ADC. The output data can vary 66 for a 16-bit ADC with 5V full input range if input voltage vary 5mV. This is designed to meet 0.1% precision requirement. A single end input ADC was proposed in here since full differential ADC driver has DC-bias error. The large current capacity MOSFET has slow switch time than small capacity MOSFET, so the switching frequency in this specific application less than 300KHz in generally. Then a 1MHz sampling ADC is fitted for this application.

ADS8329 is a low-power, 16-bit, 1-MSPS analog-to-digital converter (ADC) with a unipolar input and excellent DC performance. The ±1 dB INL allows customers to monitor DC output voltage with high precision. The device includes a 16-bit capacitor-based SAR ADC with inherent sample-and-hold and uses an external reference. This allows customers to use external precise references and get better precision. The SPI of ADS8329 can be implemented with a daisy chain to save SPI. Refer Figure 3-3. Thus 4 SPI of TMS320F28384D is designed to drive 6 ADS8329.

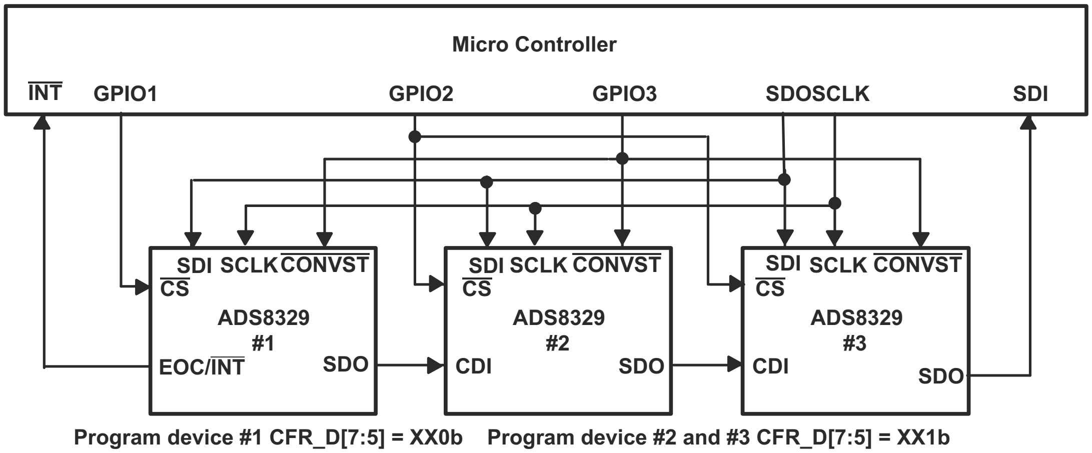

Figure 3-3. Multiple Converters Connected Using Daisy Chain Mode

A resistor divider potential need adopted since the maximum output voltage is 10V and beyond ADC full input range. Then a buffer has to be inserted to drive ADC. OPA182 is an ultra-high precision amplifier with zero-drift: 0.003μV/°C and ultra-low offset voltage: 4μV (maximum). This helps in keeping the controller to monitor output voltage with high-precision. The high-output current is also designed to drive the ADC directly and reduce the cost.

3.5 MOSFET Driver

Since the controller is on the secondary side and the system needs isolation from the primary side for safety, an isolated MOSFET driver UCC21320 can be used for this application. The specifications like 3.75kVRMS isolated voltage and 4A /6A source or sink current capacity makes UCC21320 designed for fit for this application. The typical circuit for UCC21320 is also shown in Figure 3-4. For detailed information, please refer to the data sheet of UCC21320.

For improving the converter efficiency and mitigating thermal issues, a synchronous rectifier was proposed in this application. UCC27524 was proposed to drive a rectifier MOSFET in the secondary side. ±5A sourcing and sink current capacity plus digital controller makes UCC27524 a good design for this application.

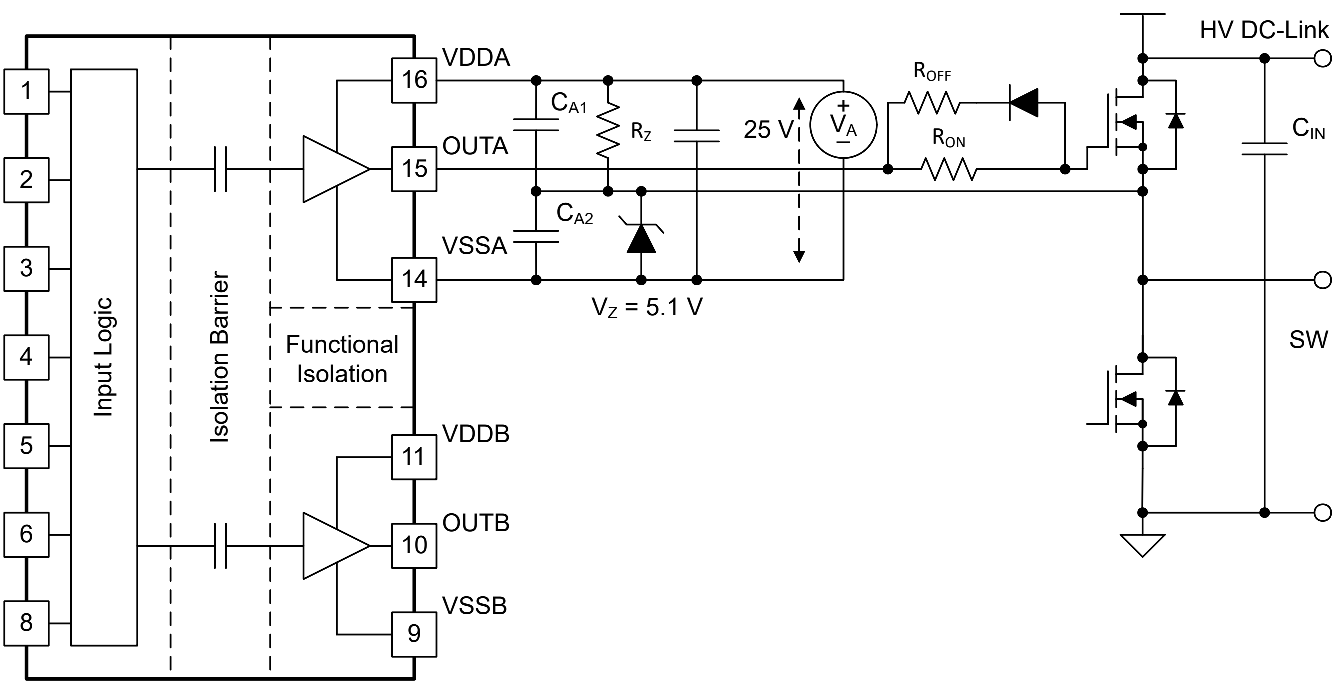

Figure 3-4. Typical Application Schematic

4 Summary

The proposed design was adopted by customers in their project and potential to meet the requirements for exciting the superconductor coil in the MRI system to produce a static magnetic field. The design solves all the challenges that were mentioned aforementioned in this document. In lower cost designs, designers can also scale this design to meet their specific requirements such as update 4-phase to 2-phase and simplify the controller method or algorithm.

5 References

1. Journal of Instrumentation, *The design and development of DAB DC- DC converter for HF MRI superconducting magnet power supply* T. Dai, F. Wang, S. Xue, P. Gao, Z. Zhang, J. Qin, C. Zhou and J. Li.
2. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, *The design of power supply for HF MRI superconducting magnet*,Tianli Dai, Chao Zhou, Jinggang Qin, Lican He, Jiangang Li
3. International Symposium on Power Electronics, *High-current low-voltage power supplies for superconducting magnets*, E. Coulinge, J. -P. Burnet and D. Dujic,
4. Peking University Press,*Magnetic Resonance Imaging Equipment and Technology* 2Hongbin Han016,
5. China Science Publishing Press, *Magnetic Resonance imaging: Principles, structures and design*, Donglin Zu.