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Project Proposal: Embedded Control of Transformer-Rectifier Flux Pump

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Abstract

Flux pumps are devices used to wirelessly power High-Temperature Superconductor (HTS) electromagnets, which are useful for creating very strong magnetic fields. Robinson Research is a superconductor lab based in Lower Hutt that is currently working on commercializing flux pumps that they've developed. As part of this, they want to move away from using large external power supplies and code running on PCs to drive and control these flux pumps. This will be done by developing an embedded system that can drive and control a transformer-rectifier flux pump. A GaN inverter will be used to produce the waveforms needed to pump the current. This will be controlled using a C2000 microcontroller. The embedded system that is developed will be compared to the preexisting non-embedded system. It can be evaluated by considering characteristics desirable for power supplies, such as high efficiency and low noise.

1 Introduction

Flux pumps are superconducting power supplies that can generate very large currents wirelessly. Robinson is a global leader in flux pump research, especially transformer-rectifier flux pumps. A goal of theirs is to commercialize the flux pumps that they develop. Transformer-rectifier flux pumps need three separate waveforms, that drive a transformer and two electromagnets [1]. This is currently provided using a rack of three large power supplies controlled by code running on a PC. This is unwieldy and expensive, and they want to move away from this in the commercial product they are developing. Instead, an embedded system needs to be developed that provides the high-power waveforms and control logic in a much smaller package.

The transformer and electromagnets will be driven by a three-output GaN inverter controlled by a Texas Instruments C2000 board. The C2000 will be programmed using PLECS, a power electronics simulator and programming tool. Once the system to control the flux pump is designed, it can be evaluated by comparing it to the non-embedded system that Robinson currently uses for driving flux pumps.

2 The Problem

Currently, for controlling flux pumps, Robinson uses a rack of three room-temperature kiloampere power supplies. This is unwieldy, and it would be much more convenient to have a small, self-contained control mechanism. This also would be desirable for Robinson's goal of commercialization, as flux pumps have broad applications in fusion energy, electric aircraft, and magnet technology.

This project aims to implement and evaluate a system for controlling a transformer-rectifier flux pump using a microcontroller. This system should enable the flux pump to pump current without needing multiple external power supplies or a PC to control it.

3 Proposed Solution

Due to others in the organization using it, the system will be implemented using a Texas Instruments C2000 real-time microcontroller. A transformer-rectifier flux pump requires three high-current signals acting in sync to control it - one powering a transformer, and two controlling the rectification. A three-phase inverter daughter board (BoostXL GaN) can be controlled by the C2000 using PWM, and this will provide power to the flux pump. The system will be programmed in PLECS, software designed for simulating and designing power electronics systems that can also program C2000 boards.

The tools and specifications have been provided by Robinson, now they must be turned into a functional system. The plan for doing this, and the timescale, is as follows.

1. Get familiar with using the C2000 microcontroller, the 3-phase inverter daughter board, and the PLECS programming environment. I'll do so by trying to get a small 3-phase AC motor to spin - this ensures I know how to get a specific output from the inverter. Two weeks.

2. Drive high-inductance loads using just one channel of the board - ensure it can work with asymmetric outputs. Hour or so.

3. Optimise the output signal, focusing on low noise in a current supplied to an inductor. This may include designing a power supply. Four weeks.
4. Operate the inverter's three outputs individually, with different amplitudes and signal shapes. Also, ensure the timing of the outputs is synced to the same clock, and they can stay in phase indefinitely. One week.
5. Do the above but with three different inductances on each output. One week.
6. Drive an HTS secondary loop using a transformer, and sense the current and voltage of the loop to check the signal transfer. Two weeks.
7. Drive an electromagnet (to be used in rectification) and sense the magnetic field across the air gap to check this is behaving as expected. Two weeks.
8. Run two switches and transformers at the same time. One week.
9. Drive a superconducting transformer rectifier flux pump. One week.

With the completion of the tasks above, an embedded system for driving a transformer-rectifier flux pump will have been developed. Robinson has also indicated other tasks that would be desirable to accomplish if everything above is done earlier than expected.

1. Create a SPICE model of the system, using a PWM block connected to a transformer with a superconductor coil on the secondary loop. This would help gain an understanding of the system.
2. Do the above with a simple ohmic (non-superconducting) half-wave rectifier in the secondary circuit.
3. Design a GaN driver board in KiCad or similar based on the TI BoostXL that could replace it.
4. Get the board made, and test it with the same inductors to compare the performance.
5. Design a board that includes a C2000 chip and PWM unit to control this inverter board, to move away from using the evaluation board currently being used.

The literature related to the project is also important. Early on and throughout the experimental part of the project, literature will be read and reviewed.

1. Using PWM to drive inductors/transformers.
2. Transformer design for switched-mode power supplies.
3. Signal smoothing considerations.
4. Ohmic transformer-rectifier systems.
5. Superconducting transformer-rectifiers.

4 Evaluating your Solution

Robinson has an existing method for controlling a transformer-rectifier flux pump. The system I design can be compared to this, and evaluated on several desirable characteristics of a power supply. These include efficiency, low noise, and high maximum output. The system can also be evaluated on how compact it is, as this is why a new system is being designed.

5 Resourcing and Ethics

5.1 Hardware

All of the hardware needed for the project will be provided by Robinson. This includes:

- TI C2000 LaunchPad evaluation board.
- 3PhGaNInv daughter board.
- Benchtop laboratory power supply.
- Oscilloscope, at least three channels.
- Large inductors.
- A transformer.
- Two C-core electromagnets.
- Simple solid-core wire.
- Banana/croc cables.
- Wire strippers.
- Loop of HTS tape.

5.2 Software, Datasets and Models

- PLECS simulation platform for power electronic systems with C2000 programming addon. This will be used to design the program to be put on the C2000 board.
- KiCad with SPICE for modeling the system designed.

5.3 Space, Virtual Resources and Access

I will be doing the work at Robinson's Sydney Street site. They have provided a lab space and a desk. I'll also use a desk on CO239 for doing work at Kelburn.

5.4 Budget

All materials will be provided by Robinson. No need to purchase anything with the ENGR489 budget.

5.5 Ethics

There are no ethical considerations for this project.

5.6 Safety

- This project involves working with benchtop power supplies and microcontrollers, so standard safety procedures need to be taken for working with these.
- The flux pump will provide potentially thousands of amperes - Robinson has lots of experience working with very high currents and there are existing safety protocols to follow.

- The system will be tested using high-temperature superconductor, which operates submerged in liquid nitrogen. This is at 77K, so caution has to be taken when working with this. Robinson has cryogenic safety equipment to use, and I have been given training on safe use.

5.7 Intellectual Property

Robinson has provided an IP form which I have signed. Any intellectual property produced during this project will be assigned to Robinson to be used.

References

[1] Z. Wen, H. Zhang, and M. Mueller, "High temperature superconducting flux pumps for contactless energization," *Crystals*, vol. 12, no. 6, 2022, ISSN: 2073-4352. DOI: 10.3390/cryst12060766. [Online]. Available: https://www.mdpi.com/2073-4352/12/6/766.