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Preliminary study of pulsed powering

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ABSTRACT: The standard solution for powering the electronics of particle physics detectors is to supply direct current. In this report, we investigate several advantages of using a Pulsed Powering scheme. Pulsed Powering could achieve 2-wire, point-of-load voltage regulation over typical low voltage power cables. This could be a reliable and serviceable solution for point of load voltage regulation in the high radiation environment of the High Luminosity Large Hadron Collider. Pulsed Powering might also be exploited to provide an inexpensive solution for the elimination of voltage offsets among ATLAS Pixel Detector subsystems and offer new low mass techniques for distributing power to particle detectors.

KEYWORDS: Particle tracking detectors; Voltage distributions; Si microstrip and pad detectors

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1 Introduction

Charged particle tracking detectors, in particular those composed of silicon p-n junctions, play an important role in high energy particle physics experiments. Their primary role is in the identification of secondary vertices from the decay of particles having lifetimes of the order of a picosecond, for example particles composed of b quarks. Silicon charged particle *trackers* are composed of high resistivity silicon wafers that have either strip or pixel p-n geometries that allow the localization of charged particle trajectories on the order of micrometers.

Each silicon detector *module* is composed of both a sensor and *front-end electronics* that converts the sensor signals into signals that can be transmitted out of the high radiation *experiment hall* to a low radiation *service hall* containing the readout electronics. Because access to the experiment hall is very limited, the low voltage power supplies for the front-end electronics are installed in the service hall, which can require cable lengths of up to 100 m. In this report, we propose supplying the power to the front-end electronics using time varying currents, which we call “*Pulsed Powering*”, instead of using dc power. By exploiting the ac characteristics of the power distribution system, it may be possible to place the complex and less reliable voltage regulation circuitry in the service hall, which is normally accessible in case an intervention is required. The experiment hall is not accessible when the experiment is running. Within the detector, itself, access may never be available during its lifetime. Furthermore, we argue from an engineering perspective that the innate simplicity of dc powering of particle physics detector front-end electronics comes at too high a price, compared to the features of Pulsed Powering. We will suggest several areas in which the use of Pulsed Powering techniques could increase reliability and serviceability while simultaneously reducing costs.

This study examines the potential for Pulsed Powering techniques to provide capabilities for current and future particle detectors, including the planned upgrades to ATLAS [1] and CMS,

which are designed to fully exploit the discovery potential of the High Luminosity Large Hadron Collider (HL-LHC).

2 Pulsed powering

Pulsed Powering is defined as a train of voltage pulses delivered over a power distribution system that allows dc current to flow, as well. The dc value into the input of the power distribution system, is the average value of a pulse train. This allows the system designer to exploit the ac characteristics of the system, including the cable. The pulse integration takes place at the load at the end of the cable, i.e., at a module's front-end electronics without need of a rectifier. The signal at both ends of a typical power cable is shown in figure 1a, which demonstrates one type of Pulsed Powering signal, a half-wave rectified sine wave. The capability to read the integrated dc value across the load from the input, between pulses, gives rise to the idea described in subsection 2.1, remote point of load regulation and power delivery over two wires. In the second example of Pulsed Powering, subsection 2.2, the properties of resonant inductive coupling are described, which is a type of air core transformer circuit that could provide efficient coupling to allow isolated, ac regulation of multiple modules. The final subsection 2.3 describes a specific application of Pulsed Powering, which is to achieve electrical isolation between ATLAS Pixel Detector module front-end electronics power supply channels without the need to rewrite any of the existing power supply control or monitoring code.

In each of the three applications, it is assumed that an integrating capacitor is connected electrically near, i.e., $R < 0.1$ Ohm, and across the load at the end of the cable in figure 2b. The required size of the integrating capacitor can be greatly reduced by choosing a proportionately higher frequency. Space and material are both highly constrained in silicon trackers.

2.1 Remote point of load regulation using two wires

The input current consumed by the front-end electronics varies roughly by a factor of 20 over the full range of operating conditions from standby to maximum data processing speed. Because of the IR voltage drop in the cable(s), the power supply voltage required to deliver the nominal operating voltage to the front-end electronics, while operating at maximum current, can be higher than the maximum the electronics can safely handle. Therefore, in order to avoid damage to the electronics, local (close to the electronics) voltage regulation or voltage limiting is required. The distance between the local regulators and the front-end electronics is approximately 11 m in the present ATLAS Pixel Detector [2]. The design of regulation systems must protect against a short circuit from the input to the output of the regulator in order to avoid the application of damaging voltages across the front-end electronics. The risk of damaging shorts can be significantly reduced or even eliminated by exploiting the ability to measure the voltage across the load during intervals between power pulses when there is no current in the cable(s) figure 1a. During these zero current intervals, the two wires of the power circuit are available to act as voltmeter leads, allowing an accurate sample of the voltage across the load through the cable(s). Since the exact voltage across the load can be periodically sampled over the same two wires that deliver power to the front-end electronics, it may be possible to eliminate the need for a local regulator in the experiment hall or detector by performing the regulation from the service hall. Furthermore, since the voltage sent

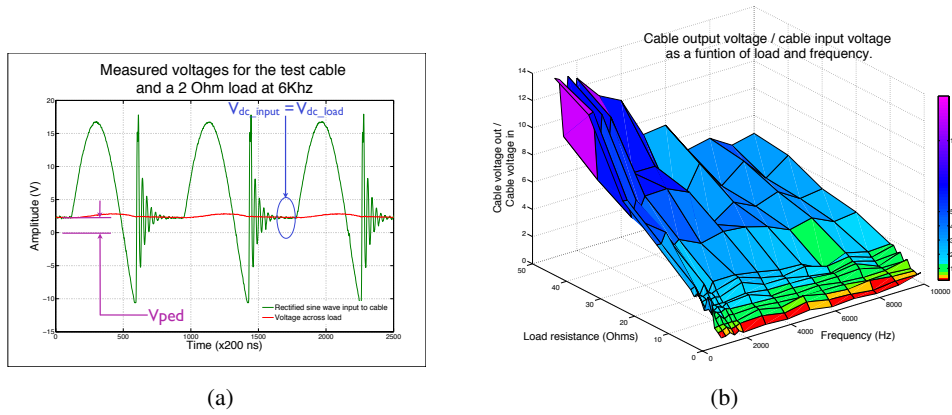


Figure 1: (a) The cable input signal (green) and voltage across the load (red) for the test setup described in figure 2 is shown. The measured voltage at the input includes the dc output voltage, by superposition. Note that the measured input and output voltages are equal during the period wherein there is no drive voltage at the input of the cable (blue oval). (b) The ratio of the dc output voltage over the (rms - dc) input voltage, as a function of load resistance and frequency for the same test setup. The green regions indicate a range of values over which the ratio is approximately one.

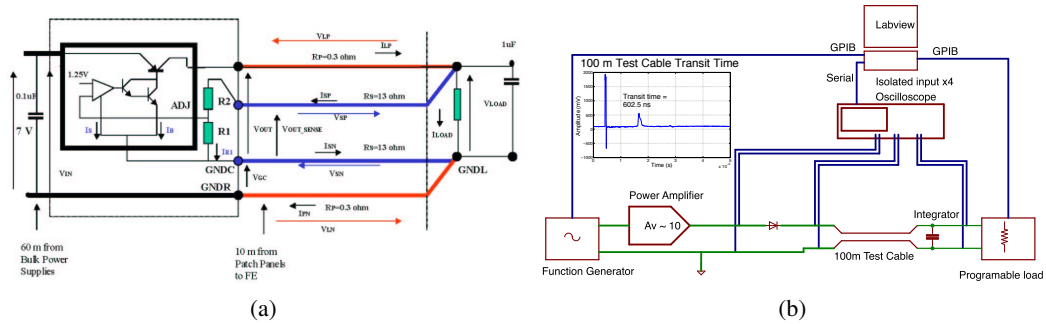


Figure 2: (a) A 4-wire regulator circuit, wherein the voltage between the sense and sense return wires (inner loop on the right) is compared to a 1.25 V precision reference and the error is corrected in the voltage sent to the load. By inspection, one can determine that a break in the sense circuit would cause the regulator output voltage to rise to the value at its input, possibly damaging sensitive front-end electronics at the load. (b) The test setup for a 100 m sample of ATLAS Pixel digital power, including the time response of the sample.

from the power supply in the service hall is based on the instantaneous current required for the front-end electronics, the voltage across the integrating capacitor at the load should never exceed the nominal operating voltage, that is, the system is inherently fail safe, unlike the familiar 4-wire, linear voltage regulator circuit of figure 2a. In addition, the integrating capacitor required for Pulsed Powering provides buffering against sudden voltage fluctuations across the front-end electronics, providing a time buffer in which the regulator safety circuits could respond to a catastrophic circuit failure that could send a damaging voltage to the front-end electronics. One unfortunate limitation

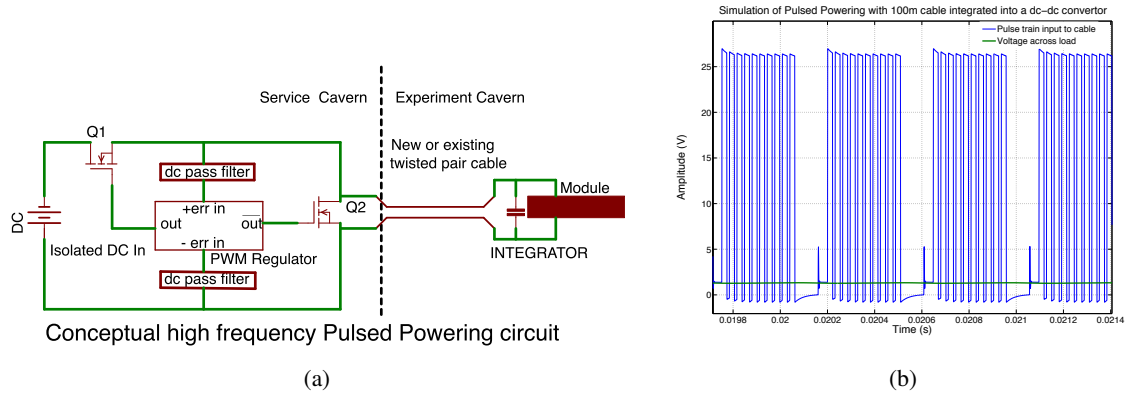


Figure 3: (a) The circuit depicts a Pulse Width Modulated (PWM) regulator in which the reactance of the cable and its signal transit time are exploited to maximize the transfer of energy at about 800 kHz. Q1 is either cutoff or saturated, inversely to Q2, which can operate in three states: cut off, saturated or 100 Ohm resistance to damp oscillations when Q1 cuts off. (b) Simulated trace of the circuit.

to point of load regulation over two wires described above is the maximum current that can be accommodated by the available services cross sectional area through a detector, just as for dc powering. For a 100 m length of the (AWG14x2)x7 ATLAS Pixel cable used for delivery of digital power, the maximum practical current is about 2A per circuit because of I^2R heating and limits on how much heat can be removed from any detector subsystem. For higher load currents, it is necessary to transmit an acceptably low current through the long cable and step up the current by using a transformer or dc-dc converter as close to the front-end electronics as practical.

Whenever the frequency of the powering pulses are tuned to the natural resonance of the system, i.e., the frequency corresponding to the round trip transit time of the cable(s), (about $1.2 \mu\text{s}$ for the test sample of figures 1a and 2b), extra measures must be taken to damp the ringing long enough to sample the voltage across the load. By switching the pulse source out of the circuit while simultaneously switching a load across the input to the cable for the period of about 10 cycles, as in figure 3, it is possible to sample the voltage across the load before the load voltage sags below 10% (or less) of nominal and the pulse source must be switched back in. The potential benefit of maintaining the capability to provide remote point of load regulation at high frequencies will become apparent in the subsection 2.2.

2.2 Resonant inductive coupling

As mentioned in the previous section, module currents above about 2A require transformers or dc-dc converters at the load. However, there are several strict requirements for trackers that become more severe as the sensor position becomes closer to the beam line. There is very little space, with layers of modules becoming only millimeters apart. The experiment is increasingly sensitive to mass near the beam line, too, with increased mass being roughly equivalent to increased noise in the experiment results. There is also an intense magnetic field of up to 2 T in present trackers, which severely restricts the use of magnetic materials. Most trackers exist in a sealed envelope,

with a controlled gas environment. All subsystems in modern detectors must be thermally neutral, meaning heat must be removed. Implementing the transformer circuit using resonant inductive coupling could address all the above concerns.

Resonant inductive coupling is implemented by adding a capacitance to an inductor circuit such that the frequency of resonance, which is inversely proportional to \sqrt{LC} , is equal in all circuits of the system. If two or more inductors are magnetically coupled, they act as a transformer. The fraction of the primary field lines that are coupled to the secondary inductor(s) is referred to as the coupling coefficient of the transformer and scales how efficiently power is transferred from the primary inductor to the secondary inductor(s). The coupling coefficient in resonant inductively coupled systems is typically < 0.5 and can go below 0.01 in some applications, which is called *loose* coupling. Loose coupling facilitates resonance in a circuit by nature of its narrow bandwidth.

In practical resonant inductive coupling, a secondary circuit presents a very low impedance to energy transfer from the primary, overcoming the losses normally associated with loosely coupled inductors. Further, when a pulse energizes the primary coil, it will ring for many cycles if there is no load to carry away the energy. As long as more energy is absorbed by the secondary coil(s) during each "ring" than is lost to heat and radiation, efficient energy transfer can be achieved - very near unity if the inductors are within a coil diameter or two of each other. When the coils are less than 1/4 wavelength apart, there is very little radiative loss of the power signal. Resonant inductive coupling systems are usually tuned to frequencies above 20 kHz, motivating the use of air core transformers to avoid high power losses in the magnetic core.

A resonant inductively coupled system is still a form of isolation transformer, as described in any text on basic electronics. As such, it steps the voltage and current up and down proportionately to the ratio of the number of turns between the primary and a secondary coil. Given the conditions described in this section for implementing an efficient resonant inductive coupling system, the transformer regulation, defined as the ratio of the secondary circuit potential at maximum load to its no load potential voltage, can be within a tenth of a volt or less across the load, which is adequate for most modern front-end electronics circuits and allows one to provide point of load regulation for multiple, isolated secondaries through a single primary coil supplied by a regulated voltage.

For Pulsed Powering applications incorporating resonant inductive coupling, a single primary coil can drive any number of secondary coils that can be accommodated within about two coil diameters at an efficiency $> 90\%$. Air core transformers can also operate just as efficiently through gas barriers made of magnetically neutral material as through air. Combining the characteristics of resonant inductive coupling with the application of Pulsed Powering described in the previous section yields a power distribution system with the potential to provide isolation between load circuits, remote, point of load regulation from an accessible location, with reduced mass in the detector and no requirement for physical penetration of detector gas barriers and a circuit which is inherently fail safe.

2.3 Isolation

For reasons of preventative maintenance, the ATLAS Pixel collaboration undertook to rebuild the mechanical structures and wiring that bring services into the detector modules and route the data/control links into and out of the detector. One goal was to move the 272 circuit boards containing the optical communication links out of the Pixel Detector and into an area where they can

be accessed for replacement. In the process of verifying the new design, it was discovered that communication through this chip to the existing Pixel front-end electronics could be interrupted. The problem was traced back to parasitic current sharing that arises from certain fault conditions, cable resistances, the difference in input offset operating voltage ranges between the mixed technologies and in the details of the Pixel grounding and powering schemes. Presently, one power supply channel is shared among 6 to 7 Pixel modules. Fortunately, communication is not lost if each power supply to each module is isolated from all others. This prevents parasitic currents from entering the neighboring channel's digital power return wire whenever a module is switched off, thereby eliminating the shared current return paths to the power supplies.

For the limited application of Pulsed Powering to achieve isolation between front-end channels, the advantages over dc powering primarily arise from the use of high frequency pulses, eliminating the need for bulky transformers and filters. It might also be possible to tune the system so that the input voltage to the cable is the same as at the end of the cable, in figure 1b, thus reducing the risk arising from a shorted regulator. The existing, regulated power supplies could be used to drive resonantly coupled circuits to supply an isolated, regulated voltage to each module.

Application of Pulsed Powering to provide isolation is dependent on the filtering capacity of the installed local regulator of the ATLAS Pixel Detector. Tests have been prepared to qualify the suitability of Pulsed Powering for isolation of the Pixel Detector on a functional copy of the Pixel front-end electronics power distribution system, including the local regulators and a Pixel module.

3 Challenges for pulsed powering system design

A important feature of Pulsed Powering is that although the base frequencies of interest may fall outside the domain where a particular cable "acts like a transmission line", the rise and fall times of the pulses are relevant to power system performance. Whenever the switching times are fast enough to interact with the cable reactances, it can lead to power loss and equipment damage from ringing. This is one reason why it is helpful to have accurate, well behaved simulation models. Simulations of a typical tracker power cable were compared to measurements of a sample of the real cable. As shown in figure 4, the simulations are only accurate and convergent for a single frequency (this is a well documented shortcoming of the model used in the simulations [3]).

Better models and/or methods of simulation must be found in order to make Pulsed Powering system design efficient and cost effective. The push in recent years for the test equipment, simulators and tools generally used for transmission line design has been toward multi-GHz applications. Because of the large wire gauges generally required for power delivery, most frequencies of interest in Pulsed Powering fall below 1MHz. We have begun exploring the use of various techniques and products to provide improved modeling and simulation.

4 Conclusions

The cost to develop and manufacture the specialized voltage regulation circuits that must operate for 10 years within the high radiation environment of the HL-LHC is much higher than for similar development using off-the-shelf components for Pulsed Powering, for which there are suitably radiation tolerant components for producing a low loss rectifier and for the capacitive integration

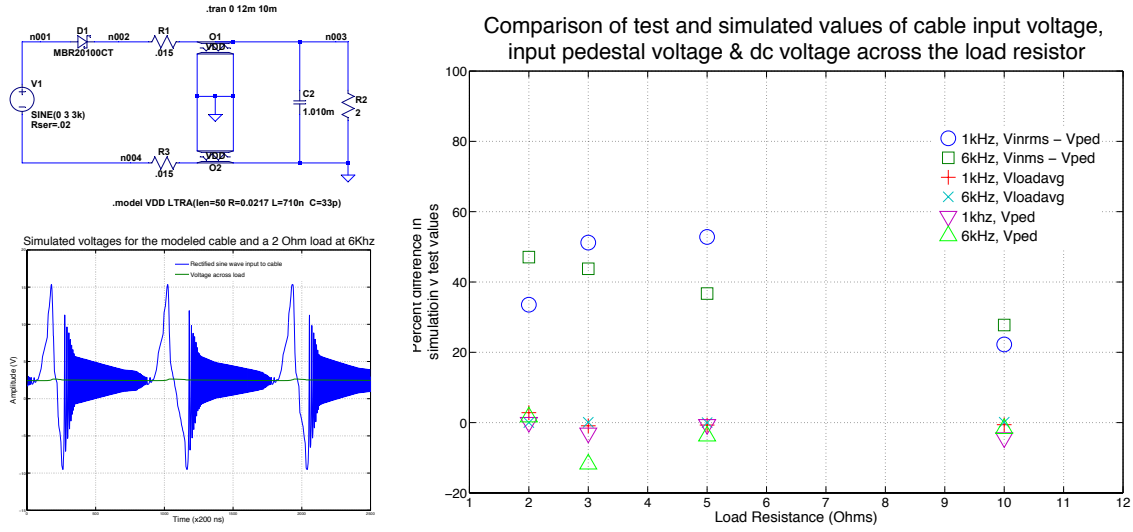


Figure 4: Left: Simulation circuit and results for the same frequency and load as in figure 2. Right: Comparison, as a percent age difference, between measured and simulated results.

required for Pulsed Powering applications. Additionally, Pulsed Powering might allow the reuse of components of the existing detector cable plants, where other considerations don't require their removal, by keeping the maximum current in them to their design values with the use of transformers near to the loads ($I_{\max} R_{\text{cable}} < 0.1\text{V}$) to allow point of load regulation over the same two wires that deliver the power. One not only saves the money otherwise spent for new cables but also avoids the costly removal, handling and disposal of radioactive material [4]. The resonant inductive coupling application of Pulsed Powering can allow power transfer across gas barriers without penetration, as well as providing the needed current step down in the cable plant for upgrade detector electronics.

Of course, it remains to be shown that Pulsed Powering systems that meet the demands of particle detector systems can be designed and built. It is always challenging to design robust voltage regulators. The transit time and small sample time will only complicate the design of two-wire point of load regulation. Similarly, the application of resonant inductive coupling techniques to our systems also needs to be shown to be reliable, safe and compatible with the sensitive front-end electronics of neighboring sub-detectors, as well as the detector being powered.

5 Future plans

In the near term, we hope to complete validation of isolation of the front-end electronics power supply channels of the ATLAS Pixel Detector modules, as described in section 3. We also plan to integrate the equations which describe transmission line behavior into simulation tools in hopes of improving the accuracy of simulations, as compared to bench tests. The next step in bench testing is to construct a pulse amplifier capable of driving loads down to $0.5\ \Omega$. The test system should also be improved with a programmable load, current probes and oscilloscope capable of operating up to 1 MHz. Those improvements would allow us the opportunity to confirm the engineering principles

for inclusion of Pulsed Powering in particle detector system designs, as well as verify simulation models needed for efficient design.

Acknowledgments

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