An Improved Method of Regulating a High Voltage Power Supply for use in Oil Well Logging Applications

by

Prashun R. Patel

Submitted to the Department of
Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the
Degrees of

Bachelor of Science
and
Master of Science in Electrical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1994

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Abstract

Certain functions performed by well logging tools employ brushless dc motors requiring a power supply capable of delivering 50 volts dc (±10%), at up to 20 Amps. The impedance of the system is large enough that supply load changes adversely affect the voltage. To regulate the supply, the voltage of the output is sampled by a dedicated board. This value is transmitted to the surface along with other telemetry data acquired by the tool. A surface acquisition system compares the value to a reference and appropriately adjusts the surface generator. The acquisition system is ill-suited for real time control and has performed poorly in field operation. The goal of this study was to characterize the existing system electrically, to develop a better method of regulation, and to demonstrate the performance gains over the existing system.

Experiments were conducted to characterize the components of the power delivery system. Several alternative methods of regulation were investigated. The proposed method offered the best balance between performance, cost, and feasibility.

A third order Least Squares relation is calculated prior to real time regulation which describes the relation between the surface current and the desired surface voltage which will yield 50 volts downhole. Real time control proceeds by monitoring the surface current at the head of the cable via a sensing resistor, computing the desired surface voltage from the calculated relation, and adjusting the generator with a hardware controller.

The performance of the system was demonstrated in a laboratory. An IBM PC was used as the controller. Communication with the supply generator was handled by a 1 MHz data acquisition card. The experimental system and the old system were compared at cable lengths between approximately 6,000 and 30,000 feet. While the proposed system offered no benefit in the maximum or minimum deviation of the supply voltage in response to load changes, it was successful in doubling the regulation speed of the voltage to acceptable levels (worst case). Other system bottlenecks were identified as targets for future improvement.

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Introduction

Background

Ever since its inception in 1925, the oil well data logging industry has seen rapid and remarkable growth. The original logging tools were only able to perform rudimentary electrical measurements. The main reason for this was the extreme conditions in the oil well hole. Modern oil wells may be as deep as 30,000 ft [1]. Transmitting signals over such distances was a challenge beyond initial oil field technology. In addition, the downhole temperatures can exceed 200°C with pressures of up to 15,000 psi[2]. Electronic equipment was simply not capable of withstanding such extreme conditions.

The introduction of electronics suitable for downhole use between 1945 and 1970 offered an increase in the accuracy of oil well logging tools. In addition, tools were able to perform more sophisticated acoustic and nuclear measurements of the oil well hole environment[3]. Today's oil well logging tools are capable of performing a wide variety of functions to provide a great deal of information about a oil well hole.

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[1]John Dewan, Essentials of Open-Hole Log Interpretation, (Tulsa: PennWell Publishing Co., 1983), p. 1.

[2]Ibid.

[3]Ibid., p. xii.

Modular Dynamics Formation Tester

The Modular Formation Dynamics Tester (MDT) is such a tool[4]. MDT is comprised of individual modules, each capable of performing a specific function such as measuring permeability, recovering samples of well hole fluid, or purging unwanted fluid from a sample. By combining modules, a custom tool can be built to provide exactly the information a client is interested in.

Power Requirements

Most motors in MDT require a "low voltage" supply, or a constant 5 v or 15 v supply. To perform some of its more ambitious tasks, such as pumping reservoir fluid, MDT employs brushless dc motors (e.g. hydraulic pump motors or dc motor driven seal valves) which require a 50 v , or "high voltage", dc supply. These motors, when operated simultaneously, are capable of drawing up to 20 A of current. Therefore, in addition to a low voltage supply, MDT requires a stable 50 v supply, capable of delivering up to 1 kW of power downhole. This power, supplied from the surface of the oil well, must be transmitted to the bottom of an oil well via an electrical logging cable. Oil well depths, and therefore logging cables, can vary in length

[4]Schlumberger Educational Services, MDT Modular Formation Dynamics Tester (Houston: Schlumberger Educational Services, 1992), pp. 1-2.

between 12,000 ft and 30,000 ft[5]. This makes supplying constant voltage difficult.

A "Lossy" Supply

Logging cables are essentially insulated copper conductors. Although copper is an excellent conductor, it posseses a finite resistance which can amount to a significant impedance at long cable lengths. For example, a 30,000 foot cable has a resistive impedance of approximately 120 Ω[6]. To minimize loss in the cable, power is transmitted at high voltage and low current. This power is then transformed downhole to provide the 20 A that the motors require at full load. At full load, approximately 4 A of current will be on the cable. The formula for power dissipation is:

$$\begin{aligned} P &= i^2 R \\ &= 4\text{A} \cdot 120\Omega \\ &= 1920 \text{ watts} \end{aligned}$$

Hence, almost 2000 W of power are lost in the cable. Loss along the cable can be compensated by transmitting excess power from the surface. This has been the chosen method for compensation to date.

A more difficult problem introduced by the cable impedance is the problem of regulation.

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[5]John Dewan, Essentials of Open-Hole Log Interpretation, (Tulsa: PennWell Publishing Co., 1983), p. 2.

[6]Pardue, George and Gollwitzer, Lee. "Cable Technology Review...Part I," Schlumberger Technical Review 20:4 (December 1972): 40.

The Problem of Regulation

When a motor turns on downhole, it causes more current to be drawn from the supply. This causes the current in the cable to increase, which increases the power dissipated in the cable. Because the voltage drop across the cable is proportional to the square root of the power dissipated in it, the voltage drop increases. However, in the absence of manual correction, the surface voltage remains constant, which means that the increase in voltage drop in the cable must be balanced by a decrease in the voltage across the downhole supply. In other words, when the downhole load increases, the supply voltage drops. Conversely, when motors turn off, the current decreases, the power lost in the cable drops, and the amount of surface voltage dropped across the cable decreases, which causes the supply voltage to surge.

Either of these situations is unacceptable. Prolonged low voltage will cause motors to stall, and the tool to "fail". High voltages stress the components in the tool, which decreases tool life. To avoid these sags and surges, the surface voltage must be adjusted up or down.

To date, the method of regulation has been to sample the downhole supply voltage and transmit it up the cable to a surface computer. The surface computer then compares this value to a 50 v reference, and issues commands to the surface generator to either increase or decrease the voltage. In many cases, there is no way to predict when motors will turn on or off. Hence, regulation must be reactive rather than predictive; the system must respond to changes instead of anticipating them and correcting ahead of time. The supply is specified to maintain the downhole voltage at 50 v , plus or minus

10%. The 10% tolerance is permissible because the dc motors can function well at slightly higher or lower than 50 v.

Unfortunately, the current system fails to meet this specification. Regulation simply happens too slowly in response to load change. Consequently, for large changes, the voltage sags or surges beyond the 10% tolerance limits, and remains out of the acceptable range for dangerously long periods of time before the uphole voltage is corrected.

Figure 0.1 shows a typical response of the downhole supply voltage to a load change from 11 to 511 W[7] with 22,525 ft of cable[8]. In this particular case, the voltage fell to 28.1 v before the system could respond. It took almost 2.1 s for the voltage to return to an acceptable level. Figure 0.2 shows a typical response of the voltage to a 511 to 11 W load change. In this case, the voltage reached a high of 86.3 v . The system took 1.5 s to correct. This slow performance is unacceptable. In the logging environment., load changes of 700 or 800 W are not uncommon, resulting in even larger deviations for longer durations than shown here.

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[7]The lightest load in an actual logging operation is 11 watts. The circuitry used to change the downhole loads for this experiment accounts for this.

[8]Individual cables of lengths 6025 ft and 16500 ft were connected to provide the total length of 22525 ft. Logging cables vary in length roughly between 6000 and 30000 feet. The delay introduced by the cable length is negligible compared to the overall delay of the system. Hence, the system performance at this cable length is indicative of performance at all other relevant cable lengths.

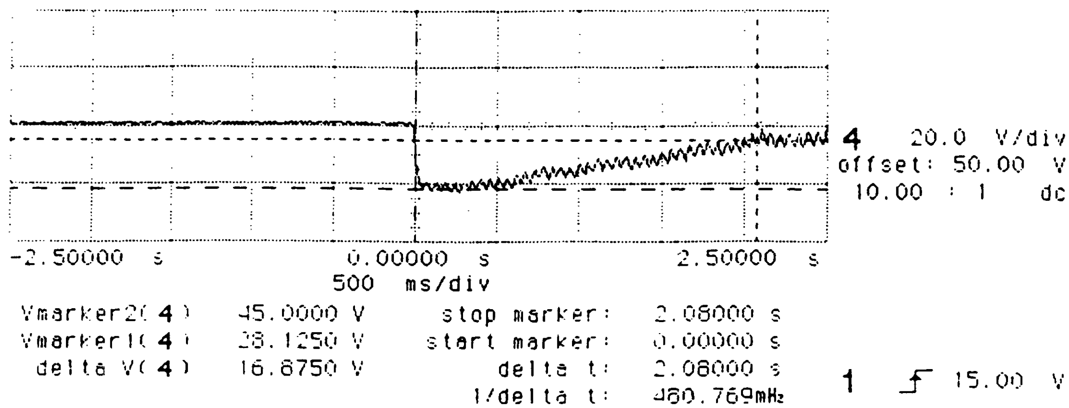

Figure 0.1: Response of downhole supply voltage to load change of 11 to 511 watts. (Cable length = 22525 ft.)

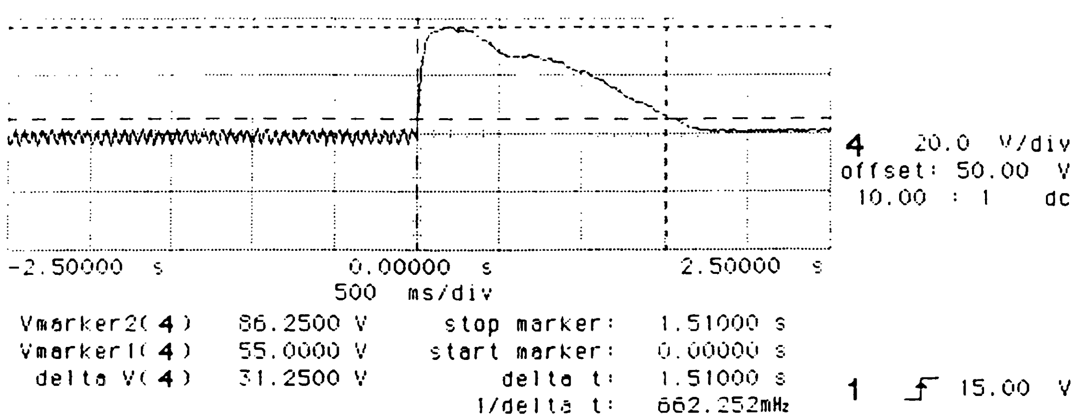

Figure 0.2: Response of downhole supply voltage to load change of 511 to 11 watts. (Cable length = 22525 ft.)

Scope of Study

This study will address the issue of regulating the high voltage power supply. The present system will be analyzed. The sources of delay in that system will be identified. Several alternatives to this method, aimed at improving regulation performance, will be explored. A superior method of regulation which balances performance and cost will be proposed. An experimental system will be designed to demonstrate the effectiveness of this proposed solution in a laboratory environment. Research was conducted entirely at Schlumberger Well Services between June 1, 1993 and January 1, 1994. This document embodies the results of that research.

Chapter 1 describes the system used to deliver power to the tool. The individual components that comprise the power system will each be examined.

Chapter 2 discusses the method used currently for regulating the high voltage supply. The bottlenecks, or aspects of the system where improvement is possible, will be identified. This will provide a starting point for formulating potential solutions.

Chapter 3 proposes several possible alternative regulation methods. It begins with a discussion of the selection metrics used in comparing the methods. The regulation techniques can be split into two broad categories: those that regulate from the surface and those that regulate from downhole. Block diagrams and descriptions of each method will be presented, as well as the benefits and drawbacks of each.

Chapter 4 discusses the best of the proposed solutions in detail. The theory behind the method, and data showing that it is feasible will be shown.

Chapter 5 describes the implementation of the method in a laboratory test system that was used to prove the effectiveness of the proposed solution. The hardware and software used in the test system will be discussed, as well as the experiments used to compare the performance of the old and new systems. Last, the relative performance of the new and old systems will be shown.

Chapter 6 presents the issues involved in preparing this solution for field use. A block diagram of the circuit board to be used in the actual system will be detailed. A description of the necessary modifications to the surface computer software will also be included.

Chapter 1

Power Delivery System

Figure 1.1 shows a block diagram of the system used for generating the high voltage power supply downhole. There are three main components to the system: a surface AC power generator, the transmission line or cable, and a downhole AC to DC converter. The salient features of each component will be discussed in this chapter. For a more detailed discussion of the circuit characteristics of these components, refer to Appendix A.

1.1 Surface Power Panel

A power panel is used at the surface of the well to generate the levels of power demanded by the tool. This panel converts a 115 v AC signal to a variable 0 to 900 v AC signal between 0 and 4 A. This level of surface power is necessary to compensate for loss in the cable, as will be shown in the next section.

The surface panel takes a 115 v AC line signal as input. This signal is connected to two parallel step-up variacs which convert this signal to a variable AC signal between 0 and 140 v at up to roughly 20 A. Two transformers are used to double the current capacity of the power panel. In addition, a single variac capable of handling such power would have exceeded the size constraints in the original panel design. The variable 0 to 140 v signal is then stepped up by a 1:6 transformer to a 0 to 900 v variable AC signal at up to 4 A. The step-up transformer allows the power to be transmitted at high voltage and low current, which reduces the necessary diameter of the logging cable conductors.

The variacs are connected together with a belt and driven by the output of a 6 v stepper motor. The stepper motor is software-controlled from a surface computer unit. The controller will be discussed in more detail in Chapter 2.

1.2 Logging Cable

The logging cable performs two essential tasks: transmitting power from the surface to the downhole tool, and transmitting logging data from downhole sensors to the surface for data acquisition[1]. Power to the tool is in the form of a low frequency, 60 Hz, analog wave form. Logging data, on the other hand, is transmitted upward digitally. Measurements made by individual tools are digitized into bits, which are serially sent upward at a rate of 100 kHz, where the data is stored by a surface computer unit.

There are several different types of logging cables. All cables contain seven parallel copper conductors. The differences between the types is due to the material and thickness of the insulation used between the conductors. For a more complete discussion of cable structure and circuit properties, refer to Appendix A.

[1] P. Theys, Log Data Acquisition and Quality Control, (Paris: Editions Technip, 1991), pp. 160-166.

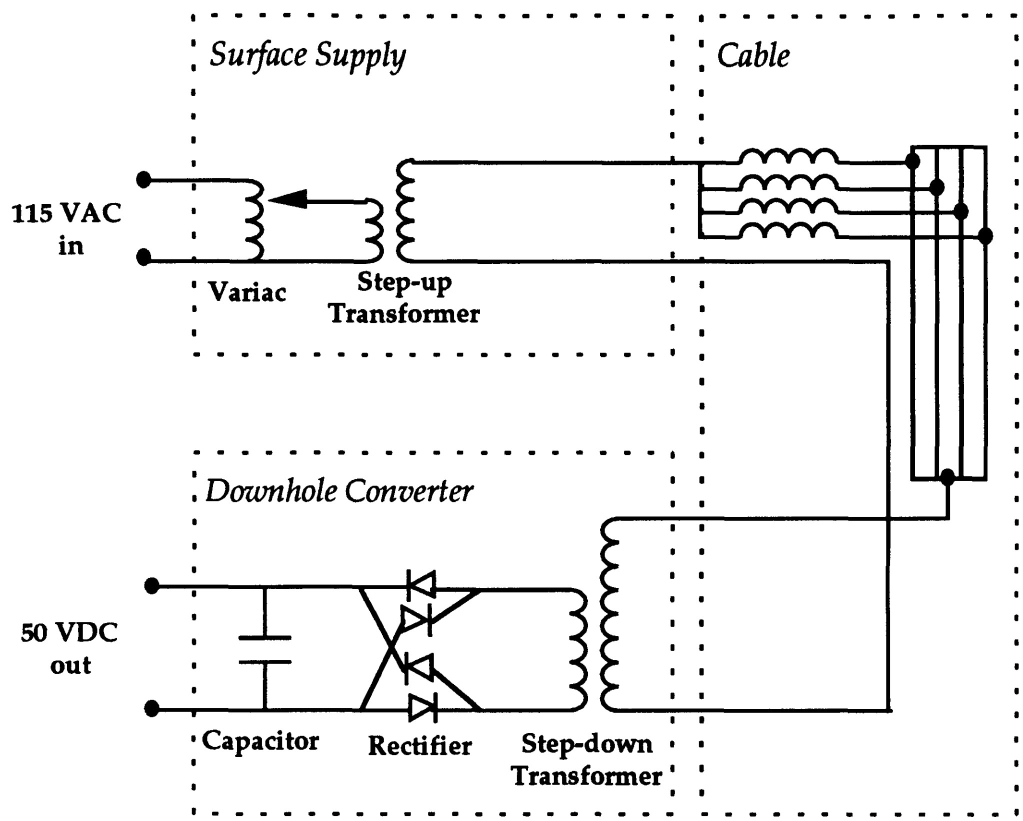

Figure 1.1: Block Diagram of Power System

Conductors 1 and 4 are used to transmit low voltage power to the tool. Conductor 1 serves as the voltage signal, and 4 serves as the return. Conductor 7 is used to detect breaks or damage in the cable. Conductors 2, 3, 5, and 6 are used for high voltage power transmission as well as telemetry transmission. The armor sheath enclosing the cable is used as the signal ground.

The digital telemetry contains frequency components in the kilohertz range or higher. The downhole AC/DC converter introduces a degree of non-linearity which adds frequency components to the 60 Hz power signal.

However, the signals are far enough out of range of one another that frequency multiplexing on the same line is possible.

Although the copper used in the conductors conducts excellently, it has a finite resistance of .0109 Ω/ft. The armor of the cable has a resistance of .00125 Ω/ft. These can cause significant loss over thousands of feet. Sending the power over four conductors in parallel reduces the effective resistance, which reduces the amount of power dissipated along the cable. At 30,000 ft, the power signal faces a total resistance of up approximately 120 Ω. At 4 A, this amounts to a loss of almost 2 kW. This loss is compensated for by simply generating excess power at the surface.

The signal from the power panel is split into four conductors inside a separate module, the "Tool Module" between the power panel and the cable. Four inductors serve as a filter to pass only low frequency signals onto the cable. This is necessary to prevent interference with the high frequency telemetry signals also on the cable.

The signals from conductors 2,3,5 and 6 are combined at the bottom and transformed to DC power, usable by the motors in the tool.

1.3 Downhole Converter

The signal at the bottom of the cable is roughly 400 v, AC. In the converter, it is first stepped down by two parallel 8:1 transformers. Again, a parallel configuration is used to double the current carrying capacity of the converter. An equivalent single transformer would have required space exceeding the original size specifications of the converter.

After the voltage is stepped down it travels through a full-wave bridge rectifier circuit, which converts the AC signal to one of constantly positive polarity. A capacitive filter bank of 4500 μF smoothes the signal, providing the 50 v DC output.

Chapter 2

The Regulation Method

2.1 Definition of "50 volts, DC"

It must be noted that the output of the downhole high voltage supply is not a constant 50 v DC. Figure 2.1 shows the rectifier and filter portion of the downhole converter. The resistance at the terminals of the supply models a load motor. Because of the diodes in the full-wave rectifier, the capacitive output filter stores charge when the alternating signal at its input increases. After the input voltage reaches its maximum, the voltage at the output exceeds the input voltage, causing the diodes in the rectifier to stop conducting current. The capacitance and the resistance form a closed loop, which causes the energy in the capacitor to discharge into the resistance. The voltage decays with a time constant of:

$$\tau = R_{\text{Load}} \cdot C$$

The voltage decays at this rate until the alternating signal becomes larger than the voltage at the output, at which time the diodes in the rectifier conduct, causing the capacitors to store charge again.

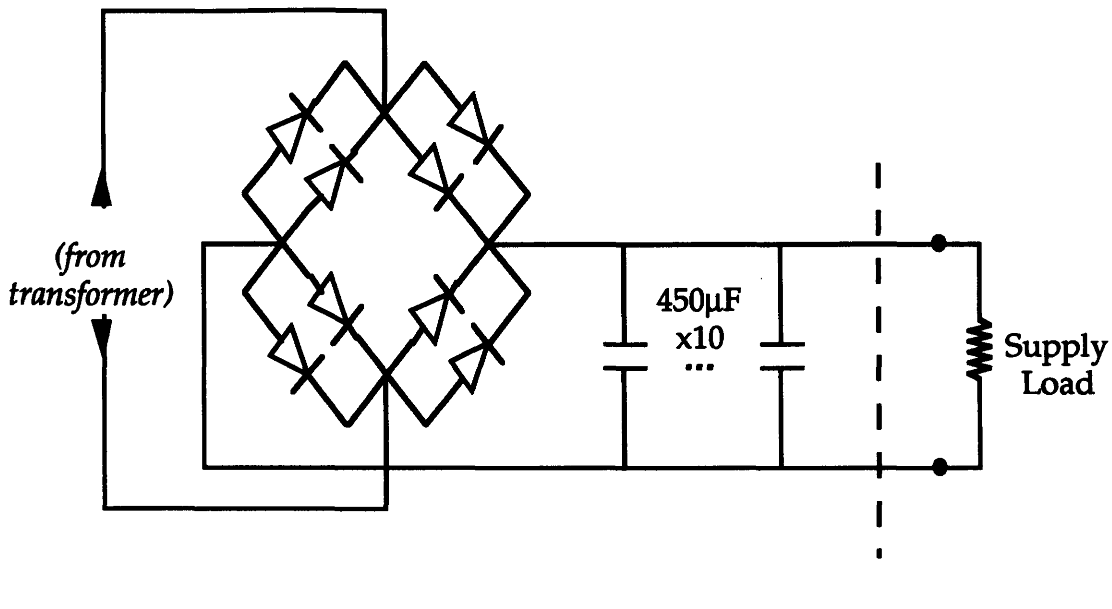

Figure 2.1: Rectifier and filter portion of Downhole Converter

If the time constant, τ, is large compared to the period of the peaks on the input signal, in this case 1/120 seconds, the discharge will be slow enough to make the output of the supply appear as a constant voltage, equal to the peak of the alternating input signal, 50 v. This corresponds to the light load case (high resistance). In the limit of the unloaded supply (infinite resistance), there is no place for the capacitance to discharge to when the diodes do not conduct, so the output stays at a constant 50 v exactly.

When the supply is loaded, however, there is a finite amount of ripple on the output voltage. Figure 2.2 shows the supply ripple when it is fully loaded at 1000 W. To determine the appropriate resistance of the load for these desired loads, it was noted that:

$$R = V^2 / P$$

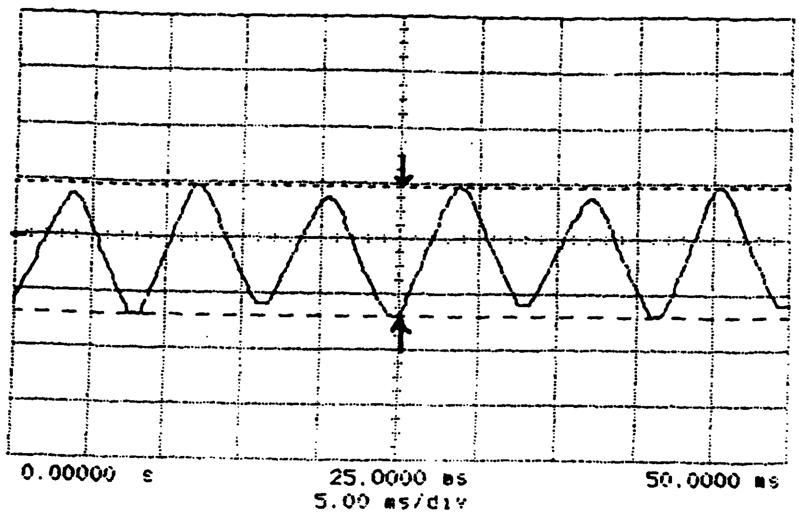

Figure 2.2: Supply voltage ripple at full load. (11.8 volts, peak to peak).

In the worst case, when the supply is fully loaded, the power is 1000 W. At 50 v, the load has an equivalent resistance of 2.5Ω.

The plot shows that in the worst case, the ripple on the output voltage is almost 12 v. Fortunately, the motors using the supply can tolerate such a ripple. The current system regulates the output such that it has an *average* value of 50 v[1]. It is 'DC' only in the sense that it contains a 50 v DC component. Therefore, in keeping with this convention, the systems in this study attempt to improve the regulation of the average value over one period of the signal to 50 v.

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[1] Interview with Miles Jaroska. Mechanical Engineering. Schlumberger Well Services, Houston, TX, June 1, 1993.

2.2 Regulation Method

An external mechanism for regulating the voltage level of the supply is required. The extreme conditions of the downhole environment prevent the use of a conventional, linear, dissipating regulator downhole. Such a regulator would require a heat sink capable of dissipating 1 kW of power at 200°C for hours at a time. Such a device would require a tremendous amount of space downhole, a resource that is not available (see Chapter 3). To circumvent the problem of downhole space limitations, the voltage is regulated from the surface.

Figure 2.3 shows a block diagram of the regulation scheme used. A dedicated monitor board taps the output of the high voltage supply. The voltage is divided down to levels that the telemetry can handle by a resistive divider. A capacitor is used to smooth the voltage before it is sampled and converted to a digital signal. By doing this, it is the average value of the voltage that is sampled. This is necessary because the actual output signal contains a significant ripple. This value is then transmitted to the surface along with telemetry data collected from other parts of the tool. Groups, or "frames" of data are sent at a rate of 15 Hz; the supply voltage is sampled 15 times a second.

At the surface, the telemetry frame containing the 50 v data is decoded, and passed to the surface computer unit. Each frame contains a large amount of additional information besides the 50 v data. It contains a mechanism for decoding the frame and processing each fragment of data in turn. The 50 v data is placed in a queue. When it is dealt with depends on what other data comprises the frame.

Eventually, the surface computer compares the 50 v data with a reference value and commands the surface generator to either increase or decrease the voltage that it outputs to the cable. The surface voltage is varied by adjusting the position of the variacs within the surface generator (see Chapter 1). The variacs are in turn driven by a 6 v stepper motor. The motor steps in discrete intervals, corresponding to approximately .75 v per step[2].

When current is delivered to a winding in the stator portion of the motor, the motor will "step" once so as to align the rotor and stator. To make the motor step a number of steps, the four windings comprising the stator must be properly energized in turn and for just the right amount of time.

The Tool Module contains a Stepper Motor Controller circuit which takes as input from the computer a 4 bit step size (1-16) and a direction bit (0=up, 1=down). It decodes this information to deliver current to the appropriate windings in the stepper motor, causing it to step the right number of steps in the appropriate direction. For a detailed description of this circuit, see Chapter 5.

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[2]This figure was computed as the average voltage increase per step over 100 consecutive steps.

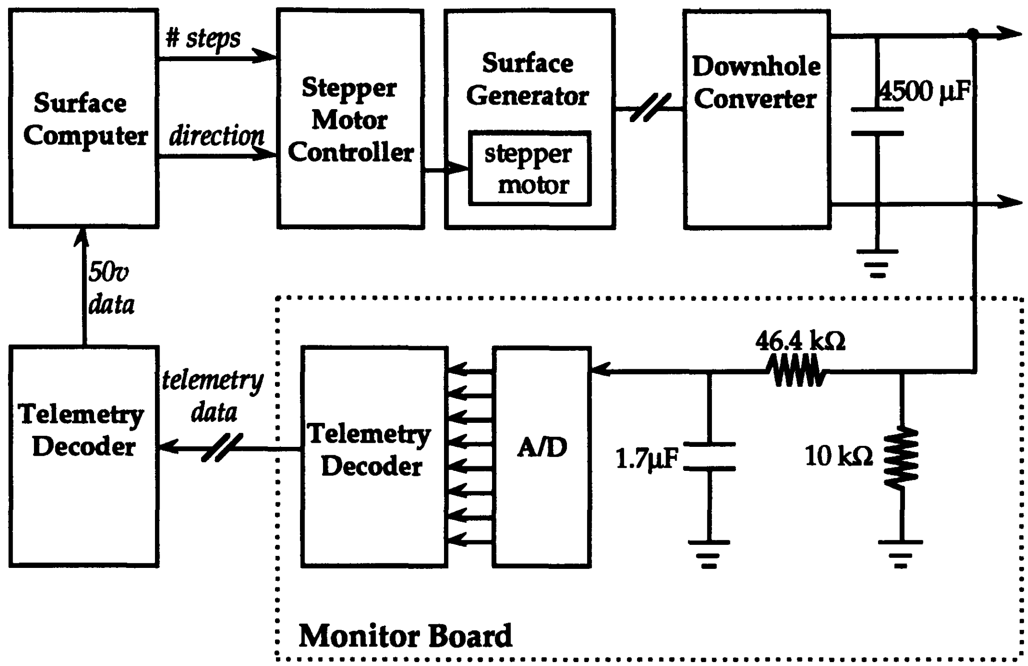

Figure 2.3: Existing Regulation Method

The computer decides how many steps to adjust based on the difference between the actual and desired voltages. If the difference is greater than 10 v, then the system increments or decrements 4 steps. For voltage differences less than 10 v, the system adjusts only 1 step. This is done to avoid overshooting and hysteresis. After the computer issues the step command, it awaits the arrival of the next 50 v data word, which should reflect the adjustment. Telemetry comes up at a constant rate of 15 Hz. If it takes longer than 66 milliseconds (1/15 Hz) to process the data and adjust the voltage, then there is the possibility that data will arrive to the surface faster than the rate at which the computer processes it. Data is queued in dedicated buffers precisely for this reason. However, the system is primarily a data acquisition system. For most data, queuing is acceptable, since all of the data will eventually be processed. However, the voltage regulation happens in real time. If the queued 50 v data were processed exactly as it came up, the system may overcorrect itself.

Consider, for example, the case when the voltage is low, say 40 v. If there was a delay in the system for 300 milliseconds, then four successive measurements of 40 v would be queued in the buffer. When the computer is able to process the data, it would correct on the first measurement (40 v), by increasing the voltage. The system would respond, and the voltage would increase, say 3 v. However, the next measurement would say the voltage is still at 40 v. The system would correct thinking the system is at 40 v, when it was actually at 43 v. If this continued, the system would overcorrect itself. To prevent this, the system only reads the most recent measurement. All previous, buffered measurements are ignored.

This completes the loop. The entire process repeats until the actual voltage is within 1 v of the desired (i.e. between 49 and 51 v).

2.3 System Bottlenecks

As mentioned above, one reason for the poor performance of the existing regulator is that the computer unit is primarily a data acquisition system, ill-suited for real time control. Telemetry frames are buffered and individual data words are processed in turn. There is no guarantee that the 50 v data will get processed first, or even before the next frame of data arrives. Consequently, there is a delay between when the data arrives to the surface, and when the surface computer unit can react to it. It is difficult to quantify this delay because it depends on the other tasks that the computer unit is performing at the time and the other data words comprising the frame. There are a number of additional reasons why the present system performs poorly.

First, the use of the telemetry system limits the rate of the feedback to 15 Hz. One iteration of the loop takes 66.6 milliseconds at best. Convergence upon a stable voltage level could take several iterations. Therefore, barring all other delays in the system, the above method will always take on the order of several hundred milliseconds to regulate.

Next, the downhole filter used to remove the ripple from the signal before it is divided down, sampled, and transmitted with the telemetry adds delay to the system. This adds additional delay of approximately 80 ms.

$$\begin{aligned}\tau &= RC \\ &= 46.4\text{k}\Omega \times 1.7\mu\text{F} \\ &= 78.8 \times 10^{-3}\text{s} \\ &\approx 80 \text{ ms}\end{aligned}$$

Perhaps the most frustrating aspect of the above system is the variac / stepper motor mechanism. The variacs do not step monotonically. To prove this, an experiment was conducted. The variac was commanded to repeatedly advance a number of steps (between 1 and 16) then a pause for a specified time (between 0 and 1 second). It was found that the motor/variacs stepped uniformly for all step sizes when there was no pause after each step increment. However, when the pause was longer than 12.5 milliseconds (1/80 Hz) between increments, the variacs did not step uniformly for increments of less than 5 steps.

One possible explanation for this phenomenon may be that the variacs contain a finite inertia. When there is no pause between step increments, the inertia is overcome by the first step, so successive steps will adjust the variac appropriately. However, when there is a significant delay between step increments, the motor must overcome the inertia of the variac at each step. Step sizes of 1 or 2 may not provide the force to overcome the inertia. For larger step sizes of 15 or 16, the inertia may be overcome in the first 1 or 2 steps. Once this happens, the remaining 13 steps in that increment will cause a uniform change in the variac. Thus, while the "inertia" effect may be present for any size step increment, it may be masked for larger step sizes.

Another possible explanation is that voltage of a variac is adjusted discretely. The tap which controls the voltage level brushes against discrete coils in the variac which determine the voltage. There is no reason to believe that for each step of the motor, the tap should be on one winding only. If the tap is sometimes touching two adjacent windings, and other times touching only one, then small step increments would result in non-uniform voltage increases.

Another problem with the variac system is the step rate. The amount of torque required to turn the stepper motor and two variacs puts a limit on the rate at which the motor can be stepped. As will be described in Chapter 5, the windings to the stepper motor are alternately energized at a rate of 80 Hz. It has been proven that stepping any faster than this rate will not generate enough torque for each step, which will causes the motor to skip[3]. In response to large load changes, the variac voltage may require adjustment of up to 50 v (see Chapter 4).

$$50 \text{ volts}\left(\frac{1 \text{ step}}{.75 \text{ volts}}\right)\left(\frac{12.5 \text{ ms}}{\text{step}}\right) = 833 \text{ ms.}$$

[3]Interview with Dan Stehling. Mechanical Engineering. Schlumberger Well Services, Houston, TX, July 12, 1993.

Therefore, even if the new variac voltage were known exactly, it would take almost an entire second just to turn the variac to that position.

An additional flaw in the system is the stepping algorithm used by the computer unit. Currently, the computer issues steps based on the downhole voltage. This method is used uniformly across all cable lengths. Unfortunately, the same voltage difference requires different amounts of surface adjustment for different cable lengths. A 30,000 foot cable, for example, contains five times as much impedance as a 6,000 foot cable. Therefore, a 10 v gradient between the desired and actual voltage will require a great deal more surface correction for longer cables than shorter ones. The current system does not account for this. It conservatively adjusts for the shortest cable length case to avoid over-correction. This system is therefore unnecessarily slow for longer lengths of cable. Unfortunately, cable impedance is not uniform. Different cable types contain different electrical characteristics which makes it difficult to uniquely characterize all cables. Hence, it is not trivial to incorporate a correction factor for cable length into the algorithm that adjusts the voltage. A better algorithm for stepping would have more accurate knowledge of the amount of correction necessary as well as the direction correction must be in.

It must be noted that although there is a finite amount of reactive impedance in longer cables, the delay imposed by this is insignificant compared to the delay in the rest of the system. Even a 30,000 foot cable has a capacitance of 8 μF and a resistance of 120 Ω (see Appendix A). This gives a time constant of

$$
\begin{aligned}
\tau &= RC \\
&= (120\Omega)(8\mu F) \\
&= .96\text{ms} \\
&\approx 1\text{ms}
\end{aligned}
$$

At shorter cable lengths, this time is even less. Therefore, compared to the typical regulation time, which is on the order of seconds, the delay imposed by the cable is insignificant.

2.4 Existing System Performance

Before alternative methods of regulation can be compared to the current system, a quantitative measure of performance must be developed. For the purposes of this study, the reaction of the system to an instantaneous downhole load change was analyzed. Figure 2.4 shows the experimental set-up used to test the performance of the system. (See Appendix C for a circuit diagram of the device used.)

The components of the power system were available in the laboratory. Cables of the following lengths were also available: 6025 ft, 12175 ft, and 16500 ft. The three lengths could be connected in series in any combination to yield lengths spanning the entire range of cables used in actual field operations.

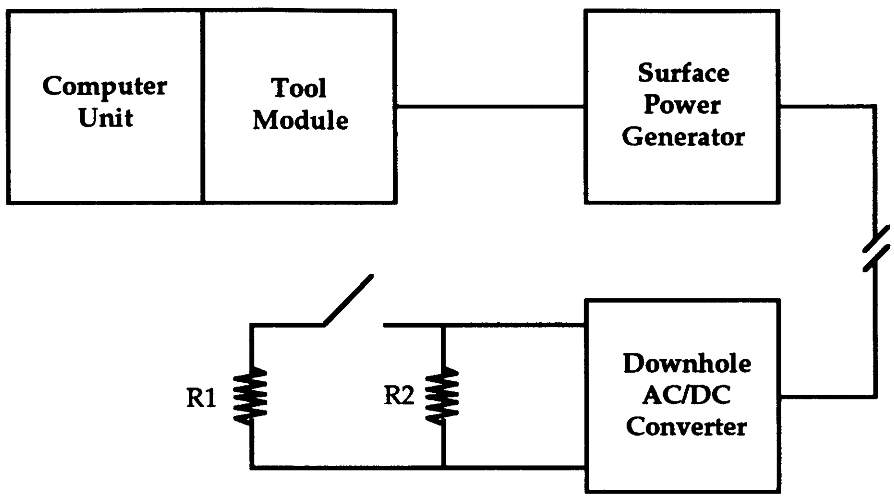

Figure 2.4: Experimental Set-up used to test performance of system. Cable length varied between 6025 ft and 28675 ft.

To measure the performance of the system, an adjustable load switching circuit was connected to the output of the supply. Power resistors served as the loads, R1 and R2. Initially, when the switch was open, only R1 drew current from the supply. The system was allowed to regulate and stabilize to 50 v. When the de-bounced switch was manually closed, R2 was added in parallel with R1 to provide an instantaneous load increase. The system response to this increase was recorded by an oscilloscope triggered on the switch. Conversely, when the switch was opened, the load on the supply was instantaneously decreased. The system response to this change was also noted.

Load changes in actual operation often do not occur instantaneously. The operator can manually adjust the surface voltage. Hence, if he plans to initiate a sequence that will cause a motor to turn on downhole, he can anticipate the sag in voltage and compensate by manually increasing the generator voltage before he turns the motor on. Using the response of the system to instantaneous load changes therefore gives an indication of performance under worst case conditions.

The performance of the system was judged on two criteria: speed and overshoot. Overshoot refers to the maximum deviation from 50 v in response to the switch. For load increases, it is the minimum voltage the supply level reaches. For load decreases, it is the maximum voltage the supply level reaches. Speed refers to the amount of time it takes for the voltage to return to within ±10% of 50 v after the load has been switched.

The system response was examined for load changes of 250 w, 500 w, and 750 w. This was done with cable lengths of 6025 ft, 22525 ft, and 28675 ft. Therefore, this experiment gave an indication of performance of the system over the entire range of operation.

In addition, the experiment was conducted with no other modules in the tool string. With no other data to handle, regulation of the 50 v supply was the only task that the computer had to do. Therefore, the measurements indicate the best-case performance. In order to confidently conclude that an alternate method of regulation performs better than the current system, it must be shown that the new system performs better at its worst case than the current system performs at its best case.

Table 2.1 shows the results of an experiment designed to test the system's response to an instantaneous load change. 'Maximum deviation' was the amount that the supply voltage either surged or sagged in response to the change. 'Regulation time' is the time it took for the system to return the voltage to within 50 v ±10%.

Cable Length (ft)	Load Change (watts)	Regulation Time (ms)	Maximum Deviation (v)
12175	11-261	1220	14.4
12175	261-11	980	15.9
12175	11-511	1300	18.8
12175	511-11	1110	26.9
12175	11-761	2420	23.4
12175	761-11	1420	37.5
12175	261-761	1810	14.4
12175	761-261	1040	15
22525	11-261	1000	16.2
22525	261-11	1730	19.1
22525	11-511	2080	21.9
22525	511-11	1510	36.3
22525	11-761	2980	25.6
22525	761-11	1940	51.9
22525	261-761	2240	17.8
22525	761-261	1360	19.1
28675	11-261	1500	17.5
28675	261-11	1240	23.8
28675	11-511	2380	25
28675	511-11	1460	41.3
28675	11-761	2880	27.5
28675	761-11	2360	58.8
28675	261-761	1750	18.1
28675	761-261	1210	23.1

Table 2.1: Regulation time and Maximum deviation of supply voltage in response to an instantaneous load change.

Chapter 3

Possible Solutions

Several different alternatives to the current method of regulation were explored. This chapter discusses the benefits and drawbacks of each of them, as well as the selection criteria used for evaluation.

3.1 Selection Criteria

In selecting a new method for regulating the high voltage supply, several characteristics were desired. The "best" alternative was the one that provided the optimal balance between the desired qualities. The methods discussed in this chapter were not quantitatively compared. An in depth exploration of each method was beyond the scope of this study. Hence, no quantitative measurements of the following system characteristics were developed. The qualitative analysis performed here serves only to illustrate, not to justify, why the proposed method of regulation was pursued[1].

[1] Interview with Vic Wichers. Mechanical Engineering. Schlumberger Well Services, Houston, TX, September 21, 1993.

3.1.1 Performance

The first, and most important, aspect of the proposed methods was system performance. Performance consisted of two qualities: regulation speed and accuracy. Regulation speed refers to the amount of time it takes for the system to stabilize the voltage to the correct level in response to rapid voltage changes. Accuracy refers to the ability of the system to return the voltage to 50 v . It was important to design a system that not only reacted quickly to voltage changes, but also converged on the correct voltage level with minimal overshoot. Conceivably, a system could posses one quality and not the other.

3.1.2 Reliability

The second criteria used for selection was reliability. The extreme environmental conditions in the bore hole place severe limitations on the types of electrical components that can be used downhole. Heat generation was of paramount concern. Heat generated downhole requires some mechanism for dissipation to the outside environment. High downhole temperatures make this difficult to do without causing tool components to heat. The heating of electrical components decreases their lifetime. Reliable solutions either generated little or no excess heat or regulated from the surface of the well, where excess heat generation was not an issue.

Another important aspect of reliability was the number of components needed. Large circuits with many electrical parts, or regulators containing many separate circuits are less reliable than smaller, less involved circuits because there are more individual chances for failure.

3.1.3 Robustness

The ability of the system to adapt to the changing needs of MDT was an important consideration. A system was desired that would be flexible enough that minimal hardware or software modifications would be necessary as new modules and additional functions were added to MDT.

Robustness was also defined as the ability of the system to improve all of the flaws in the current system. Improvements were usually targeted at removing one of the bottlenecks in the system, such as the software delay or the variac controller. Robust solutions, however, were able to improve many aspects of the current system.

3.1.4 Complexity

Several hundred MDT's are currently in field use. A compact system was required that could be manufactured in the plant, taken to the field, and switched into the current system easily with minimal modifications to the existing hardware or software.

A system was also desired that would be transparent to the user. The job of the field engineer is complicated enough. Any system that relies on interaction with the field engineer, or required additional knowledge on his part, provides a window for failure.

From a production standpoint, a simple system was preferable over a complex one because it is easier to build, debug, and test. A rough measure of this is the number of functional blocks in the system.

3.1.5 Size and Weight

Space is at a premium in the downhole environment. The oil well hole diameter is 9 inches[2]. Tool modules are designed to make maximal use of the available space. Smaller modules are desirable because they require less steel casing and because they are unwieldy, and are therefore easier for tool operators to handle. It is also desirable to keep tool modules light. Like large tools, heavy tools are difficult for field engineers to handle. In addition, lighter tools place less strain on the logging cables which must support them. Solutions that involve additional circuitry downhole may have to be contained in separate modules, adding both size and weight to the tool string.

3.2 Alternative Methods of Regulation

The set of possible solutions to the problem of regulating the downhole voltage can be divided into two broad classes: systems that reside at the surface of the well hole, heretofore referred to as "uphole solutions", and systems that operate near the supply, itself, or "downhole solutions".

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[2]P. Theys, Log Data Acquisition and Quality Control, (Paris: Editions Technip, 1991), pp. 160-166.

Any regulation scheme contains three essential components: an element to monitor the variable attempting to be regulated, a controller to make corrections based on that variable or an estimate of it, and a feedback mechanism to transmit information from the point of output or regulation to the point of control. Downhole solutions offer the advantage of placing the point of control and output very close to each other. Any latency or transmission inadequacies caused by the impedance of the cable are eliminated, giving downhole solutions the potential for extremely fast and accurate regulation.

Unfortunately, downhole regulators pose several problems. First, tool modules are designed to minimize weight. The entire tool string is suspended by the transmission cable. Heavy modules or long tool strings place a greater strain on the cable than do their lighter or shorter counterparts. The additional heat sinks or circuitry involved in a downhole regulator may add significant weight to the string, which limits the available room for other tools on the string. In addition, as described above, the current design of tool modules leaves little space for additional circuitry. Downhole regulators will either require an extension of the downhole converter casing or a new module altogether.

Uphole solutions are limited in speed because of the latency the cable introduces, they are in general more reliable and do not face the same size constraints as their downhole counterparts. In addition, heat generation is more tolerable in uphole solutions because it is easier to dissipate heat at the surface of the well than it is do dissipate it downhole.

There were several possible methods of regulation that were explored. Each of these will now be discussed in detail.

3.2.1 Linear Dissipating Regulator

Figure 3.1 shows a block diagram of the first alternative explored. This is the conventional method of regulation. The heart of this regulator is a downhole controller and a 1 kW variable resistor placed in parallel with the load.

Under this method, the surface always transmits maximum power to the downhole converter. The controller is responsible for monitoring the downhole supply output and directing exactly enough of the incoming power to the load such that the voltage will remain at 50 v . The excess power is dissipated in the variable resistor. The controller controls the amount of power dissipated in the load by varying the resistor's resistance. The resistor simply serves as a sink for excess power until it is needed by the load.

Recall from Chapter 2 where it was stated that the ripple on the supply output is proportional to the load. Under this system, the supply ripple will always be roughly 11 v . To eliminate or reduce the ripple, a capacitive filter would be used between the supply output and the load/variable resistor combination.

There are two benefits to this method. First, this system would be considerably faster than the current method. Because the resistance can be adjusted quickly and control takes place downhole, close to the supply output, the adjustment process would be much faster and more accurate than could be achieved by the current system. Second, the design of this regulator would be fairly simple. The controller performs only two functions: measuring the 50 v output and increasing or decreasing the resistance of the variable resistor slightly.

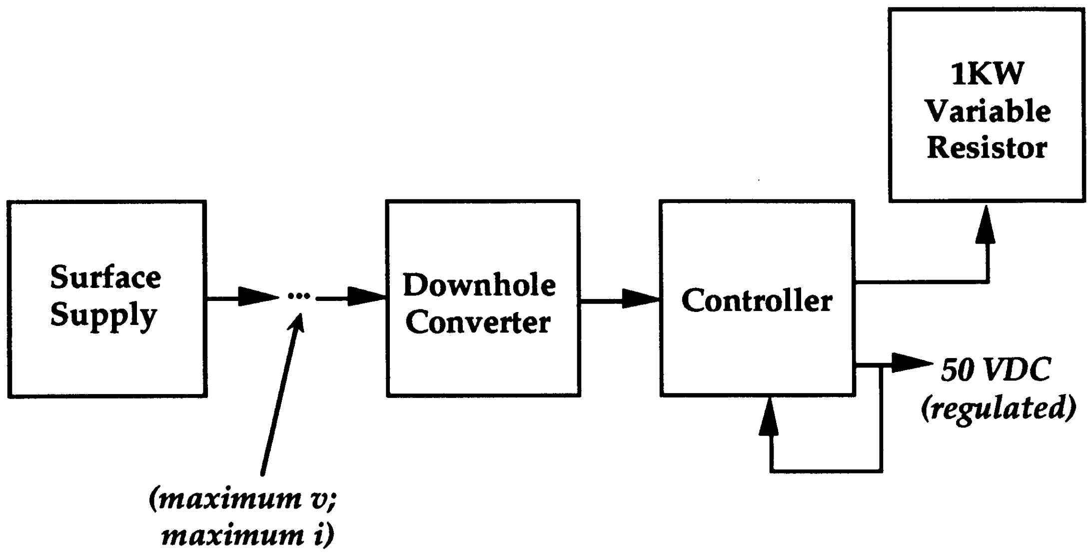

Figure 3.1: Linear Dissipative Regulator Block Diagram

Unfortunately, there are several drawbacks which make this approach not feasible. First, dissipating such levels of power in the downhole environment would result in the heating of tool components to dangerously high levels. Heat flux, or the amount of dissipation, is proportional to the temperature gradient between the tool and the surrounding earth. Downhole temperatures can exceed 200°C. Therefore, dissipating heat from the tool requires that the tool itself heats significantly above this. Most of the electronics downhole do not have maximum heat ratings beyond 200°C.

Second, this system would be prohibitively large. To offset the poor thermal conductivity of the tool, the surface area of the tool could be increased. However, this is not an attractive option. The tool is rated to deliver 1 kW. However, it only operates at full load a small fraction of the time. The system may only consume a fraction of this for hours at a time. In the worst case, the supply requires a heat sink large enough to dissipate 1 kW of power for hours at a time. A sink of this magnitude would be prohibitively large.

This method is also dreadfully inefficient. The supply always consumes maximum power. Excess power is simply wasted.

3.2.2 Gradually Dissipating Load

A variation of the previous approach uses a dissipating element for immediate correction but utilizes the telemetry and surface computer for longer term correction. Figure 3.2 shows a block diagram of this scheme.

This method works because of the nature of the downhole motors. Load changes may be instantaneous, but happen infrequently; that is, the latency between load changes is long relative to the time it takes the current software-guided system to regulate (between 1 and 4 s). This dissipating scheme handles voltage surges and sags differently.

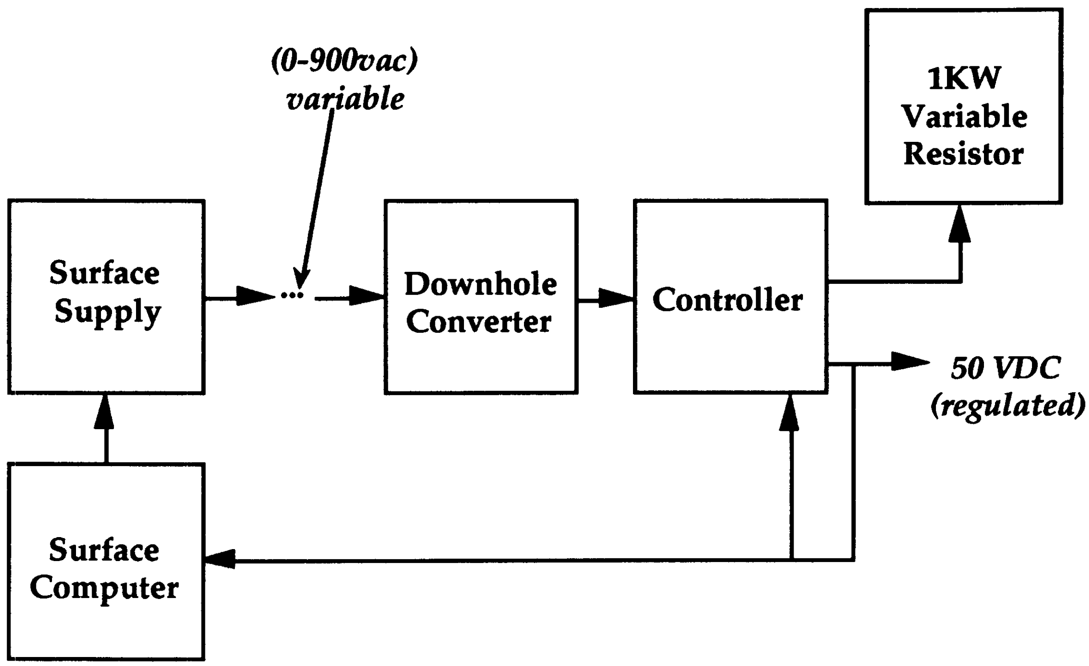

Figure 3.2: Temporary Dissipating Regulator Block Diagram.

When a motor turns off downhole, a voltage surge is avoided by directing the excess power to a variable resistor. The controller balances the resistance such that the voltage at the output of the supply is slightly above 50 v . Simultaneously, the voltage is measured and transmitted through the telemetry to the surface computer. Because the voltage downhole is slightly above 50 v , the surface computer decreases the surface voltage. The downhole controller increases the resistance gradually, such that the supply voltage stays constant. Thus, all of the excess power dissipated in the resistor is reduced until the resistor dissipates nothing. It will only take several seconds at most (the speed of the current system) to reach this "steady state".

When the steady state is reached, indicated by a sufficiently high resistance, the controller returns the supply voltage to 50 v .

This system handles voltage sags differently. The beauty of this method is that in the steady state, the resistor dissipates nothing, which means that heat is generated for a short time only immediately after a load change. However, voltage sags happen because of a lack of excess power when the load increases. A few seconds prior to a motor turning on, the surface supply output must be increased. This power will be temporarily dissipated in the resistor. Therefore, when the motor load turns on, excess power can be diverted to the load.

This method solves the major problem of excess heat generation that plagues the strictly dissipating regulator of the previous section. A heat sink would only have to be capable of dissipating 1 kW for a few seconds. While this will still require an additional module, it will be significantly smaller than the previous regulator.

Unfortunately, this approach is not robust. It works fine when motors turn off and the supply needs a temporary sink for the excess power. However, it does not work well when motors turn on. This method relies on the surface computer being able to predict when a motor will turn off so it can increase the voltage before the sag. However, there is no way of knowing this in many cases. For example, the surface computer can initiate a sequence that will cause a seal valve to open. The motor that drives the valve will draw current while the valve is opening, and stop when it is fully opened. The surface computer does not know when the sequence will be complete until after it is complete. In other words, there is no mechanism for predicting when motors will turn off. The nature of the motor loads prevents regulation from being *proactive* . It is limited to being *reactive* .

3.2.3 Switching Regulator

Figure 3.3 shows the block diagram of a proposed downhole switching regulator. The heart of this regulator is a high frequency switch. When the switch is off, no current is delivered to the load. When it is on, current is fed to the load. The controller repeatedly turns the switch on and off at a particular frequency. By varying the duty cycle with which the switch is operated, the controller can affect the average current that is delivered to the load.

The motors, however, operate on DC power. To convert the high frequency pulses to a smooth DC signal, a low pass output filter would be used. In addition, an input filter is necessary to remove the high frequency components of the power signal over the transmission line. Recall that the same conductors that transmit power are also used for telemetry communication. High frequency power signals would introduce unacceptable noise in the telemetry. An input filter before the regulator would eliminate this problem.

A switching regulator offers the speed of the dissipating regulators without the inefficiency. When the switch is open no current, and hence no power, is drawn from the surface supply. Heat dissipation is minimal. Unfortunately, while this is an improvement over the dissipating schemes, it is still problematic. Even if a FET switch is 95% efficient, a heat sink capable of dissipating 50 W for hours is necessary.

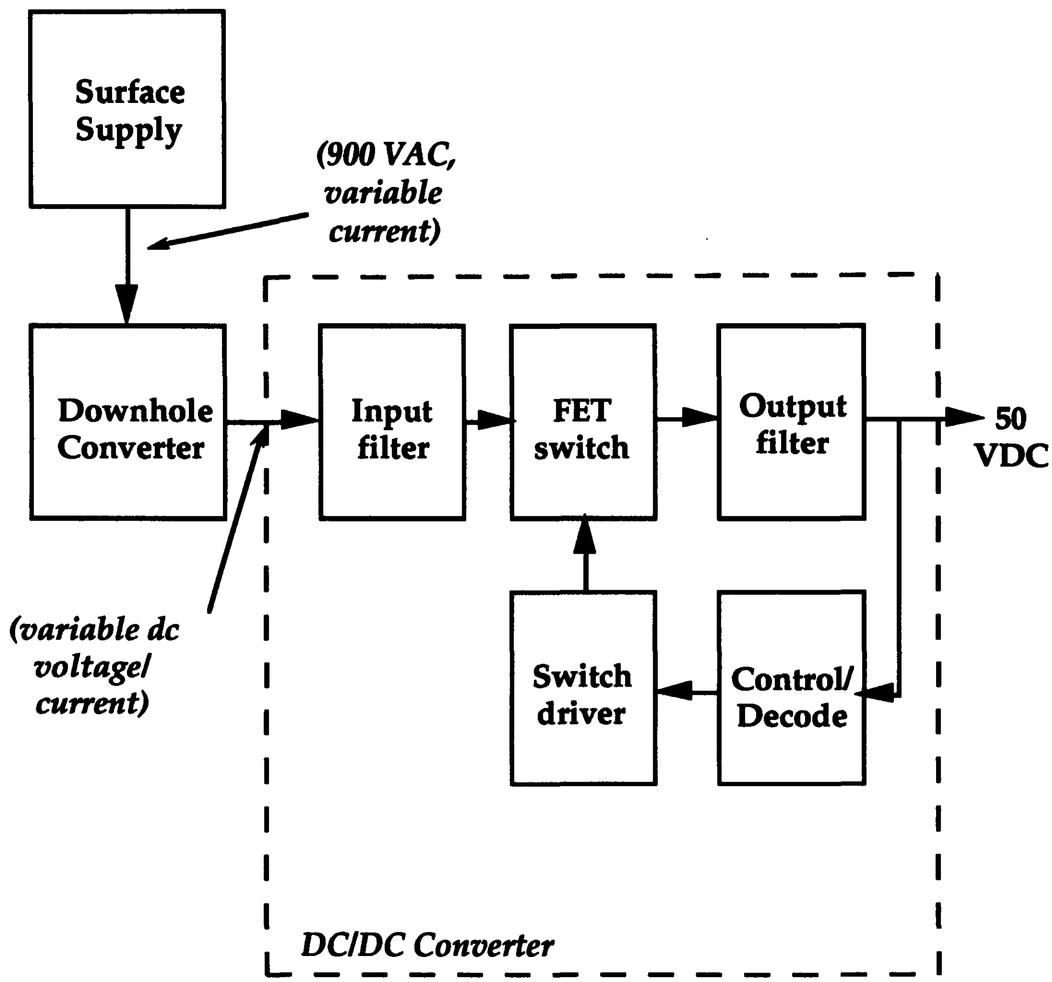

Figure 3.3: Switching Regulator Block Diagram

The major drawback with the switching regulator is its complexity. It is crucial that the input and output filters remove all of the high frequency components introduced by the switch. The design of such filters would have been a non-trivial task. In addition, this regulator requires a great deal of downhole circuitry. Because of the large component count, and the de-rating of electrical components in the downhole environment, this regulator was not expected to be reliable.

Last, as with all downhole regulators, size was a limiting factor. To switch 20 A at 200°C, several FET's would have to be used to divide the burden. This increases the size of the downhole circuitry.

3.2.4 Surface Telemetry Decoder

The next alternative explored was an uphole solution. Figure 3.4 shows a block diagram of a "surface telemetry decoder". This solution aims at removing the surface computer delay from the system. To do this, a dedicated hardware controller is used to replace the surface computer unit in the supply voltage control loop. The controller does exactly what the computer unit used to do: receives the telemetry word, decodes it and identifies the 50 v data, compares it to a reference, and issues commands to the stepper to either increase or decrease the voltage. The demodulation of the telemetry signal into the data word is already handled in a separate unit between the cable and the computer unit. Hence, the burden of demodulation is removed from the surface telemetry decoder.

The biggest appeal of this system is its simplicity. The feedback mechanism, namely the downhole monitor board and cable telemetry, are already in place. The only new component to be designed is the surface controller. The same software that the computer unit uses to process the data and control the stepper motor could be programmed into a microprocessor-based controller. This method creates nothing new; it simply moves the voltage regulation to a separate, dedicated processor.

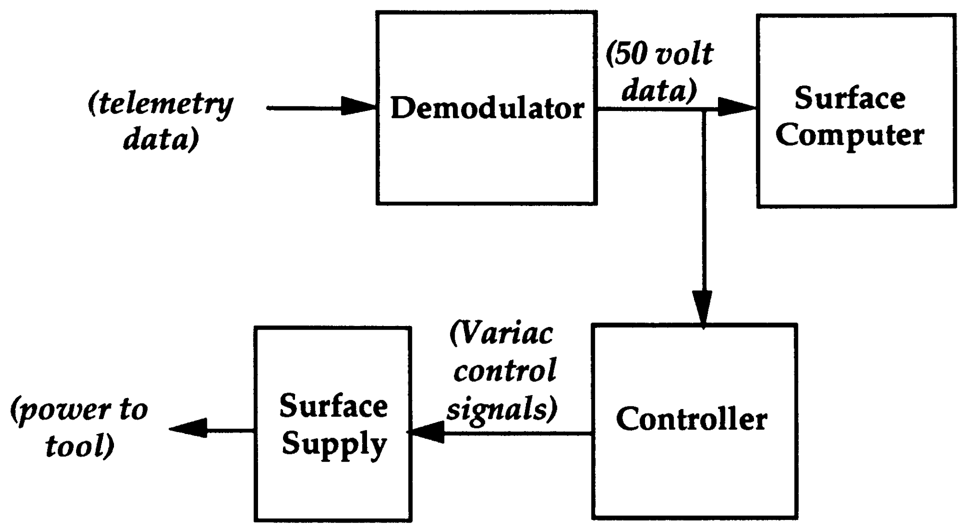

Figure 3.4: Telemetry Decoder Block Diagram

Another simplifying factor in this system is the telemetry data frame. Successive data frames arrive at the surface at the rate of 15 Hz. The format of the frame varies from job to job, depending on the configuration of the tool string and the constituent modules. However, every tool configuration requires several key components, one of which is the downhole power converter responsible for measuring the 50 v data. In every configuration, this converter is the first element in the string. Consequently, in each data frame, the 50 v data is at the start of the data frame, regardless of the tool configuration or constituent modules. This makes it trivial for the surface telemetry decoder to identify the 50 v data within the telemetry frame.

Unfortunately, this method is not robust. The 50 v data is only in the same place with respect to the start of each data frame for the current telemetry system. There are plans to change the format of the telemetry in several years. Under the new system, there is no guarantee that the 50 v data will have a fixed location within the frame.

In addition, the new telemetry system contains a mechanism for buffering data downhole before it is transmitted over the cable. This poses a problem for any real time control system. The effective regulation of the voltage supply relies on the reliable, constant transmittal of the feedback. Under the new system, measurements will occur downhole at a steady rate of 15 Hz downhole. However, the transmission rate to the surface will be less predictable. A surface telemetry decoder that simply replaces the functionality of the surface computer unit will not work with the new telemetry system.

This method is also shortsighted in that it assumes that the most significant portion of the delay in the current system is the computer processing time. It does not account for the slow variac controller and uses the same "blind" algorithm for controlling the stepper motor that the current system uses (see Chapter 2).

The final drawback of this system is its speed. The regulation rate is limited by the 15 Hz telemetry rate, which makes it significantly slower than the other methods under investigation.

In the final analysis, none of the above methods succeeded in offering a significant improvement in performance at a feasibly low cost. A downhole, linear dissipating regulator would have required too much space to be feasible. The temporary dissipating solution, while offering an improvement in this area, would have required an unrealistic mechanism for predicting changes in motor loads. A switching regulator would require complex and much downhole circuitry which challenges reliability. Finally, the only uphole solution explored lacked the ability to meet the changing needs of

MDT and would have offered only marginal improvements in performance over the current system. What is needed is a method that achieves a better balance between performance and feasibility than those thus explored. The next chapter discusses how this balance was realized.

Chapter 4

The Proposed Solution

After consideration of several alternatives to the current method of regulation, a solution was pursued which offered significant performance increase at minimal expense, in terms of complexity, modifications to existing hardware and software, and size. This chapter explores the proposed method and the theory of operation in detail.

4.1 Motivation

In designing a system to regulate the downhole high voltage supply, the natural tendency is to include a mechanism for measuring the voltage at the supply. This is, after all, the variable the system is attempting to control. This is the approach of the current regulation system used. All of the alternative methods discussed in the previous chapter also include a mechanism for monitoring the supply voltage. In the case of uphole solutions, the challenge is delivering this measurement to the surface quickly and processing it immediately. The only mechanism for exchanging information between the surface and the bore hole is the slow telemetry signal. In addition, the surface computer unit handles many tasks and is ill-suited for real-time control of the supply.

To circumvent this challenge, it would be beneficial if another variable existed which could be directly monitored at the surface of the well and which could be used to accurately predict the downhole voltage. This would allow a regulator to reside at the surface, which is desirable from a feasibility standpoint, while eliminating the reliance on the slow, modulated telemetry signal. The surface current is such a variable.

Downhole load changes result in the adjustment of both the supply voltage and the supply current. As the load increases, more current is drawn from the supply. Conversely, when the load decreases, it draws less supply current. The surface generator, the cable, the downhole converter, and the supply form a closed loop. The change in the downhole current should therefore be marked by a proportional change in the surface current. (Note: the downhole converter steps up the cable current before it reaches the supply, which is why the surface and downhole currents are proportional and not identical.)

This has valuable implications. If the relationship between the surface current and the downhole voltage as the load is varied was know a priori, then a real-time surface controller could use the surface current to accurately calculate the downhole voltage, instead of measuring it directly. This was the premise for the solution to the regulation problem.

There is one caveat, however. As previously mentioned, cables contain a finite amount of capacitance. This causes a certain amount of the transmitted current to circulate in the cable. Conceivably, the current lost in the cable could be the dominant component of the total surface current. If this is the case, then it may be difficult to identify the downhole current and use it for regulation.

Fortunately, this was not the case. The current lost in the cable is proportional to the cable length. Heavier loads draw more current from the supply than lighter loads. Hence, the ratio to current lost in the cable to current drawn by the load will be the most for the longest possible cable and lightest possible load configuration. Figure 4.1 shows a plot of the surface current against the downhole voltage for this configuration. The plot shows that as the downhole voltage varies from between 30 to 90 v, the surface current varies almost 2 A. Configurations with shorter cables or heavier loads will result in even larger surface current variations for the same downhole voltage range. Hence, it can be concluded that the surface current can be used to track the downhole voltage even under the worst conditions.

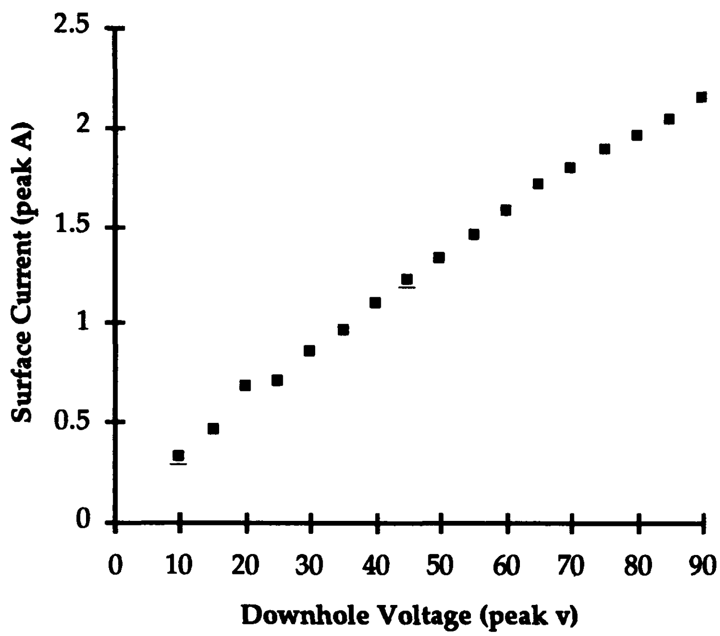

Figure 4.1: Surface Current vs. Downhole voltage.
Cable length = 28675 ft. Load = 11 watts.

Figure 4.2 shows a block diagram of the proposed controller. The surface current is measured and delivered to the controller. Based on the current, the controller calculates the desired surface voltage that will cause the supply voltage to stay at 50 v. The desired surface voltage is compared to the actual surface voltage to determine how much the surface voltage must be corrected. This value is in turn converted to the stepper commands to adjust the variac[1]. Although the variac system is a large source of delay in the system, the cost of modifying the surface generator was prohibitively expensive for two reasons. First, to prevent recalling existing units, modified generators would have to be manufactured. It is expensive to do this. Second, the alternative to the variac system for voltage control is prohibitively expensive. High-speed linear amplifiers are available which provide instantaneous adjustment of high levels of voltage and current. Unfortunately, such amplifiers are orders of magnitude greater than variacs, and are therefore prohibitively. The designers of the original surface generator understood the speed limitations imposed by the variac system. Their decision to use such a slow system reflects a desire to keep costs down.

Another advantage of variacs is their efficiency. Variacs allow the controller to draw only as much power from an AC outlet as is necessary. A linear amplifier generating an AC wave form is approximately 50% efficient. It will be less efficient at lower power levels, but the total dissipation will also be lower. A switching amplifier performs better at 85% efficiency.

1In this sense, the controller replaces the MAXIS. Stepper commands are still issued to the surface generator via the Tool Module. This will be discussed further in Chapter 5.

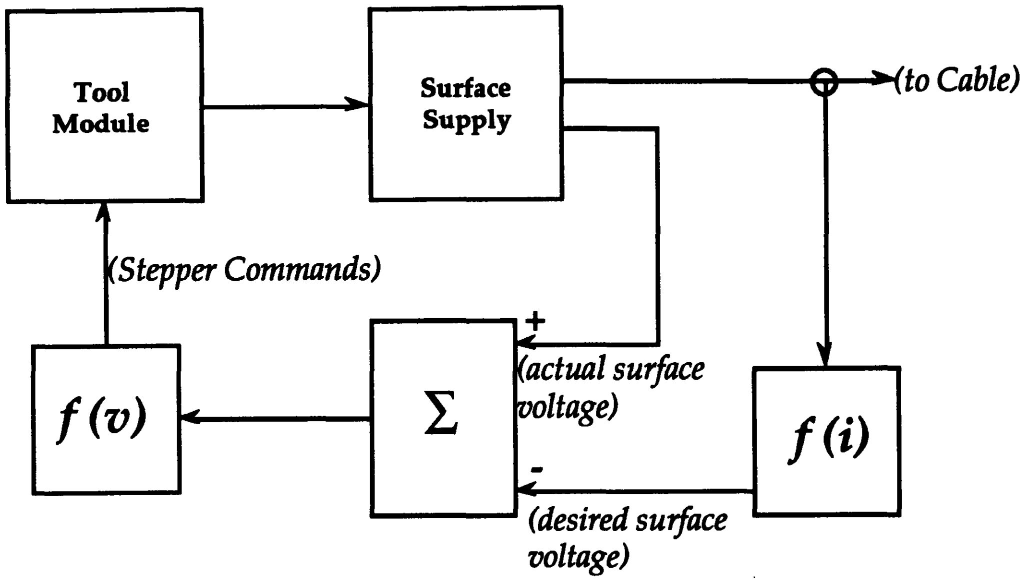

Figure 4.2: Block diagram of proposed controller

4.2 Desired and Natural Responses

Next, measurements of the surface voltage and the surface current were recorded as the downhole voltage was varied between 30 and 90 v. This was done for several different loads over most of the operating range (11 W to 811 W). Figure 4.3 shows the form of these measurements for three different loads. Each curve represents a different load condition. In a sense, these curves show the "natural response" of the system; for a particular downhole voltage, the corresponding surface voltage and current can be calculated. For clarity and simplicity, the graph only shows the points on each curve corresponding to a downhole voltage between roughly 40 and 60 v.

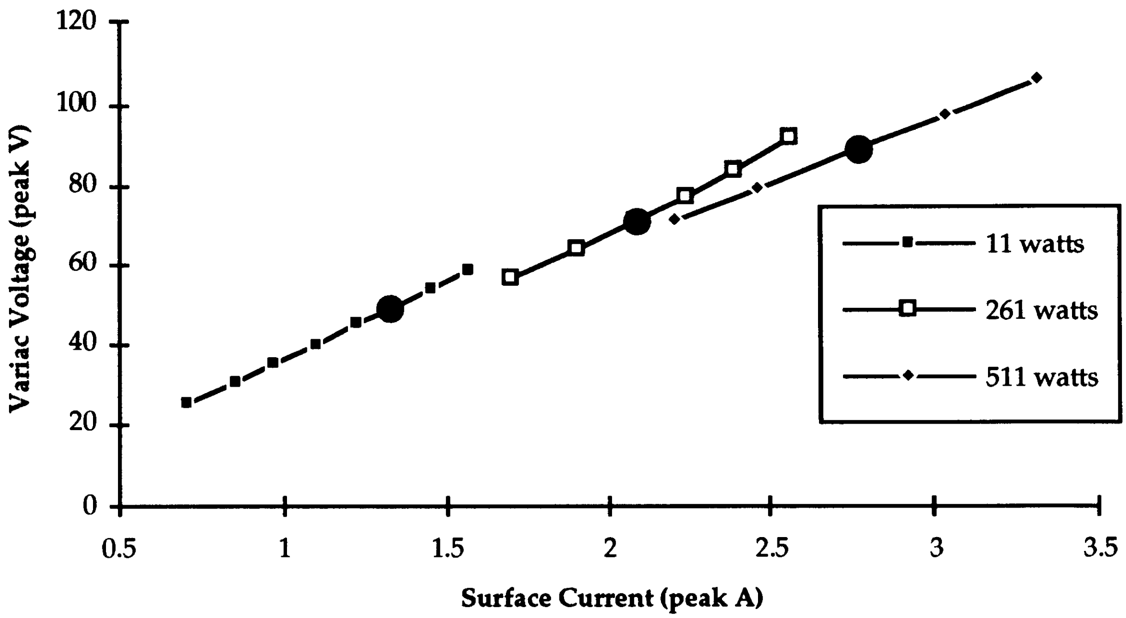

Figure 4.3: Variac (surface) voltage vs. surface current for various loads. Cable length = 28675 ft.

It must be noted that the "surface" voltage in this discussion refers to the variac voltage. Strictly speaking, the surface voltage is the voltage at the head of the cable. This is, however, a stepped up version of the variac voltage. The variac voltage was used because it only varies between 0 and 150 v, which places less strain on voltmeters than the total surface voltage, which has a range of 0 to 900 v. In this case, it is acceptable to use peak values for measurement because the average values of the signals are roughly proportional to the peak values. Using the peak is computationally less intensive than computing the RMS value over a period.

The large, shaded points in Figure 4C on each load curve correspond to the respective surface currents and voltages that result when the downhole voltage is 50 v. These points represent the "ideal" response of the system; for each operating load, the asterisks denote the desired combination of surface current and variac voltage.

Figure 4.4 shows the aggregate sum of these points for a cable length of 28675 ft. Assuming a monotonic response, a third order polynomial curve has been fit to the points. This curve shows the desired variac voltage for each measured surface current that will yield 50 v downhole for every possible load. This curve represents the brain of the controller. Assuming it is known, it now becomes possible to regulate the system. A meter will send a measurement of the surface current to the controller. The curve allows the controller to translate the current into the proper variac voltage to yield 50 v downhole.

The exact shape of this curve will vary depending on the length of the cable and on other environmental conditions. A method for deriving this curve for each specific case is necessary. This could be done by systematically manually varying a downhole load in discrete increments, allowing the existing system to regulate the downhole voltage to 50 v at each increment, recording the resulting surface current and variac voltage, and fitting a curve to this set of generated points. The cable and other environmental conditions are implicitly characterized in the sample points. This removes the burden of explicitly characterizing the system. The system and all of its impedance can be treated as a "black box" that simply has a response as indicated by the sample points.

A means for calibrating the system in real-time is possible. The specifics will be discussed in Chapter 6. For now, assume that there exists a mechanism for generating a set of surface current and variac voltage points corresponding to a downhole voltage of 50 v for several loads.

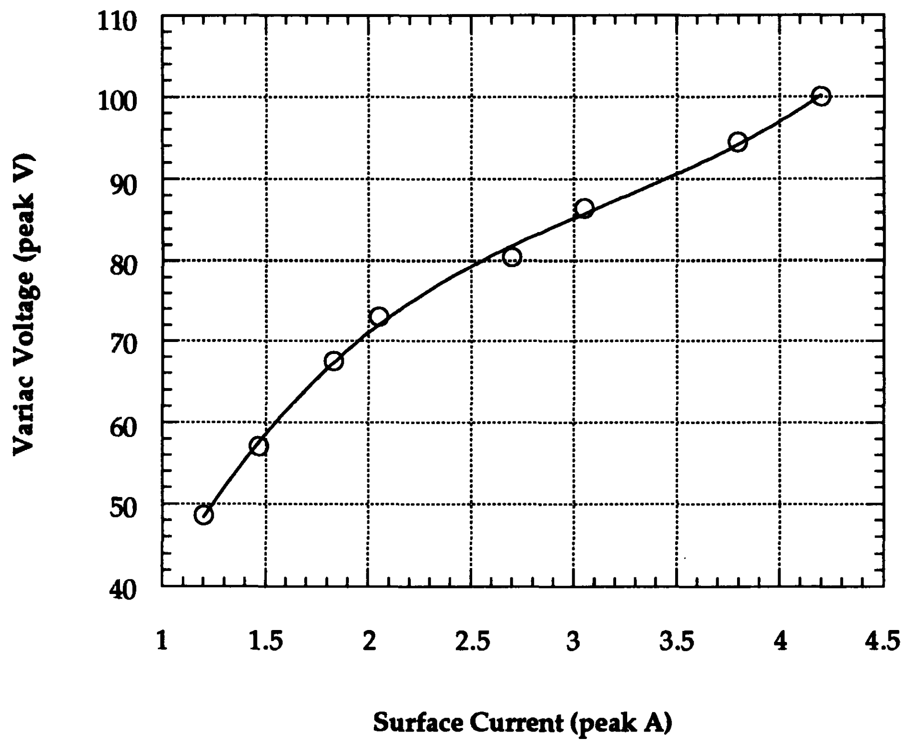

Figure 4.4: Surface current and surface voltage (variac voltage) combinations yielding 50 volts downhole for any load. Cable length = 28675 ft. ($V = -21.07 + 81.07i - 22.13i^2 + 2.31i^3$)

4.3 Curve Fitting

In real time operation, the surface current will rarely equal one of the sampled values. It is therefore necessary to generate a means of approximating the surface current and variac voltage pairs between the sampled points. The simplest method is to fit a curve to the data points. This has the advantage of expressing the "ideal response" in terms of a polynomial equation, which is relatively simple to implement compared to complicated interpolation.

The curve used in Figure 4.4 and for the data for all cable lengths was a third order polynomial derived by the method of Least Squares. Polynomial fits were compared to exponential and logarithmic fits of data for the entire range of cable lengths. In all cases, the polynomial fit described the data more accurately. Higher order curve fits may have been more accurate. However, a third order fit represented a compromise between accuracy and perceived speed of computation.

No polynomial of reasonable order will fit the data points exactly; any curve fit will be an approximation. However, as long as the points on the derived curve cause downhole voltages within the ±10% limits, this method is acceptable. An experiment was conducted to determine whether a third order polynomial was reasonable. The downhole voltage was manually set to 45, 50, and 55 v for a series of 8 loads across most of the operating range (11w, 111w, 261w, 361w, 511w, 611w, 761w, 861w). The resultant variac voltage / surface current combinations were recorded for each load. This experiment was repeated for cables between 6025 and 28675 ft.

Figure 4.5 shows data using one such cable length. The upper curve shows the variac voltage / surface current combinations that will yield 50 v downhole, the maximum allowable downhole voltage. Correspondingly, the lower curve shows the minimum allowable downhole voltage. The plot shows that the calculated curve falls between the upper and lower limits across the entire range of voltages and currents. Experiments with other cable lengths yielded similar results.

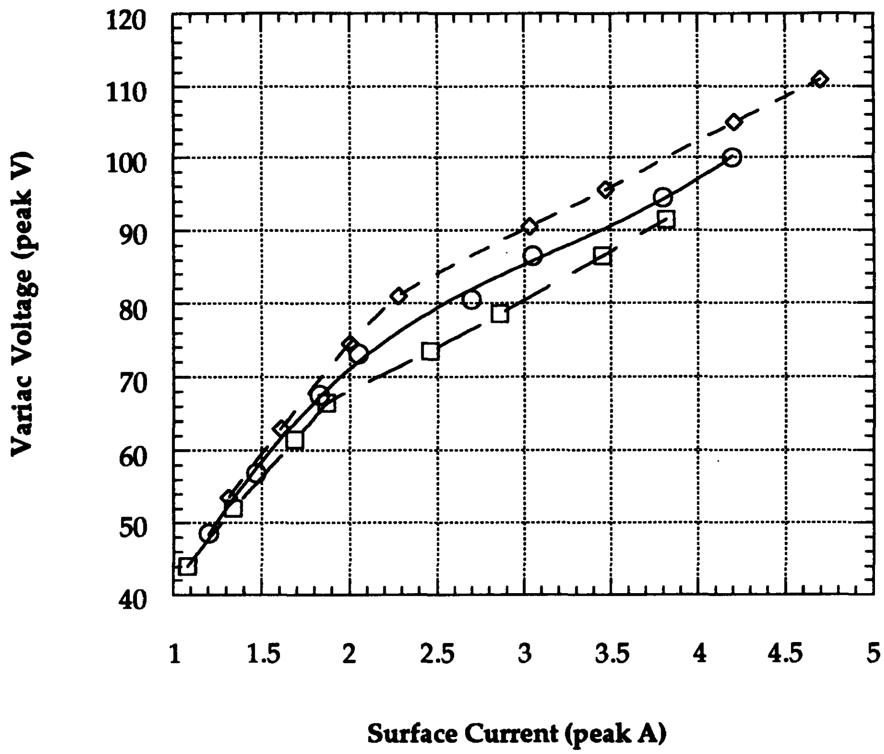

Figure 4.5: Predicted curve vs. ±10% tolerance limits. Upper and lower traces show surface (variac) voltage and current combinations that yield a downhole voltage of 55 and 45 volts, respectively.

Hence, it can be concluded that a third order least squares curve fit is sufficient for this application. Once the curve is generated, the system is prepared for real time control. Here is how it would work.

4.4 Theory of Operation

The operation of the regulator can be best understood with an example. Figure 4.6 shows a set of three curves. The dashed curves show the variac voltage and surface current pairs allowing the downhole voltage to vary and holding the load constant at 11 W and 511 W, respectively. The solid curve represents the "ideal response"; the variac voltage and surface current pairs holding the downhole voltage constant at 50 v, and varying the load.

Assume the system is initially in equilibrium at point 'A' on the graph; that is, the load is 11 W and the downhole voltage is 50 v. Now, suppose the load suddenly increases to 511 W. Recall that the variac voltage is controlled manually. Therefore, before the system can react, the variac voltage remains constant. However, due to the increase in the load, the current drawn from the supply, and hence from the surface, should increase in the short run. This causes the system to move to point 'B' in the graph. Point 'B', however, yields a downhole voltage of 30 v. This is consistent with our intuition that the supply voltage sags in response to a load increase.

The controller detects the change in current, and issues commands to increase the variac voltage to Point 'C'. However, at this new variac voltage, a 511 W load has a natural response that causes the surface current to increase to point 'D'. The controller compensates again, by increasing the variac. The process continues until the new equilibrium is reached at point 'E'. An analogous adjustment process can be demonstrated for an instantaneous decrease in the load.

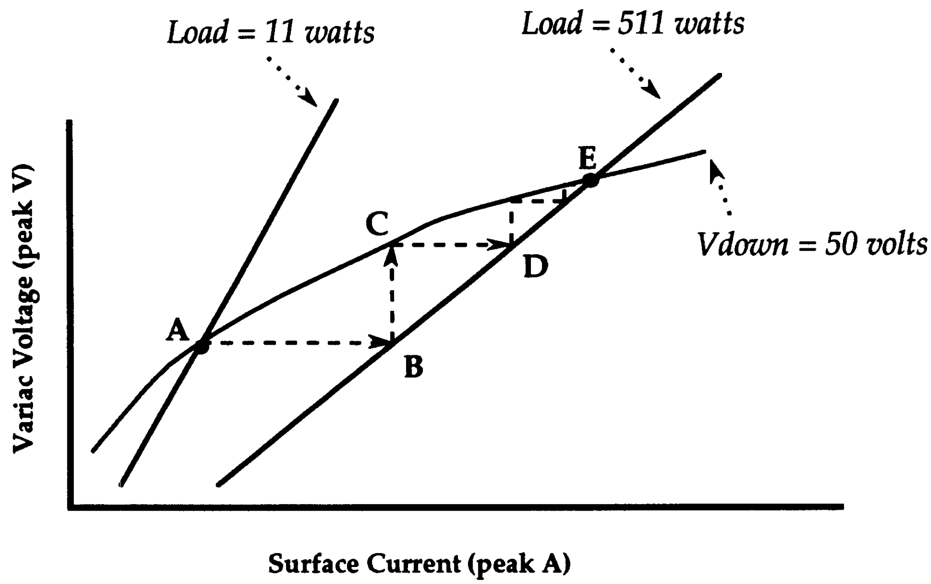

Figure 4.6: Adjustment of variac voltage based on surface current.

The process is actually smoother than outlined above. This is because the time it takes to adjust the variac voltage is much slower than the time it takes for the surface current to respond to changes in the voltage. In other words, before the variac voltage has been fully adjusted, the surface current changes, which causes a new 'desired' variac voltage. In reality, the adjustment process from point 'A' to point 'E' is as shown in Figure 4.7.

To reiterate, each load has some natural response. The controller attempts to impose some ideal response. It simply adjusts the variac voltage in the right direction until the natural and desired responses coincide.

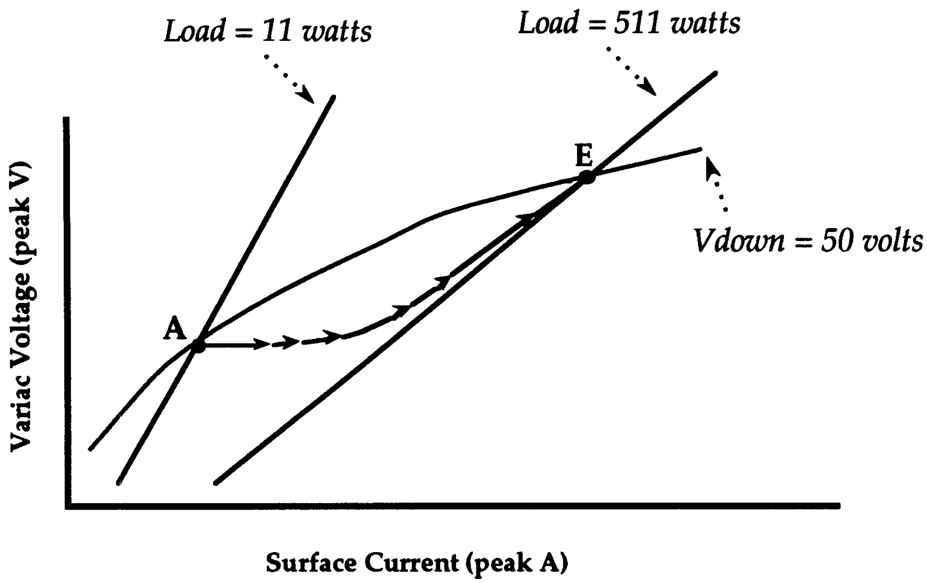

Figure 4.7: Actual adjustment of variac voltage based on surface current.

4.5 Benefits of the Proposed System

This system offers many benefits over the previous systems. First it is faster than other surface regulators that rely on the telemetry. Telemetry-based regulators are limited by the 15 Hz signal speed; it takes 66 ms to transmit the feedback from the output to the controller. The proposed system, however, is limited by the frequency of the current and voltage wave forms. because the signals are symmetric, the system can compute the peak values of them within one half of the time period of these signals. The time it takes to transmit information to the controller is therefore 1/120 Hz or 8.3 ms. This is an improvement by a factor of 8, in theory.

Of course, this is orders of magnitude slower than the speed attainable in some of the downhole solutions. However, this system is remarkably more feasible (less costly and simpler to implement) than any of the downhole solutions. This system would require only minimal modifications to existing hardware. As will be discussed in Chapter 6, the only additional hardware will be a small circuit board that will reside in the Tool Module.

This system is also more robust than the current system. It will be compatible with a host of telemetry systems. It characterizes the cable and the environment dynamically, which means it is compatible with any cable type.

This system also improves the stepping algorithm of the software regulator. Under the existing method, the variac is increased or decreased by trial and error until the downhole supply arrives at the correct voltage. However, the inclusion of an ideal response curve in the new method allows the system to "aim" at a target variac voltage. Adjustment can therefore be more swift and effective, with less fear of overshooting.

Another beauty of the system is that it can operate in parallel with the existing system; that is, the two systems can coexist. This allows the software regulator to remain in tact in case it becomes desirable to override the new controller. This turns out to be vital, because the new system requires the existing system for calibration (see Chapter 6).

Chapter 5

Comparing the Performance of Both Systems

To demonstrate the effectiveness of the proposed solution, a PC-based model of the controller was implemented in a laboratory. This first half of this chapter presents the hardware and software used for this purpose. The second half discusses the experiments used to compare the performance of this system against the existing system, and presents the results of this comparison.

5.1 Hardware Description

Figure 5.1 shows a block diagram of the test system. Refer to Appendix B for a complete diagram and more detailed specifications for the test system. The surface generator was connected to a cable. Three combinable logging cables were used to provide variable total lengths between 6025 and 28675 feet. A downhole converter was connected to the bottom end of the cable. A set of variable power resistors were used to model the supply load (see Appendix C). The components of the controller will now be discussed in turn.

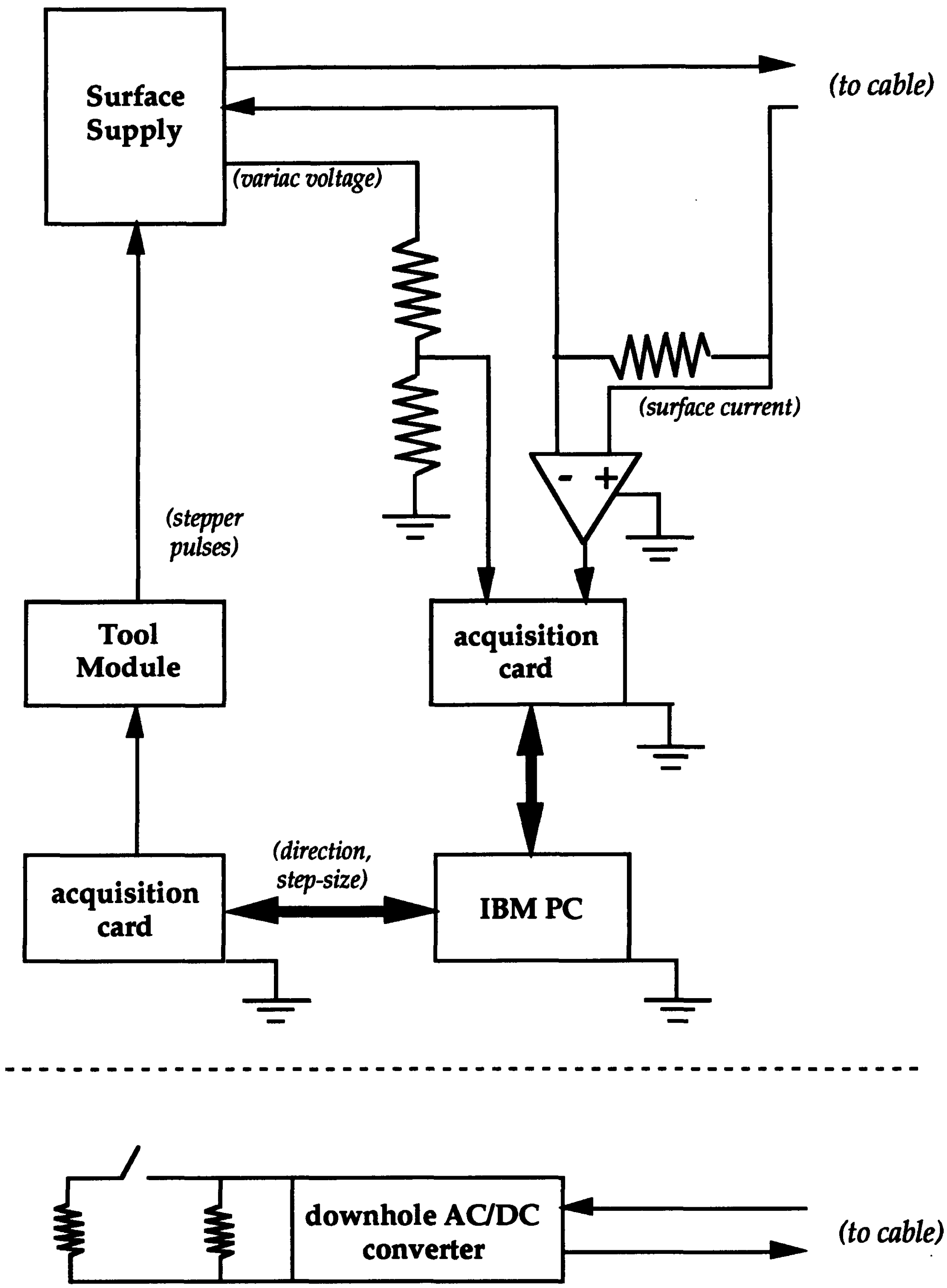

Figure 5.1: Block Diagram of Laboratory Controller

5.1.1 Surface Current Sensor

First, a mechanism was needed for measuring the surface current. This was done by using a sense resistor in series with the line. A 0.1 Ω resistor was placed in series with the return conductor of the logging cable, at the head end of the cable. Logging cables have a nominal resistance of .0109 Ω/ft per conductor. The return armor has a resistance of .00125 Ω/ft (see Appendix A). A 6000 foot cable therefore has a resistance of:

$$
\begin{aligned}
R_{\text{total}} &= \left(R_{\text{cable}} + R_{\text{return armor}}\right) \times 6000\text{ft} \\
&= \left(\frac{0.0109\,\Omega/\text{ft}}{4} + .00125\,\Omega/\text{ft}\right) \times 6000\text{ft} \\
&= 23.85\Omega \\
&\approx 24\Omega
\end{aligned}
$$

A 0.1 Ω sense resistor accounts for less than .5% of the total resistance. For longer cables, this figure is even smaller. Therefore, including it will not significantly increase the power lost in the cable.

The input range of this analog channel was set to ±1 volt. The current signal produced a voltage safely less than half of this:

$$
\begin{aligned}
V &\le I_{\text{max}} \times R \\
&\le 4\text{Amps} \times 0.1\Omega \\
&\le 0.4\text{Amps}
\end{aligned}
$$

It must be warned that because of the current and voltage levels in this system, .25 W or .5 W resistors are inadequate for this environment. The power rating on a 0.1 Ω resistor for this application must be greater than:

$$
\begin{aligned}
P_{rated} &\geq I^2 \times R \\
&\geq 4^2 \times 0.1 \\
&\geq 1.6\text{watts}
\end{aligned}
$$

A challenge in designing the laboratory controller was assuring that all parts of the system had a common ground, or grounds that were within several volts of one another. Because of the extreme levels of voltage generated by the surface supply, floating grounds could destroy the circuit boards within the PC and posed a serious health risk to the operator. The data acquisition card used to process the current signal allowed differential inputs. However, it had a common mode rejection voltage range of ±10.5 v, which meant that the differential input signal ground could not differ from the acquisition card ground (the PC chassis ground) by more than 10.5 v[1]. It was for this reason that the sense resistor was placed in the return leg of the current path. The voltage of the conductors at the head end of the cable was hundreds of volts higher than the acquisition card's ground.

It turns out that this modification can be conveniently made within the Tool Module. This will be further explored in Chapter 6.

5.1.2 Variac Voltage Sensor

As previously discussed, it was desirable to use the variac voltage as an indication of the surface voltage instead of the stepped-up voltage because it is

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[1]Omega Engineering, Inc. WB-FLASH 12 Operator's Manual (Stamford, CT: Omega Engineering Inc., 1993), p. 167.

smaller, and therefore less demanding in terms of the power rating used in the monitoring equipment.

The analog channel used for this signal, however, had a maximum voltage rating of ±2.5 v. Therefore, it was necessary to use resistors to divide the voltage to manageable levels. Figure 5.2 shows the configuration used. The 10 v zener diode was used to limit the voltage difference between the differential minus terminal (-) and the PC chassis ground (COM).

A 10 kΩ resistor was used to limit the current to the card during power-up. To turn on the surface supply, a switch is thrown which simultaneously closes the connections at 'A' and 'B'. However, due to mechanical limitations, the contacts will not close at exactly the same time. If 'A' closes first, then before 'B' closes, the only path to ground is through the acquisition card, as indicated by the arrow. The 10 kΩ resistor limits the maximum current into the card to be:

$$\begin{aligned} I_{\max} &= V/R \\ &= 150\text{volts}/10\times 10^3 \\ &= 15\text{mA} \end{aligned}$$

This is below the current rating of the card.

In the "steady state", after both switches are closed, the potential on both sides of the 10 kΩ resistor is the same, which allows the 83 kΩ and 1.2 kΩ resistors to function as a voltage divider. They effectively reduce the 150 v, maximum signal to a 2.13 v maximum signal:

$$\begin{aligned} V_{\text{card}} &\le \frac{V_{\text{variac max}} \times 1.2\text{k}\Omega}{1.2k\Omega + 83\text{k}\Omega} \\ &\le 2.14\text{volts} \end{aligned}$$

Both resistors were rated at 0.5 W. The maximum power generated across them in this configuration was only:

$$P_{max} = V^2 / R_{total}$$
$$= 150^2 / (83k\Omega + 1.2k\Omega)$$
$$\approx 0.27\text{watts}$$

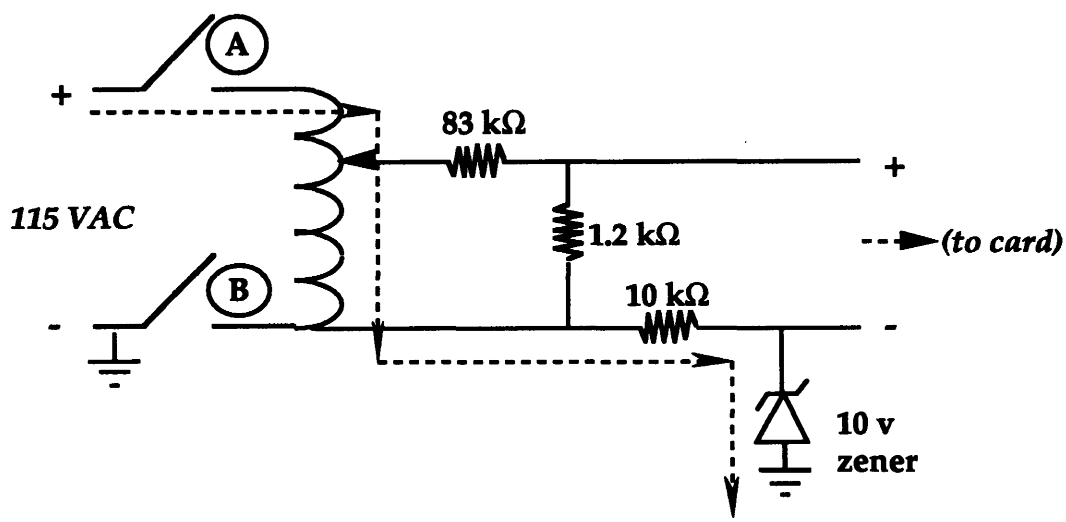

Figure 5.2: Variac Voltage Sensing Circuit

5.1.3 IBM PC and Data Acquisition Card

After the voltage and current signals were scaled down, they were passed to an IBM PC via a data acquisition card. This was the heart of the controller. The PC processed the incoming voltage and current signals. A high-speed data acquisition card was used to transform the analog voltage and current signals to digital representations[2]. The card was inserted in an IBM expansion slot. It provided the analog and digital I/O channels which allowed the PC to communicate with the rest of the system. The data acquisition card had a conversion rate of 1 MHz[3]. This allowed for many samples of the 60 Hz voltage and current wave forms each period. This particular card contained 8 differential analog inputs, 12 bit to 14 bit resolution, and 8 digital I/O lines.

This configuration was desirable in this stage of development for several reasons. First, the data acquisition card placed samples of the input wave forms in memory buffers within the PC in the form of arrays. These could then be processed by the PC's software. The software computed the peak value from these samples. However, if it later became desirable to use RMS or average values of the input signals, the software could be easily modified. In contrast, a purely hardware controller would require a completely different circuit.

A second advantage of using a PC to control the system is that it made modifying the system easy. A micro controller-based circuit would have required the burning and re-burning of PROMS, whereas PC-based controller modifications can be made quickly by simply recompiling the controlling program.

The PC was responsible for converting the voltage and current signals into the appropriate stepper commands for the variac controller. The program used to do this will be discussed later.

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[2]Ibid.

[3]This is the speed of the analog to digital conversion of the acquisition card. The maximum realizable sample rate of two analog channels with intermittent processing by the PC is a great deal slower than this. However, the relative speed of the input signals is slow enough to allow both signals to be more than adequately sampled.

5.1.4 Variac Controller

There are two components of the variac controller: the decode logic and the stepper motor drive circuit. The decode logic is responsible for translating the stepper motor commands (a step size and a direction) from the PC to a pulse stream proportional to the step size. The stepper motor drive circuit uses this stream to energize the windings of the stepper motor in the appropriate order to make it turn clockwise or counterclockwise.

It was desired to use as much of the existing circuitry as possible. This was consistent with the goal of designing a system that required minimal hardware modification. The existing stepper motor drive circuit, contained in the surface power generator, was usable in the new system without any modifications. A schematic of this circuit it contained in Appendix B. However, a complete description of the operation of the drive circuit is beyond the scope of this text. The existing decode logic was housed in the Tool Module, and was usable in the new system with only minimal modification. This section explores this circuitry.

Figure 5.3 shows a block diagram of the decode logic contained in the Tool Module. The subsystem takes as input from the PC a 4 bit step size (between 0 and 15) and a 1 bit direction (0=up, 1=down) and delivers a pulse stream as output to the stepper motor drive circuit.

An 80 Hz clock signal serves as the basis for the pulse stream that is sent to the power supply. The rest of the circuitry controls when this signal is allowed to pass to the variac circuitry in the surface supply. Although the 80 Hz clock signal limits the step rate of the variac, it is necessary to step this slow to prevent slipping. The stepper motor takes one step per pulse it receives. The motor requires a certain amount of torque to turn. The torque generated is proportional to the motor current.

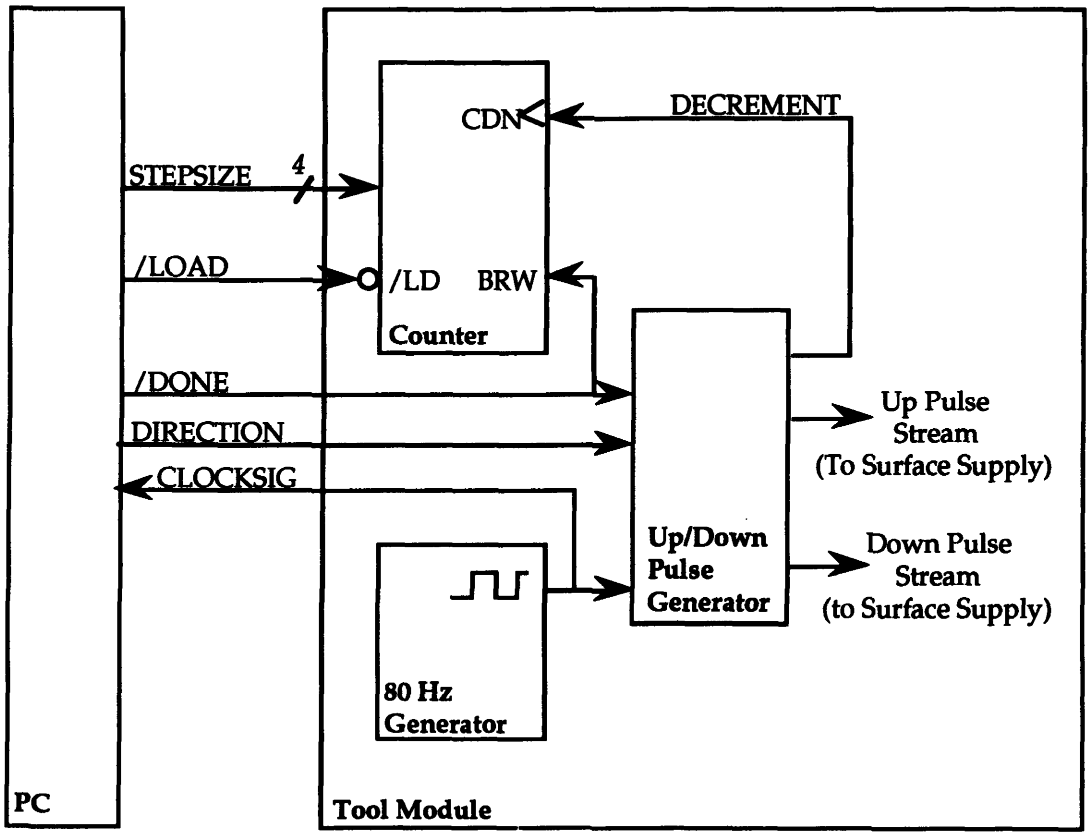

Figure 5.3: Variac Controller Block Diagram

The variac inertia requires that the torque be applied for a minimum time before the variac can move one step; if the torque is applied for too short of a time, the variac will not move at all, causing the motor to skip.

To generate the pulse stream, the step size is first loaded into a counter. The counter controls how many pulses are sent. As soon as the step size is loaded, BRW is pulled high. This enables the Up/Down Pulse Generator. The Pulse Generator gates the 80 Hz clock signal with the direction bit to decide whether the pulse stream is sent on the Up Pulse signal line or the Down Pulse signal line. With each pulse, the counter is commanded to decrement the count by one (CDN). When the count reaches 0, BRW goes low, which both disables the Pulse Generator and signals the PC that the pulse stream has been sent, and that it may send the next set of stepper motor commands.

5.2 Controller Program

The code listing for this program is contained in Appendix B. First, the acquisition card must be initialized. The number of analog input channels and the delay between samples of these channels are set. The analog input range and resolution of these channels is also set. Each of the 8 digital I/O lines are appropriately configured for input or output. The delay between channel samples is also programmed.

Next, the controller derives the regulation curve. The downhole supply must be manually set to the lightest load condition. The variac voltage is manually adjusted to provide 50 v downhole. The program captures the peak variac voltage and peak surface current at this point by recording many samples of the wave forms, and scanning the samples for the largest value. The load is then increased by 100 W. The voltage is again manually adjusted to 50 v and the second peak voltage, peak current pair is recorded by the program. This process is repeated for the following loads: 111 W, 261 W, 361 W, 511 W, 611 W, 761 W, and 861 W. The exact load increment or number of loads is not important, as long they are uniformly spaced along most of the operating range.

Chapter 6 will describe how it is possible to use the surface computer to execute this calibration sequence prior to the start of an actual logging operation. The computer unit can vary the achieve a variable load by adjusting the amount of power drawn by motors in certain modules. It then regulates the voltage much as is currently done, and sends a pulse to this controller unit to record the voltage and current at that instant.

Once the voltage and current pairs are recorded, the program performs a third-order Least Squares curve fit to the data points. This generates a "prediction curve." It is then ready to begin real-time regulation.

The program runs in a loop. In each iteration, it records samples the variac voltage and current wave forms for slightly longer than one half of the period of the wave form (8.5 ms). The delay between samples was set on the acquisition card to allow 25 samples of each channel during the half period of the 60 Hz signals. The peak of each signal is then computed.

After the peaks have been computed, the prediction curve is used to calculate the variac peak target voltage. The actual voltage is compared to the target voltage. If the actual is within a specified tolerance, there is no need to regulate, and the voltage and current are sampled again.

If, however, there is a large difference between the actual and target voltage, the step size necessary to correct is computed. 1 step of the variac corresponds to approximately a 0.8 v change in the variac voltage. Conservatively, if the voltage difference is greater than 15 v, the step size is set to 15. If the difference is between 15 and 7, the step size is 7. If the difference is between 6 and 3, the step size is 3. Less than this, the step size is

1. If the target exceeds the actual, the direction bit is set to step up, otherwise, it is set to step down.

The program then waits in a loop for the next rising edge of the 80 Hz clock signal. This is done to assure that the first pulse to the stepper drive circuit will be executed for the full period of the clock signal, which prevents slipping. After the clock edge arrives, the program raises the Load signal on the counter within the stepper motor decode logic. The step size and direction bit are presented to the counter next. The Load signal is then pulled low which causes the counter to load the values. The decode logic then begins its generation of the pulse stream, and ultimately the variac rotation.

The program waits in a loop while the variac is stepping. When BRW goes low, the system has completed stepping, and is ready for the next command. This completes the loop. The voltage and current are re-sampled, a target computed, and the adjustment process repeats.

Because the decode logic uses a 4 bit counter to generate the pulse stream, it cannot step more than 15 steps at a time. Therefore, if the voltage difference is large, the target and actual voltage will not converge after one iteration. This is acceptable. The reason is because as the actual voltage changes, the surface current will change, which will cause a new target voltage to be computed. The target voltage tells only the direction of correction, and gives only an approximation of the magnitude of the desired change. Therefore, the aim is approach - not to realize - the target voltage.

It could be argued that the system should single step and compute the new voltage and current at each period. However, while this would make the system sensitive to a rapidly fluctuating load, it limits the effective step speed to 60 Hz. In fact, the nature of the load is that it changes suddenly, but relatively infrequently. By stepping multiple times, the system can utilize the

80 Hz step speed. More importantly, if a more powerful stepper motor is used in the future, a higher clock speed may be possible. A system that steps multiple times before sampling the input wave forms will be able to take advantage of the increased clock speed.

5.3 Performance Results

With this test set-up, it was possible to compare the performance of the new system to that of the existing system. As discussed in Chapter 2, each system's response to an instantaneous load change was observed and recorded[4]. Two qualities were examined: the maximum deviation of the voltage in response to the load change, and the length of time it took to return the voltage to within the ±10% tolerance limits of the 50 v target.

The performance experiments were conducted in a laboratory. This test, therefore, fails to take into account the effect of temperature gradients in the earth and other environmental conditions. However, this experiment was intended to compare the *relative* performances of the two systems. In this sense, the experiment was adequate; both systems were subjected to the same load conditions and cable configurations.

Performance comparisons were carried out for the following load changes: 11 to 261 W, 11 to 511 W, 11 to 761 W, 261 to 761 W. This was done with the following cable lengths: 12175 ft, 22525 ft, and 28675 ft. Figures 5.4 and 5.5 show the typical response of both systems to load changes. Voltage

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[4]Refer to Chapter 2 for a description of the experiment. Refer to Appendix D for schematics of the mechanism used to switch the load instantaneously.

adjustment in the new system is much smoother and hence quicker than in the existing system. This was the case for all load changes and cable lengths.

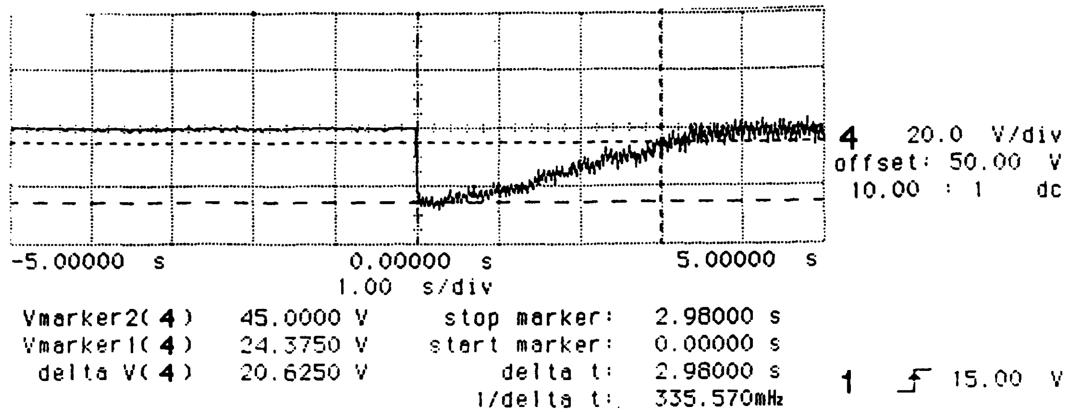


Figure 5.4A: Existing system response to load change of 11 to 761 watts. (Cable length = 22525 ft.)

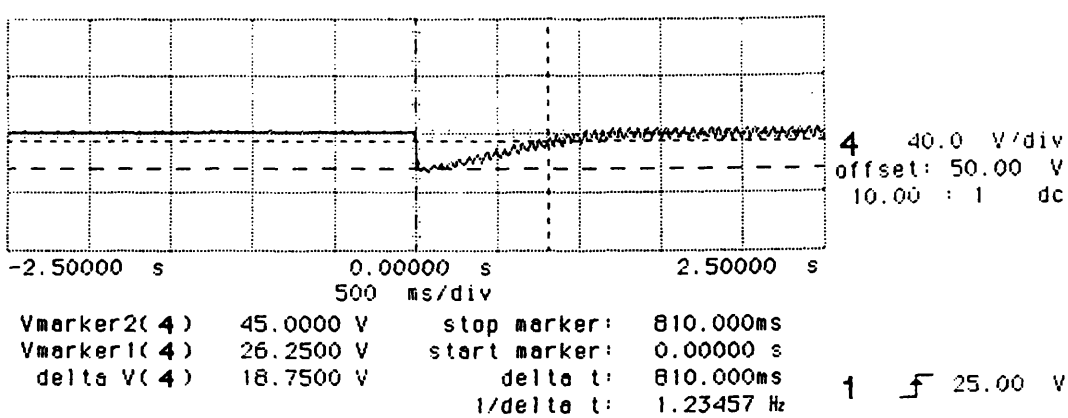


Figure 5.4B: New system response to load change of 11 to 761 watts. (Cable length = 22525 ft.)

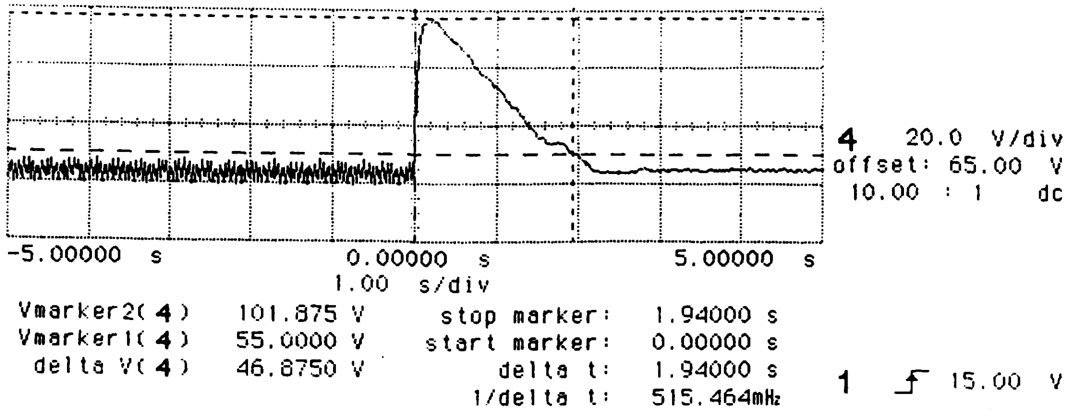


Figure 5.5A: Existing system response to load change of 761 to 11 watts. (Cable length = 22525 ft.)

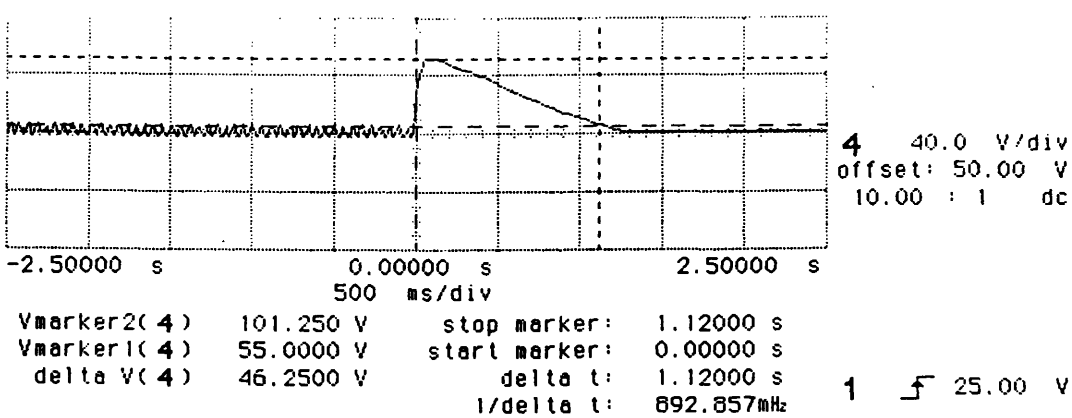


Figure 5.5B: New system response to load change of 761 to 11 watts. (Cable length = 22525 ft.)

Table 5.1 compares the maximum deviations of the supply voltage for each system in response to various load changes for different cable lengths. Unfortunately, the new system offers no appreciable improvement in the limiting how far the voltage undershoots or overshoots. The average improvement in the voltage deviation from 50 v for all loads and all cables was only 1.65 v. However, the new system offered a substantial improvement in the speed of recovery.

Table 5.2 lists the times it took for each system to stabilize the voltage after the load changes. The table shows that at 12175 ft, the new system was an average of 3.3 times faster than the existing system. At longer cables, the performance improvement seems to decrease slightly. With the maximum cable length, 28675 ft, the new system performs an average of 2.7 times better than the existing system. The table further shows that the new system performance can be as great as 5 times faster than current performance, and is always at least 1.85 times better. Thus, it can be concluded that the new system will be approximately 3 times faster than the current system, a significant improvement.

These experiments were conducted when the surface computer was not performing any other tasks besides regulating the 50 v supply. In addition, only one module was used in the string, the downhole converter. With no other tasks to perform, or other module data to handle, the delay incurred by the software was at its minimum. In an actual logging operation, this would never be the case. Therefore, it could be argues that the plots of the existing system's performance represent the "best case" performance.

Cable Length (ft)	Load Change (watts)	Existing System Voltage Deviation from 50 v	New System Voltage Deviation from 50 v
12175	11-261	14.4	11.9
12175	261-11	15.9	14.7
12175	11-511	18.8	16.3
12175	511-11	26.9	26.9
12175	11-761	23.4	21.3
12175	761-11	37.5	40
12175	261-761	14.4	13.1
12175	761-261	15	18.1
22525	11-261	16.2	14
22525	261-11	19.1	18.4
22525	11-511	21.9	19.4
22525	511-11	36.3	37.5
22525	11-761	25.6	23.7
22525	761-11	51.9	51.3
22525	261-761	17.8	16.9
22525	761-261	19.1	24.4
28675	11-261	17.5	14.4
28675	261-11	23.8	19.1
28675	11-511	25	20
28675	511-11	41.3	34.4
28675	11-761	27.5	23.7
28675	761-11	58.8	51.3
28675	261-761	18.1	15
28675	761-261	23.1	23.8

Table 5.1: Comparison of maximum deviations of supply voltage for existing and new systems in response to instantaneous load change.

However, the computer unit used in these experiments was part of a network of other surface units throughout the building. Each machine expends a significant amount of overhead to remain on the network and communicate with other machines. In an actual logging environment, surface computer units are isolated and do not face this same overhead.

Cable Length (ft)	Load Change (watts)	Regulation Time for Existing System (ms)	Regulation Time for New System (ms)	% improvement (Existing / New)
12175	11-261	1220	240	5.083333333
12175	261-11	980	340	2.882352941
12175	11-511	1300	410	3.170731707
12175	511-11	1110	600	1.85
12175	11-761	2420	540	4.481481481
12175	761-11	1420	910	1.56043956
12175	261-761	1810	380	4.763157895
12175	761-261	1040	440	2.363636364
22525	11-261	1000	410	2.43902439
22525	261-11	1730	470	3.680851064
22525	11-511	2080	600	3.466666667
22525	511-11	1510	870	1.735632184
22525	11-761	2980	810	3.679012346
22525	761-11	1940	1120	1.732142857
22525	261-761	2240	540	4.148148148
22525	761-261	1360	620	2.193548387
28675	11-261	1500	510	2.941176471
28675	261-11	1240	570	2.175438596
28675	11-511	2380	620	3.838709677
28675	511-11	1460	880	1.659090909
28675	11-761	2880	810	3.555555556
28675	761-11	2360	1110	2.126126126
28675	261-761	1750	470	3.723404255
28675	761-261	1210	640	1.890625

Table 5.2: Comparison of regulation times for existing and new systems (time to regulate supply voltage to between 45 and 55 volts after load change).

Therefore, it might be argued that this experiment was conducted under the "worst case" conditions.

The point is, the delay introduced by the software is not easily quantified, and therefore unpredictable. The performance of the new system, however, does not depend on what the software happens to be doing at a particular instant. Its performance is predictable and consistent.

5.4 Variac Problems

Originally, greater performance improvements than these were anticipated. However, there was a severe limitation to the system that prevented this system from performing faster.

By far, the greatest bottleneck in the system was the mechanism used to increase and decrease the surface voltage, namely the variac / stepper motor configuration. As discussed previously, pulses to the stepper motor windings are issued at a rate of 80 Hz. If pulses are issued any faster than this, the motor may skip.

The variac voltage varies approximately 0.8 v with each step. Large load changes, however, require large variac adjustments. At 28,675 ft, a 750 W load change demands approximately a 50 v adjustment of the variac voltage. It takes a significant amount of time to adjust the voltage by this much:

$$\begin{aligned} t &= (50 \text{ volts}) \times \left(\frac{1 \text{ step}}{0.8 \text{ volts}} \right) \times \left(\frac{1 \text{ sec}}{80 \text{ steps}} \right) \\ &= .78 \text{ seconds} \end{aligned}$$

Hence, even if the new variac voltage were known as soon as the load changed, it would take almost 800 ms simply to turn the variac. Table 5.2 shows that the total time it takes for the new system to correct from a 750 W increase is 1100 ms. The variac delay accounts for 71% of the delay.

Therefore, while a 3-fold performance increase may seem modest at first glance, it must be remembered that the constraint of using the variac system makes it impossible to realize much greater improvements than this.

This system does manage to remove all of the software delay present in the current system. Whereas the speed of the old system was limited by a combination of the variac, the software, and the telemetry, the speed of the new system is only limited by the variac system.

Another problem with the variac is that its performance varies from surface supply to surface supply. Figure 5.6 compares the response of the system to a load change of 750 to 0 W using two different power panels. The surface supply used for comparison of the existing and new system is denoted as 'A'. The alternate supply is denoted as 'B'. While adjustment of the voltage was smooth in both cases, the system with supply 'B' was slow to react to the change. With supply 'A', correction took 1120 ms. With 'B', it took 1530 ms, over 400 ms longer. The delay may be due to backlash in the variac between the brush and the windings in the variac. The point is, the performance of the variac is unpredictable, and dependent on the mechanical construction of the surface supply.

Similar plots of existing system performance using both surface supplies are not included. Performance varies unpredictably based on the software. Therefore, two trials using the same surface supply may not yield the same results. Hence, it is meaningless to compare the performance of the system using different surface supplies; it is difficult to identify how much of the regulation delay is due to the mechanical construction of the panel and how much is due to latency by the surface computer software.

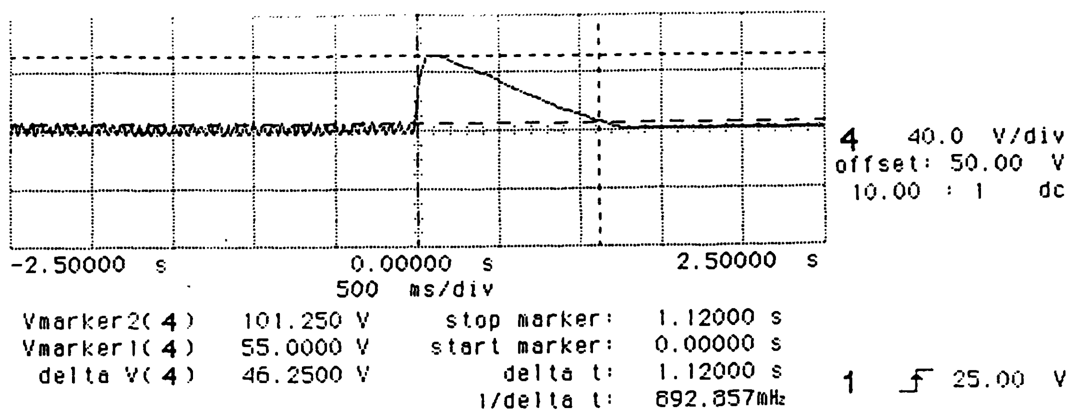


Figure 5.6A: Response of downhole supply voltage to load change of 761 to 11 watts using surface supply 'A'. (Cable length = 22525 ft.)

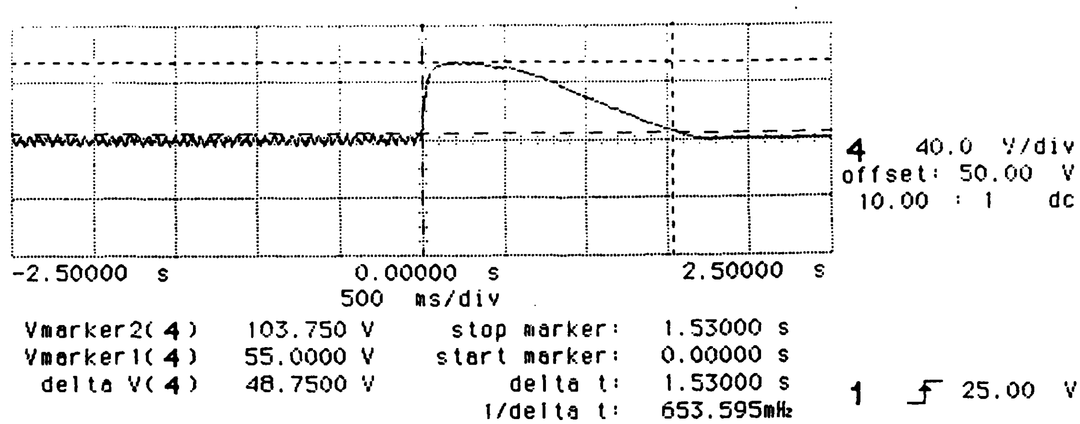


Figure 5.6B: Response of downhole supply voltage to load change of 761 to 11 watts using surface supply 'B'. (Cable length = 22525 ft.)

Chapter 6

Implementation Issues

This chapter explores the issues of implementing the proposed solution. The design of a hardware controller that embodies the PC-based controller of the previous chapter, as well as the necessary hardware and software modifications will be explored.

6.1 Hardware Implementation

Implementing the hardware for this system will require the design of new circuitry as well as the modification of some of the existing hardware.

Figure 6.1 shows a schematic diagram of the proposed circuit for the controller. The board would reside in the Tool Module, since the variac controller circuitry is contained here. This is also convenient because all of the control signals that the controller uses are accessible from within the Tool Module[1]. This is also convenient because the only piece of existing hardware that needs to be modified is the Tool Module.

[1]The variac voltage is not directly available within the Tool Module. It is possible to feed the variac voltage to the Tool Module through two unused pins within the Panel-Tool Module jumper cable. However, this would require a modification of the power panel. A more feasible solution might be to use the cable head voltage, which is available in the Tool Module.

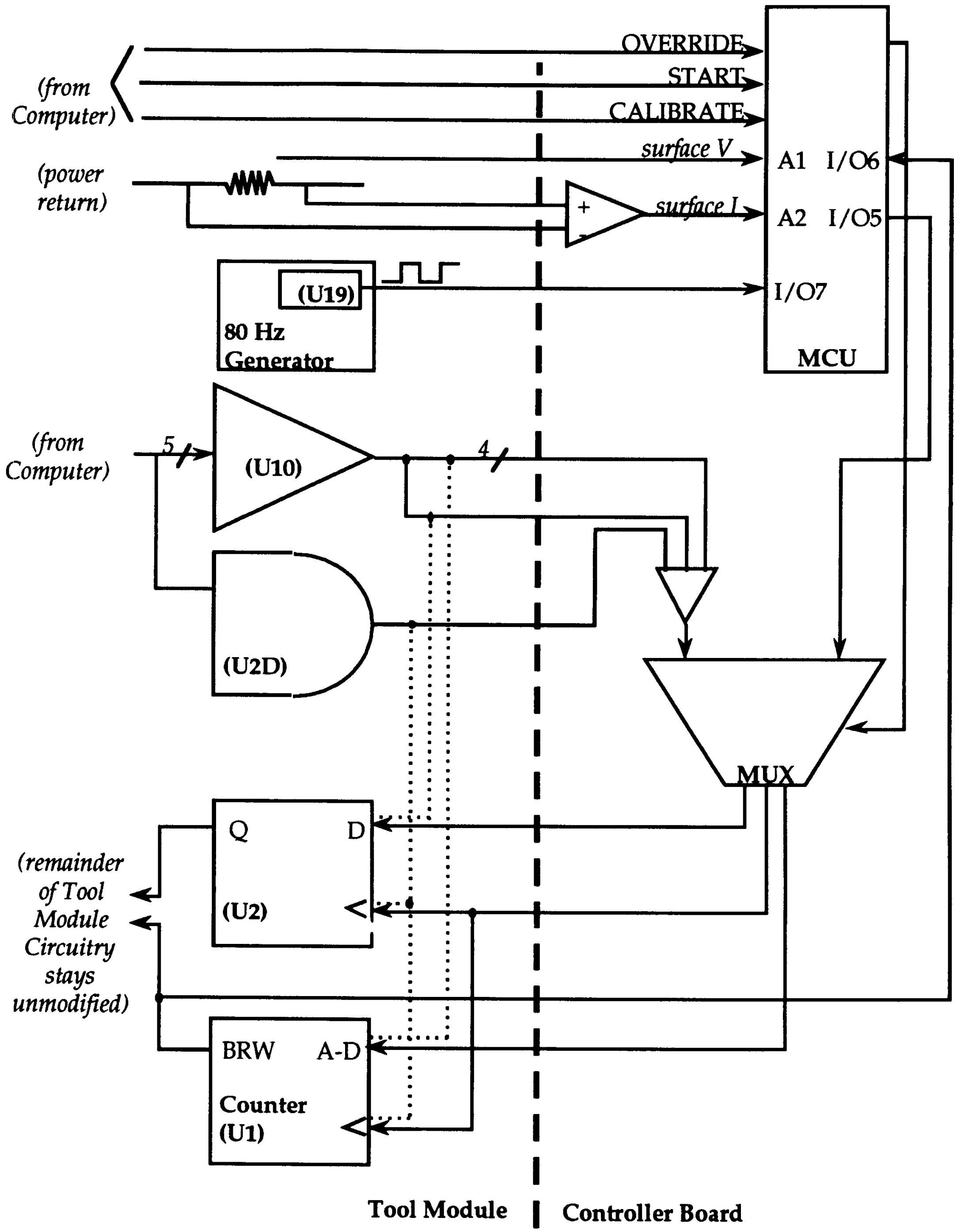


Figure 6.1: Block Diagram of Circuit Board and Necessary Modifications to Tool Module Circuitry (Dashed lines indicate old connections).

The heart of the circuit is a micro controller. One that was found to be feasible for this system was made by Philips (model 85C11)[2]. This particular MCU has analog input and digital I/O capabilities, and a 10 bit analog to digital converter. Even for conservatively large estimates of the current range, this gives a resolution of 4.88 x 10^{-3} A. For an 11 W load and 28675 ft of cable, a 5 v change downhole causes a .1 A change in the surface current. Hence, 10 bit resolution will be able to detect a .25 v change downhole. The downhole current change per 5 v downhole change is higher in all other load/cable configurations, which will result in even better sensitivity. Hence, 10 bit resolution is adequate for this application. The speed of the A/D is fast enough to allow 200 samples per cycle. The program for the controller will be burned into the PROM's located on the MCU.

The dotted lines show the old connections in the Tool Module. These will be replaced as shown. Instead of allowing the control signals from the computer unit to drive the variac controller directly, they will instead be routed through the new board. The six bits of control signals (LOAD, DIRECTION, and STEPSIZE) will be generated by both the computer unit and the MCU. A multiplexer decides which set of signals drives the variac controller. The status signals, BRW and 80HZ are fed from where they are generated within the Tool Module to the MCU. BRW signals the MCU that the stepper is finished stepping and ready for the next command. 80HZ is used to synchronize the stepper commands from the MCU with the variac control circuitry.

---

[2]Philips Semiconductors. Philips Semiconductors Micro controller Products (Philips Semiconductors, 1992), pp. 479-516.

A 0.1 Ω resistor will be inserted in the return line of the power signal. A differential amplifier will be used to generate a 0-5 v analog signal that the MCU can accept. A differential amplifier and a resistor divider will accomplish the same thing for the surface voltage signal.

The computer unit issues three signals: OVERRIDE, CALIBRATE, and STORE. OVERRIDE controls whether it is the MCU-generated or computer-generated signals that drive the variac controller circuitry. CALIBRATE switches the mode of operation of the controller. In one mode, the controller records voltage and current values and computes the curve it will use for regulation. In the other mode, the controller regulates the downhole voltage. STORE is used to store voltage and current pairs during calibration.

6.2 Software Implementation

The software of the computer unit must be modified to accommodate the new system. First, a calibration sequence is needed.

As mentioned in Chapter 4, it would be desirable to calculate the curve used for regulation in real time, taking cable length and environmental factors into consideration. The structure of MDT makes this possible.

While most of the individual modules in an MDT tool string are application specific, two components are present in almost all configurations: a hydraulic module, heretofore referred to as the MRHY™, and a reservoir fluid pump module, heretofore referred to as the Pumpout™. All tool configurations will contain either or both modules.

A detailed description of the MRHY and Pumpout modules is beyond the scope of this text. The duty cycle of the motors in each of these modules can be varied by the surface computer, which adjusts the amount of power drawn downhole. After a tool has been lowered into the hole, and before logging begins, it is possible to operate these motors through the surface computer.

An experiment was conducted to test the amount of power drawn by these motors. Tool strings were assembled containing each module respectively. The duty cycle of each module was varied and the resultant power consumption was measured. Tables 6.1 and 6.2 show the results of this experiment. The duty cycle can effectively be varied between 70% and 99%. Below this, the motors stall. However, within this range, the power drawn from the supply can be varied between 0 and 517 W for the MRHY and between 0 and 835 W for the Pumpout. This makes it possible to use either of these modules for calibration prior to operation. Calibration would proceed as follows:

Before logging begins, the computer unit places the controller in CALIBRATE mode. The duty cycle of either motor is varied between 70% and 99% in small increments. A+ each increment, the software regulates the downhole voltage to 50 V. This is possible because all of the hardware for the existing regulation method will remain in tact. During the calibration sequence the slowness of the existing system is permissible, since no other modules rely on the supply and load changes will be gradual.

At each increment, after the voltage stabilizes, the computer issues the STORE signal, which causes the MCU to store the surface voltage and surface current.

After the last voltage and current pair has been recorded, the CALIBRATE signal is pulled low. The MCU then calculates a curve to fit the data points it recorded. The controller is then ready to regulate. The

OVERRIDE signal is dropped and the controller takes over. This completes the calibration sequence. The software routines to handle the calibration have yet to be written.

Motor Duty Cycle	Surface Voltage (v)	Power into load (w)
Idle	326	5.21
70%	415	146.6
80%	467	316.5
90%	502	473.1
95%	510	508.6
99%	522	517.1

Table 6.1: Power Drawn by MRHY module alone vs. MRHY motor duty cycle.

Motor Duty Cycle	Surface Voltage (v)	Power into load (w)
Idle	326	5.21
70%	483	408
80%	519	535.4
90%	555	711.8
95%	586	789.3
99%	596	835.8

Table 6.2: Power Drawn by Pumpout Module alone vs. Pumpout motor duty cycle.

Conclusion

This study was an attempt to address the issue of regulating MDT's high-voltage power supply. The present system were analyzed and characterized electrically. The sources of delay were identified. Several alternative regulation methods were investigated. The method that offered the best performance to cost tradeoff was pursued and implemented in a PC-based laboratory controller.

The proposed method avoids the challenging problem of monitoring the downhole voltage from the surface by instead monitoring the current drawn at the surface by the combined cable and supply load. From the current, the amount of necessary surface voltage correction to maintain 50 v downhole can be computed.

The results of this study indicate that such a method is capable of delivering a 3-fold increase in regulation speed over the existing system. Unfortunately, no improvement in the maximum deviation in response to instantaneous load changes was noted.

In this system, any method of regulation will ultimately be limited by the variac. The inertia of the variac requires that its driving motor be stepped slowly. For large voltage changes, the delay imposed by the variac is several hundred milliseconds and accounts for over 70% of the total regulation time.

Performance increases of greater than the 3-fold improvement achieved here will require that the variac issue be dealt with. One option is to replace the variac and stepper motor with an amplifier capable of adjusting large amounts of voltage quickly. The high cost of this option makes it undesirable. Another option is to replace the stepper motor with a more powerful motor. This would allow the variac to be stepped at a faster rate.

However, it is unclear whether the surface generator can accommodate a larger motor. The third option is to endure the delay of the variac. The method explored in this study requires only minimal modification of the existing hardware and is therefore inexpensive to implement. In addition, the motors that use the supply can tolerate a finite deviance from the supply's rated voltage of 50 v. The moderate increase achieved in this study may be adequate to prevent motor failure. Only field performance will reveal if this is the case.

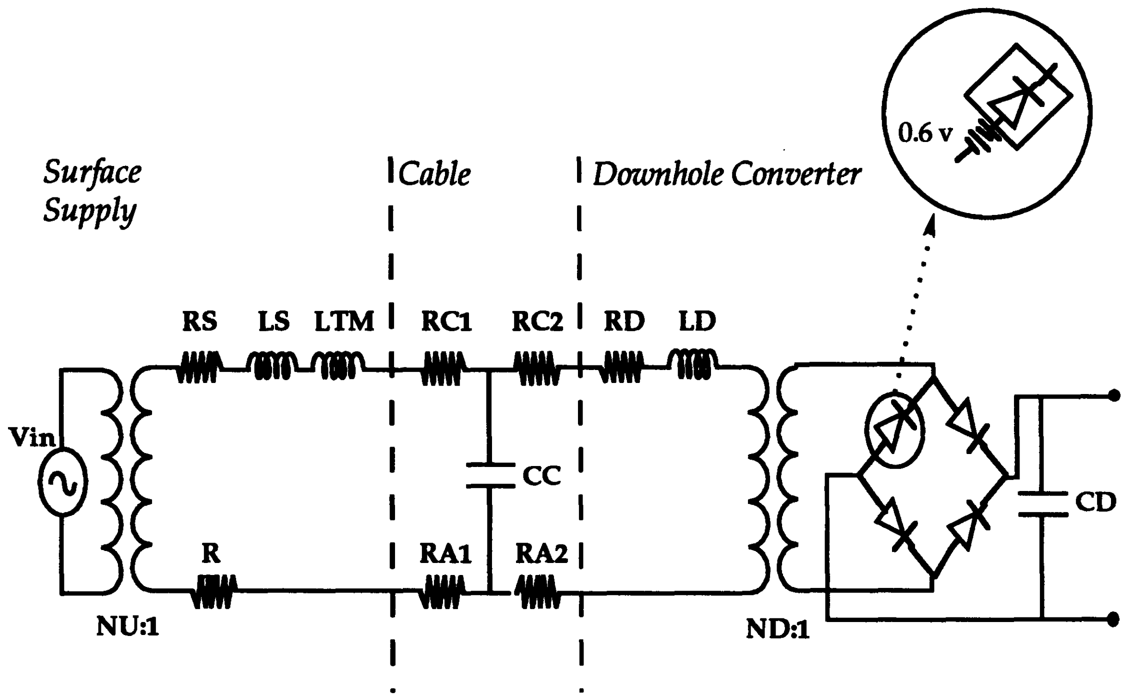
Appendix A

Electrical Characterization of Power Delivery System

To date, no accurate characterization of the system has existed. Failure to understand the nature of the system may have contributed to the poor performance of the existing regulator. Therefore, in conjunction with this study, an attempt was made to accurately characterize the system by developing a circuit model for it.

In obtaining the model, the system was broken down into its three constituent pieces: The surface power supply, the transmission line, and the downhole AC/DC converter. Each piece was analyzed individually, then the pieces were combined to provide a complete model. SPICE simulations were run to test the validity of the model. This Appendix explores the experiments used to inspect each component and presents the results of the simulations.

Figure A.1 shows the complete circuit model of the system. The following sections describe how each element in the model was derived. The schematic diagrams of the surface supply and downhole converter are confidential and therefore are not included here.



Vin = Variac output voltage
NU = Surface tr..nsformer turns ratio = **6.63**
RS = Surface transformer winding resistance = **3.156Ω**
LS = Surface transformer leakage inductance = **8 mH**
LTM = Tool Module Inductance = **2.5 mH**
RT = Current transformer winding resistance = **1.219 Ω**
RC1 = **RC2** = Cable resistance / 2 = **0.0013625 Ω/ft**
RA1 = **RA2** = Armor resistance / 2 = **.000625 Ω/ft**
CC = Cable capacitance = **260 pF/ft**
RD = Downhole . ..nsformer winding resistance = **9.31Ω**
LD = Downhole transformer leakage inductance =**7.7 mH**
ND = Downhole transformer turns ratio = **8.013**
CD = Filter capacitance = **4500 μF**

Figure A.1: Circuit Model of Power Delivery System

A.1 Surface Power Supply

There are three main components to the surface supply: the step-up transformer (T1), the transformer used in the return leg of the power signal to measure the current (T4), and the inductors within the Tool Module used to filter the high frequency telemetry signals. These were examined in turn.

(Note: No attempt was made to characterize the variacs. The winding resistance varies depending on the setting of the variacs. They were instead treated as part of the source. All "input voltages" to the system used in SPICE models were therefore taken at the output of the variacs.)

A.1.1 T1 Transformer

The dominant features of the T1 transformer were assumed to be the turns ratio, winding resistance, and the leakage inductance. To measure the turns ratio, the output of the transformer was open-circuited. A voltage was applied to the primary, and the resulting voltage was measured across the open terminals. In the open-circuit case, no current is drawn, which means the winding resistance will not effect the voltage. Table A.1 shows the results of this experiment. Taking the turns ratio (N_u) as the output voltage (V_{out}) divided by the input voltage (V_{in}) the average turns ratio was 6.63.

To determine the winding resistance of the secondary, a dc ohmmeter was connected across the output of the open-circuited transformer. The primary winding of T1 actually consists of the two secondary windings of the variacs in parallel. The secondaries were shorted together, and the parallel resistance was measured. This was taken as the resistance of the primary of T1. The resistance of the primary and secondary windings of T1 were .037 Ω and 1.89 Ω, respectively. Referred to the secondary, this gives a resistance of 3.156 Ω.

Vin	Vout	Nu=Vout/Vin
20	133.1	6.655
31.5	209	6.634920635
46	304.8	6.626086957
60.6	402	6.633663366
71.1	472	6.638537271
86.2	572.4	6.64037123
96	636.3	6.628125
104.8	695.1	6.632633588
116.9	774.4	6.624465355
135.8	900	6.627393225
145.9	967	6.627827279

Table A.1: Open circuit voltage measurements for T1 surface supply transformer. (Average turns ratio = 6.63).

To measure the leakage inductance of T1, the output was shorted. The inductance was measured across the primary (both of the variac outputs) with an ac bridge. The inductance was found to be 122 μH. To confirm, T1's primary was shorted and the inductance was measured across the output. The inductance was found to be 8.0 mH. Referring the first reading to the secondary gives an equivalent of 5.3 mH, which did not agree with the second measurement. Assuming a constant error in the measurements taken at the primary and secondary, the error in the measurement from the primary will be N_u^2 times larger than the error in the measurement from the secondary when both are referred to the secondary. Hence, the measurement at the secondary was taken as more accurate and used in the model.

A.1.2 Current Transformer

The primary winding of the current transformer (T4) is in series with the return leg of the power signal. Its presence introduces series resistance to the signal. The winding resistance was found by removing T4 from the circuit and measuring the resistance across the primary with a dc ohmmeter. It was found to be 1.219 Ω.

A.1.3 Tool Module Inductance

Each of the power conductors is fed through a 10 mH inductor within the Tool Module before the signal is applied to the logging cable. The conductors are in parallel, giving an equivalent series inductance of 2.5 mH.

A.2. Logging Cable

The logging cable consists of seven parallel conductors, insulated with polypropylene and sheathed with a stainless steel armor. There are two dominant components of the impedance: the series resistance and the parallel capacitance between each conductor and the return (the armor). The power signal for this application has a low frequency (60 Hz). The series inductance of the cable only becomes significant at high frequencies. Hence, it is permissible to treat the cable as having only resistive and capacitive components.

A.2.1 Piece wise Resistance

To measure the series resistance, three logging cables of known length were used. The resistance of each of the logging conductors 2,3,5, and 6 was measured with a dc ohmmeter. These values were then divided by the total length of the cable to determine the per foot resistance. Table A.2 shows the results of this experiment. The average resistance of these conductors was found to be .0109 Ω/ft. The equivalent resistance of the four parallel conductors was .0109/4 = .002725 Ω/ft. The armor was measured similarly and was found to have a resistance of .00125 Ω/ft.

A.2.2 Piece wise Capacitance

To measure the capacitance, a voltage was applied to the head of the cable from the surface supply. Conductors 2,3,5, and 6 were shorted together. The far end of the cable was open circuited. The surface voltage was varied and the current drawn at the surface was measured. In the absence of a load, the only current drawn from the supply should be due to the cable capacitance. Capacitive impedance is given by:

Conductor Number	Cable Length (ft)	Total Resistance (Ω)	Resistance per foot (Ω/ft)
2	6025	66	0.010954357
3	6025	68	0.011286307
5	6025	68	0.011286307
6	6025	67	0.011120332
2	12175	133	0.010924025
3	12175	132	0.010841889
5	12175	132	0.010841889
6	12175	133	0.010924025
2	16500	179	0.010848485
3	16500	178	0.010787879
5	16500	178	0.010787879
6	16500	179	0.010848485

Table A.2: Cable resistance measurements.

$$Z_C = \frac{1}{Cj\omega} \quad (1)$$

Equating this to the definition of complex impedance for any system, yields:

$$\frac{\mathbf{V}}{\mathbf{I}} = \frac{1}{Cj\omega} \quad (2)$$

Solving for C and taking the magnitudes of both sides gives:

$$C = \frac{|\mathbf{I}|}{|\mathbf{V}|\omega} \quad (3)$$

Tables A.3 and A.4 show the measured voltages and currents, and the calculated capacitances for three different cable lengths. The frequency of the signal was 60 Hz (ω=377 radians). The capacitance of the power conductors to the armor depends on the voltage on conductors 1,4, and 7 as well. The experiment was conducted with 1,4, and 7 shorted together, then repeated with 1,4, and 7 open circuited and floating. The results show that the state of conductors 1,4, and 7 has little effect on the capacitance of the line. The calculated average capacitance was approximately 260 pF/ft for all cases.

Cable Length (ft)	Surface Voltage (rms)	Surface Current (rms)	Total Capacitance (F)	Capacitance (pF per/ft)
6025	118	0.07	1.57353E-06	261.1665976
6025	205	0.121	1.56563E-06	259.8562147
6025	299	0.178	1.57909E-06	262.0899769
6025	389	0.233	1.58878E-06	263.6986572
6025	478	0.256	1.4206E-06	235.7836396
6025	598	0.359	1.5924E-06	264.2986003
6025	709	0.432	1.6162E-06	268.2496168
6025	800	0.483	1.60146E-06	265.8023047
6025	910	0.543	1.58277E-06	262.6999776
12175	103	0.122	3.14182E-06	258.0550045
12175	200	0.234	3.10345E-06	254.9033491
12175	321	0.381	3.14832E-06	258.5887478
12175	405	0.483	3.16338E-06	259.8255094
12175	489	0.583	3.16241E-06	259.7463034
12175	606	0.725	3.17339E-06	260.6483994
12175	717	0.854	3.15935E-06	259.4946419
12175	817	0.971	3.15251E-06	258.9326722
12175	923	1.09	3.13244E-06	257.2850058
16500	104	0.17	4.33585E-06	262.7787774
16500	201	0.33	4.35488E-06	263.9323278
16500	303	0.5	4.3771E-06	265.2785172
16500	405	0.67	4.38812E-06	265.9466261
16500	504	0.83	4.36824E-06	264.7416441
16500	600	0.99	4.37666E-06	265.2519894
16500	695	1.17	4.46539E-06	270.6298911
16500	783	1.29	4.37005E-06	264.8516323
16500	907	1.51	4.41599E-06	267.6358986

Table A.3: Calculating cable capacitance from voltage and current. Conductors 1,4,7 were shorted together. (Avg. C ≈ 260 pF.)

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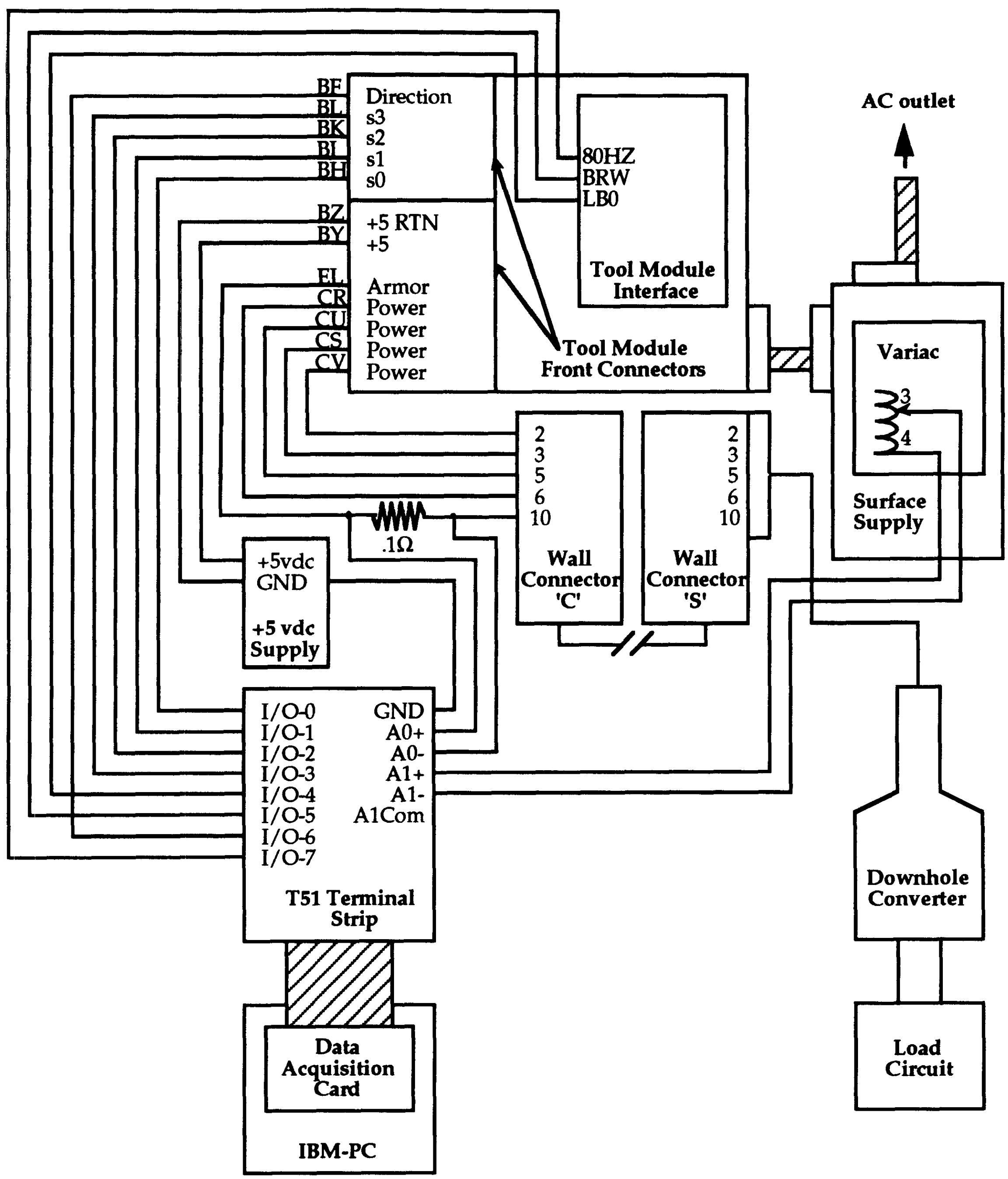
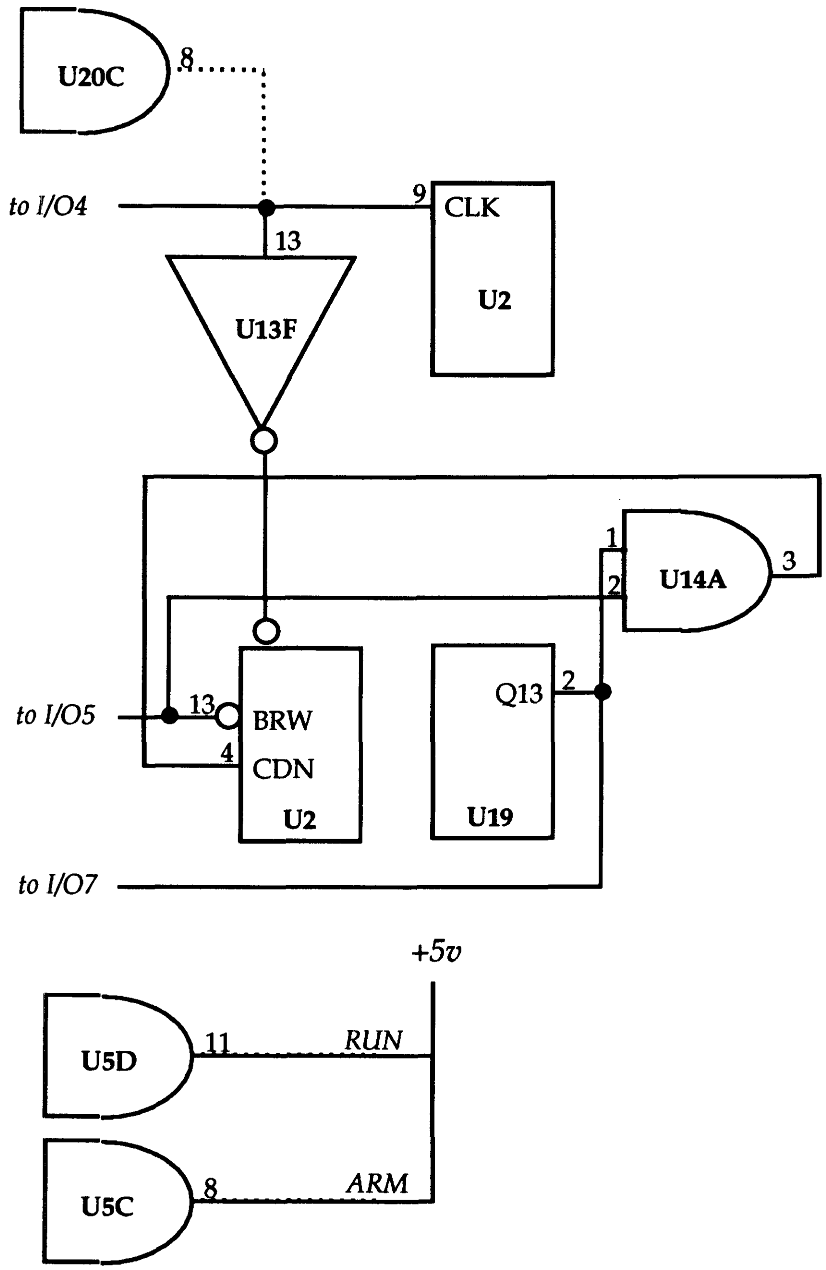
Appendix B

Laboratory Set-up Specifications



Laboratory Controller Set-up



Controller connections to Tool Module Interface

PC Controller Code

```
DECLARE SUB AM1 (SEG a%, SEG b!, BYVAL c%, BYVAL d%)
DECLARE SUB AM3 (SEG a%, SEG s%, BYVAL c%, BYVAL d%)

10 REM *** regulate; manual calibrate;  variable-step; 80hz clock ***

20 CLS
30 safe = 0
40 DATA &hb8, &h59, &h47, &hcd, &h60, &h90, &h90, &hca, &h06, &h0, 0
50 o$ = "O" + CHR$(0)
60 i$ = "I" + CHR$(0)
80 b4 = 0: b3 = 0: b1 = 0: b0 = 0
90 DIM cal(40): REM calibration array


500 REM
510 REM i/o assignments:
520 REM 0-3: step-size bits
530 REM 4: = load step counter
540 REM 5: = step counter carry out
550 REM 6: = direction
560 REM 7: = step enable clock signal
570 DIM a%(8), b(200)
580 DIM g%(8), i(8)

600 REM *** set i/o bits ***
610 c$ = "S" + CHR$(0)
620 FOR x = 0 TO 4
630 a%(x) = 1
640 NEXT x
650 a%(5) = 0: a%(6) = 1: a%(7) = 0
660 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1000 REM *** calibrate ***

1010 REM *** set number of analog channels ***
1020 c$ = "N" + CHR$(0)
1030 a%(0) = 2
1040 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1050 REM *** set range ofanalog channels ***
1060 c$ = "r" + CHR$(0)
1070 a%(0) = 11
1080 a%(1) = 9
1090 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1100 REM *** set delay btn samples ***
1110 c$ = "d" + CHR$(0)
1120 a%(0) = 170
1130 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1140 REM *** set analog resolution ***
1150 c$ = "a" + CHR$(0)
1160 a%(0) = 16
1170 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1180 c$ = "c" + CHR$(0)
1190 CALL AM1(SEG a%(0), SEG b!(0), VARSEG(c$), SADD(c$))

1200 count = 25
1210 h$ = "H" + CHR$(0)
```

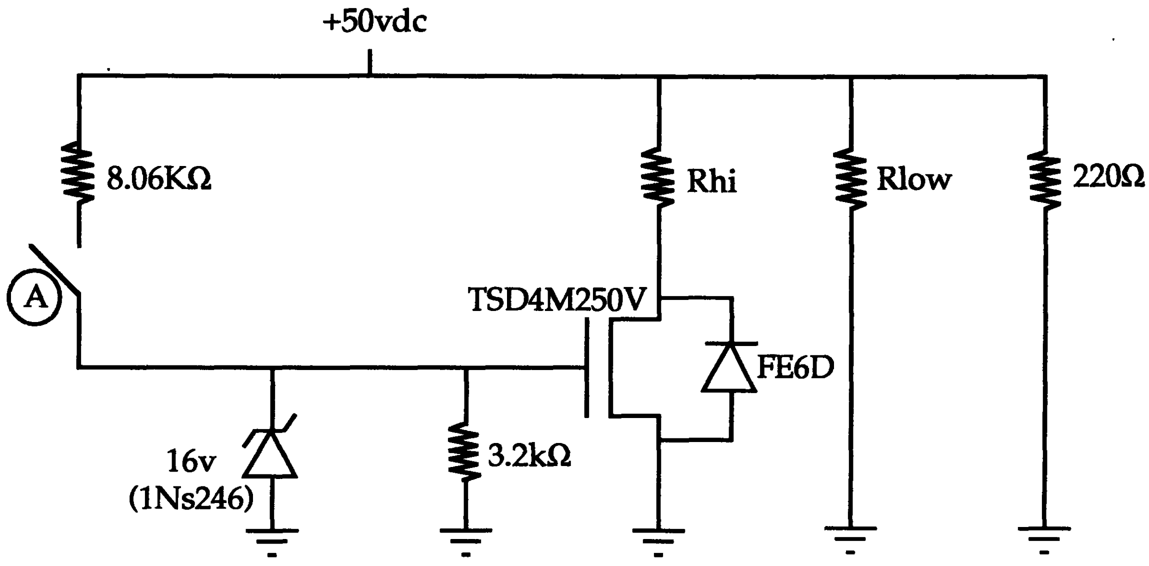
```
1220 g%(0) = count: g%(1) = 0

1300 PRINT "Current Monitor Demonstration Program"
1310 PRINT "------------------------------------"
1320 PRINT : PRINT
1330 PRINT "Entering calibration sequence...This routine"
1340 PRINT "will ultimately be controlled by MAXIS.  The downhole"
1350 PRINT "voltage must be manually stabilized 50volts for several"
1360 PRINT "different loads.  For each load, a calibration pulse"
1370 PRINT "is sent to this system, which causes the voltage and"
1380 PRINT "current to be recorded."
1390 PRINT "For this demonstration, in the absence of MAXIS, the"
1400 PRINT "voltage must be manually set for a series of loads by you."
1410 PRINT "Attach a load to the output of the supply, stabilize"
1420 PRINT "the voltage to 50, then press 'c'.  Do this for several"
1430 PRINT "loads. Press 'q' when finished."
1440 PRINT : PRINT
1480 REM *** auto calibrate ***
1499 j = 0
1500 INPUT "Enter C)alibrate or Q)uit "; q$
1510 IF q$ = "q" THEN GOTO 2100
1520 vsum = 0: isum = 0
1530 FOR y = 1 TO 50
1540 CALL AM1(SEG g%(0), SEG b!(0), VARSEG(h$), SADD(h$))
1550 ipeak = 0: vpeak = -1
1560 FOR x = 0 TO count * 2 - 1 STEP 2
1570 itest = ABS(b(x)): vtest = ABS(b(x + 1))
1580 IF itest > ipeak THEN ipeak = itest
1590 IF vtest > vpeak THEN vpeak = vtest
1600 NEXT x
1610 isum = isum + ipeak: vsum = vsum + vpeak
1620 NEXT y
1630 cal(2 * j) = isum / 50: cal(2 * j + 1) = vsum / 50
1640 j = j + 1
1650 GOTO 1500

2100 k = 0: REM *** sum of xj
2110 m = 0: REM *** sum of xj^2
2120 n = 0: REM *** sum of xj^3
2130 p = 0: REM *** sum of xj^4
2140 q = 0: REM *** sum of xj^5
2150 r = 0: REM *** sum of xj^6
2160 s = 0: REM *** sum of yj
2170 t = 0: REM *** sum of xj * yj
2180 u = 0: REM *** sum of xj^2 * yj
2190 v = 0: REM *** sum of xj^3 * yj

2200 FOR z = 0 TO j - 1
2210 k = k + cal(2 * z)
2220 m = m + cal(2 * z) ^ 2
2230 n = n + cal(2 * z) ^ 3
2240 p = p + cal(2 * z) ^ 4
2250 q = q + cal(2 * z) ^ 5
2260 r = r + cal(2 * z) ^ 6
2270 s = s + cal(2 * z + 1)
2280 t = t + cal(2 * z) * cal(2 * z + 1)
2300 u = u + cal(2 * z) ^ 2 * cal(2 * z + 1)
2310 v = v + cal(2 * z) ^ 3 * cal(2 * z + 1)
2320 NEXT z
```

```
2330 detA = j * m * (p * r - q * q) - j * n * (n * r - p * q) + j * p * (n * q - p * p)
2340 detA = detA - k * k * (p * r - q * q) + k * n * (m * r - n * q) - k * p * (m * q - n * p
2350 detA = detA + m * k * (n * r - p * q) - m * m * (m * r - n * q) + m * p * (m * p - n * n
2360 detA = detA - n * k * (n * q - p * p) + n * m * (m * q - n * p) - n * n * (m * p - n * n

2370 det0 = s * (m * (p * r - q * q) - n * (n * r - p * q) + p * (n * q - p * p))
2380 det0 = det0 - k * (t * (p * r - q * q) - n * (u * r - v * q) + p * (u * q - v * p))
2390 det0 = det0 + m * (t * (n * r - p * q) - m * (u * r - v * q) + p * (u * p - v * n))
2400 det0 = det0 - n * (t * (n * q - p * p) - m * (u * q - v * p) + n * (u * p - v * n))

2410 det1 = j * (t * (p * r - q * q) - n * (u * r - v * q) + p * (u * q - v * p))
2420 det1 = det1 - s * (k * (p * r - q * q) - n * (m * r - n * q) + p * (m * q - n * p))
2430 det1 = det1 + m * (k * (u * r - v * q) - t * (m * r - n * q) + p * (m * v - n * u))
2440 det1 = det1 - n * (k * (u * q - v * p) - t * (m * q - n * p) + n * (m * v - n * u))

2450 det2 = j * (m * (u * r - v * q) - t * (n * r - p * q) + p * (n * v - p * u))
2460 det2 = det2 - k * (k * (u * r - v * q) - t * (m * r - n * q) + p * (m * v - n * u))
2470 det2 = det2 + s * (k * (n * r - p * q) - m * (m * r - n * q) + p * (m * p - n * n))
2480 det2 = det2 - n * (k * (n * v - p * u) - m * (m * v - n * u) + t * (m * p - n * n))

2490 det3 = j * (m * (p * v - q * u) - n * (n * v - p * u) + t * (n * q - p * p))
2500 det3 = det3 - k * (k * (p * v - q * u) - n * (m * v - n * u) + t * (m * q - n * p))
2510 det3 = det3 + m * (k * (n * v - p * u) - m * (m * v - n * u) + t * (m * p - n * n))
2520 det3 = det3 - s * (k * (n * q - p * p) - m * (m * q - n * p) + n * (m * p - n * n))

2530 a0 = det0 / detA
2540 a1 = det1 / detA
2550 a2 = det2 / detA
2560 a3 = det3 / detA

2900 PRINT : PRINT "Finished calibration..."
3000 INPUT "ready to start...hit return to begin regulating : "; a$
3010 CLS : PRINT "press any key to quit..."



3400 REM *** regulation loop ***

      ; *** sample v,i waveforms ***
3410 CALL AM1(SEG g%(0), SEG b!(0), VARSEG(h$), SADD(h$))

3420 REM *** find current and voltage peaks ***
3430 icur = 0: vcur = -1
3440 FOR x = 0 .. .   .    - 1 STEP 2
3450 itest = ABS(b(x))
3460 vtest = ABS(b(x + 1))
3470 IF itest > icur THEN icur = itest
3480 IF vtest > vcur THEN vcur = vtest
3490 NEXT x

3500 REM *** calculate target voltage ***
3510 vtarg = a0 + a1 * icur + a2 * icur ^ 2 + a3 * icur ^ 3
3520 IF vtarg < .95 THEN vtarg = .97
3522 IF icur > .45 THEN GOSUB 9000: GOTO 3400: REM * safety rewind *
3525 REM PRINT icur, vcur, vtarg

3530 IF INKEY$ <> "" THEN GOTO 9999: REM timeout

3540 REM *** set direction bit ***
3541 delta = ABS(vtarg - vcur)
```

```
3542 b0 = 0: b1 = 0: b2 = 0: b3 = 0: REM default=15
3543 IF delta < .24 THEN b3 = 1: REM 7
3545 IF delta < .11 THEN b2 = 1: REM 3
3546 IF delta < .04 THEN b1 = 1: REM 1

3550 s = 0
3560 IF vcur > 1.03 * vtarg THEN s = 1
3570 IF (vcur > .97 * vtarg) AND (vcur < vtarg * 1.03) THEN b1 = 1: b2 = 1: b3 = 1: b0 = 1

4000 REM *** wait for leading edge of enable clock ***
4010 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(i$), SADD(i$))
4020 IF a%(7) = 1 THEN GOTO 4010

4025 REM *** start load pulse ***
4030 a%(0) = b0: a%(1) = b1: a%(2) = b2: a%(3) = b3: a%(6) = s
4040 a%(4) = 1
4050 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(o$), SADD(o$))

4065 REM *** load counter with step value, direction ***
4070 a%(0) = b0: a%(1) = b1: a%(2) = b2: a%(3) = b3: a%(6) = s
4080 a%(4) = 0
4090 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(o$), SADD(o$))

4100 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(i$), SADD(i$))
4110 IF a%(5) = 1 THEN GOTO 4100
4200 GOTO 3400

9000 REM *** safety rewind ***
9005 FOR z = 1 TO 6
9010 a%(0) = 0: a%(1) = 0: a%(2) = 0: a%(3) = 0: a%(6) = 1
9020 a%(4) = 1
9030 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(o$), SADD(o$))
9040 a%(0) = 0: a%(1) = 0: a%(2) = 0: a%(3) = 0: a%(6) = 1
9050 a%(4) = 0
9060 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(o$), SADD(o$))
9070 CALL AM1(SEG a%(0), SEG i!(0), VARSEG(i$), SADD(i$))
9080 IF a%(5) = 1 THEN GOTO 9070
9090 NEXT z
9100 RETURN


9999 PRINT "Program finished."
```

Appendix C

Load Switch Circuit Diagram



R_{low} and R_{hi} are the variable resistive loads, configurable by the user. When Switch A is open, only R_{low} draws current. When Switch A is closed manually, both R_{hi} and R_{low} draw current. The load wattage was computed as Power=$50^2/R$, where R is R_{low}, or $R_{high}+R_{low}$, respectively.

The 220Ω resistor maintains a minimum load of 11 watts. The FET must be capable of switching 20 Amps.

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