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Improving Manufacturing Processes Through Energy Monitoring

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College of Technology

Improving Manufacturing Processes through Energy Monitoring

In partial fulfillment of the requirements for the
Degree of Master of Science in Technology

A Directed Project Report

By

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March 29, 2012

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DEDICATION

I dedicate this project to my parents who have always been my biggest supporters when it comes to education.

I also dedicate this to the Big Guy Upstairs, because without Him I wouldn't have anything.

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I would like to thank my advising committee for their support and willingness to work with me through some of difficulties that arose throughout this project.

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EXECUTIVE SUMMARY

Energy efficiency and sustainability are very popular topics in the current field on manufacturing. With the increase in use of automation technology as well as the recent growth in the area of energy management, there is much focus on the overall improvement of manufacturing processes. For this research a project was completed to create a system that could improve both process efficiency as well as decrease energy consumption. By taking a look at the machine level energy consumption of an automated piece of manufacturing equipment, by eliminating waste in process, both energy efficiency and operational efficiency can be improved.

Using electrical specifications from a Hurco Hawk 5M 3-axis CNC machine, an electrical cabinet was built to take the signals off the machine and output them to a LabVIEW DAQ Module. A program created in LabVIEW was designed to analyze power waveform signals and determine the state of operation of a machine. Then, total power consumption and cost of energy at the different states was calculated and displayed in a fashion that would be usable by an operator or a manager to make informed decisions on how to improve the process.

CHAPTER 1. INTRODUCTION

1.1. Significance

Sustainability initiatives and operational improvements in a manufacturing plant can be identified and met through a number of different methods. One of the common methods used to tie sustainability information with operational practices is through the use energy management systems (EMSs). EMSs typically involve the analysis of current energy usage and energy waste, and that data is displayed to a manager who, based on the information, suggests potential improvements that can be made (Gorp, 2004). Another common means to gain relevant manufacturing information is through the use of manufacturing execution systems (MESs). MESs monitor at all the operational process data in a manufacturing production line (work in process, finished goods inventory, queue time, etc.) and relay that information to an operator in a practical way (Soplop, Wright, Kammer, & Rivera, 2009). The objectives of both those systems are to increase data flow to improve operations, but with different intent. This thesis explores the process of developing an EMS that works at a more focused machine level, similar to an MES system, in attempt to combine the benefits of both systems into one data acquisition and display system.

This research provides manufactures currently employing automation technology an opportunity to increase their production capabilities as well as increase energy efficiency in their operations. For this report the focus was on the monitoring of an automated manufacturing machine. Due to this fairly narrow focus, this data will

hopefully be used as groundwork research for on the effectiveness of combining sustainability initiatives and operational efficiency initiatives into one system. If considerations are made in the design phase for energy sustainability in use, then the potential benefits could be even greater than they are currently, ultimately improving operations in the manufacturing industry and decreasing the footprint left behind.

1.2. Scope

This research explores potential improvements in both energy management and operations management. Considering the magnitude of both fields, more specific intent needs to be defined. In terms of energy management, this thesis focuses on the monitoring of electrical energy used by a manufacturing machine. The power consumption of start-up, shut-down, and run-mode procedures are of particular interest. The question of study is: Can electrical energy consumption by manufacturing machines be monitored with the intent of identifying energy waste that could be eliminated and does not negatively affect machine and production efficiency? By narrowing the focus of this study in such a way, other energy losses, such as wasted heat energy, are not considered. The focus is solely on electrical energy consumption by machines. The unit of measurement will be in kilowatts (kW) and kilowatt hours (kWh).

Manufacturing machinery is a subcategory within the scope of operations management, but is still a very broad field. For this experiment, the manufacturing machines tested will be CNC milling machines. The machine will be connected to, and

the data displayed in, LabVIEW. The selection of the machinery was based on availability amongst the automation machines owned by the Manufacturing Engineering Technology Department at Purdue University and the Dublin Institute of Technology.

1.3. Statement of the Problem

Manufacturing today is a rapidly changing environment. Technologies are continuously being improved and new technologies explored in order to decrease cost and maximize efficiency and profit. At the same time however, manufacturing retailers and consumers are becoming increasingly aware of sustainability issues which, in turn, is encouraging manufacturers to incorporate sustainability initiatives into their processes (Blanchard & Spada, 2006). Approaching manufacturing from a sustainability or, to be more specific, energy efficient viewpoint is a very practical approach. The industrial sector consumes roughly 30% of the total U.S. energy consumption. Considering that manufacturing makes up 70% of the industrial sector's energy use, it is apparent that there is a lot of energy consumed in manufacturing operations (U.S. Energy Information Administration, 2009). This research has analyzed potential for energy efficient improvements in manufacturing to be made through the means of automated machine monitoring and display. Energy management (EM) is a rapidly growing industry, but there is little focus from the EM perspective on process control energy management. Process control improvements typically happen as part of a manufacturing execution

system (MES), and until recently most execution systems have not put much emphasis on sustainability (Soplop, Wright, Kammer, & Rivera, 2009).

1.4. Research Question

The main research question which this study answered is the following:

Can manufacturing operations be, through the use of automated energy monitoring, managed to both maximize energy efficiency and operational efficiency?

- a. How would energy be quantified?
- b. What type of energy information would be necessary?

1.5. Assumptions

This research was conducted with the inclusion of the following assumptions:

- The CNC machine used in the study is an accurate representation of the similar types of machines used in industry.
- The results from this study can have significance in most, if not all, manufacturing operations.
- Other types of manufacturing machinery (robots, laser cutters, presses, etc.) would provide similar energy savings results as those used in the study.

1.6. Limitations

This research was subject to the following limitations:

- The scope of machinery tested is limited to that available at Purdue University and the Dublin Institute of Technology (DIT).
- The study disregards all industrial issues aside from the manufacturing process itself.
- The electrical energy consumed is the only energy measurement taken in this experiment.
- The project will be completed at three different universities and is subject to equipment and faculty limitations as a result.

1.7. Delimitations

The research was affected by the following delimitations:

- This study will not encompass all types of common manufacturing machinery.
- The energy consumed as a result of working with different materials is not measured.

1.8. Definition of Key Terms

Automation - the technique, method, or system of operating or controlling a process by highly automatic means, as by electronic devices, is reducing human intervention to a minimum (Dictionary.com Unabridged, 2010).

Energy Management – Focus on technologies that increase energy efficiency of key energy-consuming processes and equipment (Lighting, HVAC, waste-heat recovery, and variable speed drives) (Gorp, 2004).

Sustainability – The Sustainability Ecosystem...Environmental compliance, communication, and operational efficiency (Stokes, 2009).

Manufacturing Execution System (MES) - deliver information that enables the optimization of production activities from order launch to finished goods. Using current and accurate data, MES guides, initiates, responds to, and reports on plant activities as they occur (MESA, 1997).

Start-Up Procedure –All the steps the need to be completed from the time the power is supplied to a machine until the time that the machine is ready to run a program.

Shut-Down Procedure – All the steps performed in the process of turning off a machine in the according to machines suggested routine.

Hibernation Mode – The ability of a controlled device to go into a non-operating state that requires no energy to be expended or generated.

1.9. Summary

This chapter has noted significance of the study, cause for this research and other introductory information on this subject. The assumptions, limitations, and delimitations that put constraints on this study were also identified. The following chapter explores some of the related literature on this topic.

CHAPTER 2. LITERATURE

2.1. Energy Efficiency

“Green thinking is smart thinking. At least that’s what governments, businesses and consumers all seem to agree on. Concern for the environment is no longer a fringe issue that interests only a small segment of the population, and industries...have taken heed” (Liberg, Rosqvist, & Farnsworth, 2009, p. 1). It is with that idea in mind that this directed project has focused on sustainable improvements in the manufacturing industry specifically on automation processes. In the article *Green Robotics*, aforementioned, Liberg et al. are referring specifically to the plastics industry; however the push towards improving sustainability in operations is affecting all industries. Lanz, et al. (2010) state “Over the past years, institutions in general are increasingly interested and involved in sustainability and social responsibility...Considering sustainable manufacturing, a number of indicators have been proposed and currently are being researched” (p. 1). Concentrating on sustainability improvements in the industrial sector (where manufacturing consumes 70% of the energy) is a logical place to try achieving energy savings, because the industrial sector consumes 30% of the total energy consumption with 28.2 quadrillion BTU being consumed in 2009 (EIA, 2009, p. 38). Another advantage to having an eco-friendly manufacturing mindset is that it can provide a company with a competitive edge. “The ability to make informed decisions about design aspects that have an influence on both the energy consumption and the

investment will be an important aspect of competitiveness in the future” (Dietmair & Verl, 2008, p. 574).

Increasing environmental consciousness, or having a focus on sustainability, is typically categorized under the title energy management. Energy management is a very broad trade and can be performed in virtually any environment. Van Gorp (2004) states that common energy management tactics look at energy savings that can be achieved through effective management of lighting, heating, ventilating, and air conditioning (HVAC), waste heat recovery, and the implementation of variable speed drives (VSDs) (p. 60). This approach to energy can provide savings in all types of facilities, and can have some particularly effective results in large manufacturing facilities. In older facilities, there are significant energy wastes resulting from poor practices that are overlooked and continue currently. The main cause of these energy-wasting practices is due to a lack of knowledge on how to view a facility with an aim to identify energy waste. The attitude that needs to change in order to make significant sustainability improvements is the idea that energy consumption is a fixed cost. “Energy should be regarded as a controllable operating expense and it needs to be managed with the same expertise as other parts of a business” (Goosey & Kellner, 2010, p. 42). Once the old outlook on energy is gone, the potential of energy savings can be actualized. This directed project has analyzed sustainability improvements in a manufacturing environment, but at a more specific level than typical energy management practices would focus on. In this study, electrical energy sustainability improvements through the automated monitoring of machine energy consumption were measured.

2.2. Machine Energy Analysis

The rationale behind analyzing machine energy usage lays in the fact that most manufacturing operations at some base level require machining. According to the Department of Energy (DOE) machinery consumed 204 trillion Btu of energy in 2009. Of that 204 Btu, over 50% of that energy was consumed as net electricity (EIA, 2009, p. 47). Therefore when analyzing machine energy efficiency, this report focused solely on electricity consumption for sustainability improvements. Dahmus and Gutowski (2004) report “Among manufacturing processes, machining is unique in that it can be used both to create products and to finish products” (p. 1). For this study, the term machine refers to computer numerically controlled (CNC) machines. The reason for that selection is due to the high utilization frequency of these machines, and the fact that they can be remotely controlled and easily integrated into an automated manufacturing line. Additionally, the study was subject to machine availability provided by the Universities. Most of the literature on this topic has focused on CNC machine energy. The main result of the effective monitoring of these machines will be the improvement of the sustainable ecosystem.

Vijayaraghavan and Dornfeld (2010) suggest that reducing the energy consumed by machine tools has a high potential to significantly decrease an operations “carbon footprint” (p. 21). In this study the machine tool being referenced is a CNC machine. Lanz et al. analyzed two case studies that both performed different tasks using CNC operations, in the article *Impact of Energy Measurements in Machining Operations (IEMMO)*. The energy consumption by the machine during the running of a program was

measured and examined looking for methods to optimize energy use. The data showed that, in relation to the total energy consumed by the machine, there was a considerable amount of waste during process idle time. It was reported that during some of the programs of the CNC machine, that there were times that, when idle during a program, the machine consumed more energy than when it was running a program. So were there any improvements to be made at the machine level, the article would suggest directing the majority of efforts towards reducing idle time energy wastes. The overall conclusion of the study however, in contrast to Vijayaraghavan & Dornfeld, was that focusing solely on improving CNC machine operations at the programming level was not cost effective. The energy saved did not provide enough payback to substantiate large scale implementation of the concept. The authors of this study suggested focusing more on systems level efficiency gains as opposed to single machine efficiency gains (pp. 3-6).

The results of Lanz et al.'s study are consistent to those found in other related literature. "It is evident that the [CNC cutting process] is not the dominant user of energy...Because of this manufacturing engineers of the future factory should keep to conventional wisdom and aim to optimize for operation time" (Ding, Qiu, Mullineux, & Matthews, 2010, p. 772). Likewise a case study performed by Dietmair and Verl (2008) showed that the major energy consuming process of a CNC machine was coolant control (p. 579). Considering that the machining operation is not drawing the most amount of energy, it would be impractical to try and save that energy. Sticking with the recommendations cited above, the logical step, at least regarding CNC machining, would

be to try and optimize usage of a machine as it exists in a manufacturing system process. It is suggested that by optimizing scheduling operations, the machine level sustainability improvements that can be achieved will be optimized.

An improvement than can be obtained through successful monitoring of a system is idle time reduction. Anderber, Kara, and Beno (2009) comment on machine idle time in their study, *Impact of Energy Efficiency on Computer Numerically Controlled Machining (IEECNCM)*: “[Electrical energy] constitutes a large expenditure for a company and consequently considerable savings can be made in real terms if more energy efficient machining is facilitated” (Impact of energy efficiency on computer numerically controlled machining, p. 538). The interpretation of the word facilitated is taken to mean monitored and/or controlled for optimization.

2.3. Data Acquisition Systems

There are several different suggested methods for data acquisition of manufacturing equipment. This section explores some of the more common methods being used in industry. The first data acquisition tool is MtConnect. “MtConnect [is] a standardized communications protocol designed to make it easier to collect, transmit and leverage data from discrete equipment such as MCM machine tools” (Albert, 2009, p. 61). When addressing the connection between MtConnect and an MES, Ray Peterson, senior technologist for MtConnect is quoted saying, “MtConnect will make it possible for most of our CNC machines to feed performance data into a process monitoring system” (Albert, 2009, p. 62). The process monitoring system in this case

would be the MES being used. MtConnect offers a lot of potential to increase data control and management in a universal fashion. In the article *Factory Automation*, Teresko (2009) discusses how MtConnect provides the possibility of near real-time data management connecting a number of machines that, without a system like MtConnect, would otherwise function essentially as standalone machines (Factory Automation: Getting Connected- For a Smarter Factory, p. 20). The future potential of connecting all machines is very encouraging and could significantly impact the manufacturing industry.

MtConnect also possesses great potential to aid in energy management.

Although not discussed in the previous articles, all the data gathered by a device like MtConnect could be used to improve energy efficiency in operations. Vijayaraghavan and Dornfeld used MtConnect as their data collection system, because it possesses the following capabilities: “concurrent monitoring of energy use with process data, standardized data sources, scalable architecture for large data volumes, and modular architecture to support analysis across different manufacturing scales” (p. 22).

MtConnect was only released in 2008, and could greatly aid manufacturers in accomplishing sustainability goals.

Supervisory control and data acquisition (SCADA) systems are also a popular data management system. “As the name indicates, it is not a full control system, but rather focuses on the supervisory level. As such, it is purely a software package that is positioned on top of hardware to which it is interfaced” (Daneels & Salter, 1999, p. 339). The SCADA system is a much defined means to gather data pertinent to a process

and display it to an operator. It is essentially a network of integrated sensors and other monitoring devices, and can be controlled by a control device e.g. a programmable logic controller. “The majority of the products allow actions to be automatically triggered by events. A scripting language provided by the SCADA products allows these actions to be defined” (Daneels & Salter, 1999, p. 342). This quote explains the automation capabilities of a SCADA system, the most important point being the ability to automatically trigger events based on pre-defined limits for certain sensors.

Soplop et al. comment on how SCADA systems can be coupled with a Manufacturing Execution System (MES) to achieve sustainable energy efficiency improvements. “The integrated structure allows the MES to analyze and report on sustainability metrics based on the company’s defined requirements” (p. 3558). The integrated structure is referring to the communications between a SCADA system and an MES system. If certain parameters are defined (e.g., if a machine remains at an idle state for a certain period of time) as allowable or not allowable, then as the information gathered by the SCADA system is communicated to the MES, effective control of the machinery can be accomplished.

Another software package that is useful in data acquisition applications is National Instrument’s LabVIEW software package. LabVIEW is a graphical programming language that uses object style programming to make complete applications. In a research project based on the creation of a virtual data acquisition system, the following statement was made “LabVIEW was chosen for this application because its graphical

approach and dataflow representation are very suitable for acquisition chains”

(ANTOINE NONCLERCQ, 2009). The advantages of the dataflow representation are that in LabVIEW, the programmer is able to see how the data will pass in and out of the program while the program is running, thus enabling the programmer to have a better understanding of the system.

In 2010 a data acquisition project was completed using LabVIEW to monitor and diagnose the condition of cutting tools in a NC operation. Using LabVIEW as the software medium, a program was designed to analyze a power waveform from an NC machine and indicate the condition of a cutting tool. The following were some of the listed benefits of having a LabVIEW based system. “[The labview based system] is cost-effective, and has a friendly interface and short development cycle. The characteristics of cutting tool condition monitoring are built flexibly and maintained simply and carried conveniently. The system achieved a real-time state of data acquisition and analysis for tool wear of NC machine. The system shows good performance in the continuous data acquisition.” (Chen Jie, 2010)

LabVIEW does not necessarily fit into the category of data acquisition systems like MTConnect or others do, rather it provides a platform upon which such a system can be developed. The programming language and design is well suited for programs that involve a certain level of data acquisition and interpretation. A unique benefit that LabVIEW provides over the other systems mentioned previously is the ability to design a program and user interface around the particular data that is being acquired.

2.4. Energy Monitoring Systems

“It is essential to have appropriate information upon which management decisions are based...data must be made into information by analyzing and presenting them in a form which is appropriate to a particular type of user.” That being said, the means used to collect data mentioned in the section above are useless unless that data is converted into appropriate information for an end user. There has recently been much growth in the development of energy monitoring systems (EMSs), which are systems designed to be connected with machines or devices and report their energy consumption information.

An effective method to monitor production at the systems level is through the implementation of a manufacturing execution system (MES). The main advantage that can be achieved with an MES is improved system control and data management. “Today’s manufacturing solutions have been built to improve operating cost structures including load curtailment and shedding, generator control, HVAC control...[The list goes on and makes the point that MES systems are designed to effectively monitor all the different operational functions of a manufacturing plant. The article continues and proposes the following idea:] ...Viewed from a different perspective however, these types of solutions provide energy conservation and control, building and plant automation and electrical energy management solutions” (Soplop, Wright, Kammer, & Rivera, 2009, pp. 3556-3558). Because MES systems are designed to gather data and represent it in an effective and easy to use manner, expanding the scope to include information that would be relevant to sustainability initiatives should not be that large

of a request. Soplop et al. explains that MESs can be used not only to manage materials, but can also manage energy consumption:

The most significant disconnect between sustainability requirements and existing MES functionality is that sustainability has not been a factor in the design and implementation of MES. By making slight modifications to the MES requirements, sustainability goals such as using less material and energy, reducing waste, recycling, increasing workplace and product safety or considering alternative energy, can be reached with existing MES systems (Manufacturing Execution Systems for Sustainability: Extending the Scope of MES to Achieve Energy Efficiency and Sustainability, p. 3558).

The real secret to the success of any execution system, be it an enterprise resource planning (ERP) system, material resource planning (MRP) system, or MES, is data management. Once the plan to implement an execution system of any sort is agreed to, the following questions are raised: what data is important to collect and monitor? How will the data be collected? Once the data is obtained, what is to be done with it? Without an effective data acquisition system coupled with effective display of information, an MES for example would be nothing more than an expensive set of sensors and controls.

After all relevant data is monitored and sent to the appropriate sources, the MES should have the capabilities of displaying continuous information regarding machine usage and energy consumed. As suggested by Lyons et al., (2008) the first step towards sustainability improvements would be to quantify the amount of energy that is spent on

each individual part (Introducing Sustainability Early Into Manufacturing Process Planning, p. 4). All the necessary information should be available in the MES to calculate that value. Once that is measured, the MES will be able to use the correct algorithm to provide the appropriate machine control. The MES is essentially the commanding chief of the whole efficiency improvement process. All data runs through it and it is where the relevant data will be displayed to an operator. Using either MtConnect or a SCADA system, the physical monitoring controls can be installed to the machinery for effective management. Once all the previous components are set in place, the next step is to run the correct algorithm to physically control the machines. The last component to this process is the pathway through which all the data will be transferred.

2.5. Networking

Lou (2009) suggests using a distributed numerical control (DNC) integrated manufacturing system in his article *Applications of Network Technology for CNC Machining Equipment*:

The DNC integrated manufacturing system based on Ethernet is an integrated manufacturing control and production management system which is integrated product design, process design, processing manufacture, production management. In the system, the local area network (Ethernet) can be used to rational allocation and information sharing for CNC machining equipment and achieve the seamless integration of enterprise management and production

operations management (Applications of Network technology for CNC Machining equipment, p. 908).

What that basically means is DNC control via Ethernet has the potential in achieving full integration of many different operations. CNC machining is highlighted in this article, but Ethernet can be the data pathway for any machine that has the port available. Ethernet communications provide the following:

1. Realization of remote control – In the DNC computer you can set the machine parameters, modify machine parameters, modify CNC machining process, monitor the current status of each machine, so that product quality is guaranteed.
2. Realization of production scheduling management automation...
3. Timely processing of information acquired and statistical analysis (Lou, 2009, p. 908).

Ethernet is the primary suggestion for networking and communications. All of the operations that need to be taking place via control from the MES system can be communicated via Ethernet. Serial control of machines is also possible, but functional capabilities are decreased with serial communications.

2.6. Conclusion

In conclusion, through the combination of techniques discussed in this section, it is the belief that a fully automated monitoring system can be implemented into a manufacturing line, with the primary focus being the increase of the sustainability

ecosystem. Through the implementation of an MES or similar type of program, real-time data acquisition and display, energy efficiency in operations can be adequately monitored, ultimately enabling managers to have a better sense of how much energy they are consuming and where they can make improvements.

CHAPTER 3. PROCEDURES EMPLOYED

This project presents quantitative research exploring the ability to develop an energy monitoring system that will itemize the energy consumption of a manufacturing machine at different stages in its operation. It is categorized as applied research, and this experiment will provide a proof of concept methodology that managers and operators currently in industry can adopt to improve the sustainability ecosystem at the machine level in their facility. Recall section (1.8) for a more elaborate definition of the sustainability ecosystem.

3.1. Research Approach, Hypotheses and Variables

The following sections explain the approach to the experiment, the hypotheses tested, as well as important variables that were noted and monitored.

3.1.1. Approach

The experimental method for this study will analyze electrical energy consumption statistics of a manufacturing CNC machine. The experiment can be divided into two main parts. The first is to discover the energy profile of a CNC machine, determining what conditions can be used to identify when the machine is in different modes of operation. The next part develops a monitoring system to show how much energy is consumed by the machine during those different operational modes. The

information from this monitoring system must be available to operators in a usable fashion. Operations were measured for energy efficiency and process efficiency. Of primary concern was the second aspect of the project, or the focus on the monitoring system. The following hypotheses based on the research question in section 1.4 was tested:

3.1.2. Hypotheses

1. The energy consumption readings from manufacturing machinery enable a quantifiable value for a machine, and systems, energy efficiency.
2. By distributing energy efficiency information to an operator, the data can be analyzed to optimize system operational management and improve the sustainability ecosystem.

3.1.3. Variables

In this study there are a number of dependent and independent variables that affect the energy consumed per machine. They are detailed more in the following sections:

Independent Variables

Machines Operation:

- A key independent variable crucial to this study is the fact that there are many different CNC machines. The energy consumed by this machine is not necessarily indicative of what other similar machines may consume.
- Not all machines will operate on the same power source.

Machine hours logged by the different machines:

- The machine wear could potentially affect the energy efficiency. The more a machine is used its efficiency could decrease.

Dependent Variables

- The dependent variable for this experiment will be energy savings and will be measured in both Kilowatt hours (kWh) and dollars per kWh (\$/kWh).

3.2. Instrumentation

The instrumentation used in this project was subject to availability at the different Universities. This project was completed in one year through continued study at three different universities, Purdue University in the United States, Dublin Institute of Technology in Ireland (DIT) and Universitat Politecnica de Catalunya in Spain (UPC). The majority of the project and the primary equipment used was from DIT. Due to the machine availability at DIT, the machine to be monitored was a Hurco Hawk 5M CNC machine.

In addition to the CNC machine, the following equipment was used:

- LabVIEW software package
- National Instruments CompactDAQ Chassis
- National Instruments DAQ Module

- Custom Designed Energy Conversion Cabinet
 - LEM Current Transducers
 - LEM Voltage Transducers
 - Dell Vostro 1510 Laptop PC
 - +/- 15 V DC Power Supply
 - Calculated Resistors from Radionics

3.3. Data Collection

The data for this project was collected through the use of a CompactDAQ Module and Chassis. The module received the information from the machine by connection to a custom designed energy conversion cabinet. The cabinet is directly connected to the machine and will scale the electrical signals to the appropriate level for the DAQ module to input into LabVIEW. The CNC machine in this project is a Hurco Hawk 5M CNC machine that is used in a laboratory course at DIT. The main focus of this project was directed at the wasted energy cost of a machine, so the particular energy consumption and cost of machining a physical part is not of primary concern. As a result, run time energy consumption and cost was not of primary importance. It was monitored and displayed to an operator but it is not likely to be a helpful parameter in reducing electric energy waste. To help identify the value added energy from the wasted energy, the machine operation was segmented into four categories. They are as follows:

- Start-up: Amount of power consumed from initial power supplied until the machine is ready to run a program
- Run time: Amount of energy consumed while a program is being run on a machine
 - Machine speed (0-100%)
 - Load capacity (0-100%)
- Idle time: Amount of energy consumed when a machine is on but no program is being run.
 - Idle time can be further divided
 - Idle-time servo's engaged
 - Idle time servo's disengaged
- Shut-down: Amount of energy consumed from idle time to power being disconnected

Of these four categories, the only the run time energy adds any value to the product. It is the mandatory cost of manufacturing a particular product. The other three stages of the machines operation do not add any direct value to the product; therefore effort should be given to minimize these expenses. Of the three non-value added categories, of greatest significance is the machine idle-time consumption. Start-up and shut down operations are a necessary waste for the machine, yet the whole time that the machine is powered and not running a part, the energy consumed there is pure waste. The energy cost could be further divided into two types of energy consumption. When the machine is idle and the servo motors are engaged, that is one form of energy

waste. It is also likely to be the larger form of idle waste over a given time interval, because the servo motors will be used to just hold position. The second idle waste is when the machine is powered yet the servo motors are not engaged. This stage is likely to consume less energy because only the CPU processor for the machine should be powered. All of the energy consumption information was input to LabVIEW where a program was created to analyze the machine data and report the relevant information to an operator.

3.4. Data Analysis

With all the data inputted to LabVIEW, a software program analyzed the consumption at the four different stages and made that information available to an operator. In order to make the data valuable to a manager, the wasted energy consumption will be reported in both kWh and cost in dollars. The Hurco Hawk 5M CNC is the only machine to be used during this study, but the program was written to include the capability to analyze multiple machines and provide a systems level report. The data collected was appropriately displayed to an operator so that he or she could be able to quantify the energy expense of an individual machine. In knowing the energy profile of a machine as well as where there is waste, he/she should be more capable to make decisions to decrease wasted energy cost and save money.

For each of the four stages mentioned earlier, it was planned that a dollar amount would be assigned to each. For Start-up and Shut-down Procedures, it was assumed that the process would be the same every time in both duration and total

energy consumed. Therefore the operator can know how much money is being spent every time the machine is turned on or powered off. For run time, the operator would be able to see the total electrical energy spent per part, and what the cost is for that energy. Since there are typically multiple programs on a machine to run different parts, the run time energy value will change every time. Having the data on how much energy is spent in making a part could be useful to an operator however in determining pricing for example, and, at the very minimum, should give him/her a more thorough understanding of the actual cost of manufacturing a product. Machine idle time cost should be displayed as dollars per hour for each idle stage. Since idle time consumption is rarely ever on a fixed time interval like the start-up and shut down procedures, it was more useful to calculate the waste cost per hour then combine that with the measured idle time of a given machine. This was the most useful data for the operator to have in managing the idle time waste to achieve the largest energy savings possible.

For this study, energy savings was directly related to cost savings. Every kWh reduced or kW of peak demand saved had an cost associated with it. As a result in the display every energy measure has a cost associated to it as well.

3.5. Summary

This section explained the method for which the data will be collected, and the key components of the experiment. Hypothesis and independent variables are discussed

and the data capture/analysis tactics are explained. The following section contains the results and the effectiveness of the monitoring system.

CHAPTER 4. PROJECT AND RESULTS

4.1. Overview

This chapter explains the process of developing the energy monitoring system. A comparison of the proposed methodology to the actual built system was addressed first, then documentation of the project from a fabrication and programming standpoint, and lastly a summary of the capabilities of the monitoring device and the usefulness of the data collected.

4.2. Amended Procedures

In Chapter 3, the procedures to be employed in this project were explained. In the actual completion of the project however, not all the goals and aims in the methodology came to fruition. Namely, the energy profile of the machine was not calculated, and thus the project became focused on the proof of concept from a more theoretical perspective. The system was still designed to work with the Hurco Hawk 5M as originally planned, however, the software program was not specifically tailored to the machine, and instead arbitrary values are calculated which are designed to reflect real values that would be received with information from the machines energy profile.

Idle time waste was proposed to be separated into two categories; idle time with servo motors engaged, and idle time with servos disengaged. The actual experiment did

not take the different type of idle machine waste into account, rather one overall idle time waste was included. Adding this type of accuracy to the system would be helpful though and would be a good future improvement to this study.

Additionally, in the methodology it was mentioned that the start-up and shut down time would be given as a dollar amount per cycle; however that was not the case for the program. Both machine states have the energy consumption statistics based on the time in that particular state, and it is subject to change. Essentially, the exit criteria from each of the two states has no time dependency, which actually provides better data from the start-up procedure and has no effect on the stop procedure. For the start-up procedure, having no time limit to the cycle will enable the machine to read consumption information beyond the simple powering-up of the CPU. Sometimes with CNC starting procedures, the spindle has to go through a warm-up cycle or the system needs to be calibrated. Both of these operations will still log data under the start-up procedure, and would not have done so if the program analyzed the start-up routine as a time based mode of operation.

4.3. Fabrication

For this project there were two main aspects to the fabrication process. The first step was to build an electrical interface cabinet to convert the electrical signals coming from the machine to a level that could be accepted by the DAQ module. Secondly, the program on LabVIEW had to have the ability to read the signals coming from the

electrical cabinet, store the relevant data, interpret the data, and display the energy consumption and cost information in an easily decipherable fashion.

4.3.1. Electrical Cabinet

Overview

The electrical cabinet in the project was a custom built device for the Hurco Hawk 5M. The calculations used to size the equipment were based on the electrical schematic of the CNC provided by DIT. A copy of the CNC electrical schematic used can be found in Appendices E and F. The Hurco Hawk 5M is a 380 volt 3 phase machine and the decision was made to measure the phase voltage for each voltage input. By measuring the phase voltage (each input line to common), all the lines share the same common line, which made the wiring significantly easier. It also lowered each voltage measurement value from 380 volts to 240, which was more desirable from a safety perspective. If the device were to have measured line voltage (IE: Line 1 to Line 2), each measurement would have been 380 volts. To convert the input voltage (240 VAC) to the correct output voltage (10 VAC), two resistors were required for each line. The specifications of the transducers and the calculations used to size the resistors and can be seen in the sections below.

The CNC machine was also rated at 6.4 KVA. Considering it is a 380 volt machine, that means it consumes $6,400\text{VA}/380\text{V} = 16.84$ Amps at maximum load. Assuming a balanced system, that would allow for 5.61 Amps on each line. Similar to

measuring voltage, for this system one current transducer was required for each line. Specifications for the current transducers are also included below.

Voltage and Current Transducers

Both the current and the voltage transducers were sized significantly larger than was needed. Additionally, each device would output a current that, using calibrated resistors, could be inputted as a voltage to another device. For the voltage measurements, three LEM LV 25-P transducers were installed. The voltage capacity maximum for these transducers is 500 V, and the maximum voltage expected was 240 volts. The transducers also require the input current to be at 10 mA. For further information on the Voltage transducer, refer to the specification sheet in Appendix C.

For the voltage transducers, two resistors were needed for each line. The first resistor (R1) was installed before the wire connected to the transducer. The purpose for R1 was to lower the current coming from the machine to 10 mA. The second resistor, called the measuring resistor (R_{m_v}), was installed on the output of the voltage transducer and used to scale the signal to the appropriate level for the DAQ card.

The current transducers used in this cabinet were LEM LA 55-P current transducers. The maximum current allowance was 50A for these transducers, which was far above the expected current levels (5.6 A per Line). The current transducer reduces the measured current by a factor of one-thousand, and only one measuring resistor (R_{m_c}) was required to scale the voltage to the correct level. The data specification sheet for these transducers is provided in Appendix D.

Both the current and voltage transducers used in this system could be externally powered by a +/-12 or a +/- 15V power supply. A +/-15 Volt DC power supply was used in this system in order to maximize the resistance capacity that would be used to scale the transducer output signals.

Resistor Calculations

For the resistors, the equations were based on Ohms Law $V = I * R$ where V is voltage, I is current and R is resistance. The limitations for the calculations were subject to the allowable range as denoted by the transducers specification sheet, as well as the maximum allowable range of voltage inputs, subject to the DAQ card. The maximum voltage range acceptable to the DAQ card was +/- 10 V, and the allowable range for the resistors was different for the voltage and current transducers.

LV 25-P Voltage Transducers

To calculate the resistance for the voltage transducers, the calculation of R1 was the first step. Because R1 is installed before the transducer, there was no range of acceptable resistor values that had to be met; the current just had to be dropped to 10 mA. With Voltage = 240 V and the required current 10mA the equation $V = I * R$ can be rewritten:

- $R = V/I$ or $R1 = 240V/.01 \text{ A}$.
- R1 comes out to be 24,000 Ohms or 24 kOhm

The power consumed by the resistor was also necessary to calculate so that the resistor was sized with enough capacity to not burn out. The power dissipated (P_d) in a resistor was calculated by taking the primary nominal current (I_{PN}), squaring that value, and multiplying it by R_1 .

- $P_d = (I_{PN}^2) * R_1 = (.01^2) * 24,000$
- $P_d = 2.4 \text{ Watts}$

It was suggested that standard practice when sizing resistor power capacity is to size it 300-400% greater than required, so in this case the power rating on the resistor should be at a minimum $2.4 * 3 = 7.2 \text{ watts}$.

Calculating the R_{m_v} was subject to more limitations. Because a 15V power supply was being used and the input current to the transducer was 10 mA, the range of acceptable resistors was between 100 and 350 Ohms. The same equation was used to calculate the resistor. According to the specification sheet, the voltage transducers output a current of 25 mA and the DAQ card can accept up to 10 V the equation was set up as follows:

- $R = V / I$ or $R_{m_v} = 10 / .025$
- $R_{m_v} = 400 \text{ Ohms}$

Because this value is outside of the range of acceptable resistor values, the voltage input to the DAQ card had to be lowered in order for the resistor to be in the

acceptable range. The decision was made to input +/- 8 volts to the DAQ card instead of 10.

- $R_{m_v} = 8/.025$
- $R_{m_v} = 320 \text{ Ohms}$

This resistor value is within the acceptable range and was thus the value used in the machine. Calculations to identify the minimum power capacity that the R_{m_v} should have are:

- $P = (I_{pn}^2 * R_{m_v}) * 3$ or $P = (.025^2 * 320) * 3$
- $P = .6 \text{ watts}$

In summary, for the LV 25-P transducers to connect to the Hurco machine and output +/- 8 volts, the R1 resistors should be 24 kOhms with a power rating of at least 7.2 watts, and the Rm resistors should be 320 Ohms with a power rating of at least .6 watts.

LA 55-P

As aforementioned, there was only one calibrated resistor (R_{m_c}) that was needed for the current transducers. This calculation again used ohms law and it is worth noting that the output voltage requirement was 8V to remain constant with the input from the voltage transducers. The max output current (I_s) from the current transducers is 70 mA and the resistor and power equations are as follows:

- $R = V/I$ or $R_{m_c} = 8/.070$

- $R_{m_c} = 114.39$ - can be rounded up to 115 Ohms
- $P = (I_s^2 * R_{m_c}) * 3$ or $P = (.070^2) * 3$
- $P = 1.7$ watts

By using a 115 ohm resistor with a power capacity of at least 1.7 ohms, the current transducers will output between +/- 8 Volts. It is worth noting that the only time that 8 volts will be output is when the full 50 A are being read by the current transducer.

The calculations present the ideal conditions for the resistor values in order to output the desired values to the DAQ card. However in purchasing, it was difficult to find resistors to exactly match the calculations. The actual resistors used in the machine were as follows:

- R1 – 25,000 Ohms with a power capacity of 25 watts
- R_{m_v} – 270 ohm resistor connected in series with a 50 ohm resistor
 - o 10 watt power rating for both
- R_{m_c} – 100 ohm resistor connected in series with a 15 ohm resistor
 - o 10 watt power rating for both

The power ratings for all the resistors used far exceeds the minimum requirement from the calculations. However, since this was just a minimum requirement, largely oversizing the resistors has no negative effect of the function of the resistors. As for R1, instead of 24 kOhm a 25 kOhm resistor was used, and working back through the calculations, that only changes the input current from the machine to the

transducers to 9.6 mA instead of 10, which, since it is below the rated value, has no negative effect on the system.

Assembly

The entire assembly of the electrical cabinet took place at DIT, who provided all the materials needed. All the soldering of the components was completed by the researcher as were all hardware installations. For safety reasons it was decided that the electrical cabinet should have the capability to be portable to an extent, and so connectors were installed on both the machine and the cabinet. Some hardware had to be installed in the machine itself, and as a result is not easily removable.

4.3.2. LabVIEW

Overview

The software program for this energy monitoring device was completed using LabVIEW. LabVIEW is a product from National Instruments, and was made available by DIT for the purposes of this project. This section documents the process through which the researcher created the data capture and analysis portion of the project. This program was structured in a similar fashion to the example project mentioned in Section 2.3. In the same way that the LabVIEW was used to analyze waveforms and detect tooling conditions, similar style of waveform analysis was used to determine the different operational states of a machine.

It is important to mention that due to minor electrical complications and time constraints during the construction of the electrical cabinet, real signals from the CNC were not obtained. As a result the signals that are generated for the purpose of testing the LabVIEW program are simulated signals, and the program will read the data from these simulated signals and operate with arbitrary values as indicators of the machines operational state. These power consumption indicators may not actually reflect real consumption statistics from the machine, but are effective as a proof of concept that LabVIEW can be effectively used in this type of industrial setting.

Planning

The planning stage for this program involved the analysis of many of the articles about energy management systems and what information is relevant for operators to have. As mentioned earlier the decision was made to separate the machine into four different operational states; Start-up, idle, run, and stop. It was then necessary to consider what data from each of these states is important, and also how the data should be presented in a fashion that is efficient and effective for improved energy management of a particular machine. That being said, the most important data for the program to display was the following:

- Overall Power consumption

- By combining the consumption levels at all the different stages, a complete understanding of the current cost of manufacturing a part can be identified.
- Additionally, in the event that strategies are taken to reduce the waste energy consumption, the overall power consumption statistics will serve the as indicators of the starting point.
- Waste Energy
 - The waste energy in this program can also be called the non-value-added energy. This value calculates the total energy of all stages excluding the run stage, which as mentioned earlier is the only machine state that adds value to a product.
 - Identifying waste energy is necessary for the purposes of reducing consumption. All products will require a set amount of machining time, so that value will remain unchanged. What can be changed, and thus reduced, is the consumption of the waste energy.
- Cost of Energy
 - Both the overall energy consumption as well as the waste energy consumption values should have a cost associated with them.

Considering that not all operators will know how to interpret data displayed in kWh, putting a dollar amount to the values make them understandable for any business individual.

- Time spent in each state
 - This value is important in order to see where the major costs are coming from. Of the four operational states, of most important regarding time spent is the idle time consumption. Idle time consumption does not have a routine interval, and as a result can be the location where, though informed and educated control, the greatest cost savings are achieved.
- Overall power chart
 - This visual provides an easy way for managers or operators to get a general understanding of how the power consumption values change through a cycle.
- Power at each phase
 - It is helpful to have each phase power consumed in the event that the system is not a balanced system, whereupon this fact would be easily noticeable if one line consumed significantly more than the other.

These parameters provide a base of important information that became the driver of the program. The actual program provides more output data in addition to what has been mentioned previously.

Programming

The most complicated aspect of this program was getting all the data measured in real time in a synchronized fashion, compiling the data in a useful manner, and making sure that the program was designed with a sufficient amount of user control. It is impractical to design a system that only works for one machine and one application, so the program was created to enable use in similar applications (power monitoring and display) but for a number of machines. By simply changing a few parameters to scale the software to the hardware, this system can be used for more machines than just a Hurco Hawk 5M.

As mentioned in the introduction to this section, the signals that are inputted to the software are simulated signals, and the power consumption indicators that are used to step the program through the different operation modes are arbitrary values. It was assumed that once the power profile of a particular machine is identified, the real data would be used by the program, and the system would work the same. In the program, the changing variables were the current of each line. This simulated the machine moving through different modes. In a real setting rather than functioning as controls, the current consumption values are indicators for the operator. Voltage is assumed to be the same on all three lines (240 V), and is shown as merely an indicator in the current program. It is assumed that this would not change in a real setting. The following are additional assumptions made for the parameters used to indicate what state the machine is in:

- The minimum and maximum limits to indicate that the machine is in idle time are 3.75 amp and 4.25 amps respectively on each line.
- Once the machine has all three lines within the idle limit range for a period of 30 consecutive seconds, it is then in idle mode and the program will start recording data as such
- From the idle mode, if consumption on any line breaches the upper limit, it is indicative of the machine starting a run time operation and the program will move into run mode.
- Alternatively, if, while in idle, the lower limit is breached, is indicative of the machine beginning its shut down procedure and the machine will move into stop mode.
- Any time the power consumption increases from zero that the machine is in a start-up procedure.
- The start-up procedure will always lead to an idle mode before moving into either run or stop mode.
 - o The range of power consumption in this state has no limits and only will change state when the idle time condition is met. This will allow for different warm-up procedures to be run (machine calibration or spindle warm-up procedures in addition to the CPU turning on)
- Once in stop mode the power consumption will always move to 0 kWh.

- Similar to start, there is no range or limit of power consumption values permitted in the stop mode. Only the total power consumption of 0 kWh will allow a change of state.

These assumptions are used as the criteria for the machine to step through different states and record assumption data for each state. In order to process a real machine with this program, an analysis of the power profile must first be conducted to determine the idle time limit and verify that the other concepts are applicable for that machine. There may be some redefining of logic for use in other machines but the main functioning body of the program was designed for fairly simple interchangeability.

The logic for the LabVIEW program can best be explained through the use of a flow chart. Figure 4.1 below can be helpful in understanding the logic hierarchy of the program and what decisions need to be made by the software. Additionally figure 4.2 is a screen shot of some of the sample code used in the program.

One of the main benefits of using LabVIEW as the software medium for this project was the ability to customize the program to capture the necessary data. In LabVIEW there are objects called shift registers that enable data to be transmitted back through a program during subsequent iterations. This functionality enabled the real time data to be passed back and compiled through the iterations. The image below is a screen shot of some of the code used in the LabVIEW program. As can be seen, the main base for the program was through the use of a case structure embedded in a while loop.

Process Flowchart

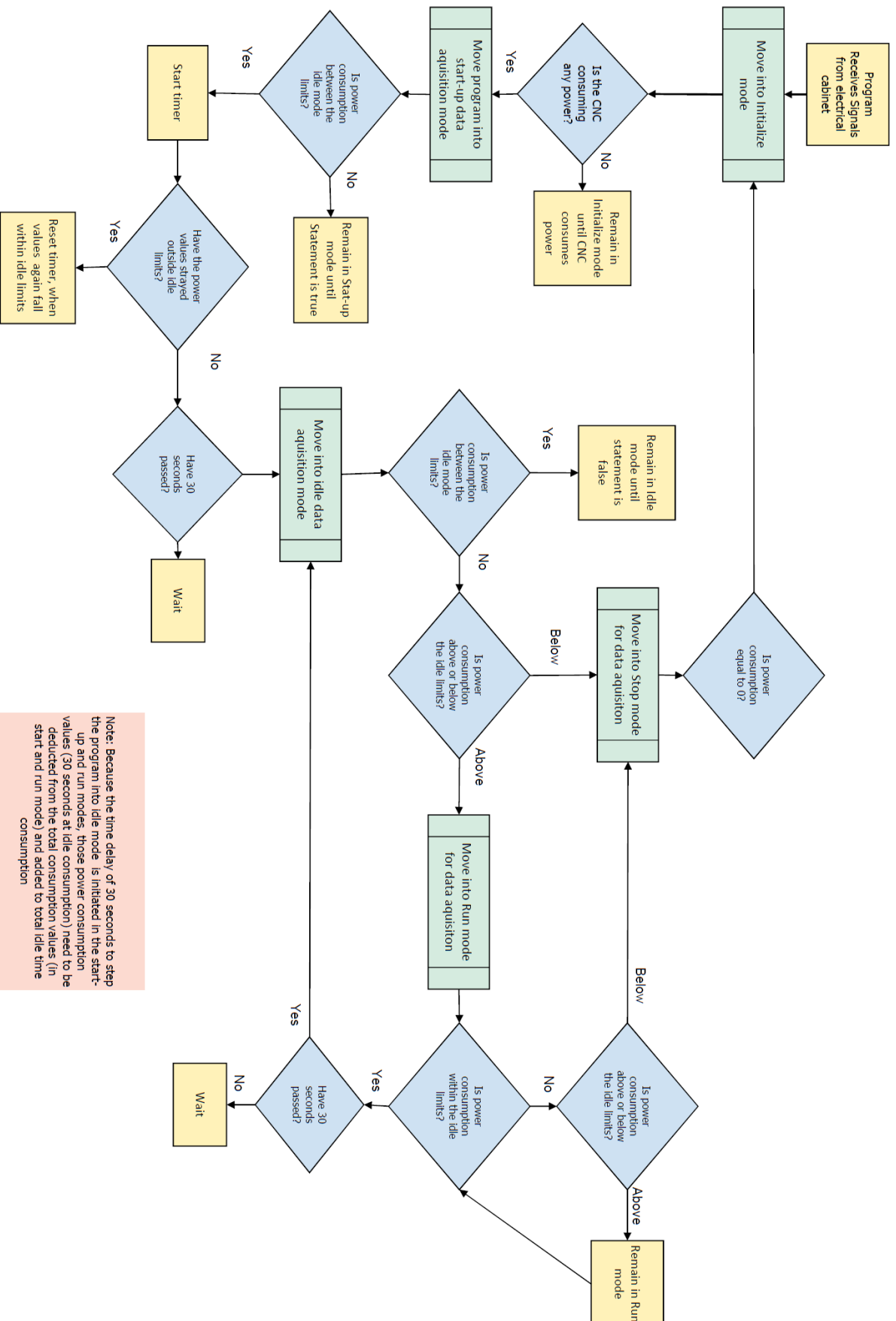


Figure 4.1 Process Flow Chart

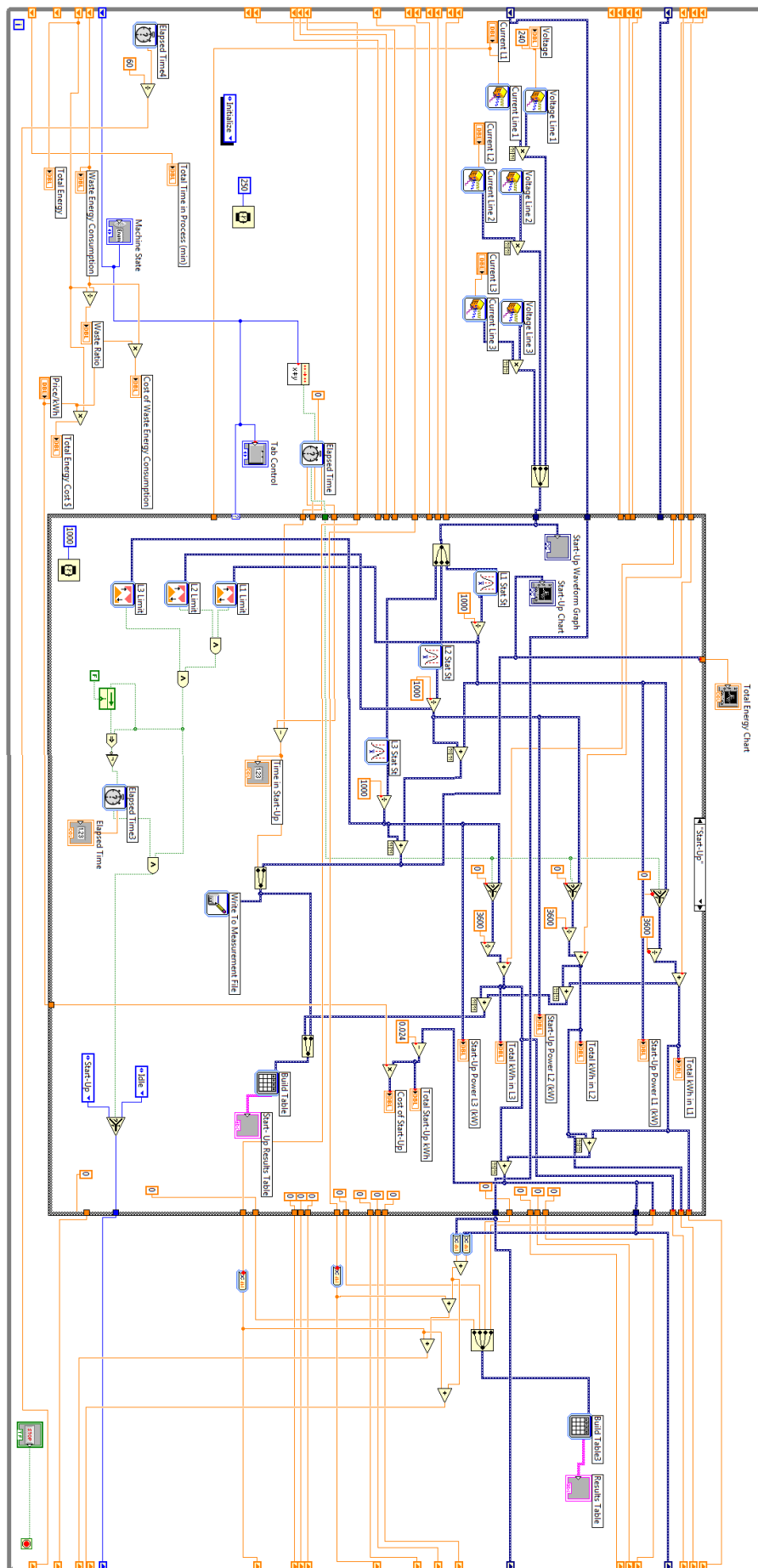


Figure 4.2 Sample LabVIEW Code

Although there are only four main states that the machine is measuring, there are five cases for this case structure. An initialize case is the default scenario and enables the software to run even if the machine is not operating. Additionally, at the end of the stop mode, the program will again move into the initialize case and wait to start again.

The main input signals into the program were six simulated sine waves, three for the voltage at each phase and three for the current at each phase. Since the voltage was not changing in this program it was represented as a constant, whereas the current values are controls that can be adjusted on the main screen. In order to see a screen shot of the main screen refer to *figure 4.3* below. By multiplying the current and voltage signals for each line, power was calculated according the formula $\text{Power (p)} = \text{Current (i)} \times \text{Voltage (v)}$. As the power from each phase was calculated and sent through the system, it was converted to kWh and displayed. In order to continue to accrue the data a shift register passes the consumption value out of the loop and back in again for each iteration. This allowed the software to compare the new power value to the existing value that re-entered the system via shift register, and through simple math, the total running power consumption could be calculated at each line.

All the cases in the case structure were set to run at one second intervals which allow an easier conversion to kWh as well as enables the count of iterations to double as a timer as well. Enumerated data values pass in and out of the case structures to step the program through the different operational modes. For each change of state, a timer resets and starts counting the time that the program has been in the new operational mode. The criteria for each state was programmed into the case structure of the state

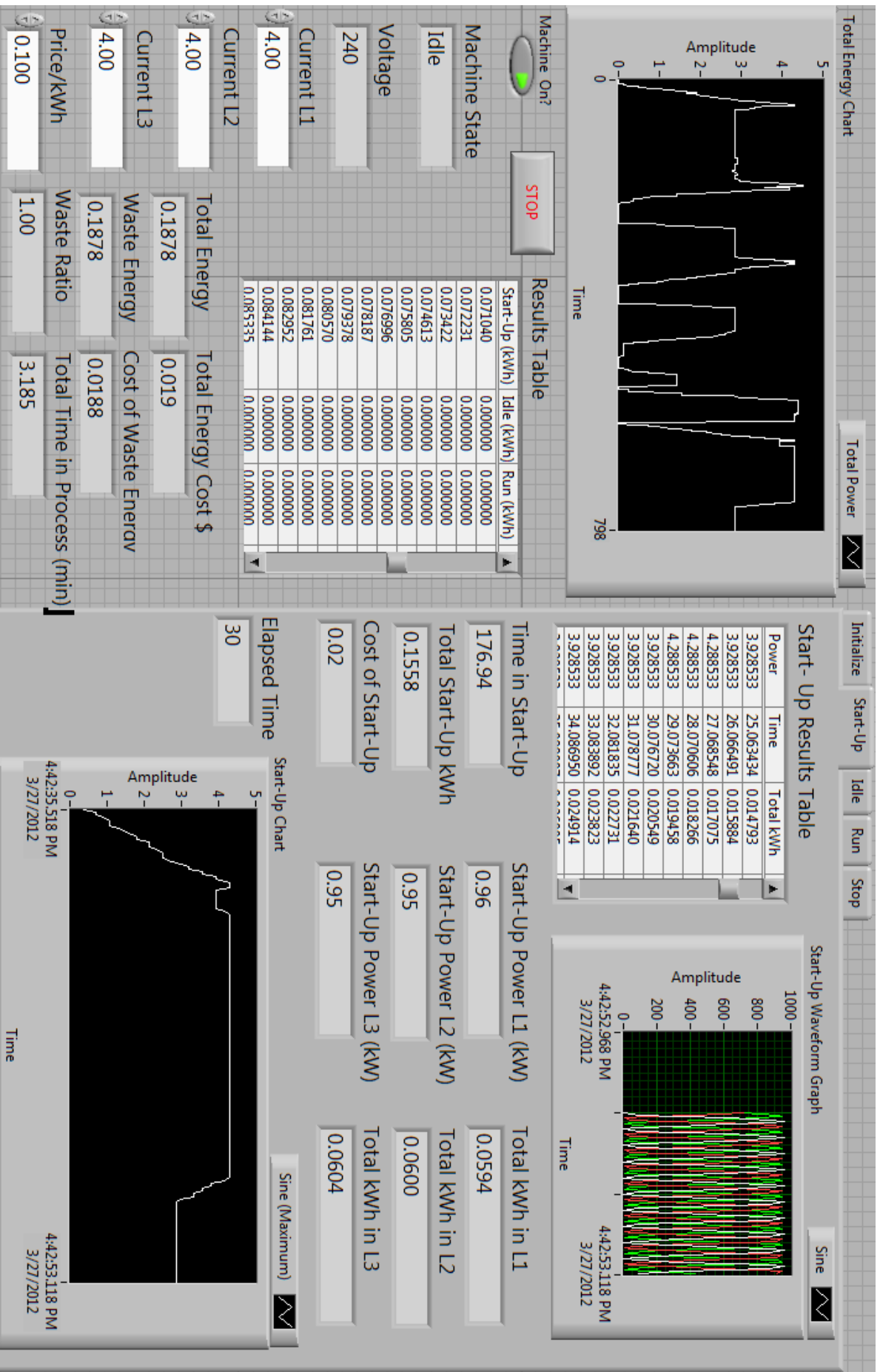


Figure 4.3 Main LabVIEW Display

prior, an example can be seen in the sample code above. The case is the start-up case and all the criteria for the next step, idle mode, is programmed into the start-up case. This way, once all the criteria for idle mode has been met, the case structure passes out the idle enumerated data, into a shift register, and back into the decision box of the case structure, thus moving the program into idle mode monitoring.

Overall the software program successfully reads data and, based on that data, determines the operational state of a machine and logs data relevant to that mode in a table. Additionally the relevant cost information is available to the operator as well as other summary energy information. The completion of the program was not met without complications however, which are documented in the following section.

4.3.3. Complications

Both aspects of the fabrication portion for this project were met with some complications, which was to be expected due to the nature of this project. This section aims to identify some of those complications and the effect they had on the project.

From the side of the electrical cabinet, the main complication was time. The construction of the cabinet required a number of parts to be ordered and then manually assembled. Although this whole process was completed on time, there was a small troubleshooting error that was unable to be fixed. As mentioned in the delimitations section in chapter one, the transfer from DIT to UPC became an obstacle for the troubleshooting of the electrical system. Were ample time available to address this issue,

it would have enabled a more accurate program that would hold real data values as operational state indicators instead of the arbitrary values used.

From the programming side of this project, the main complication was a lack of knowledge. The LabVIEW software package was new to the researcher, and again due to the timeframe of when this software portion was completed, access to faculty and resources was more limited in this field. The program completed is a functional program, but if the software was better understood from the beginning of the project, a more advanced program could have been created. Some of the future additions to the program will be documented at the end of this report in the further work section.

4.4. Results

Despite the setbacks that arose in the completion of this project, it was still quite successful. The electrical cabinet successfully took in signals from the CNC machine and output the values expected according to the calculations included earlier. The electrical quality of the output signals is an area of focus for the troubleshooting errors mentioned, however, according to the volt-meters used in measurement, the output signals matched the expected values.

Of all the important data that was output by the software program, the key points of interest were there. A screen shot of the main display with the start-up mode visible is shown below. All the energy was displayed in kWh for each of the modes of operation, and the cost associated with those consumption values was included as well.

Waste energy, cost of waste energy and the waste energy ratio were included in the main display and will likely be the best indicators to managers or operators, of energy improvement availability of a particular machine. For example, if the waste energy ratio is above 50%, that indicates that a particular machine is in idle, start-up or stop mode for over half the operating time of that machine. These values are designed to enable quick analysis of the machine to interested parties.

Also included on the software side of the project was the energy demand by each phase in each operational state. This information is more appropriate for energy quality assessment and not necessarily for energy consumption, yet it is still useful data to include in the project. The graphs displayed on the main window and in each of the state tabs help provide a visual display of what the signals look like. Again from a troubleshooting standpoint, knowing how the signals are being input to the system can prove to be quite helpful.

Despite the theoretical connections assumed between the output of the electrical cabinet and the input to the software system, both systems function well.

4.5. Practical Use

With all the information that is provided to an operator or manager, the question of what to do with it is raised. The main benefit to this type of system is increased information upon which managerial decisions can be made. With the rise in popularity of strategies like lean manufacturing and others that look to eliminate waste, this type

of program is designed to help identify waste. In the manufacturing of a product, lean manufacturing looks at activities that do not add value to the manufacturing of a part, and effort is expended to minimize that waste. The same approach is intended for use with this energy management system. The system will output the waste energy consumption value as well of the cost of that waste. The decision would then fall into the hands of the manager to determine what actions to take to minimize the amount of waste from the machine.

Another benefit that can be achieved from this system is a more accurate understanding of the true value of manufacturing a part. Once a manager understands the breakdown of costs within a CNC machine, it would provide better insight as to how valuable a part actually is. This information could be used in a pricing scheme that is based on machine energy cost or in a labeling system where the real energy cost of manufacturing is a parameter of the total value of a product.

The overall benefit is increased data flow. This increase will provide a manager with more information with which he or she will be better suited to make decisions that will reduce energy consumption and ideally reduce cost of manufacturing as well.

CHAPTER 5. CONCLUSION AND FUTURE WORK

5.1. Conclusion

The goal of this project was to learn about and develop an energy monitoring system at a manufacturing machine level. This applied research project has concluded in the development of such a system.

Overall this project was successful, both from an educational standpoint as well as from a practical standpoint. Throughout all the research and the project work at all the different universities; there has been much to learn. Primarily, much has been learned regarding energy management systems, the thought and work that goes into them and what information they should provide to an end user. Additionally there has been much education in the nature in intercontinental collaboration projects. Some of the major difficulties experienced in this project were due to the international mobility aspect of the Atlantis graduate program. However, it has all been a successful endeavor and the conclusion of the project has been a prosperous one.

5.2. Future Work

This project has many different potential areas for future work. This section will address a few of them.

Connecting Electrical Cabinet to Software

This is the primary point of future work, for it will result in the complete ability to analyze a real machine and get real data that can be used for energy management. The one area for trouble shooting is how to connect the output of the cabinet to the DAQ module and receive the correct signals. The trouble is either in the electrical cabinet, or the software set up. If the problem is in the cabinet, it could mean that the signals that are read by the volt meter are not that actual signals being output. In this case an oscilloscope should be attached and the raw values being output should be analyzed. In the event that the problem is in LabVIEW, it should be easier to solve by calling National Instruments, explaining the project and receiving help from them.

Improve the Electrical Cabinet

Although the hardware in the electrical cabinet is specific to the Hurco Hawk 5M CNC machine, a project could be pursued to identify what type of equipment would be necessary to be effective on a larger number of machines without any complications. Could it be in the pursuit of adjustable resistors or some other equipment that would enable such mobility?

Improve the LabVIEW Program

Considering the purely functional nature of the LabVIEW Program, there is much room for improvement. Whether it is through the addition of SubVIs to the existing program or increasing the functionality to provide more information in a better means to an operator, there could be significant improvements made to the LabVIEW program.

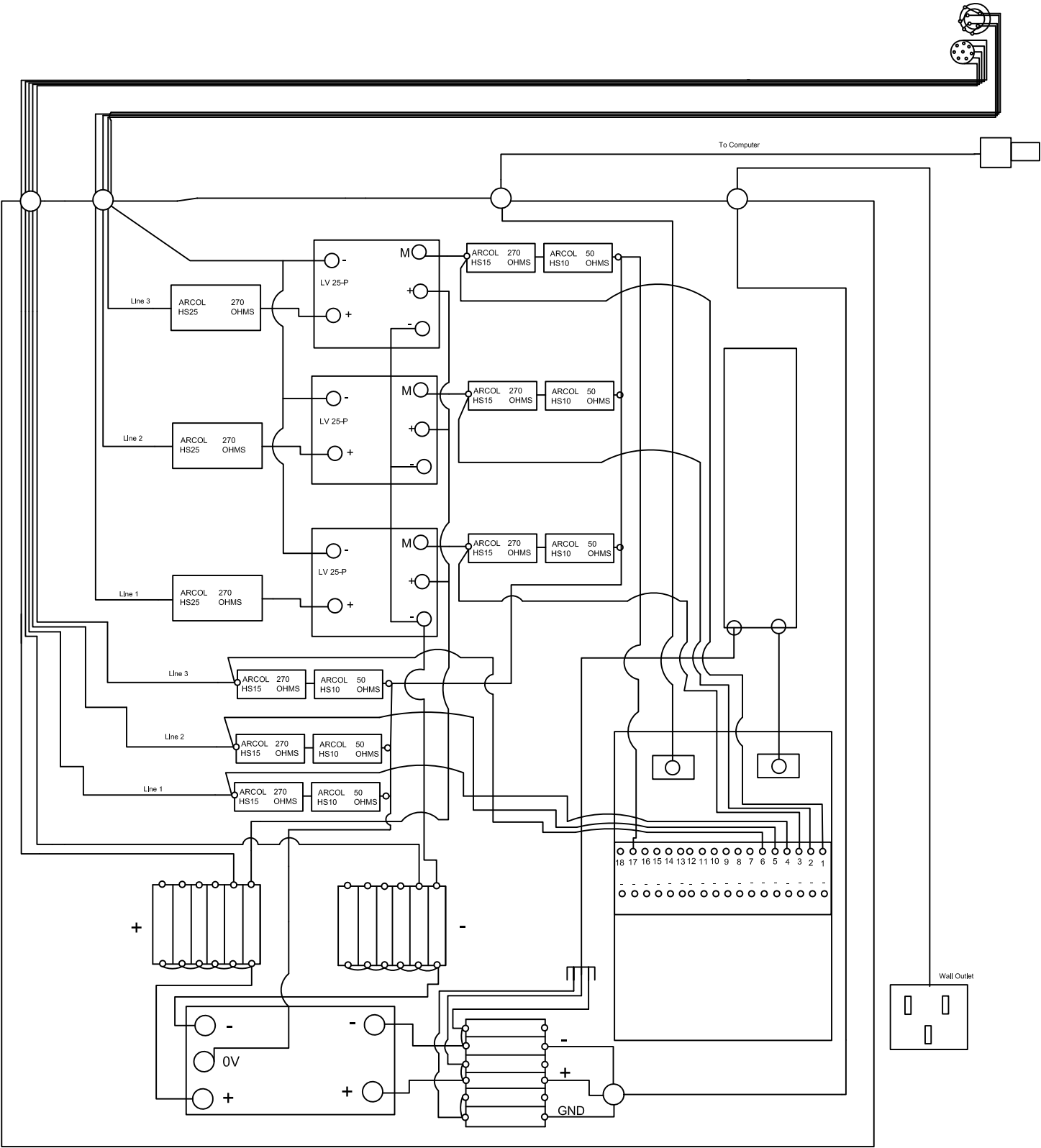
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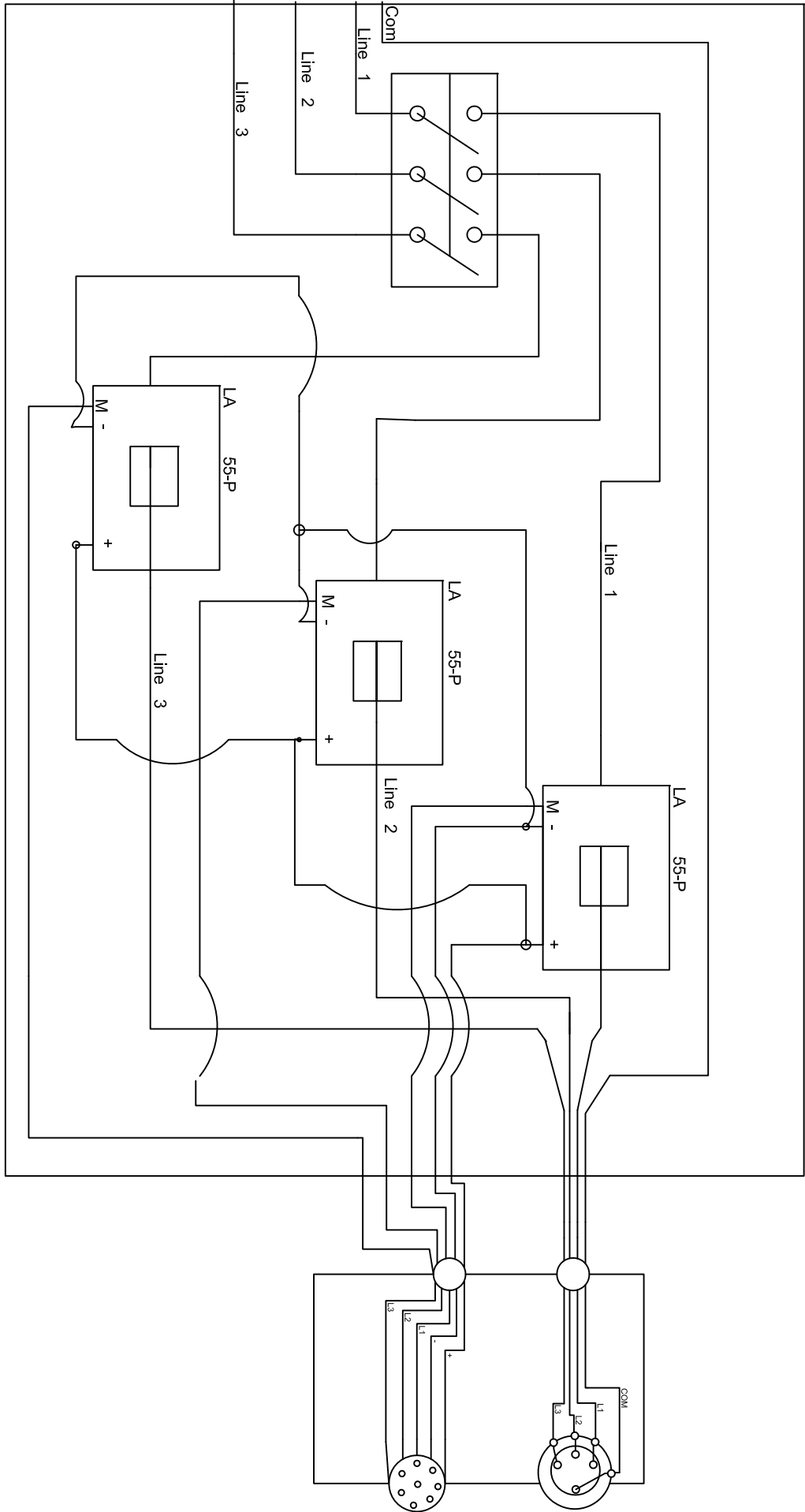
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APPENDICES





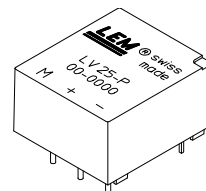
Voltage Transducer LV 25-P

For the electronic measurement of voltages : DC, AC, pulsed..., with a galvanic isolation between the primary circuit (high voltage) and the secondary circuit (electronic circuit).



$$I_{PN} = 10 \text{ mA}$$

$$V_{PN} = 10 \dots 500 \text{ V}$$



Electrical data

I_{PN}	Primary nominal r.m.s. current	10	mA
I_P	Primary current, measuring range	0 .. ± 14	mA
R_M	Measuring resistance	$R_{M \min}$ $R_{M \max}$	
	with $\pm 12 \text{ V}$	@ $\pm 10 \text{ mA}_{\max}$	30 190 Ω
		@ $\pm 14 \text{ mA}_{\max}$	30 100 Ω
	with $\pm 15 \text{ V}$	@ $\pm 10 \text{ mA}_{\max}$	100 350 Ω
		@ $\pm 14 \text{ mA}_{\max}$	100 190 Ω
I_{SN}	Secondary nominal r.m.s. current	25	mA
K_N	Conversion ratio	2500 : 1000	
V_C	Supply voltage ($\pm 5 \%$)	$\pm 12 \dots 15$	V
I_C	Current consumption	10 (@ $\pm 15 \text{ V}$) + I_S	mA
V_d	R.m.s. voltage for AC isolation test ¹⁾ , 50 Hz, 1 mn	2.5	kV

Accuracy - Dynamic performance data

X_G	Overall Accuracy @ I_{PN} , $T_A = 25^\circ\text{C}$	@ $\pm 12 \dots 15 \text{ V}$	± 0.9	%
		@ $\pm 15 \text{ V}$ ($\pm 5 \%$)	± 0.8	%
e_L	Linearity		< 0.2	%
I_O	Offset current @ $I_P = 0$, $T_A = 25^\circ\text{C}$	Typ	Max	
I_{OT}	Thermal drift of I_O			
		0°C .. + 25°C	± 0.06	± 0.25 mA
		+ 25°C .. + 70°C	± 0.10	± 0.35 mA
t_r	Response time ²⁾ @ 90 % of $V_{P \max}$	40		μs

General data

T_A	Ambient operating temperature	0 .. + 70	$^\circ\text{C}$
T_S	Ambient storage temperature	- 25 .. + 85	$^\circ\text{C}$
R_P	Primary coil resistance @ $T_A = 70^\circ\text{C}$	250	Ω
R_S	Secondary coil resistance @ $T_A = 70^\circ\text{C}$	110	Ω
m	Mass	22	g
	Standards ³⁾	EN 50178	

Features

- Closed loop (compensated) voltage transducer using the Hall effect
- Insulated plastic case recognized according to UL 94-V0.

Principle of use

- For voltage measurements, a current proportional to the measured voltage must be passed through an external resistor R_1 which is selected by the user and installed in series with the primary circuit of the transducer.

Advantages

- Excellent accuracy
- Very good linearity
- Low thermal drift
- Low response time
- High bandwidth
- High immunity to external interference
- Low disturbance in common mode.

Applications

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Power supplies for welding applications.

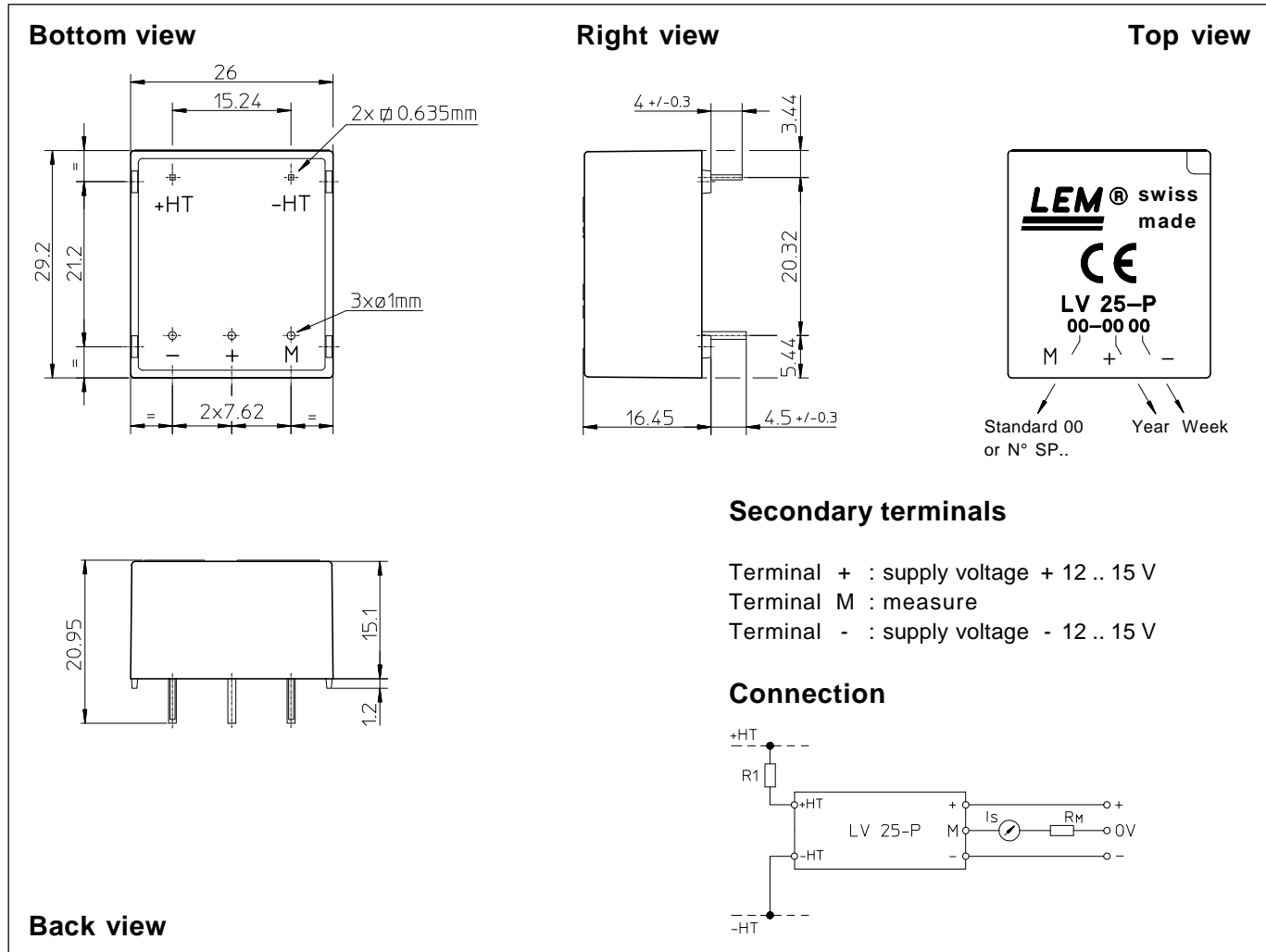
Notes : ¹⁾ Between primary and secondary

²⁾ $R_1 = 25 \text{ k}\Omega$ (L/R constant, produced by the resistance and inductance of the primary circuit)

³⁾ A list of corresponding tests is available

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Dimensions LV 25-P (in mm. 1 mm = 0.0394 inch)



Mechanical characteristics

- General tolerance ± 0.2 mm
- Fastening & connection of primary 2 pins
0.635 x 0.635 mm
- Fastening & connection of secondary 3 pins $\varnothing 1$ mm
- Recommended PCB hole 1.2 mm

Remarks

- I_s is positive when V_p is applied on terminal +HT.
- This is a standard model. For different versions (supply voltages, turns ratios, unidirectional measurements...), please contact us.

Instructions for use of the voltage transducer model LV 25-P

Primary resistor R_1 : the transducer's optimum accuracy is obtained at the nominal primary current. As far as possible, R_1 should be calculated so that the nominal voltage to be measured corresponds to a primary current of 10 mA.

Example: Voltage to be measured $V_{PN} = 250$ V

- a) $R_1 = 25$ k Ω / 2.5 W, $I_p = 10$ mA Accuracy = ± 0.8 % of V_{PN} (@ $T_A = +25^\circ\text{C}$)
b) $R_1 = 50$ k Ω / 1.25 W, $I_p = 5$ mA Accuracy = ± 1.6 % of V_{PN} (@ $T_A = +25^\circ\text{C}$)

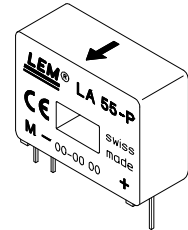
Operating range (recommended) : taking into account the resistance of the primary windings (which must remain low compared to R_1 , in order to keep thermal deviation as low as possible) and the isolation, this transducer is suitable for measuring nominal voltages from 10 to 500 V.

LEM reserves the right to carry out modifications on its transducers, in order to improve them, without previous notice.

Current Transducer LA 55-P

$$I_{PN} = 50 \text{ A}$$

For the electronic measurement of currents : DC, AC, pulsed..., with a galvanic isolation between the primary circuit (high power) and the secondary circuit (electronic circuit).



Electrical data

I_{PN}	Primary nominal r.m.s. current	50	A
I_P	Primary current, measuring range	0 .. ± 70	A
R_M	Measuring resistance @	$T_A = 70^\circ\text{C}$ $T_A = 85^\circ\text{C}$ R_{Mmin} R_{Mmax} R_{Mmin} R_{Mmax}	
	with $\pm 12 \text{ V}$	@ $\pm 50 \text{ A}_{max}$	10 100 60 95 Ω
		@ $\pm 70 \text{ A}_{max}$	10 50 60 ¹⁾ 60 ¹⁾ Ω
	with $\pm 15 \text{ V}$	@ $\pm 50 \text{ A}_{max}$	50 160 135 155 Ω
		@ $\pm 70 \text{ A}_{max}$	50 90 135 ²⁾ 135 ²⁾ Ω
I_{SN}	Secondary nominal r.m.s. current	50	mA
K_N	Conversion ratio	1 : 1000	
V_C	Supply voltage ($\pm 5 \%$)	$\pm 12 \dots 15$	V
I_C	Current consumption	10 (@ $\pm 15 \text{ V}$) + I_S	mA
V_d	R.m.s. voltage for AC isolation test, 50 Hz, 1 mn	2.5	kV

Accuracy - Dynamic performance data

X	Accuracy @ I_{PN} , $T_A = 25^\circ\text{C}$	@ $\pm 15 \text{ V}$ ($\pm 5 \%$)	± 0.65	%
		@ $\pm 12 \dots 15 \text{ V}$ ($\pm 5 \%$)	± 0.90	%
e_L	Linearity		< 0.15	%
I_O	Offset current @ $I_P = 0$, $T_A = 25^\circ\text{C}$	Typ	Max	
I_{OM}	Residual current ³⁾ @ $I_P = 0$, after an overload of $3 \times I_{PN}$		± 0.2	mA
I_{OT}	Thermal drift of I_O		± 0.3	mA
		0°C .. + 70°C	± 0.1	mA
		- 25°C .. + 85°C	± 0.1	mA
t_{ra}	Reaction time @ 10 % of I_{Pmax}	< 500		ns
t_r	Response time @ 90 % of I_{Pmax}	< 1		μs
di/dt	di/dt accurately followed	> 200		A/ μs
f	Frequency bandwidth (- 1 dB)	DC .. 200		kHz

General data

T_A	Ambient operating temperature	- 25 .. + 85	°C
T_S	Ambient storage temperature	- 40 .. + 90	°C
R_S	Secondary coil resistance @	$T_A = 70^\circ\text{C}$	80 Ω
		$T_A = 85^\circ\text{C}$	85 Ω
m	Mass	18	g
	Standards ⁴⁾	EN 50178	

- Notes : ¹⁾ Measuring range limited to $\pm 60 \text{ A}_{max}$
²⁾ Measuring range limited to $\pm 55 \text{ A}_{max}$
³⁾ Result of the coercive field of the magnetic circuit
⁴⁾ A list of corresponding tests is available

Features

- Closed loop (compensated) current transducer using the Hall effect
- Printed circuit board mounting
- Insulated plastic case recognized according to UL 94-V0.

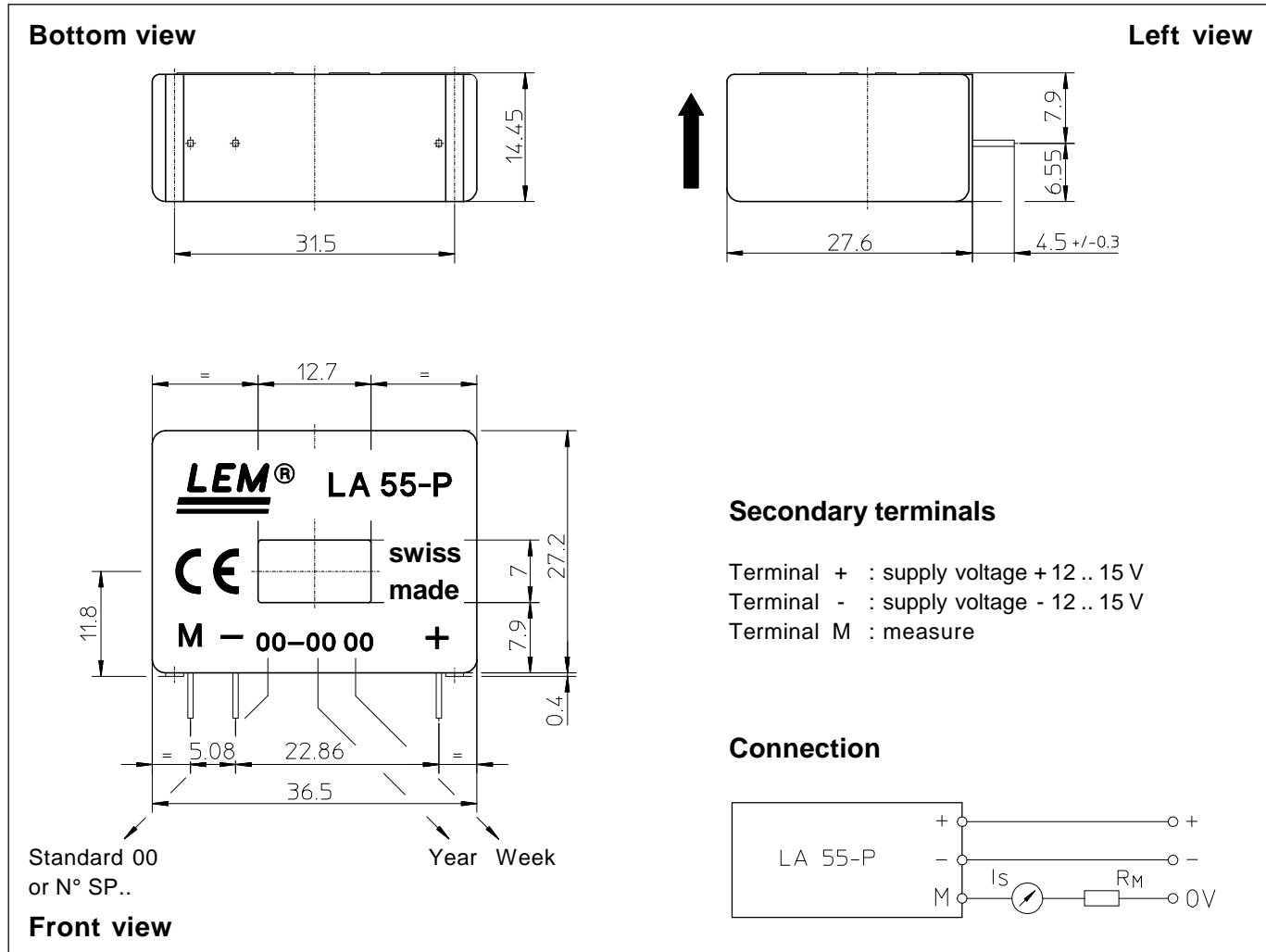
Advantages

- Excellent accuracy
- Very good linearity
- Low temperature drift
- Optimized response time
- Wide frequency bandwidth
- No insertion losses
- High immunity to external interference
- Current overload capability.

Applications

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Switched Mode Power Supplies (SMPS)
- Power supplies for welding applications.

Dimensions LA 55-P (in mm. 1 mm = 0.0394 inch)

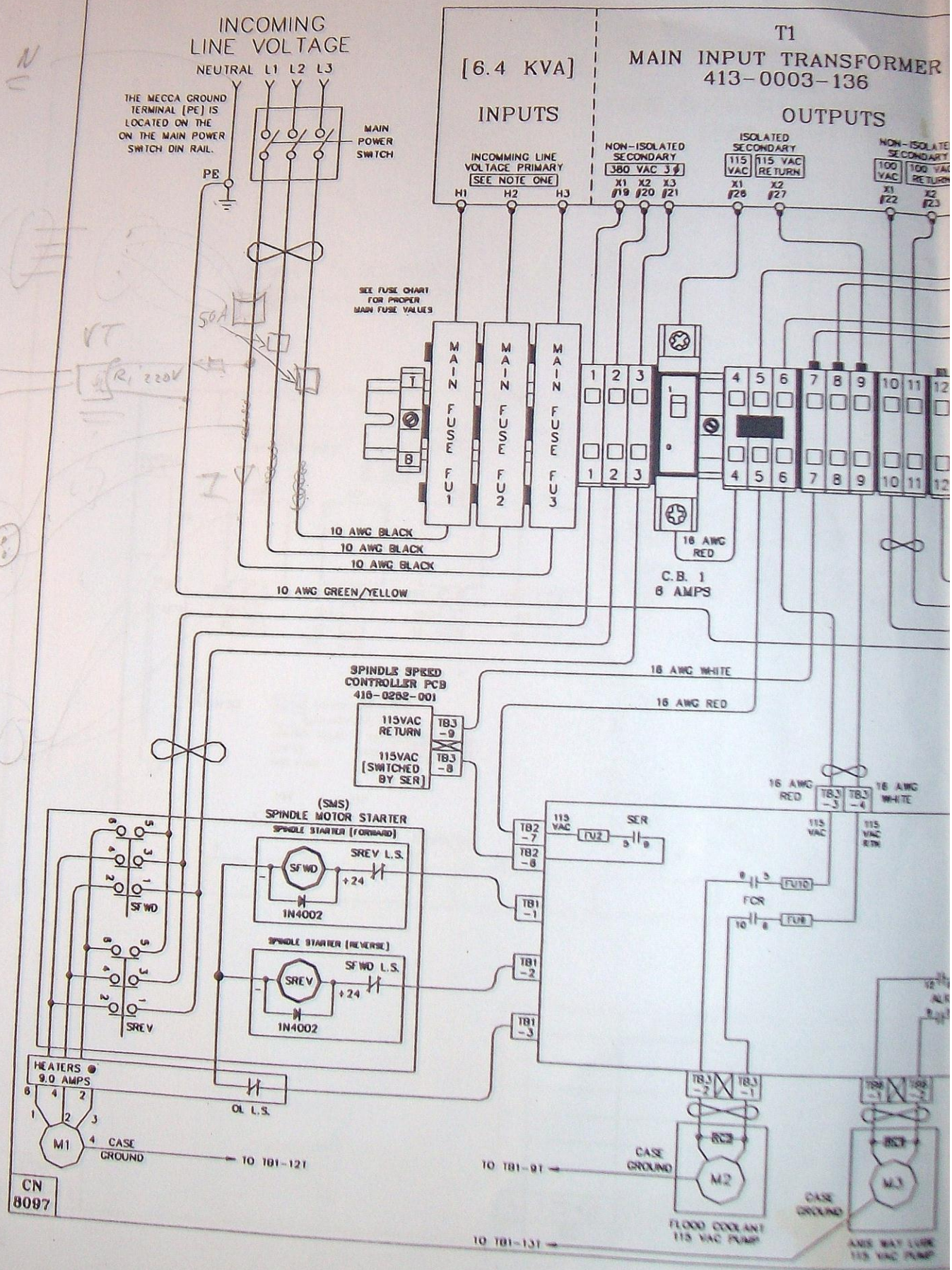


Mechanical characteristics

- General tolerance ± 0.2 mm
 - Primary through-hole 12.7×7 mm
 - Fastening & connection of secondary 3 pins 0.63×0.56 mm
- Recommended PCB hole 0.9 mm

Remarks

- I_s is positive when I_p flows in the direction of the arrow.
- Temperature of the primary conductor should not exceed 90°C.
- Dynamic performances (di/dt and response time) are best with a single bar completely filling the primary hole.
- In order to achieve the best magnetic coupling, the primary windings have to be wound over the top edge of the device.
- This is a standard model. For different versions (supply voltages, turns ratios, unidirectional measurements...), please contact us.



MAIN DISCONNECT FUSE CHART

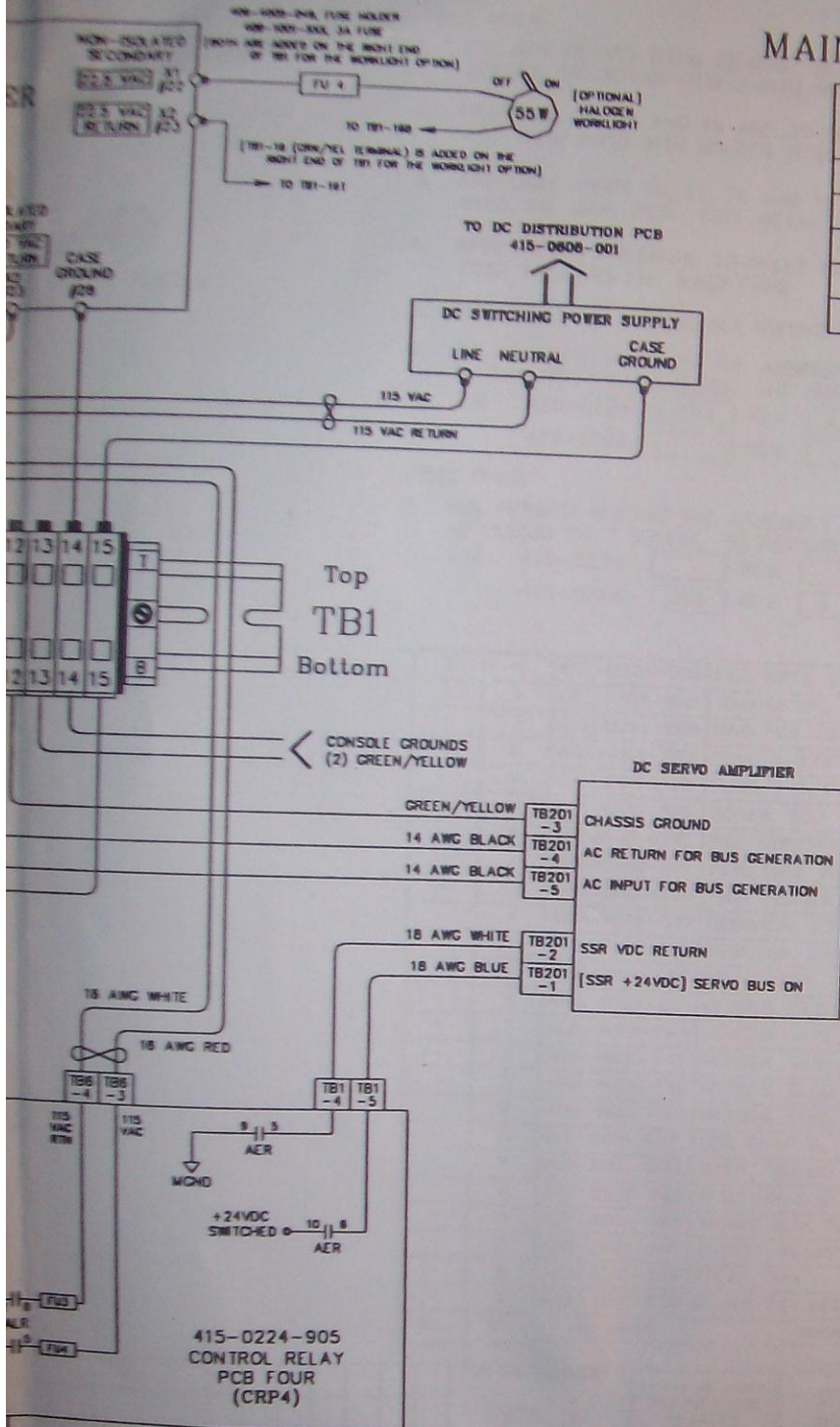
INCOMING VOLTAGE	FUSE TYPE AND RATING	
	HAWK 5M	PART NUMBER
200/208 VAC	ATQ-30	409-1001-129
240 VAC	ATQ-25	409-1001-082
380/415 VAC	ATQ-12	409-1001-128
480 VAC	ATQ-12	409-1001-128
600 VAC	ATQ-10	409-1001-079

ABBREVIATIONS

AER	AXIS ENABLE RELAY
ALR	AXIS LUBE RELAY
FCR	FLOOD COOLANT RELAY
SER	SPINDLE ENABLE RELAY
SFWD	SPINDLE FORWARD
SREV	SPINDLE REVERSE

NOTES:

1. SELECT THE APPROPRIATE TAP ON T1 TO MATCH THE CUSTOMER LINE VOLTAGE.
2. CUSTOMER WIRING TO THE MACHINE MUST BE SIZED FOR A 10 KVA LOAD.
3. INSTALL THE APPROPRIATE FUSE VALUE FOR THE SELECTED CUSTOMER LINE VOLTAGE.
4. TB1 IS THE MAIN POWER DISTRIBUTION TERMINAL STRIP.
5. THE MECCA GROUND TERMINAL STRIP IS LOCATED ON THE MAIN POWER SWITCH RAIL.



A 13143 ORIGINAL RELEASE		HAWK 5M		SCHEMATIC, CONTROL VOLTAGE HAWK 5M	
DATE 10/24/84		CHECKED TJW		APPROVED TJW	
SCALE 1:1		UNIT OF MEAS D		002-4222-002	