An Electric Actuator Selection Aid for Low Cost Automation

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: …………………….. Date: ……………………...

ABSTRACT

Low Cost Automation (LCA) is of immense importance to industry, and even more so for small scale industries. In implementing LCA determining cost effective and efficient actuator alternatives present challenges for design engineers. Most often decisions are experiential or entirely based on manufacturer recommendations. Experience based decisions are most often biased with respect to the engineers' knowledge. Similarly, manufacturer recommendations are restricted to their own products and are as such also biased. Either way, sub-optimum drive alternatives may sometimes be chosen. This demonstrates the need for making better informed decisions based on more than experience and what is available for use.

This thesis reports the development of an electric actuator selection procedure and aid for use in the early layout design phase. It provides readily accessible information on technically viable actuator options. Experiential knowledge of experts in the field, commercial information, as well as data obtained from experimentation was used in its development. Being orientated towards LCA, the procedure has been targeted at the application of electric motors and their associated control technologies but can be extended to hydraulic, pneumatic and other actuators. In achieving a wider applicability of the selection aid, a generic set of actuator properties descriptive of most actuators was formulated.

An AC drives control evaluation was conducted for developing the selection procedure and aid. It provided a means to validate some selection aid rules associated with actuator controllability. Quantitative data on speed and positioning accuracies of common AC three phase motors and their associated inverter technologies were the targeted results of the experimentation.

OPSOMMING

Lae Koste Outomatisering (LKO) is van uiterste belang vir die industrie en juis te meer vir kleinskaal industrieë. Met die implementering van LKO, bied die bepaling van koste-effektiewe en gepaste aktueerder keuses 'n uitdaging vir ontwerpingenieurs. Besluite word gewoonlik op ervaring of slegs op vervaardigers se aanbevelinge gegrond. In ervaringgedrewe-besluite lei die ingenieur se kennis gewoonlik tot vooroordeel. Net so word vervaardigers se aanbevelinge beperk to hul eie produkte en is dus ook onderhewig aan vooroordeel. In beide gevalle word sub-optimale aktueerders soms gekies. Dit demonstreer die behoefte aan beter ingeligte keuses, gegrond op meer as ondervinding en beskikbare produkte.

Hierdie tesis beskryf die ontwikkeling van 'n elektriese aktueerder keuseprosedure en -hulpmiddel vir gebruik in die vroeë uitlegontwerpfase. Dit voorsien maklik bekombare inligting oor tegnies lewensvatbare aktueerder opsies. Ervaring van kenners in hierdie gebied, kommersiële inligting, asook data verkry vanaf eksperimente, is gebruik in die ontwikkeling daarvan. Aangesien die prosedure op LKO gerig is, is die toepassing van elektriese motors en hul meegaande beheertegnologieë geteiken, maar kan uitgebrei word na hidrouliese, pneumatiese en ander aktueerders. Ter wille van die wyer toepaslikheid van die keuse hulpmiddel, is 'n generiese stel aktueerder eienskappe geformuleer wat die meeste bestaande aktueerders beskryf.

'n WS aandryfbeheerder evaluering is gedoen vir die ontwikkeling van die keuseprosedure en -hulpmiddel. Dit voorsien 'n bevestiging van sekere van die keusereëls geassosieer met aktueerder beheerbaarheid. Kwantitatiewe data van spoed- en posisioneringsakkuraathede van algemene WS drie-fase motors en hul meegaande omsettertegnologieë, is geteiken in die eksperimentele resultate.

DEDICATION

This thesis is dedicated to God, my family and to the CAD research group, Department of Mechanical and Mechatronic Engineering, Stellenbosch University.

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I would like to express my gratitude towards the following persons and organization:

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- My colleagues for their motivation and advice

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Abbreviations

ACIM – AC induction motor

AMTS – Advanced Manufacturing Technology Strategy

CFC – Current controlled flux vector control

DAQ – Data acquisition

EAP – Electroactive polymers

ERFs – Electrorheological fluids

LCA – Low cost automation

LDT – Linear displacement transducer

MRFs – Magnetorheological fluids

MSM – Magnetostrictive materials

PZT – Piezoelectric

SMA – Shape memory alloys

VFC – Voltage controlled flux vector control

CHAPTER 1 INTRODUCTION AND OVERVIEW

1.1 Actuator selection and low cost automation

Actuators are integral components of most automation schemes and engineering systems. Being ubiquitous and significant to engineering processes and systems, their proper selection is a task the system/design engineer must contend with quite often. Automation in industry plays an important role by improving competitiveness and efficiency. In order for small scale industries to be competitive and efficient in this regard, low cost automation (LCA) is a necessity.

LCA refers to any technology that creates some degree of automation around the existing equipment, tools, methods, and people, using mostly standard components available off the shelf (Ramakrishnan, 2002). As described by Francisco (1972), low cost automation generally involves building into and around existing standard equipment, mechanisms and devices to convert selected manual operations to automatic operations.

Proper actuator selection aids in achieving some LCA goals. The appropriateness of a selected actuator for a particular application may vary from industry to industry. Some of the more important reasons for this variation in appropriateness are cost and accuracy. A choice however must be made, and as explained by Crowder (2006), “the final selection of an actuator is left to the system engineer, who is able to balance the relative pros and cons on an objective basis”. It is for this reason this research is oriented towards LCA, and aimed at providing quick access to information on feasible off the shelf actuator options for LCA systems in the early layout design phase.

The term low cost will be used interchangeably with affordable, therefore a low cost actuator alternative in this thesis refers to an affordable off the shelf electric motor.

The Department of Mechanical and Mechatronic Engineering at Stellenbosch University is presently undertaking the development of a pool playing robot as part of an Affordable Automation Research Platform. This research platform forms part of the

Advanced Manufacturing Technology Strategy (AMTS) flagship program "Affordable Automation". Employed in the pool robot design are a wide variety of actuators and sensors with particular emphasis on affordability.

This thesis focuses primarily on electric motors as the most viable LCA candidates for automated actuation. This research is limited to low cost automation, and has been conducted such as to allow for incorporation of a wider variety of actuation technologies, such as hydraulics and pneumatics to allow for a broad spectrum of choice in actuator selection.

1.2 Problem statement and objectives

Actuators are available off the shelf in numerous brands, operating principles, and with widely varying functionality. The task of selecting one which provides efficiently the required functionality for an application is a challenge. The ready availability of manufacturer product catalogues, outlining characteristics and ratings of actuators helps in some cases. However, because of inconsistencies in manufacturer information, most engineers resolve to choose based on experience. The question thus arises – *what happens where there is no relevant experience?*

The scope of this thesis with regards to electric motor selection is defined by automation applications and restricted to affordable automation alternatives. It is important to note that actuators could be custom made to suit application requirements, however because this thesis is focused on affordability, only off the shelf products are considered. Automation applications will furthermore be limited to those with the following features:

- Discrete parts manufacture, but with significant production volumes
- Series production
- Reconfigurable machines within these automation applications
- Motors below 50 kW power rating
- Rated speeds below 7500 rpm

The objectives of this research are embodied in better informing the system/design engineer on determining optimum electric motors/electric motor - driver combinations for applications in early design. It aims at providing an easy and integrated approach to the more critical aspects of the selection process by supplying information based on actuator design and their associated drivers. The objectives can be listed out as follows:

- Formulating a generally applicable and easy to use actuator selection procedure oriented towards LCA, with primary focus on electric motors and their interfacing with drivers.
- Compilation of the developed procedure into an actuator selection aid expandable to more actuator types. The selection aid is intended to enable designers to quickly determine actuator types which are technically viable options for a design at hand.

1.3 Motivation

The matching of system requirements with actuator characteristics is an essential phase of the selection process because it provides a reference with which available actuators may be compared and selected. Presently, matching of system requirements with actuator characteristics is to a large extent experiential in nature. This is suggested by people in the field and a lack of available literature on adequate procedures for proper implementation of this phase of the selection process. “The engineer who specifies the control valve often selects an actuator at random” (Bhasin, 1990).

During the conceptual design phase it is usually of great importance to determine the proper actuation system to be used. An important reason for proper actuator selection is, perhaps, because the choice actuation solution may define the structural design layout.

Where electric motors are the choice actuation system in use, a vast number of motor designs exist to choose from, each of which have peculiar characteristics which may be used in deciding their viability for an application. Designers involved with electric motor selection rely mainly on experience or turn to manufacturers for advice and information on electric motor suitability. A problem associated with information amongst manufacturers is inconsistency. Information from different manufacturers on the same application is most often different. An engineer selecting a motor from a particular manufacturer catalogue is usually provided with motor specifications as well as their typical applications of use. The actuation requirements of some automated engineering systems may deviate from those commonly defined by typical applications in catalogues.

Experiential selection poses an inherent threat to system efficiency, especially with the fast growth in new drive technology. Pitfalls of solely experiential selection are not necessarily obvious but the possibility of economic as well as general system inefficiency in the low cost automation context is of importance.

LCA requires that design cost be kept to a minimum and so prevents exhaustive actuator searches especially in the layout design phase. In actuator selection for LCA, cheaper alternatives may be available which also suit system requirements. These alternatives will go unidentified and unutilized if selection is based solely on experience. Furthermore, advancement in actuator technology has also brought along more alternatives, which designers may be unfamiliar with. Previously suitable alternatives become less suitable with advancement in technology, but more importantly they could just be unnecessarily expensive or uneconomical.

In view of such inadequacies, it is important to improve the decision making process especially for LCA systems in the early design phase, by developing a systematic and efficient affordable procedure for the proper selection of actuators. This procedure is expected to provide a broad variety of electric motors for selection as well as motor – driver interfacing information for optimum actuation and system efficiency. In other words, it should bring the choices to the designer and more importantly give information on why they are feasible choices. Minimizing experience dependency in the selection process is an expected outcome of the developed procedure. Reduced cost in automation through cost effective decision making and improved drive efficiency in LCA applications by providing a broad base of applicable alternatives for selection are also expected outcomes.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter describes actuators, their classification/types, criteria required for their selection, selection of low cost automation (LCA) actuator alternatives, etc. Most importantly it describes some contemporary procedures available for actuator selection as the main interest of this thesis. It finally describes the concept of knowledge-based expert systems as a means through which the development of the selection aid is achieved.

Actuator selection procedures will be discussed in terms of their effectiveness with regards to selecting from a wide range of actuators and their applicability with respect to affordable off the shelf alternatives. For electric motor selection, focus will be on a wide range of designs as well as the inclusion of drivers in selection. It is important that the LCA context is kept in mind throughout this thesis.

2.2 Actuators

Actuators are basically the motion drive components behind mechatronic systems that accept a control command and produce a change in the physical system by generating usually mechanical output such as motion, heat, flow, etc (Jose, 2005). Their appropriate selection is as such of immense importance to general system efficiency. Before actuator selection can be discussed it will be appropriate to give the necessary background for their understanding.

2.3 Classification of actuators

Actuators can be classified in many ways according to their application, actuation technology/physical law guiding them, type of motion, etc. Traditional and emerging actuators are a more common means of classification. Under the traditional classification, actuators are essentially electrical, electromechanical, electromagnetic, hydraulic, or pneumatic types. The new and emerging generation of actuators includes smart material actuators, microactuators and nanoactuators. Transducing materials of some smart material actuators include: piezoelectric (PZT) ceramics, shape memory alloys (SMA), electroactive polymers (EAP), magnetostrictive materials (MSM), electrorheological (ERFs) and magnetorheological fluids (MRFs) (Anjanappa et al, 2002).

2.4 Actuator selection

The following paragraphs present some contemporary selection procedures and aids, their merits and demerits with reference to the specific selection issues mentioned earlier.

2.4.1 Selection procedures

The process of actuator selection is one that can be located anywhere within the design process depending on the applications for which it is required. For conceptual designs in early development, actuator selection may be required while the general layout attributes of the system are still being determined. For example, the choice of using an electric or hydraulic actuation system is influenced by system structure/layout and vice versa. Actuator selection procedures can also be made use of in redesigning existing systems, general maintenance or for system upgrades. In the LCA context, selection must be carried out with only off the shelf commodities in maintaining the orientation of this thesis.

A prerequisite for the selection of any actuator is its ability to provide the functionality necessary for the system to perform its required task as and when needed, and for as long as required through all operating conditions. The suitability of an actuator is dependent on a number of factors, which could include a particular actuation requirement that is intrinsically required by the system (Jose, 2005), energy consumption or economic constraints. Actuator selection requires that the system designer has in-depth understanding of system requirements, so as to be able to match correctly these requirements with actuator characteristics.

Actuator selection procedures can be classified into software or literature based procedures as illustrated in Figure 2-1. Software based procedures are those which aid a user in selection via a developed software application, while the literature based procedures typically give literature on calculation methods, guidelines or tips applicable to actuator selection. In software based procedures the user is essentially required to supply information about the intended system or is required to choose based on displayed property options, from a database of actuators. Software selection procedures can further be categorized based on their source as: Manufacturer software applications, Research software applications, and Miscellaneous or Organization software applications (organizations such as US Department of Energy). Similarly, literature based selection procedures can be sourced as: Manufacturer catalogues and manuals, Handbooks/Textbooks and Research type literature, and Miscellaneous or Organization type literature.

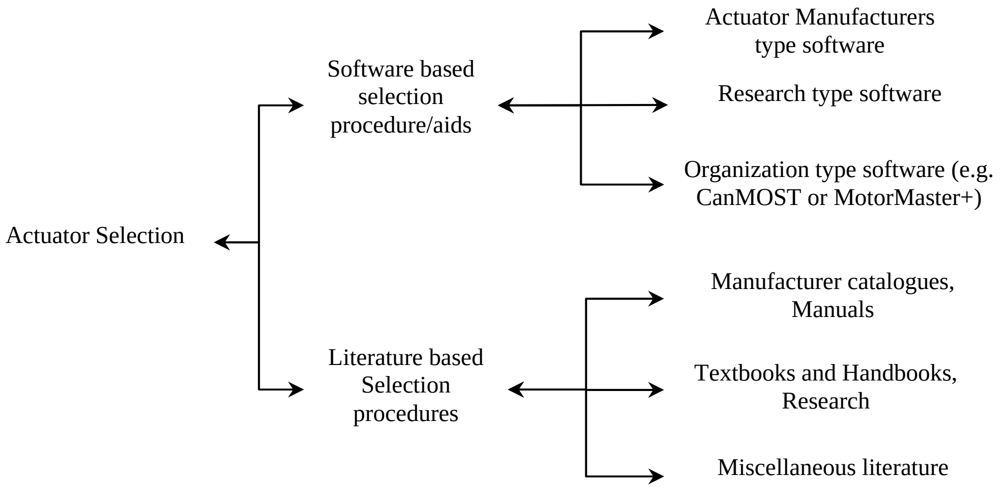

Figure 2-1 Actuator selection procedures

In general, selection procedures could be described as generic or specific. While generic procedures have no specific actuator technology or design as their main focus, specific selection procedures refer specifically to a particular actuation technology, design, or a company’s products.

Literature describes software based procedures which aid the purchaser in selection, in terms of types, products available, characteristics, energy savings and cost analysis. Literature based selection procedures, such as handbooks describe calculation procedures for determining system requirements, while others include tips/guidelines describing certain steps through which suitable actuators may be selected.

2.4.2 Software based selection procedures/aids

2.4.2.1 Research type software

Amongst the software based selection procedures is a web-based actuator selection tool by Madden and Filipozzi (2005). This software allows actuator technologies in its database to be compared and evaluated based on volume, mass, work, power and power source requirements. This selection software represents a more generic approach with operating principle and technology as determining factors for actuator suitability. The web-based tool however focuses on linear actuator technologies (thermal shape memory alloys, ferroelectric polymers, conducting polymer actuators, skeletal muscle, etc.). It addresses the selection process by enabling device designers to input basic needs (force, displacement, frequency, cycle life, dimensions, voltage and power available) and to retrieve an initial evaluation of the suitability of the various linear actuator technologies in the database. In the LCA context, this selection procedure is of very little importance as its focus is on the more esoteric actuator technologies.

Another software based selection procedure proposed by Zupan et al (2002), and representative of mostly linear actuators, is by far the most robust encountered in literature at this time. The strategy is demonstrated by software that includes a database of some 220 actuators from 18 families, and an advanced selection engine. It relies on the comparison of actuator performance attributes and so called “normalized” actuator attributes as well as system performance, weight and cost. The performance attributes, unique to an individual product can be found in a record for commercially available actuators. These normalized attributes are to an extent characteristic of most actuators and of linear actuators in particular.

The software (Zupan et al, 2002) allows plots of any pair of attributes, mapping the chosen plotted attributes against those in the database, thereby eliminating those outside the required range. The selection engine identifies those actuators which fall within the required range and makes the specific actuator records available. This software addresses selection from a technologies standpoint, but is devoid of electric motors which are a commonly used means of actuation in automation today. It focuses more on the linear actuators and also consists of the more esoteric actuator technologies which are outside the realm of LCA.

2.4.2.2 Actuator manufacturer type software

Some actuator production companies have similarly developed software to aid in selection of their own actuators based on prescribed automation applications. The Danaher Motioneering Engine (Danaher Motion, 2006) is an example of such software. It functions by enabling the user to create projects by first selecting a particular application from six alternatives: lead screw, conveyor, rotary, nip roll, rack and pinion and linear mechanisms. System parameters are then defined, from which other parameters may be derived. Possible actuator alternatives are then proffered from their range of servo and stepper motors. Other tools for checking speed-torque graphs etc. for these brands are available (more or less like an electronic catalogue). This selection aid places restrictions on application types and focuses solely on Danaher servo and stepper motors, it however provides off the shelf commodities.

Other companies in literature with similar selection aids have a somewhat wider application set, however the motors are restricted to the company’s models. One such software applications is the Mselect3E developed by Panasonic, 2007.

2.4.2.3 Organisation type software

The MotorMaster+ International (U.S. Department of Energy, 2006) and Canadian motor selection tool (Natural Resources Canada, 2006) are similar organization type software. These Software applications are characterized by huge databases of electric motors. The MotorMaster+ International has a manufacturer’s database of about 32,000 NEMA* and IEC† motors while the CanMOST (Canadian motor selection tool) has a database of 43,000 North American and European motors. These databases are built up from specific manufacturer models of the major motor suppliers in North America, leading to the large number of entries.

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[*] *NEMA (National Electrical Manufacturers Association)*

[†] *IEC (International Electrotechnical Commission)*

The CanMOST and MotorMaster+ focus only on AC induction motors as the only actuator alternatives within their databases. They function by using values deduced from system specifications inputted by the user to provide a list of applicable and available alternatives from the database.

These software applications focus more on detailed design where specific solutions are required and assume the need for AC motors, restricting choice to their pool of alternatives based on the detailed design specifications. No insight is given into motor – driver compatibility and interaction as it affects the driven system. Being limited to AC motors, other feasible LCA alternatives are not explored. For instance DC motors perform better where quick responses to control signals are required (Rosaler, 2002). DC motors may also be the choice alternative when small size is a constraint on the required actuator. Similarly, a combination of motors and drivers may be a better option for driving the system. These important aspects are not factored into the framework of the mentioned selection procedures. However, a very important feature in the LCA context is that they provide cost analysis and energy-savings on applicable alternatives.

2.4.3 Literature based selection procedures

Many handbooks are available which provide calculation steps for determination of system characteristics in relation to actuators. Even though these general calculation steps are very important with respect to selection, these handbooks fail in providing possible alternatives for the determined relationships, with the result that there exists a gap between calculated values and feasible design types. An excerpt from a system – motor matching procedure for selection is - “The motor must have sufficient starting and pull-up torque to bring the driven machine to operating speeds” (Lawrie, 1996). Before such a guideline can be utilized the designer must know what actuator type or technology is applicable. The mentioned guideline is also hampered by specificity of actuator type. In this case, it referred to squirrel-cage induction motors. This excerpt may not be readily generalized to provide suitable results especially for electric motor - driver combinations.

In general selection of actuators for most systems is affected by the system drive components in entirety (i.e. the interaction between the driver, the actuator itself and the feedback response). “The role of the actuator in most systems is to establish the flow of power by means of some control actions (inputs) in response to process models or sensory data so that the desired trajectory is effectively accomplished” (Jose, 2005). These interactive factors play an important role in determining the overall efficiency of the system. The procedures mentioned thus far, fall short in this regard as they provide no information on such selection intricacies.

The discussed selection procedures address the selection process from different approaches and perspectives but aim to accomplish the same objective of selection. While some of these selection procedures refer to commercially off the shelf products as prescribed by LCA, others are simply outside the realm of LCA.

2.5 Actuator selection criteria

In the selection of actuators, certain requirements are necessary to describe systems. These requirements in turn may be used as criteria to determine viable actuators for the described system. The determination of these criteria is necessary to provide a basis for the comparison and selection of different actuator technologies and types. The following paragraphs highlight some general selection criteria with a more in-depth discussion presented in Chapter 3 about the selection criteria implemented in this thesis. Suitability of actuators for particular purposes may vary as mentioned earlier. Depending on the circumstances or the application for which actuators are being selected, selection criteria are prioritized by the design engineer and vary from application to application.

2.5.1 Operational, performance and environmental selection criteria

Selection criteria in relation to system actuation requirements as described by Vaidya (1995) may be broadly classified into operational, performance and environmental. Selection of the proper actuator type is of higher priority than power requirements or coupling mechanisms of the systems which they drive. Under operational criteria, the need for coupling mechanisms in some cases may be completely avoided if the actuator provides an output that can be directly interfaced with the system. For example, the selection of a linear actuator rather than a rotary actuator obviates the need for a coupling mechanism with the function of converting rotary to linear motion.

Performance criteria of importance in the selection of actuators for a specific need include continuous power output, range of motion, resolution, accuracy, peak force/torque, heat dissipation, speed characteristics, no load speed, frequency response, and power requirements (Anjanappa et al, 2002).

Another important criterion in selection is duty cycle. The duty cycle of the actuation system defines the speed and load variations during one complete cycle of operation. The power requirement during each segment of the duty cycle may be calculated from the knowledge of torque and speed. Load types can be classified into different duty cycles describing operating time and load variations (Dederer, 1997). These duty cycles are defined as continuous, intermittent and repetitive. Continuous duty can be defined as essentially constant load for an indefinitely long period of time. Intermittent duty refers to load which alternates between indefinite intervals of load and no-load; load and rest; or load, no-load and rest. Repetitive duty refers to loads for various intervals of time which are well defined and repeating. Other duty cycle definitions more specific to electric motors, as prescribed by NEMA and the IEC, are available in Appendix B.

Environmental requirements also play an important role in the selection of actuators. Under such requirements, important concerns include corrosiveness of environment, ambient temperature, cooling medium and method, shock, vibration, altitude, humidity, etc. For actuators such as motors, their materials and construction become an issue. As a result of the wide range of environments in which motors are required to perform, enclosure types are used as a means of classification.

2.5.2 Energy considerations in actuator selection

The efficiency with which actuators perform in terms of energy consumption is becoming of major concern in most developed countries because of increasing energy costs. Electric motor driven systems are estimated to consume over half of all electricity in the United States and over 70% of all electricity in many industrial plants

(U.S. Department of Energy, 2006). As a result there is heightened interest in the development of more energy efficient actuation systems.

In developing and third world countries where sustainable development is of more importance than optimization of extant technologies, the issue of energy efficiency may not be of great concern. It is however necessary to implement energy efficient decisions and systems most especially in the LCA context to avoid the need for upgrades of these same systems in the future. In selection for energy efficiency, running costs of actuators are far more important than first costs. Running costs which depend on efficiency must therefore be given due consideration within the selection process (Desai, 1996). Cost in this context has a profound influence over selection for LCA and is significantly dependent on the economics associated with the designed systems.

2.5.3 Control considerations in actuator selection

Several terms have been used to refer to electric motor power electronics such as controllers, amplifiers, drivers, converters and inverters depending on the drive of focus. In this thesis the term that will be used when referring to general actuator control is driver, while when referring specifically to AC motor control, the term inverter will be used.

A driver can be described as a device which regulates the state of a system by comparing a signal from the sensor located in the system with a predetermined value and adjusting its output to achieve the predetermined output (IEEE, 1996). Control selection in itself is dependent on the particular type, size, and application of the actuator to be controlled and the particular characteristics of the driven load.

Some of the issues relating to the effects of control on actuators and their selection are protection, starting, stopping, speed, position and torque control, acceleration and deceleration (Dederer, 1997). In general, the function of a driver in any system is to control speed, torque, or both, to keep currents within allowable limits and to control acceleration and deceleration as well as position. Some actuators are inherently better suited for certain speed conditions, but drivers influence actuator selection in this regard. Speed control could either be open loop where no feedback of actual actuator speed is used, or closed loop where feedback is used for more accurate speed regulation. Adjusting speed in motors to meet demand can yield substantial energy savings compared to running them and throttling the driven system.

Some of the more subtle issues of selection are that some actuator characteristics are in part determined or influenced by drivers. Due to the high demands for precise control, there is an increasing need for sophisticated controllers. To cater for application demands for precise actuator control from both position and dynamic standpoints, an actuation system may require a cost-effective driver with the flexibility and speed to process complex control algorithms.

The intricacy of selection with regard to system component interaction most often requires optimization of existing configurations. Iterative selection procedures have been proposed which are aimed at such selection intricacies, as demonstrated by Skelton and Li (2004).

2.5.4 Electric motor selection for affordable automation

Electrically actuated systems are very widely used in control systems. Some of the advantages of electric motors which make them an intrinsically viable candidate for LCA are their easy accessibility (off the shelf products), ready availability of compatible electric drivers and availability of power which can easily be routed to them. Electric motors, unrivalled because of their versatility, reliability and economy, are a suitable choice in LCA. Motors provide the motive power required for a wide variety of domestic and industrial engineering systems. Successful motor applications depend on selecting a type of motor which satisfies the kinetic starting, running and stopping of the driven system (Shaw and Cornelius, 2004). Sometimes, in order to achieve these successful and efficient motor applications, drivers must be used.

2.6 Trade-offs in actuator selection

Trade-offs are most often made in reaching decisions on actuators and drive systems to implement. Purchase cost, development cost and maintenance cost present such trade-off challenges. Set up time for any new system, the time required to understand new processes and software associated with setting up the drive system have to be taken into consideration. For example, a trade-off in most cases must be made between the purchase cost of a modular off the shelf drive system and the cost of putting together a drive system that is of the same functionality which may be cheaper. The difference in cost between these situations may determine which drive system to select, however it still comes back to what is regarded as acceptable extra costs which varies from one situation to another.

Trade-offs will always occur depending on the specific application, its economics and the engineering requirements which it must satisfy in order to operate. The responsibility eventually lies with the engineer to determine the most advantageous proffered or operational drive solution for the application. The “big picture” must be brought into focus in coming to conclusions on selection choices.

2.7 Knowledge-based systems

The following paragraphs address knowledge-based systems as an important concept in the development of the actuator selection aid.

The terms expert system, knowledge-based system and knowledge-based expert system are often used synonymously. As explained by Giarratano and Riley (2005), an expert system makes extensive use of specialized knowledge to solve problems at the level of the human expert. Alternatively, knowledge-based systems are computerized systems that use knowledge about some domain to arrive at a solution to a problem from that domain. This is depicted in Figure 2-3. This solution is essentially the same as that concluded by a person knowledgeable about the domain of the problem when confronted with the same problem (Avelino and Dankel, 1993). The concept of knowledge-based systems is being applied commercially in several fields of life including engineering and medicine. An example of a commercial expert system is the XCON/R1 system of Digital Equipment Corporation, used in configuring computer systems.

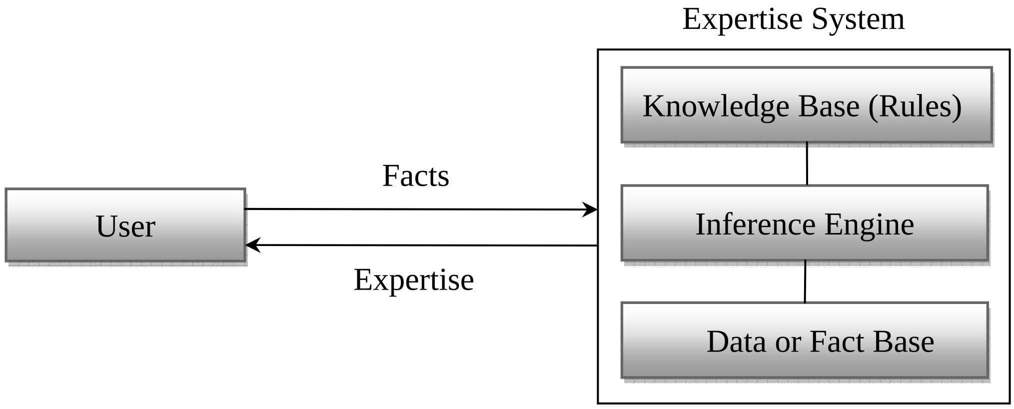

Figure 2-2 Function of a knowledge-based expert system [Giarratano and Riley, 2005]

The following are important terms related to expert systems:

- User interface – the mechanism by which the user and the expert system communicate.
- Data or fact base – a database of facts used by implemented rules.
- Inference engine – makes inferences by deciding which rules are satisfied by facts or objects, prioritizes the satisfied rules, and executes the rule with the highest priority.
- Knowledge-base – a set of rules based on accumulated knowledge (commercial and expert information)

Having defined these terms, a knowledge rule-based system could be defined as a system governed by a set of rules used in drawing inferences and conclusions on a particular problem (Avelino and Dankel, 1993). In a rule based system, the knowledge-base contains the domain knowledge needed to solve problems coded in the form of rules. In the case of any selection aid, heuristic rules defined by experts, or obtained as commercially available knowledge are aimed at providing solutions to the selection problem. In this thesis, the problem domain is actuators and the specific problem being faced is actuator selection. The rules would ideally govern choice of drive alternatives based on the designer’s inputs. The data or fact base would contain actuators and their corresponding properties, while the inference engine would be the logic built into the aid for implementing the appropriate rules.

Rule based reasoning associated with these systems play a very important role in the development of the selection aid because of its similarity to the human reasoning. This is because experts often assess and draw conclusions expressible in an *IF-THEN* rule format. For instance, in actuator selection: if an application requires high speed and accuracy, then a feasible choice maybe a servomotor.

Rule-based systems utilize inference to manipulate rules. Using search techniques and pattern matching, rule based systems automate reasoning methods and provide logical progressions from initial data such as system requirements to the desired conclusions (feasible drive solutions). This progression may cause new facts to be derived and lead to a solution of the problem (Avelino and Dankel, 1993).

Another important concept in rule based systems is forward reasoning. Forward reasoning starts with a set of known data and progresses naturally to a conclusion. Forward reasoning involves checking each rule to determine if the elicited user inputs negate the premises of any of these rules. Backward reasoning functions on the same principles but starts from the desired conclusion and decides if the user inputs support the derivation of a value for this conclusion. Due to the nature of the actuator selection problem, forward reasoning is the intuitive reasoning method of choice.

The discussed concepts provided by knowledge-based expert systems make it a good choice for developing the actuator selection aid.

In conclusion, having discussed some of the core issues related to actuators, electric motor selection and knowledge-based expert systems employed in developing the selection aid, the following chapters provide insight to the efforts made to develop the actuator selection procedure and aid.

CHAPTER 3 SELECTION PROCEDURE DEVELOPMENT

3.1 Introduction

This chapter is dedicated to providing information key to formulating the set of selection criteria used herein. These selection criteria form the subjects of the knowledge-based rules introduced in Chapter 2 and discussed in detail in Chapter 4. This chapter furthermore addresses the approach and ideas implemented in the selection procedure and software development.

3.2 Terminology

Certain terms are necessary in understanding and describing the approach adopted in meeting the set objectives. Some of these terms can be viewed and explained from two perspectives. These perspectives are the application/design engineer's perspective and the actuator perspective. The following definitions in relation to the thesis subject and the above mentioned perspectives will help in clarifying some of these ideas.

Application:

> This is the name given to any system for which actuator selection is performed. This includes systems at the design stage as well as existing systems requiring maintenance or modification and could range from a simple fan to robots. The applications of focus in this thesis are however those in the early design phase.

Application requirements:

> These could also be called the systems' actuation requirements and refers to the functional requirements that the system/application requires to perform its designated task as prescribed by the design engineer. An application can for example be described as a high speed application, a low starting torque application, a constant power load application, etc. This term basically refers to any property that the engineer uses to describe effectively his application.

Actuator properties:

> From the actuator perspective, these are properties that can be used in describing an actuator or drive solution (i.e. motor, or motor and inverter). Actuator properties and application requirements may have a one to one correlation. This is evident in the fact that an application possesses certain properties by virtue of its design and requires the actuator to provide those properties necessary to achieve the design objectives. For example a high speed application will require a high speed actuator to deliver the necessary high speeds. As such, actuator properties in many instances share a common name with their corresponding application requirement (e.g. high speed actuator and high speed application requirement).

Actuation scenario:

> This refers to a combination or a set of application requirements. Actuation scenarios describe in totality the conditions that must be provided for the application or system to function properly. For example, a predefined actuation scenario used in the selection software aid is: High starting torque with low starting current, where limited speed control is required. This comprises high start torque, low start current and limited speed control as individual application requirements, but together forms the scenario necessary to drive the application.

LCA motor set:

> This refers to all motors which fall under the umbrella of low cost or affordable automation. In this thesis, the LCA motor set is further limited to motors readily available in South Africa and under 50kW, etc. as mention in the Chapter 1.

3.3 Selection criteria

Selection criteria can be viewed from the actuator perspective as “actuator properties” and from the design engineer’s perspective as “systems’ actuation requirements”. They can also be of a generic or specific nature. Generic type selection criteria are representative of all actuators, specific selection criteria on the other hand are representative only of a particular actuator type or classification. Range of actuator motion, for example, is a generic criterion and used to describe all actuators. Using this criterion, actuators could be either rotary or linear. In many cases defining the range of motion may be used as a first step to selection of actuators for particular applications. This approach is adopted in the selection aid as the first step to obtaining applicable LCA solutions for user defined applications.

In determining selection criteria which are characteristic of electric motors and also generally applicable to the larger set of actuators, it became necessary to divide the selection process into three phases. The first phase entails the selection of motion range/type required by the user’s application as already discussed. The second phase considers system parameters such as speed, torque, control, etc. Finally, the third phase considers selection criteria such as cost which have mainly economic relevance with respect to the appropriateness of the actuator to the intended application/system. These phases are further discussed in Chapter 4.

3.4 Criteria considerations

There are an almost limitless number of actuator designs that can be employed in a given system using any number of mechanisms (Smith and Seugling, 2006). Criteria for actuator selection or comparison differ from classification to classification and from type to type. However, in describing actuators, certain attributes (generic criteria) must be addressed which are characteristic of actuators as a whole. Some of the criteria of most importance in specifying applicability or performance of actuators for a specific system or application may include range of motion (linear/rotary), power requirements, speed characteristics, machine volume/actuator volume, accuracy/resolution or precision requirements, load characteristics, frequency response and operating temperature range.

Actuator specific selection criteria may include rated speed (rpm) and torque (Nm) in the case of electric motors, stroke (m) in the case of hydraulic cylinders or bandwidth (Hz) in the case of piezoelectric actuators, etc.

3.4.1 Criteria definition

Identifying a list of selection criteria representative of all actuators (generic criteria) is of great importance if comparisons and selection are to be made across a wide variety of designs and technologies. The following is a list of selection criteria adopted in the selection aid and a breakdown of their applicability with reference to describing actuators. These criteria as much as possible provide a general description for all actuators, but at the same time cater for the specific requirements necessary for the selection of rotary actuators, more specifically electric motors.

- Range of motion
- Available power supply – Type of power (AC or DC), number of phases
- Speed
- Torque
- Load characteristics – Nature of load imposed by system or driven loads
- System control – Type and nature of control required by the application, such as open or closed loop, speed control, position control, torque control and overshoot requirements
- Drive configuration and directional operation modes – Direct or indirect connection with actuator (electric motor) and need for forward and backward motion or movement
- Noise and thermal emission considerations
- Environmental considerations
- Speed variation
- Starting current
- Start duty and duty cycle
- Cost
- Size, Mass

Although some of these requirements such as starting current are of a specific nature with regards electric motors, most of them are applicable in determining viability of actuators in general for any particular application. Each criterion in the list was formulated as an application system requirement, which can be decided by the design engineer even if he/she does not have previous experience with or knowledge of the actuator properties. These criteria formulated as system requirements were used in defining the knowledge-based rules implemented in the selection aid.

In discussing selection criteria, certain significant distinctions can be made from a design engineer’s perspective; some selection criteria are functional requirements, while others are constraints, as classified in Axiomatic Design by Suh (1990). Functional requirements are simply the specific requirements stemming from the application design objectives. System constraints are limitations imposed by the system in which the design solution must function, while Input constraints are constraints in design specifications. With respect to actuator selection, functional requirements are those criteria which influence selection based on their direct relationship with the application requirements (design objectives). In the same light, system constraints are criteria necessary for the specified application to function, while input constraints are criteria expressed as bounds on size, weight, materials and cost.

3.4.1.1 Range of motion

An application requirement's range of motion can be classified as one of the following:

- Rotary with an infinite displacement capability
- Rotary with a finite angular displacement/stroke
- Linear with a finite displacement/stroke

It should be noted that mechanical power transmission devices, mechanisms or drive components (e.g. slider-crank mechanisms, belts and ball screws), can be used to convert one type of range of motion into another. Since these devices are very diverse, they are excluded from consideration in this thesis. Range of motion is regarded as a system constraint.

3.4.1.2 Available power supply

This criterion in a broad sense specifies the nature of the power required by the actuator to function. Power could be sourced in the form of heat, sound, electromagnetism, etc. The type of power available for use by actuators may be a necessary criterion for choice. Having said this, it is important to note that power could be supplied in one form, converted and delivered in a more suitable form as dictated by the working principle of the actuator. Presently it is possible to convert one source of energy to practically any other form. However this conversion implies added resources in equipment and cost; this reduces the economic viability of the selected actuation system. It is therefore important to, as much as possible, prevent the need for any conversion and in so doing restrict the power supply to that which can directly be utilized by the actuator. This is important in keeping to LCA objectives.

In most automation applications, the power required by the automation itself will not be so large that the available wattage would be important. The wattage was therefore not used as a selection criterion.

For electric motors, electric power could be required as AC single-phase, AC three-phase or DC. Conversion between these power supplies can be achieved with relative ease and fairly cheap equipment. However in certain cases such as battery powered applications, DC power supply becomes the only alternative for use. A conversion of power in such a case will be uneconomical unless there are other advantages to be derived in doing so. Such an argument makes power supply of significant importance when selecting electric motors. For the design engineer, power supply represents a system constraint and may be varied within the options of AC single phase, three phase and DC power.

3.4.1.3 Speed and torque

Since actuators in the automation context are typically devices that impart movement, rotational/linear speed and torque/force are fundamental requirements. The range of approximate or exact values of the speeds and torques required by the application (note that both the upper and lower limits may be important) determine whether a particular actuator is viable. In electric motor selection, determination of system speed and torque/force form the basis of most selection calculations and speed-torque/load characteristic curves. The process of determining these values for applicable motors is most often referred to as “electric motor matching”.

Speed and torque, as selection criteria, are representative of all actuators with rotary ranges of motion. While some actuators are capable of delivering speeds of up to

7500 rpm, as in the case of servomotors, others can only deliver speeds up to 1400 rpm as in the case of some AC induction motors. Similarly while some actuator technologies can supply torques as high as 3000 Nm, others can only supply torques of 0.5 Nm. Some motor-driver combinations will only give smooth operation down to a certain minimum speed. If the application requires lower speeds, the use of a speed reduction device, such as a gearbox, may be used to bring that speed within the operating range of the motor. Since the range of possible gearboxes and belt & pulley combinations are too large to include in the selection aid database, the designer will have to consider the use of such devices before formulating the application requirements.

When an application requires linear motion, speed may also be defined in terms of m/min, while force will replace torque as requirement. Speed and torque represent functional requirements derived from the application design objectives.

3.4.1.4 Load characteristics

All applications/systems can be described by their load characteristics. Similarly all actuators can be described by the load characteristics they are capable of sustaining. This fact makes load characteristics important as a selection criterion. For electric motors, typical loads can be described as:

- Constant torque, variable speed loads
- Variable torque, variable speed loads
- Constant power loads
- Constant power, constant torque loads
- High starting/breakaway torque followed by constant torque

Certain motor designs are inherently better suited for some of the above mentioned load characteristics than others. Other motors may be adapted to sustain these load characteristics by using drivers. Determining what load characteristics a system presents provides a means for determining the applicability of an actuator. For the design engineer this is viewed as a system constraint and most often cannot be compromised.

3.4.1.5 Controllability

Depending on the function of the application to be driven, some amount of control will be required for speed, position or torque. Similarly a choice of open or closed loop control describes the degree of control precision required by the application. Speed, position and torque control are system constraints which are necessary for proper functioning of the application. Applications may require control with respect to the mentioned parameters in different combinations and to different degrees and accuracies. It is important to note that in the case of electric motors, the controllability of the mentioned parameters is highly influenced by the use of drivers. This as such, determines the selected motor as well as the driver to be used if necessary.

An overshoot limitation may be an important factor to consider in certain respects and is included within the controllability requirement. In closed loop control overshoots are often encountered. The extent to which this is an issue is dependent on the requirements of the application. Overshoot can however be regulated within certain limits by using drivers with tighter closed loop control tolerances which prevent excessive deviation from the target position. Overshoot limits are typically system constraints.

3.4.1.6 Directional requirements

Directional requirements can be either unidirectional or bidirectional and can refer to the direction of the motion or the torque. For example, a fan with blade rotation in only one direction requires a unidirectional motion while a conveyor that moves back and forth requires bidirectional motion or reversibility. Some applications may require the actuator to act as a brake during some stages of operation, and then the torque requirement is bidirectional. Drivers are capable of altering the directional operation modes of electric motors. These criteria are obviously viewed as system constraints by the design engineer.

3.4.1.7 Noise and thermal emission

Noise and temperature considerations refer to the application needs with respect to sound and heat, and are constraints on the system. Applications in which these are of concern, usually require that sound and heat generation are kept to a minimum. Some peculiar characteristics of motors make them viable candidates in this respect. For example the brushless DC motor possesses low thermal emission properties, which makes it suitable for applications in which temperature is a constraint on the operation of the application. Similarly the ability of an actuator to function as silently as possible could be used as a possible criterion for its selection, as in the case of DC servos.

3.4.1.8 Environmental considerations

This criterion prescribes the working condition capabilities of the actuator. Working conditions of any engineering system are always viewed as system constraints and have great influence over applicable actuators. Some actuators are able to function normally in harsh/corrosive environments by virtue of their design or enclosures, others by virtue of their technology, operating principle or size on the micro and nano-scale.

For electric motors, enclosures are designed which are specifically suited to environments which are corrosive, dusty, explosive, fluid dripping, splashing, etc. By virtue of its design the DC brushless motor is capable of functioning in a vacuum, making it suitable for aerospace applications. Some actuator technologies on the micro and nano-scale by virtue of their size are better suited to operation in a wide variety of environmental conditions. The working environment of the actuator and driven system constrains applicable actuators to those capable of functioning effectively within these environments. A list of some enclosure types designed to equip electric motors for the wide variety of environmental conditions in which they are expected to perform, is given in Appendix B.

3.4.1.9 Speed variation

Speed variation is common to operation of all actuators because they all have speed characteristics. However the manner with which it is addressed in this thesis is in specific regard to electric motors, and will be discussed as such. Electric motors could inherently be constant speed, variable speed or adjustable speed. They could also be a combination of variable and adjustable speed or constant and adjustable speed as prescribed by their inherent and acquired properties (properties acquired by using drivers).

Due to nomenclature irregularities in definitions of variable and adjustable in literature it will be necessary to adopt definitions which will be adhered to herein. Adjustable speed property of a motor is thus, the ability of motor speed to be manipulated by the user when necessary, while a variable speed property of a motor is characterized by speed fluctuation about the mean synchronous speed and is dependent on loading conditions.

As a selection criterion therefore, the application speed variation requirements dictate in cases where drivers are not used, whether a constant, variable or adjustable speed motor will suffice.

3.4.1.10 Starting current

Starting current is another criterion with specific regard to electric motors, and is viewed by the design engineer as a system constraint. Electric motors can be described as requiring high current or low current to start up. Some motors exhibit both high and low starting current properties. A high starting current could mean a high starting torque and vice-versa, similarly a low start current could mean a low starting torque and vice-versa. In some cases motors are capable of exhibiting a low starting current property with high starting torque as in the case of some three-phase AC motors. These properties provide a basis for selection of these motors depending on the torque or current requirements of the application or driven system for which the motors are to be selected. However, this criterion is only effective for solutions without drivers, as drivers may be used to overcome the starting characteristics of the different motor designs.

3.4.1.11 Start duty and duty cycle

These two criteria constrain applicability of actuators in the sense that certain actuators are capable of sustaining only certain modes of start duties and duty cycles. Start duty may be described as a combination of frequency of start as well as the loading conditions at start up. Certain literature refers to duty cycle as life cycle or robustness depending on the technology of reference. Duty cycle could be of two main types, i.e. continuous and intermittent. With reference to electric motors, several other types such as repetitive duty have been defined. Other duty cycles as defined by the IEC‡ are available in the Appendix B.

Actuators may be better suited to either continuous or intermittent duty cycles depending on their design, type or technology. Actuators can as such be selected based on their suitability for different duty cycle conditions.

3.4.1.12 Purchase cost

Cost, by its definition, is a design constraint, which limits applicability of an actuation system by virtue of available funds for purchase. The purchase cost of an actuation system may depend on the required accuracy and control, in the sense that a balance must be struck between the accuracy/control required and the cost of achieving such accuracies or control. For certain applications where control and or accuracy cannot be compromised, expensive, accurate actuators and drivers must be used. On the other hand, where these performance parameters are less important, cheaper actuation systems may be utilized to achieve the required performance of the system.

For the selection aid, purchase cost will be referred to in terms of a "Cost Index". A non-dimensional index was chosen because, though the quantity may originally have been a Rand value, the selection aid does not keep track of price fluctuations over time and differences in prices quoted by different suppliers. Some of the reasons for price fluctuation from company to company are exchange rates variations, special arrangements between a buyer and a supplier, special rates, discounts, etc. As such, referring to cost directly as used at the time of development of the aid may be misleading. The cost index is rather a relative cost indication amongst applicable actuators and may be used as a rough estimate of actuator drive costs but cannot be used as the true prices for reasons mentioned above.

3.4.1.13 Size, mass

Size is also a very important criterion in actuator selection. It is fundamental to all actuators and may be used as a limiting factor in the choice of actuators for use. Size in design represents a system constraint. In actuator selection, size in many cases has a

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[‡] *IEC (International Electrotechnical Commission)*

direct relationship with weight particularly within the same actuator technology, as such the smaller the actuator the lighter it is. This is of great importance in aerospace or small/miniature robotics applications where there are rigid weight and or size constraints imposed by the functionality of the application or its operating environment.

3.4.2 Selection criteria conclusion

In conclusion, certain actuator properties cover the criteria for electric motor selection. These generally include the properties that enhance performance, and make the motor suitable for a given application. Weight, size and enclosure are critical and generally treated as important constraints. Reliability and maintainability are important, particularly in large complex machinery operating away from maintenance facilities. The most important issue is the cost of the motor that provides all the required performance characteristics (Vaidya, 1995). While all the above mentioned performance criteria are important, the determination of their specific values can only be of use after the decision on what types of actuators are applicable and are capable of providing the required performance. This is one of the objectives of the actuator selection aid, to give insight into what actuators are applicable and efficient with respect to prescribed user applications.

3.5 Selection procedure design

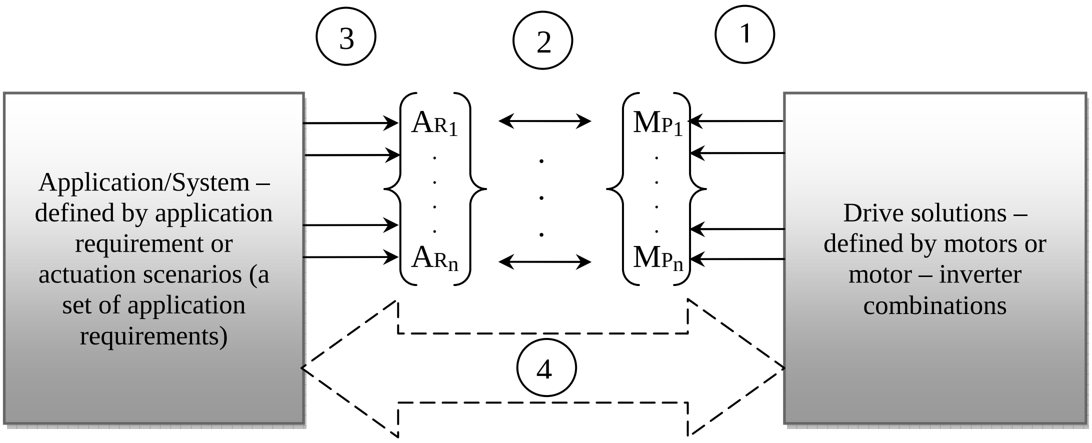
In order to ensure accuracy and efficiency in the development of the selection procedure, systematic engineering approaches were utilized. Top-down and bottom-up are approaches on which traditional engineering design methods are based. A top-down approach starts with the view of a system as a whole and involves understanding how all its components fit together (Blanchard and Fabrycky, 1998). In the case of the selection procedure this would involve establishing connections between applications, application requirements, actuation scenarios, actuator properties and actuators. A top-down approach is implicitly performed by the design engineer in selecting an actuator. A bottom-up approach builds on fundamental sub-system aspects in order to create relationships necessary to understanding the system as a whole. In relation to the selection procedure the bottom-up approach involved starting with a set of known fundamental actuator properties and building upwards on new and established connections towards related applications.

3.6 Selection procedure methodology

In the development of the procedure, applications were defined by the requirements necessary for their operation using a top-down approach. Using functional application names such as fans, hoist, trolley, etc was infeasible for several reasons. One of such reasons is that several actuation scenarios could be used in describing similar applications. Fans as an application for example, can be appropriately correlated to several actuation scenarios, they may be small, medium or large sized for various purposes all differing appropriately in their respective application requirements. Where some fans are used in domestic applications they can also be used for industrial purposes with distinct actuation scenarios. Due to the numerous names under which applications exist, such an exercise would be futile.

A bottom-up approach was used to provide a traceable path for all correlated data and involved the definition of fundamental links between motor designs, motor properties, and their related application requirements. These determined connections were required to establish the basis for proffered actuator options and formed the platform on which the knowledge-based inference engine (software logic) and rules were built.

The formulation process involved a correlation of motor design to corresponding motor properties. This was followed by a correlation of the mapped motors and their properties (actuator properties) to corresponding application requirements. The correlation process in itself was independent of specific applications. However, it provided definitive mapping paths for the correlation of application requirements or actuation scenarios to any desired applications. These mapping paths result in the creation of direct links between any chosen application and applicable motors. Figure 3-1 is an illustration of the formulation process for the selection procedure.



Actuation scenario (AR_1 – AR_n)
Application requirement (AR_i)
Motor properties (MP_1 – MP_n)

1 – Correlation of motor designs to motor properties (MP_1, …, MP_n)
2 – Correlation of motor properties (MP_1, …, MP_n) to application requirements (AR_1, …, AR_n)
3 – Correlation of any defined application to application requirements (AR_1, …, AR_n)
4 – Link between user defined application and drive solutions created by 1, 2 and 3

Figure 3-1 Selection procedure formulation process

An important step in the development of the selection procedure involved formulation of selection criteria options as application requirements specific to actuator (electric motor) properties. For example, environmental operating conditions as an application requirement could be normal, vacuum or corrosive/harsh with motors having a corresponding property which allows them to operate in vacuum or corrosive/harsh environments. Many of these requirements are either interrelated or mutually exclusive, lending themselves to the logic and rules implemented within the selection aid. This means that some requirements can be inferred from the choice of others or the choice of certain requirements may obviate the need for others.

The definition of the knowledge-based rules from the application requirements discussed above and specific to actuator properties, required expert and commercial information to ensure that the proper definitions were made. These rules showing the relationship between application requirements, actuator properties and the actuators themselves are discussed in greater detail in the following chapter.

3.7 Nomenclature and descriptive irregularities

The nomenclature used in the selection procedure and aid is of immense importance to its usability. Factors which attracted particular attention in this regard include inconsistency in property description. This arises in situations where multiple descriptions are possible for the same property. Certain property descriptions may be understood to mean the same thing, but may have subtly varied meanings with respect to the particular property in question. Making affected terms distinct and unambiguous was necessary to also ensure clarity, consistency and adaptability of the procedure to other actuator types with similar properties. For this reason a glossary of terms (Appendix B, accessible within the software selection aid also) was compiled with respect to electric motors, and expandable to other actuator types.

3.8 Drivers and their effect on selection

A very important aspect of electric motor selection is the use of drivers whereby overall drive characteristics of a system can be manipulated to provide drive outputs not usually achievable by motors alone. Motion control can be categorized into: sequencing, speed control, point to point control and incremental control. Recent years have seen significant advancements in control technologies such as vector control.

These control technologies have the effect of increasing applicability and general efficiency of motors. For example, the application of inverters to constant speed AC induction motors may be used to produce high precision adjustable speed servo drives. A concurrent selection of applicable drivers is therefore indispensable if optimum choices are to be made. With this in mind, it was necessary to incorporate a concurrent selection of drivers into the design framework of the selection procedure and aid for optimum performance.

Drivers, unlike motors, require considering the resultant performance of the drive components together. In the development of the selection procedure, the use of drivers is a decision entirely dependent on system requirements. If a driver is essential to the driven system, only options with drivers are viable options (i.e. optimum control and drive options are made available to the user). If however, a driver is not required, drive options with drivers included are still viable, providing the user with optimum alternatives in all situations. If application tolerances with regard to speed, torque and position are close, then drivers are most likely a necessity. Such control conditions also require the use of components such as tachometers, resolvers or encoders. A choice of these mentioned components is dependent on the specific requirements of the driver being used.

Having taken the above considerations into account, the available choice of drivers applicable for any situation is based on either customized or off the shelf brands. However, because this thesis is focused on LCA, only drivers available off the shelf are considered. To handle the myriad of drivers available off the shelf, operating principles and functional capability were used to provide a means of selection for drivers accompanying actuators. Voltage flux vector control (VFC) and current controlled flux vector control (CFC) inverters accompany AC motors, regenerative and non-regenerative drivers accompany DC motors, while wave, two phase and half step drivers accompany stepper motors.

In conclusion, the concepts discussed thus far under definition of selection criteria, selection procedure design and methodology, and drivers sum up to provide some fundamental ingredients necessary for the development of the selection aid. The development process for the software selection aid is presented in the next chapter.

CHAPTER 4 SELECTION AID DEVELOPMENT AND DESIGN

4.1 Introduction

This chapter explains the process by which the selection software aid was developed. It presents arguments for software nomenclature and structure. Most importantly, it explains the rules implemented in the aid which represent the important decisions in terms of applicable actuators and drivers necessary for optimum actuator drive selection.

4.2 Software development

The development of the software from the formulated procedure required that a feasible actuators list be created either by a process of addition or elimination from a design space of electric motor actuators. The non-uniqueness of solutions for any particular application is a reason for using elimination in preference over addition. Similarly, because the selection aid focuses on the early design phase, elimination becomes an intuitive choice where there are incomplete user inputs (application requirements). The elimination process formed the basis for most of the software aid design decisions and is eventually reflected in the rules presented further on in this chapter.

Having introduced the concept of elimination, two factors played an important role in the implementation of the procedure as software, i.e. the effort required in performing selection and the rate of alternative elimination from the design space. Reducing the effort with which the selection process is performed was given priority over the elimination of inapplicable alternatives.

Minimizing the selection effort required that the relevant application requirements arising from specific motor properties in the formulated procedure had to be reduced in number from the original set. This was achieved by harnessing requirements’ interrelatedness or mutual exclusivity as mentioned in Chapter 3. User input requirements were designed to incorporate several application requirements as well as elicit as many corresponding decision points as possible. A process of refinement in stages was also adopted in minimizing the number of application requirements by breaking the selection process into phases. These different phases act to remove inapplicable actuator alternatives from the design space, ensuring that the rate of elimination is also effectively handled.

Structuring the phase by phase elimination of actuator alternatives required that the input options (application requirements) format starts out as general as possible with absolute answers (i.e. a choice between rotary or linear actuation). The options then narrows down to specific details regarding the application requirements with relative choices (i.e. choice in degree of particular system requirements). For example, speed control or positioning accuracy have different degrees to which they may be required in an application (e.g. $<\pm 360^o$, $< \pm 5^o$ to $\pm 45^o$, $<\pm 1^o$ positioning accuracy). Elimination ends with cost and size. These phases are explained below and illustrated in Figure 4-1.

- The first phase entails the selection of motion range required by the user's application. This selection has to be done first because the subsequent selections steps depend largely on the motion range.
- The second phase requires the user to specify main actuation requirements such as speed, torque, control type, etc. These criteria are used to decide whether a particular actuator is at all capable of satisfying the actuation requirements. The result of this step is a set of technically viable actuators for the inputted set of application requirements.
- In the third phase, criteria that are used to select the most attractive option, such as cost and size, are applied to further reduce the selection set.

Worth noting is that the first two phases in the selection process may eliminate all actuators that have a "low enough" cost or "small enough" size for cases where these two factors are high priority criteria. Fortunately these factors are unlikely to be subject to hard constraints in the early layout design phase.

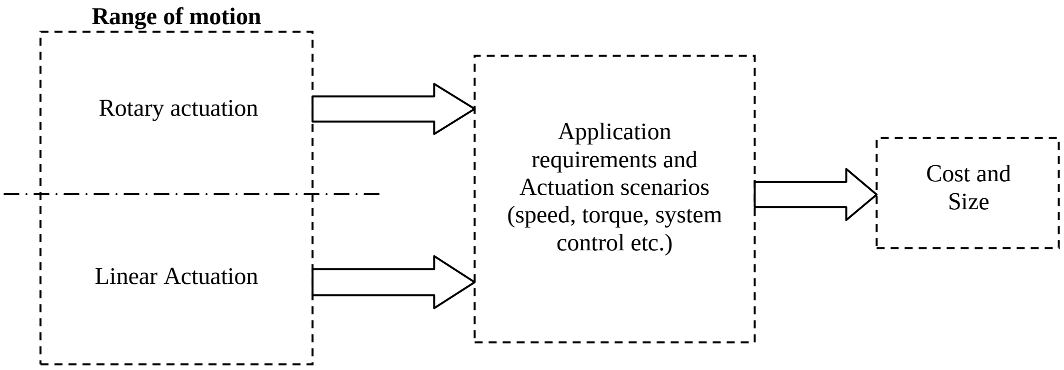


Figure 4-1 Progression of phase by phase elimination of drive alternatives

4.3 Selection aid design

Figure 4-2 shows the major components and functional relationships within the selection aid. The user supplies information about his/her application by inputting application requirements on the user interface. The input rules as illustrated below control option manipulation in search modes 1 and 2 (discussed in the next section). These input rules provide information on which application requirements/actuation scenarios have been applied to the inference engine. With this information the output rules via the inference engine determine what actuators in the actuator database can satisfy the requirements and thus through a process of elimination, the infeasible drive solutions are removed from the design space with the remaining drive solutions displayed to the user on the interface.

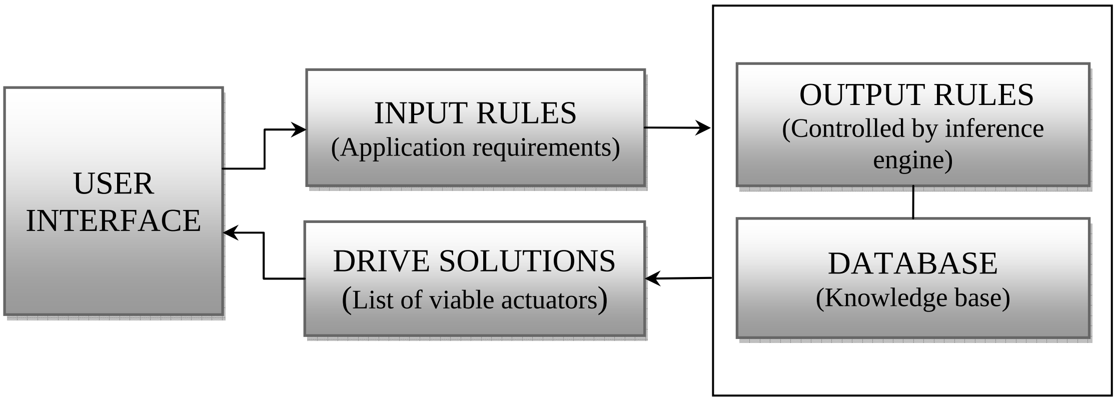


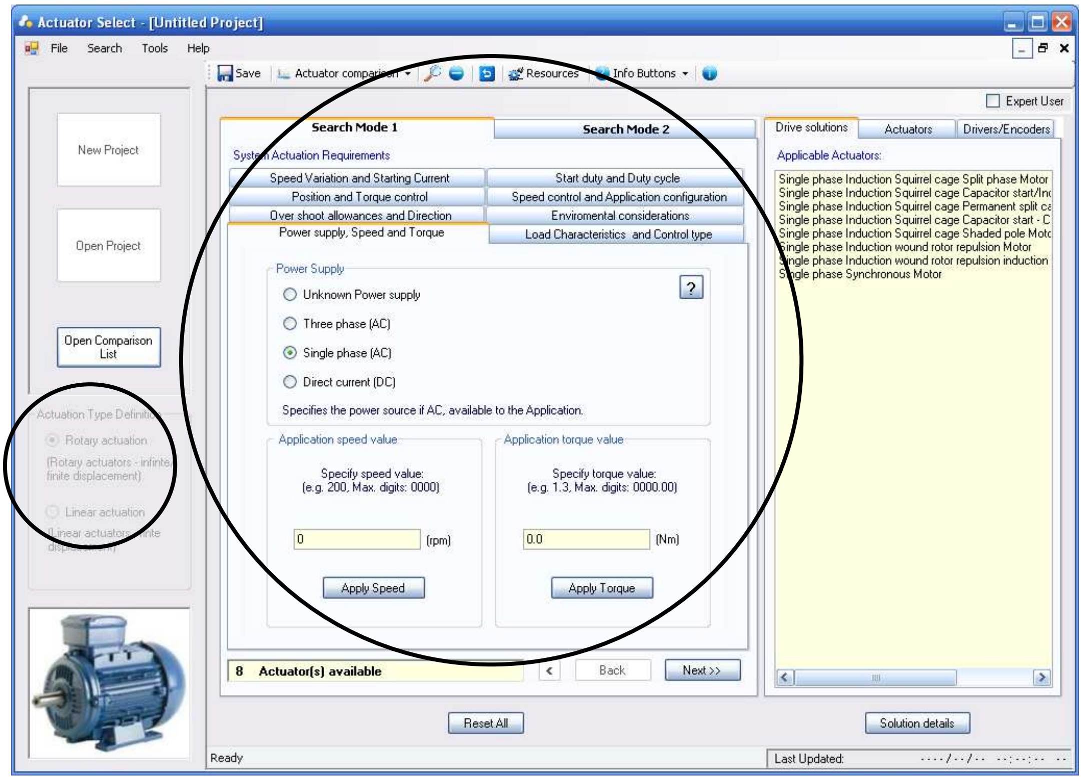
Figure 4-2 Software selection aid functional relationships

4.3.1 Selection aid search modes

The versatility and ease of use of any selection aid is important. The software design employs two search modes from which selection can be initiated in achieving some degree of versatility and robustness. These search modes are described in the following paragraphs.

4.3.1.1 Search mode 1

This mode, being the default search mode, provides options on possible application requirements, which could be characteristic of any intended or working system. A combination of these options helps generate possible actuation scenarios (i.e. helps define the requirements of the users' application/system) from which the procedure concurrently extracts information necessary to determining viable drive solutions. This mode gives the user the freedom to experiment a little with the possible requirements of the application. Its results are entirely dependent on the user's inputted application requirements. Search mode 1 is displayed in Figure 4-3.



☐ Expert User

Actuation Type Definition

● Rotary actuation

(Rotary actuators - infinite/finite displacement)

○ Linear actuation

(Linear actuators - finite displacement)

○ Unknown Power supply

○ Three phase (AC)

● Single phase (AC)

○ Direct current (DC)

Specifies the power source if AC, available to the Application.

Specify speed value:
(e.g. 200, Max. digits: 0000)

0 (rpm)

Specify torque value:
(e.g. 1.3, Max. digits: 0000.00)

0.0 (Nm)

8 Actuator(s) available

Single phase Induction Squirrel cage Split phase Motor
Single phase Induction Squirrel cage Capacitor start/Inc
Single phase Induction Squirrel cage Permanent split ca
Single phase Induction Squirrel cage Capacitor start - C
Single phase Induction Squirrel cage Shaded pole Motc
Single phase Induction wound rotor repulsion Motor
Single phase Induction wound rotor repulsion induction
Single phase Synchronous Motor

Ready

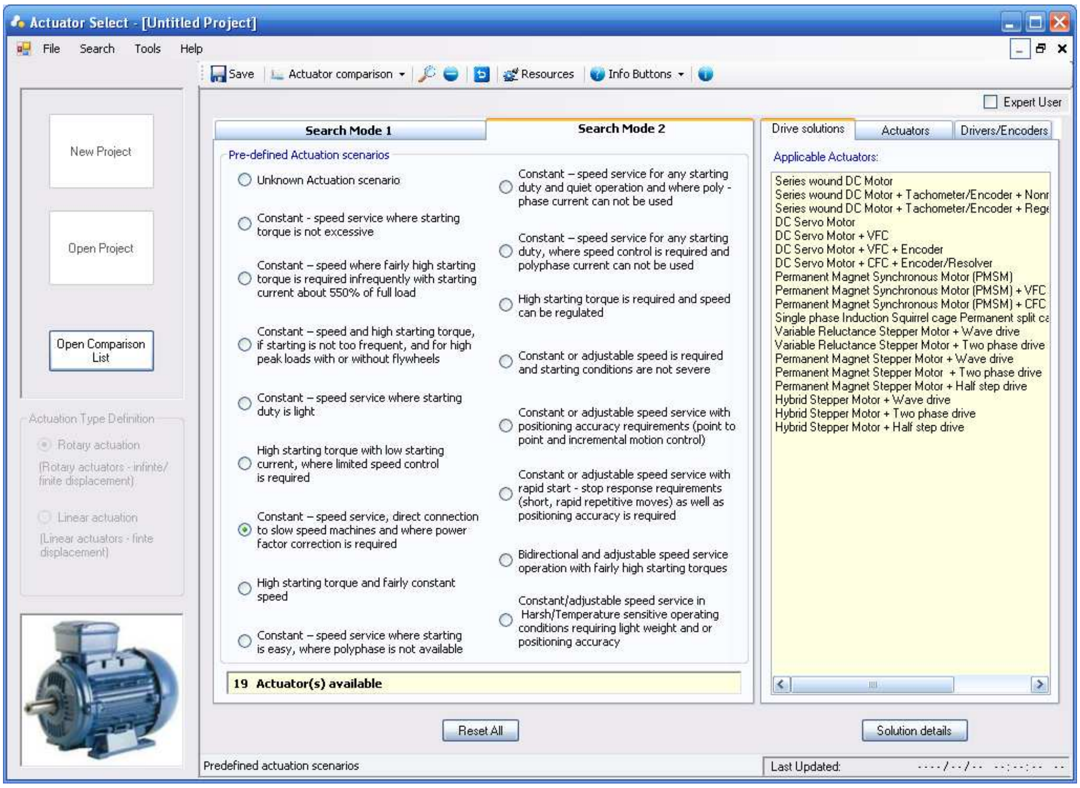
Last Updated: ----/--/-- --:--:-- --

Figure 4-3 Search mode 1 (User defined requirements – Tab page organization)

Figure 4-3 also shows the earlier mentioned first two phases of the selection and phase by phase elimination process. The smaller indicated region shows the greyed out (inactive) first phase and the bigger region indicates the active second phase with application requirements organized in tab pages.

4.3.1.2 Search mode 2

This mode consists of a list of predefined actuation scenarios presented to the user and focuses specifically on electric motors. It lists available scenarios characteristic of common engineering systems driven by electric motors. This feature makes search mode 2 dependent on predefined application types and not the applications' requirements as in mode 1. Search mode 2 contains a few different application requirements such as speed variation and starting torque. It also lacks load type definitions and control accuracies available in mode 1. Most results obtainable in this mode are reproducible in mode 1. Figure 4-4 shows a screenshot of search mode 2 with radio buttons corresponding to the predefined actuation scenarios.



☐ Expert User

Pre-defined Actuation scenarios

○ Unknown Actuation scenario

○ Constant - speed service where starting torque is not excessive

○ Constant – speed where fairly high starting torque is required infrequently with starting current about 550% of full load

○ Constant – speed and high starting torque, if starting is not too frequent, and for high peak loads with or without flywheels

○ Constant – speed service where starting duty is light

○ High starting torque with low starting current, where limited speed control is required

● Constant – speed service, direct connection to slow speed machines and where power factor correction is required

○ High starting torque and fairly constant speed

○ Constant – speed service where starting is easy, where polyphase is not available

○ Constant – speed service for any starting duty and quiet operation and where poly - phase current can not be used

○ Constant – speed service for any starting duty, where speed control is required and polyphase current can not be used

○ High starting torque is required and speed can be regulated

○ Constant or adjustable speed is required and starting conditions are not severe

○ Constant or adjustable speed service with positioning accuracy requirements (point to point and incremental motion control)

○ Constant or adjustable speed service with rapid start - stop response requirements (short, rapid repetitive moves) as well as positioning accuracy is required

○ Bidirectional and adjustable speed service operation with fairly high starting torques

○ Constant/adjustable speed service in Harsh/Temperature sensitive operating conditions requiring light weight and or positioning accuracy

19 Actuator(s) available

Applicable Actuators:

Series wound DC Motor
Series wound DC Motor + Tachometer/Encoder + Nonr
Series wound DC Motor + Tachometer/Encoder + Rege
DC Servo Motor
DC Servo Motor + VFC
DC Servo Motor + VFC + Encoder
DC Servo Motor + CFC + Encoder/Resolver
Permanent Magnet Synchronous Motor (PMSM)
Permanent Magnet Synchronous Motor (PMSM) + VFC
Permanent Magnet Synchronous Motor (PMSM) + CFC
Single phase Induction Squirrel cage Permanent split ca
Variable Reluctance Stepper Motor + Wave drive
Variable Reluctance Stepper Motor + Two phase drive
Permanent Magnet Stepper Motor + Wave drive
Permanent Magnet Stepper Motor + Two phase drive
Permanent Magnet Stepper Motor + Half step drive
Hybrid Stepper Motor + Wave drive
Hybrid Stepper Motor + Two phase drive
Hybrid Stepper Motor + Half step drive

Predefined actuation scenarios

Last Updated: ----/--/-- --:--:-- --

Figure 4-4 Search mode 2 (Predefined actuation scenarios)

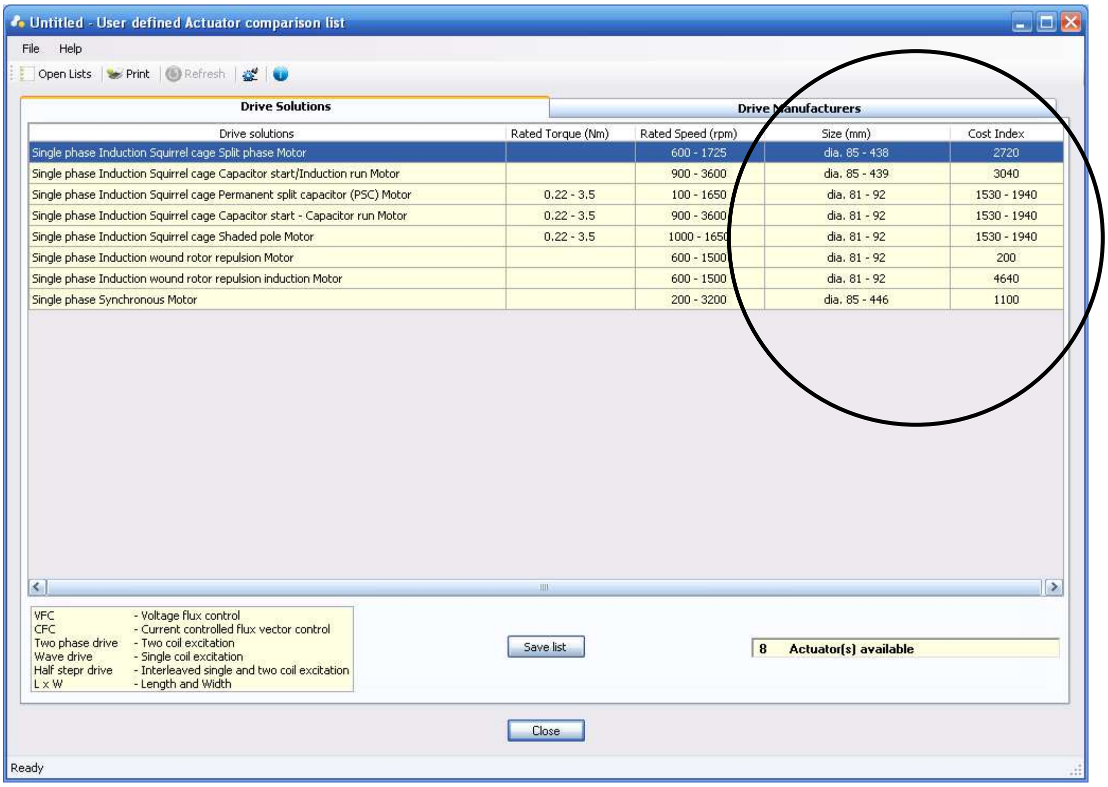
In this mode the user selects a predefined scenario most closely matched to his application. Although search mode 2 restricts the user to defined scenarios and applications, it has the advantage of quick results on viable options for closely matching scenarios. The disadvantage of this mode is that there are too many resulting solutions for any one predefined scenario as shown in Figure 4-4. This is due to the inability to further refine the search from fixed predefined scenarios, however this mode can be used as a starting point with further refinement performed in mode 1.

4.3.2 User interface structure

Proper structuring of any program helps in conveying required information to its user. Using this selection aid is heavily dependent on the user knowing exactly what is required for the intended system as well as the terms related to the selection aid. To achieve this, it is very important that the concepts contained within the aid be explicitly described and defined. These definitions and explicit descriptions have a tendency to make the user interface rather busy (too much text for reading). The Visual C++ tab controls, pages and buttons were thus employed to control text display per screen.

Space restrictions influenced the display of the tab page contents, however criteria related to each other were as much as possible displayed together. Criteria such as power supply, speed and torque were displayed first as criteria which would normally be addressed early in the design phase (see Figure 4-3). Contents of the search mode tab pages (selection criteria and requirement inputs) are tabulated in Appendix A.

Figure 4-5 shows the final phase of the selection process, indicating cost and size as the remaining selection criteria by which selection may be performed. This window consists of a solution comparison table and displays the details of the viable solutions under the headings of design, rated torque (Nm), rated speed (rpm), size (mm) and cost index (non-dimensional). The table enables the user to compare the viable options based on their cost index and size, and provides manufacturer information and access to the associated websites (Figure 4-6). The comparison table window is accessed by clicking the “solution details” button shown in Figure 4-3 and 4-4.

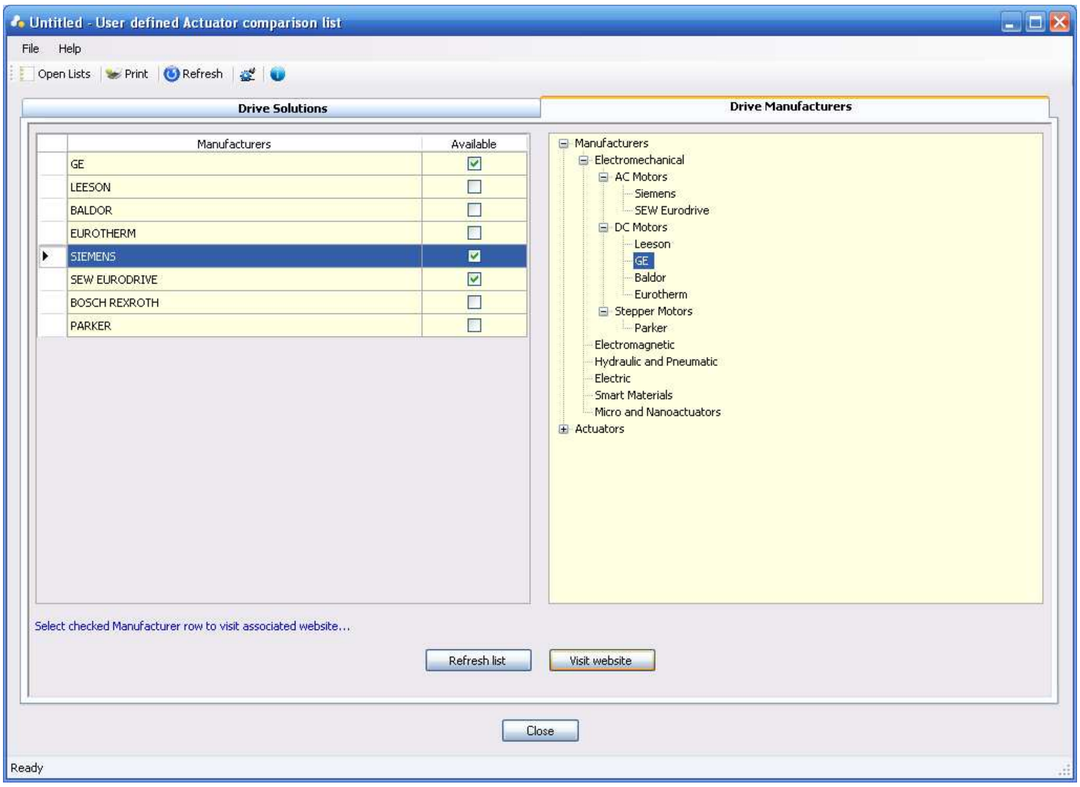


Drive solutions	Rated Torque (Nm)	Rated Speed (rpm)	Size (mm)	Cost Index
Single phase Induction Squirrel cage Split phase Motor		600 - 1725	dia. 85 - 438	2720
Single phase Induction Squirrel cage Capacitor start/Induction run Motor		900 - 3600	dia. 85 - 439	3040
Single phase Induction Squirrel cage Permanent split capacitor (PSC) Motor	0.22 - 3.5	100 - 1650	dia. 81 - 92	1530 - 1940
Single phase Induction Squirrel cage Capacitor start - Capacitor run Motor	0.22 - 3.5	900 - 3600	dia. 81 - 92	1530 - 1940
Single phase Induction Squirrel cage Shaded pole Motor	0.22 - 3.5	1000 - 1650	dia. 81 - 92	1530 - 1940
Single phase Induction wound rotor repulsion Motor		600 - 1500	dia. 81 - 92	200
Single phase Induction wound rotor repulsion induction Motor		600 - 1500	dia. 81 - 92	4640
Single phase Synchronous Motor		200 - 3200	dia. 85 - 446	1100

VFC	- Voltage flux control
CFC	- Current controlled flux vector control
Two phase drive	- Two coil excitation
Wave drive	- Single coil excitation
Half stepr drive	- Interleaved single and two coil excitation
L x W	- Length and Width

8 **Actuator(s) available**

Figure 4-5 Comparison table



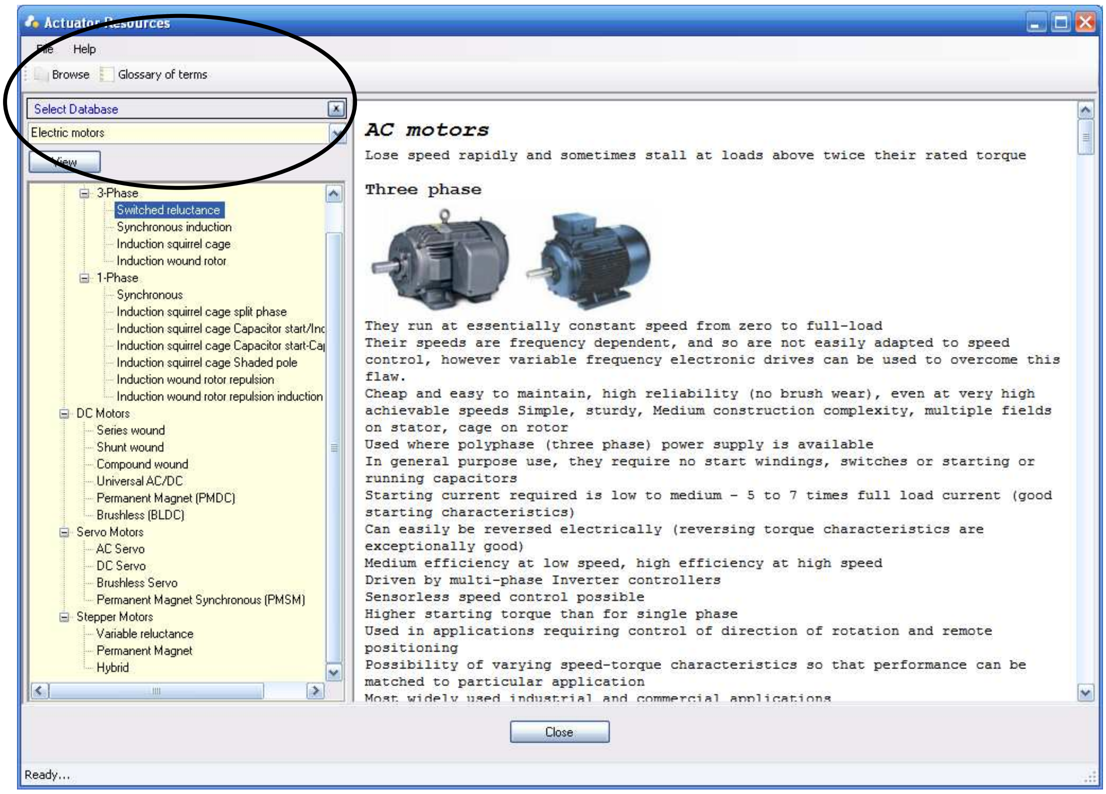
Manufacturers	Available
GE	☑
LEESON	☐
BALDOR	☐
EUROTHERM	☐
SIEMENS	☑
SEW EURODRIVE	☑
BOSCH REXROTH	☐
PARKER	☐

- Manufacturers
  - Electromechanical
    - AC Motors
      - Siemens
      - SEW Eurodrive
    - DC Motors
      - Leeson
      - GE
      - Baldor
      - Eurotherm
    - Stepper Motors
      - Parker
  - Electromagnetic
  - Hydraulic and Pneumatic
  - Electric
  - Smart Materials
  - Micro and Nanoactuators
- Actuators

Select checked Manufacturer row to visit associated website...

Figure 4-6 Comparison table (Manufacturer links)

Figure 4-7 shows the actuator resources window (3 phase AC motor characteristics currently displayed). This window is accessed by clicking the resources button located on the tool strip in Figure 4-3. Actuator characteristics and glossaries of associated terms can be viewed in this window by using the controls in the indicated region.



AC motors

Lose speed rapidly and sometimes stall at loads above twice their rated torque

Three phase

They run at essentially constant speed from zero to full-load
Their speeds are frequency dependent, and so are not easily adapted to speed control, however variable frequency electronic drives can be used to overcome this flaw.
Cheap and easy to maintain, high reliability (no brush wear), even at very high achievable speeds Simple, sturdy, Medium construction complexity, multiple fields on stator, cage on rotor
Used where polyphase (three phase) power supply is available
In general purpose use, they require no start windings, switches or starting or running capacitors
Starting current required is low to medium - 5 to 7 times full load current (good starting characteristics)
Can easily be reversed electrically (reversing torque characteristics are exceptionally good)
Medium efficiency at low speed, high efficiency at high speed
Driven by multi-phase Inverter controllers
Sensorless speed control possible
Higher starting torque than for single phase
Used in applications requiring control of direction of rotation and remote positioning
Possibility of varying speed-torque characteristics so that performance can be matched to particular application
Most widely used industrial and commercial applications

Figure 4-7 Actuator resources window

4.4 Predefined actuation scenarios

Actuation scenarios as defined by literature (Andrew et al, 2005) were found to be easily related and translatable to motor properties. This was the initiative behind creating search mode 2. In most cases, a redefinition of these scenarios as a group of corresponding motor properties (or application requirements) aided the correlation process. For example, an actuation scenario defined as – “Constant speed service where starting torque is not excessive”, was redefined in motor properties terms as – “Constant speed with low to medium starting torque”. It was also observed that the actuation scenarios as defined by Andrew et al (2005) were inadequate in providing descriptions applicable to the entire LCA set under study. This necessitated description of more scenarios to cater for the wider variety of applications and motors indicative of the LCA motor set which were implemented in search mode 2 discussed above. The adopted predefined actuation scenario list is still however not exhaustive in this respect.

Certain criteria were included to cater for the specific needs of electric motor selection. As such, to a large extent the predefined actuation scenarios refer to electric motors, however, some predefined actuation scenarios are provided which are not specific to electric motors (i.e. those not containing electric motor specific selection criteria discussed earlier). The predefined actuation scenarios may therefore be used in the selection of other actuator technologies.

4.5 The actuator selection aid as a rule-based system

Rules as prescribed by knowledge-based systems form the basis for the process of determining most suitable drive alternatives available to the design engineer for system actuation requirements supplied to the selection aid. Figure 4-2 illustrates the basic concept behind the selection aid as a knowledge-based (rule based) system. The use of a commercial expert shell to implement the selection aid was considered but was however dropped due to the associated purchase and development cost. Expert shells such as MP2, ART Enterprise and Exsys CORVID may be easy to use and have several useful features (Salim et al, 2003) however, Exsys CORVID for example cost as much as $12000 (approximately R84000).

Another reason to develop in-house software instead of using an expert shell, was that it simplified the integration of the selection aid into other design support software being developed by the Computer Aided Design Research Group (CADRG) at Stellenbosch University.

4.5.1 Rules development and structuring

In structuring the selection aid rules, certain concepts have been implemented. Inference by forward reasoning (explained in Chapter 2) required for the selection aid can be divided into the distinct steps of matching, and rule execution. The process of matching involves determining what rule must be applied for a requirement selected by the user. Rule execution is performed to obtain results each time a matching rule has been determined by the matching process. Elimination of actuators from the design space (database) is the result of rule execution.

Each rule is defined independently of the others. The selection of an application requirement of most importance to the user triggers a corresponding rule which is executed immediately. Therefore, the selection of a high priority requirement triggers a corresponding high priority rule. Whether a requirement is of high priority is totally dependent on the application for which the actuator is being chosen, and will vary from user to user and from application to application. The selection aid therefore does not apply priorities in its inference process, but leaves that to the user.

Several rules must be defined and implemented in order to accommodate the possibilities related to different applications. Where a single rule may be sufficient to draw an appropriate conclusion on a particular application, a single rule may not suffice for other applications. As such, combinations of two or more rules become necessary in making appropriate inferences and conclusions about most applications.

Search modes 1 and 2 inherently lend themselves to the use of rules linking user options to eventual actuator drive solutions (Figure 3-1). The development of these rules is essential to defining paths between user application requirements and display of appropriate actuator solutions as well as provides documentation of appropriate selection paths to choices.

The first step in the development of rules involved the correlation of motor drive solutions to properties and these properties to application requirements, as illustrated in Figure 3-1. The next step involved creating a list of all mutually exclusive application requirements; these represent input rules which will be discussed shortly. Following this is the determination of the relationships between inputted application requirements and the resulting drive solutions. This was done such that for each application requirement selected, drive solutions with properties corresponding to mutually exclusive requirements are eliminated. This final step represents the formulation of the output rules discussed and outlined shortly. Once this has been done, a combination of applicable inferences and rules dependent on a user’s situation can be linked and applied to arrive at suitable solutions.

The implemented rules are defined in two groups, i.e. input rules and output rules, as mentioned above and are explained in-depth in the following sections. Input rules govern the effect of the application requirements on each other only. For example, under the control type requirement the input rule which governs the selection of the individual control type criteria prevents a concurrent selection of closed loop and open loop control, i.e. the input rule ensures mutual exclusivity amongst control type criteria. The output rules which comprise the knowledge-based rules, on the other hand, govern the effect of the application requirements on the drive solutions, e.g. if a user selects high speed and accuracy, then a servomotor is a feasible drive solution. This represents an output rule governing the selection of high speed or accurate response requirements.

4.5.2 Input rules

Mutual exclusivity of options under the same actuation category is managed effectively by the radio button, combo box and group box features of Microsoft C++ Visual Studio. Radio buttons possess an in-built mutual exclusivity characteristic. Other features include using check boxes and enabling/disabling features of Microsoft C++ Visual Studio. Check-boxes were used to implement input rules for requirements belonging to the same criteria classification but not mutually exclusive to one another, e.g. AC and DC power requirements under the general category of power supply. The exact implementation of the input rules is given in Appendix A.

4.5.3 Output rules

The output rules form a major part of this thesis and represent the information critical to deciding when to use different motors or motor – driver combinations. Each output rule defines which motor/motor – driver combinations are eliminated from the design space for a specific input selection. The following is a description of each output rule implemented in the software and its application to choice of motors and drivers as drive solutions.

4.5.3.1 Search mode 1 output rules

Application requirements in Table 4-1 are simultaneously also actuator properties. The associated output rules are therefore to eliminate all actuators that do not have the required properties. The default would be for the user to make no choice, thus not eliminating any actuator from the design space (database). The remaining application requirements not sharing a one to one correspondence or with more involved interactions have been displayed in Tables 4-2 to 4-9. The properties marked “X” refer to the properties of the eliminated actuators for the selected application requirements.

Table 4-1 Selection criteria and associated application requirements

Selection criteria	**Application requirements**
Available power supply	Unknown/AC 3-phase/AC 1-phase/DC
Control type	Unknown/Closed loop/Open loop
Torque control	Torque control – Yes/ Torque control – No
Rapid response	Rapid response – Yes/ Rapid response – No
Drive configuration	Direct drive application/Indirect drive application
Directional requirements	Unidirectional/Bidirectional
Quiet running	Quiet running – Yes/Quiet running – No
Temperature sensitive	Temperature sensitive – Yes/Temperature sensitive – No
Environmental considerations	Normal/Vacuum/Corrosive or harsh

In general, criteria such as “quiet running” and “temperature sensitive” are not absolutes, however with a focus on electric motors, certain designs may be described as such.

Each actuator in the database possesses minimum and maximum speed and torque ranges. Inputting a value for speed or torque, the output rules in Table 4-2 determine what actuators are unable to support the inputted value, and eliminate them based on the outcomes.

Table 4-2 Speed and torque values

Speed	IF inputted value ≠ 0 Min. Speed > value Max. Speed < value	Eliminate all drive solutions which satisfy these conditions
Torque	IF inputted value ≠ 0 Min. Torque > value Max. Torque < value	

Table 4-3 describes the output rules implemented for speed variation.

Table 4-3 Speed variation

Application requirement	**Properties of eliminated actuators**		
	Variable speed	Constant speed	Adjustable speed
Adjustable speed	X	X	
Variable speed		X	
Constant	X	X	X

Table 4-4 describes the output rule for starting current requirement.

Table 4-4 Starting current requirement

Application requirement	**Properties of eliminated actuators**	
	Low starting current	High starting current
Approximately less than or equal to operating or rated full load current		X
Greater than operating or rated full load current	X	

Table 4-5 describes the output rule for starting duty requirement.

Table 4-5 Start duty requirement

Application requirement	**Properties of eliminated actuators**		
	Light start duty	Mild start duty	Severe start duty
Less than nominal loads with infrequent starting			
Nominal loads with infrequent starting	X		
Greater than nominal loads with frequent starting	X	X	

Table 4-6 describes the output rules for application load characteristics. It should be noted that the rules here are influenced by use of drivers. A motor incapable of sustaining a particular load type on its own may be able to do so when controlled with a driver. This motor – driver relationship was considered in the formulation of the rules described in Table 4-6.

Tables 4-7, 4-8 and 4-9 focus on control related rules, and are the subjects of validation experiments presented in Chapter 5. Table 4-10 provides a list of the implemented predefined actuation scenarios and the associated actuator properties eliminated by their selection.

Table 4-6 Application load characteristics

Application requirement	**Properties of eliminated actuators**						
	Constant torque and variable speed	Variable torque and variable speed	Constant power	Constant power and constant torque	High start/breakaway torque followed by constant torque	No torque control	Low start torque
Constant torque and variable speed		X	X		X		
Variable torque and variable speed	X		X	X	X		
Constant power	X	X		X		X	
Constant power and constant torque		X			X	X	
High-start or breakaway torque followed by constant torque	X	X		X		X	X

Table 4-7 Position control requirement

Application requirement	**Properties of eliminated actuators**			
	Position control > 360°	Position accuracy < ±360°	Position accuracy < (±5° to 45°)	Position accuracy < ±1°
Position control > 360°				
Position accuracy < ±360°	X			
Position accuracy < (±5° ~~-~~ to 45°)	X	X		
Position accuracy < ±1°	X	X	X	

Table 4-8 Speed control requirement

Application requirement	**Properties of eliminated actuators**			
	Speed control - No	Speed deviation 0.20% - 1.8%	Speed deviation 0.17% - 1.5%	Speed deviation 0.03% - 1.0%
Speed control - No				
Speed deviation 0.20% - 1.8%	X			
Speed deviation 0.17% - 1.5%	X	X		
Speed deviation 0.03% - 1.0%	X	X	X	

Table 4-9 Overshoot restrictions

Application requirement	**Properties of eliminated actuators**			
	Overshoot restrictions > 360°	Overshoot < ±360°	Overshoot < (±5° to 45°)	Overshoot < ±1°
Overshoot restrictions > 360°				
Overshoot < ±360°	X			
Overshoot < (±5° - 45°)	X	X		
Overshoot < ±1°	X	X	X	

4.5.3.2 Search mode 2 output rules

Table 4-10 Output rules for predefined actuation scenarios

Predefined actuation scenarios		Properties of eliminated actuators														
		Variable speed	Adjustable speed	Low starting torque	High starting torque	Low starting current	High starting current	Intermittent duty cycle	AC 3-phase	Quiet running - No	Temperature sensitive - No	Position control - No	Speed control - No	No rapid response	Indirect drive application	Unidirectional
1	Constant – speed service where starting torque is not excessive	X	X		X											
2	Constant – speed where fairly high starting torque is required infrequently with starting current about 550% of full load	X	X	X		X										
3	Constant – speed and high starting torque, if starting is not too frequent, and for high peak loads with or without flywheels	X	X	X				X								
4	Constant – speed service where starting duty is light	X	X		X			X								
5	High starting torque with low starting current or where limited speed control is required			X			X						X			
6	Constant – speed service, direct connection to slow speed machines and where power factor correction is required	X	X												X	

Continued on next page

Table 4-10 continued

7	High starting torque and fairly constant speed	X	X	X												
8	Constant or adjustable speed service in Harsh/Temperature sensitive operating conditions requiring light weight and or positioning accuracy (Aerospace applications)	X									X	X				
9	Constant speed service for any starting duty and quiet operation and where multiphase current cannot be used								X	X						
10	Constant speed service for any starting duty, where speed control is required and multiphase current cannot be used	X							X				X			
11	High starting torque is required and speed can be regulated	X		X									X			
12	Constant or adjustable speed is required and starting conditions are not severe	X			X											
13	Constant or adjustable speed service where positioning accuracy is required (point to point and incremental motion control)	X										X				
14	Constant or adjustable speed service where rapid start - stop response requirements (short, rapid repetitive moves) as well as positioning accuracy is required	X										X		X		
15	Bidirectional operation and adjustable speed service where starting torque if fairly high	X		X												X
16	Constant speed service where starting is easy, where multiphase is not available	X	X		X				X							

4.6 Rule implementation

Implementation of the rules requires the inference engine to run through both input and output rules and determine what rules are applicable as a consequence of inputs changing (selection of requirements) on the interface. Each click of a checkbox or radio-button and click of the mouse may result in a change on the interface and possible actuator solutions. It is worth noting that the sequence in which the rules are applied or their positions within the inference engine does not affect viable drive solutions. However, the sequence with which criteria are applied by the user is important as it determines the compatibility of succeeding criteria and consequently determines the resulting viable drive solutions. For example, selecting “vacuum” as an environmental operating condition may remove alternatives capable of providing other important actuation requirements. Criteria of most importance to the user are therefore to be selected first for more accurate results.

4.7 Database development and structuring

Information entered into the database (Figure 4-2) is determined by the actuator properties and attributes. These actuator properties are translated into application requirements on the user interface and used as criteria for actuator selection. For the selection of electric motors, properties peculiar to specific designs were sourced mainly from textbooks and academic literature. Specific values and data concerning motor designs such as rated speed, torque, dimension and cost were sourced from motor catalogues and integrated with the textbook information to form the database. Several problems arose in trying to achieve this integration. These problems influenced the eventual structure and content of the database and selection process.

Firstly, making the database specific with regards to manufacturer models was difficult as no one company provides all the motors considered to be LCA alternatives. Indicating models also would make the database unmanageable with excessive drive alternatives of similar performance and properties (redundancy). In order to overcome this problem, adherence to motor designs was necessitated, with the database totally independent of manufacturer models. Making the database “design dependent” has the advantage of helping to incorporate other actuator technologies such as hydraulic and pneumatic designs in the future.

Secondly, most manufacturers tend to use names indicative of motor enclosures or some other motor characteristic specific to the manufacturer. Motor manufacturers may refer to their motors as asynchronous or synchronous or totally enclosed DC, geared or watertight, etc, not necessarily identifying them by their specific motor designs. This naming inconsistency posed a problem in identifying and integrating corresponding design properties from textbooks with catalogue information. This also constituted a reason for adopting a design dependent database.

An important consideration for development of the database is maintenance. Unlike the MotorMaster+ and CanMOST discussed in Chapter 2, the design specific nature of the database ensures a limited content. This database feature makes for easier updating and maintenance. In a situation where the cost index for example, which is subject to fluctuation, requires updating, the smaller number of entries in the database makes it a lot easier to update even all the cost index entries. If a user wants to add a new database entry without revising all the existing entries' cost indices, then a sample of existing entries could be used as a reference to determine the "scale factor" between actual cost and the cost index.

4.8 LCA motor types database

It was discovered that a lot of the motors which could be classified as LCA motors with respect to this research were not necessarily LCA motors with respect to South Africa. While certain motors such as the single phase Permanent Split Capacitor (PSC) motor can be found readily elsewhere in the world, they are not readily available in South Africa. Special requests have to be made in order to obtain them, which would mean added cost. Some of the more general motors’ most readily available and in use everywhere according to Traister (1994), are squirrel cage motors, synchronous motors, wound rotor induction motors, as well as a few DC brush and brushless motors.

The eventual decision on what motors fully describe the choice available to the engineer is dependent on a number of factors. One factor of most importance to this thesis is the off the shelf availability of the motor as defined by the term LCA and discussed in earlier chapters.

The following is a list of motors which is best representative in type and design of the LCA motor set in South Africa: AC induction motors (asynchronous), AC synchronous motors, stepper motors, servomotors, brushless DC motors, and brush DC motors. From the economics or cost point of view the squirrel cage motor (Asynchronous ACIM) is the least expensive requiring very little control equipment or power electronics, the wound rotor is more expensive requiring additional secondary control, while synchronous motors are the most expensive requiring DC excitation, as well as special synchronizing control.

It is important to note that as size decreases and power requirements diminish (i.e. battery power applications), DC motors become the choice alternatives for applications as they become more economical than their AC counterparts (Crowder, 2006). The size limitation on applications plays a major role in the selection of applicable motors. For very large applications, AC motors become the economical choice as large DC motors with the required properties tend to be very expensive. DC drivers are however generally cheap and not as complex as those required for AC motors.

CHAPTER 5 AC DRIVE CONTROL EVALUATION

5.1 Introduction

AC drives are the most commonly used drives in automation today, mainly because of their easy accessibility and robustness. As such they are unrivalled by their counterparts, i.e. DC and stepper drives. This chapter presents an experimental evaluation carried out to determine performance data for servo and AC induction motor (ACIM) drives.

Most often the degree of control required for an application determines the inverter sophistication. This directly influences cost which is an underlying factor in automation and more specifically low cost automation.

As discussed earlier, because motors have similar operational capabilities (inherent properties), the decision when to use one or the other is not readily apparent, more so when selecting motors in combination with inverters for optimum performance. The more sophisticated an inverter is, the more expensive it and its accompanying accessories will be. It is important to know exactly what degree of control, if any, is required for an application as well as what degree of control can be provided by different inverters available off the shelf. Unfortunately quantitative data on such issues is difficult to come by and engineers involved in actuator selection become reliant on their own experience, the experience of others and information supplied by motor drive manufacturers.

The experiments presented in this chapter were designed and carried out to specify quantitatively, some operational performance data for servo and AC induction motor drives and, in so doing, validate controllability requirement rules implemented in the selection aid. This evaluation focuses on AC motors and inverters which function on voltage flux vector control (VFC) and current controlled flux vector control (CFC) technology.

5.2 Experimental set up

For evaluation to be performed, a test bed was designed to furnish the experiments with automation type conditions as will be discussed in the following sections. This application was designed capable of being set up in two configurations i.e. as a servo drive with a ball screw, or as an AC drive with a toothed belt and pulleys as shown in Figure 5-1 and 5-2. These basic configurations are consistent with automation today.

The test bed was designed around parts from old projects. This explains the different linear bearing shaft lengths on either side of the test bed as shown in the figures. In designing the test bed, simplified representations of typical application scenarios were used to provide working conditions similar to what can be expected in practice. The carriage and linear bearings provide the necessary axes for motion of loads, where varying certain parameters such as the accelerations, speeds, etc. provides the desired conditions for evaluation. Loading the application ensured that the resulting accuracies are true representations of the drive control capabilities. The travel range (see Figure 5-2) of the test bed provides linear translation as well as a means for checking positional and speed accuracies of the drives.

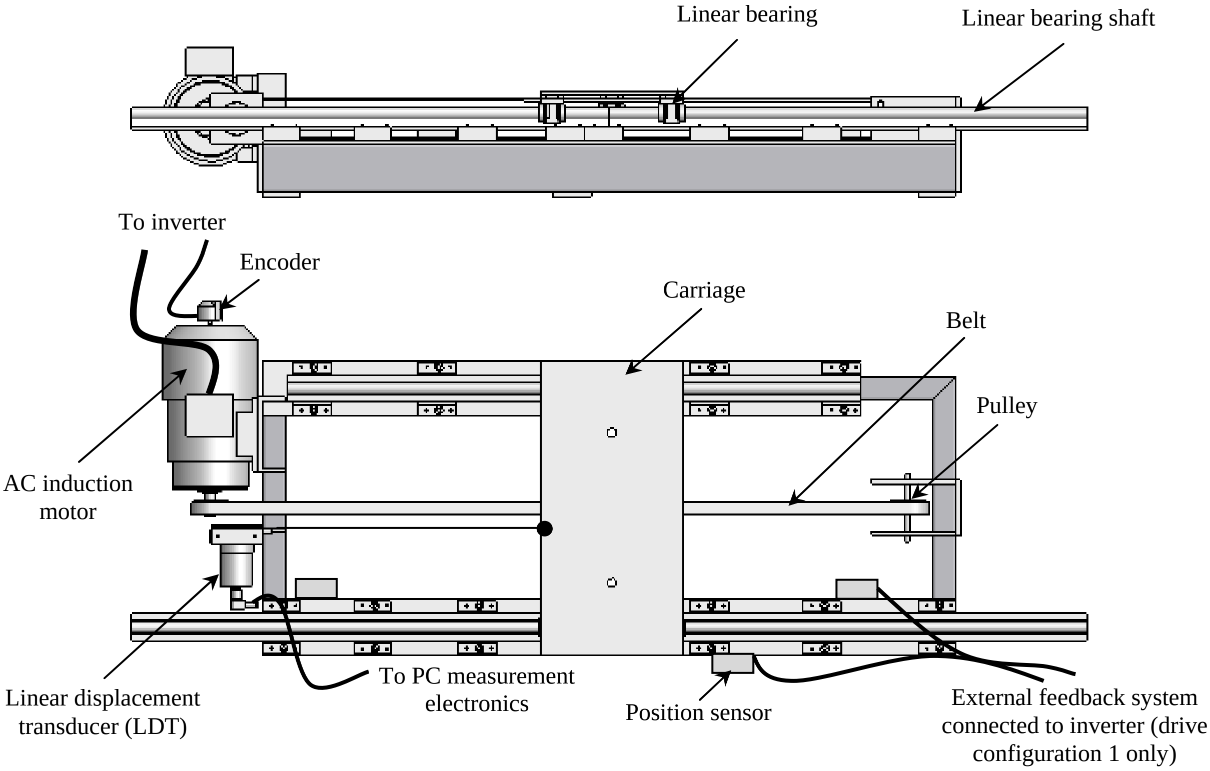


Figure 5-1 AC induction motor - belt and pulley configuration

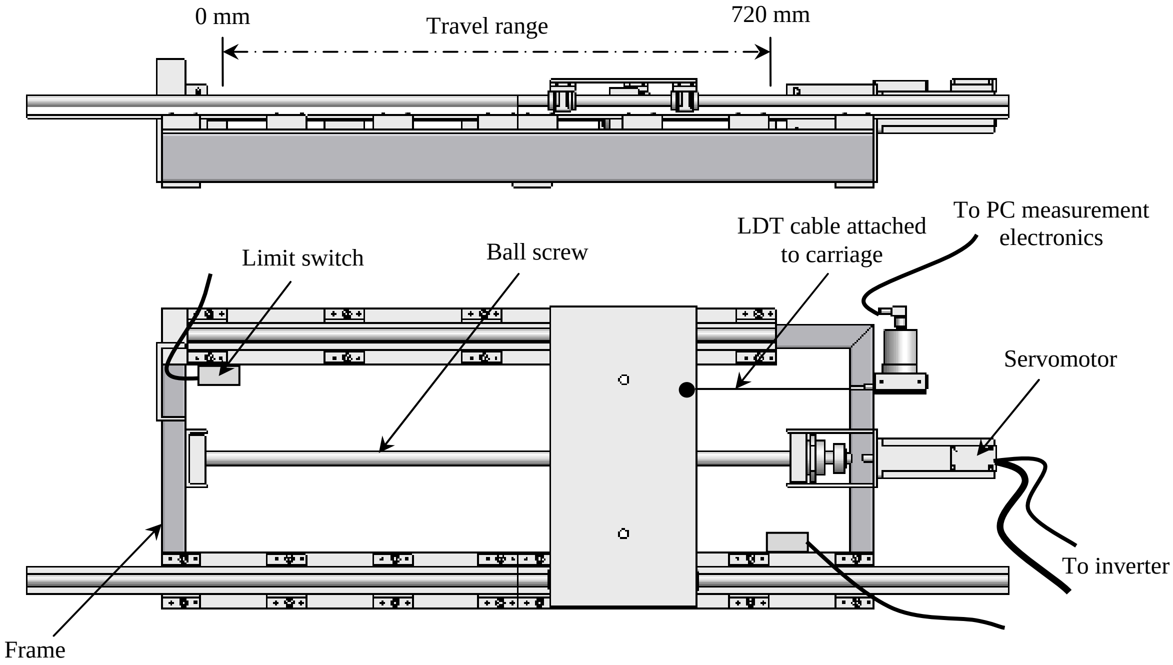


Figure 5-2 Servo and ball screw configuration

5.2.1 Terminology

Some of the terms regularly used in this chapter include: drive, accuracy, resolution and absolute error. A drive here is taken to be composed of an electric motor and accompanying accessories such as inverters and encoders, necessary to create the required motion in an application. Accuracy of a measurement refers to an ability to indicate a true value exactly (Richard and Donald, 2000, p15). As explained by Cetinkunt (2007, p217), resolution refers to the smallest change in the measured variable that can be detected by a sensor. Absolute error (ε), is defined as the difference between the actual value and the measured value.

$$\varepsilon = \left| \text{Actual value} - \text{Measured value} \right| \tag{5.1}$$

From this, accuracy (A) is found by

$$A = 1 - \frac{\varepsilon}{\text{Actual value}} \tag{5.2}$$

5.2.2 Control and data acquisition

5.2.2.1 Control software

The following are brief descriptions of the software used for motor control and displacement measurement. A full description of these software applications is available in Appendix C.

MOVITOOLS - MOTIONSTUDIO:

This SEW software was used in conjunction with Type 1 Movitrac inverter for open loop control of the AC induction motor without an encoder. It provides a means to parameterize and start up the motor, as well as an oscilloscope function (SCOPE) to diagnose faults and to monitor drive properties. For the experiments it also served in data acquisition for speed control.

MOVITOOLS - MT MANAGER:

This SEW software was used in conjunction with Type 2 Movidrive inverter for closed loop control of the AC induction motor and encoder. Functions of interest within this software are: SHELL for parameterization and start up of the motor, and SCOPE for drive diagnosis and monitoring. This software also served in obtaining speed control data.

INDRAMAT - DRIVETOP:

This Bosch Rexroth software was used in conjunction with Type 3 Ecodrive inverter for closed loop control of the servomotor. It provides a means to parameterize and start up the motor, as well as an oscilloscope function to monitor (speed control data acquisition) and diagnose the drive.

HBM Catman Easy:

The HBM Spider8 PC measurement electronics with this software were used in conjunction with the linear displacement transducer (LDT) for independent displacement data acquisition. It was used in calibrate the LDT for measurement using data acquisition (DAQ) projects. The conversion resolution of the Spider8 PC measurement electronics is 4096 (2^{12}) and the range of the LDT is 2000 mm/10 V. The resolution of measurements attainable with this configuration is given by:

$$\text{Resolution in mm} = \frac{2000\,\text{mm}}{4096} = 0.4883\text{ mm (approx. 0.5 mm)}$$

5.2.2.2 Motor sensors

This section gives a brief description of the motor sensors used.

The resolution of the encoder on the ACIM motor is 1024 (2^{10}) and for a pulley of diameter 76.42 mm, its resolution for a revolution of the ACIM shaft is given by:

$$\text{Resolution in mm} = \frac{\pi \times 76.42\,\text{mm}}{1024} = 0.2345\text{ mm}$$

The resolution for the servo encoder is 32768 (2^{15}) and is determined programmatically within the Drivetop software. For a ball screw of pitch 5mm, its resolution in mm is given by:

$$\text{Resolution in mm} = \frac{5\,\text{mm}}{32768} = 0.000153\text{ mm}$$

5.2.2.3 AC inverters

In this chapter, AC inverters (AC drivers) have been classified into three groups of increasing complexity:

Type 1 inverter:

Open loop voltage flux vector control (VFC): These inverters are incapable of programmatically controlled positioning. They do not function with encoders but are capable of speed control using optimized voltage/frequency (V/Hz) operation. Position control for this inverter was provided using a proximity sensor and limit switch as illustrated in Figure 5-3. The SEW Movitrac inverter forms the basis for this classification.

Type 2 inverter:

Closed loop voltage flux vector control (VFC): This classification is based on the SEW Movidrive inverter. These inverters are capable of programmatically controlled positioning via encoder feedback. Speed control is also improved by encoder feedback information.

Type 3 inverter:

> Closed loop current flux vector control (CFC): These inverters are also capable of programmatically controlled positioning and speed control via encoder feedback information. These are more complex inverters than the two already mentioned and are also capable of torque control provided by sophisticated digital control algorithms. The Bosch Rexroth Ecodrive inverter represents this classification.

5.2.3 AC Drive schematics

Figure 5-3 shows the schematics of the drive configurations implemented in the experiments. The chain lines in configuration 1 below indicate the feedback used in providing position control.

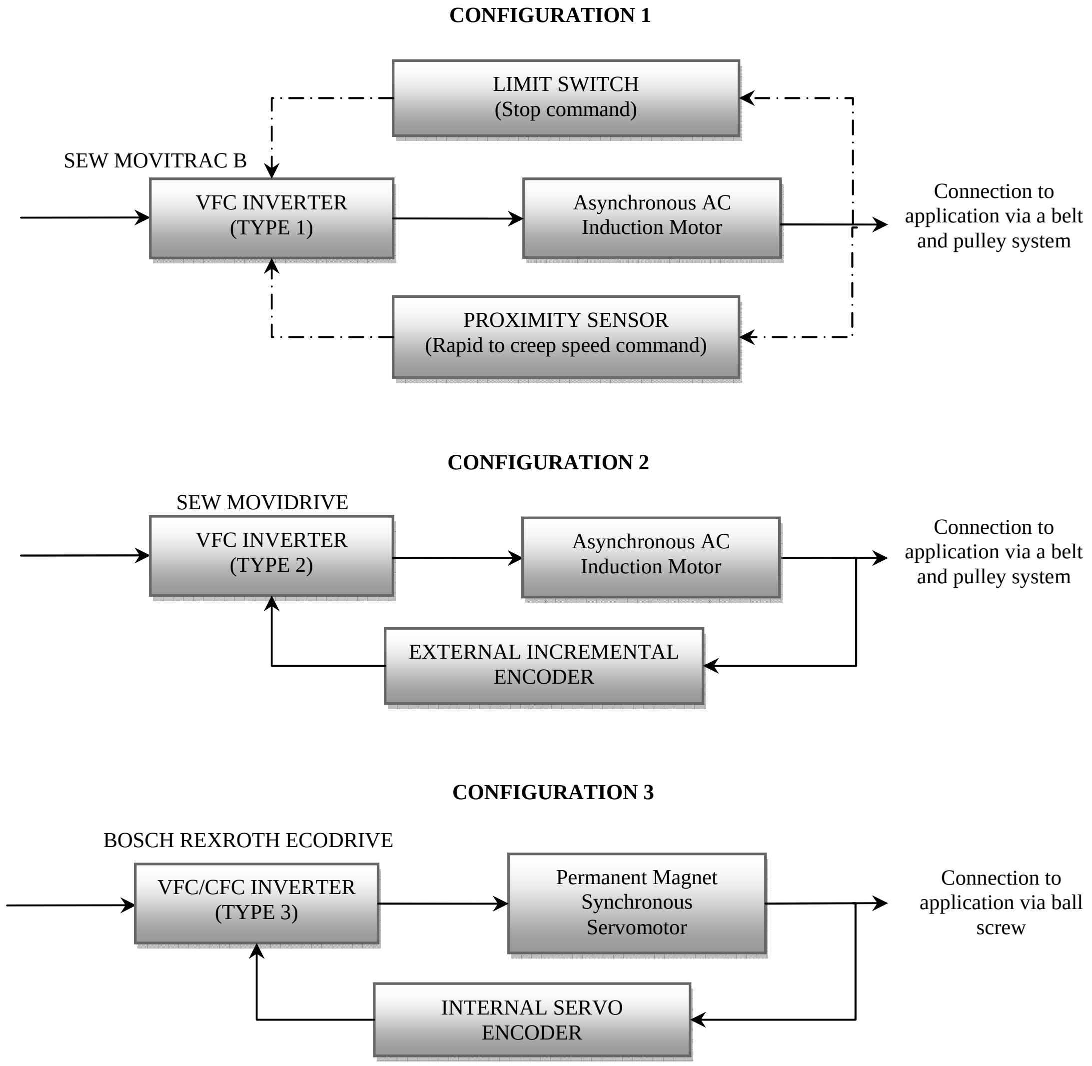


Figure 5-3 Schematic diagrams of test configurations

The illustrated drive configurations have been presented in increasing cost and complexity. A confidentiality agreement prevents the actual cost from being reported, however, in terms of relative cost, if configuration 1 costs R100, then configurations 2 and 3 cost R209 and R322 respectively.

5.3 Common experimental procedures

Quantitative data that can be used as a basis for the selection of drive configurations is the focus of these experiments. In order to evaluate servo and AC drives' performance, it was necessary to study them under conditions which reflect the necessity to use servo drives as well as AC drives. These conditions are provided by the designed test bed and include:

1. Operations requiring fast starts and stops.
2. Operations requiring acceleration and deceleration of loads.
3. Acceleration and deceleration with and without loads according to different speed profiles.
4. Operations requiring accurate positioning.

The performance of the drives under the mentioned conditions was investigated and deductions were made based on the quantitative results. Positioning accuracy of the drives was expressed as absolute error in millimetres, while accuracy of speed operation was expressed as a function of percentage speed deviation.

Certain conditions were necessary in order to make appropriate and meaningful measurements with due consideration to the test bed. These are explained below:

- Maximum linear speed adopted on the test bed was restricted to about 35,000 mm/min for both ACIM and servo configurations. This corresponds to the maximum speeds achievable by the servo at 7000 rpm and 148 rpm for the ACIM. All the experiments were conducted at about this linear speed.
- The distance travelled was limited to about 720 mm by test bed dimension which is approximately 800 mm (see Figure 5-2).
- Ramp times for all experiments were limited to four seconds and below, above which accelerations would be too small for the test bed length. Similarly, limiting

the ramps to four seconds ensured that fast enough speeds could be attained during travel.

- A maximum of 40kg was the imposed loading condition. This was constrained by test bed dimensions and the applied accelerations especially for the belt and pulleys configuration. This load is however consistent with the rated torques of the motors used and ensured reliable test conditions.

Finally, experiments conducted required knowledge of the exact motor ratings and capability. However, in order to generalize recommendations and make inferences on controllability issues for the drive configurations, the analysis process was isolated to performance irrespective of particular motor ratings and specifications.

5.4 Position control experiments

5.4.1 Objectives

The objective of these experiments was the determination of positioning accuracies achievable with ACIM and VFC inverters, and servomotor and CFC inverters under varying conditions. This experiment primarily provides basic quantitative position control data relevant to electric drive selection. The position control experiment objectives can further be broken down into:

- Determination of actual output position (final rest position).
- Determination of positioning absolute error (ε_p) in millimetres.

$$\varepsilon_p = \left| \text{Final rest position - Setpoint target position} \right| \tag{5.3}$$

- Determination of overshoot in millimetres, given by:

$$\text{Overshoot} = \text{Max. displacement - Setpoint target} \tag{5.4}$$

Overshoot only occurs when the maximum displacement is greater than the set target position.

These experiments involve setting a predefined position target for the drive configurations. These positional targets are run with the intent of checking consistency of the setpoint values and the output/actual values. With Types 2 and 3 inverters mentioned above, actual position information values are available on the associated inverter software interfaces as feedback information from the encoders. The displacement data for the configurations was however obtained using independent PC measurement electronics and a LDT attached to the travelling carriage as illustrated in Figure 5-1 and 5-2.

5.4.2 Configuration 1 position control experiment procedures

It was observed that if position control is required, external sensing equipment must be incorporated into the drive system to provide the necessary feedback. To this end, a positioning trolley application (SEW Eurodrive, 2006b) with rapid and creep speeds was set up using a proximity sensor and limit switch to supply the necessary position feedback information. The sensor and limit switches were used to trigger a change from rapid speed to creep speed and to trigger the eventual stop. Rapid and creep speed values were varied to determine positioning accuracy capabilities of the drive for such applications. The following procedures were implemented:

1. Ensure that all connections necessary for the positioning trolley application have been made (SEW Eurodrive, 2006b, p.60). Also make the necessary connections for the LDT to the Catman Easy PC measurement software.
2. Configure the attached AC motor for start up using the Motionstudio software. Input the necessary rapid and creep speeds, the ramp up/down and stop times, (default settings are maintained for all other settings). Also calibrate the LDT for use on the Catman Easy defining its measuring range under “sensor adaptation” in a new DAQ project.
3. Move the carriage to the zero point of travel range along the linear shafts. The proximity sensor and switch must be active and correspond to positions along the travel range at which the carriage speed is expected to change from rapid to creep and stop respectively. For this experiment the travel length was calibrated to 720 mm, the distance between the speed change trigger and stop was fixed as 200 mm, this distance allows enough time for transition from rapid to creep speed and stop.
4. Reset the LDT reading with the zero balance function on the Catman Easy software in the DAQ project.

5. Start the DAQ project, the graphical view must indicate the reading from the LDT as a straight line on zero.
6. On the Motionstudio software interface, open the manual operation module and deactivate manual operation to trigger rapid speed operation for the positioning trolley application.
7. After the carriage has come to a stop at the limit switch, stop the DAQ project and store the results. The Catman Easy software provides data storage in Excel and other formats. These results provide real time displacement measurement from zero to its actual stop position.

Exact procedures for use of the inverters and their software are available in SEW Eurodrive manuals (SEW Eurodrive, 2006b).

5.4.3 Configuration 1 position control observations

The accuracy of the carriage stop position was observed to be dependent on a combination of several factors. These factors include: the response of the feedback sensing equipment, creep speed, the ramp down and stop time programmatically set on the control software. The distance between the speed change trigger and stop limit switch also affects the stop position, however if this distance is sufficient to allow a complete transition from rapid to creep speed, its effect is minimized. The ramp up/down and stop times were set to zero as the fastest response that can be provided by the SEW Movitrac inverter, while the limit switch response was assumed to be instantaneous. These settings and assumptions as much as possible isolated positioning capability dependence to the creep speed value. Table 5-1 provides absolute error readings for varying rapid and creep speed values for loaded and unloaded conditions. Overshoot for this application was not considered.

Table 5-1 Configuration 1 absolute error readings

Rapid speed (rpm)	**Unloaded**	**Loaded (40 kg)**		
	Creep speed			
	10 rpm		**20 rpm**	**30 rpm**
100	0.5 mm	1.5 mm	2 mm	2.5 mm
146	0.5 mm	1.5 mm	2 mm	4 mm
160		2 mm	2 mm	5 mm
200	1 mm			

5.4.4 Configurations 2 and 3 position control experiment procedures

The procedures for these two configurations are essentially the same except for their control software. These software differences are specified in the procedures.

1. Ensure all connections between the ACIM and Movidrive or servo and Ecodrive inverters have been made (see SEW Movidrive, 2005, and Bosch Rexroth, undated).
2. Configure the attached AC motor for start up using the shell module in Movitools or for the servo in the Drivetop software. The software applications take you through a series of steps necessary to setting up the motors. Specify the operating mode, for the ACIM: VFC n-control & IPOS (SEW Eurodrive, 2005), while for the servo: Position mode with encoder (Bosch Rexroth, undated). These operating modes enable position target definitions.
3. Set position target using the “Table positioning application” in the Movitools shell module for the ACIM. This can also be achieved for the servo with “Position mode with encoder” set as the primary operation modes in the Drivetop software.
4. Set up the LDT for use with the Spider8 PC measurement electronics, using the Catman Easy to define its measuring range under “sensor adaptation” in a new DAQ project.
5. Load (40 kg) and move the carriage to zero point of the travel range along the linear shafts. The distance of travel must fit within the software limit switches.
6. Ensure that the encoders have been reset to zero for either the ACIM or the servo. For the ACIM, the travel has to be referenced within Movitools (referencing of the travel resets the encoder position to zero), while for the servo, this is achieved by resetting the encoder value to zero within Drivetop.
7. Reset the LDT reading with the zero balance function on the Catman Easy software DAQ project.
8. Configure the scope function on Movitools or the oscilloscope function on Drivetop.
9. Start the DAQ project. The graphical view must indicate the reading from LDT as a straight line on zero.

10. Start the scope or oscilloscope functions and then execute start positioning or position strobe command on Movitools or Drivetop respectively.
11. After the target position has been reached and the carriage is at rest, stop the scope function and load the data to view the displacement – time graph on Movitools. For Drivetop, the oscilloscope function is automatically terminated at the end of record time and loaded automatically with its graph displayed.
12. Stop the DAQ project. Record the setpoint target position value (720 mm for all the experiments). The DAQ gives you output data on position from the LDT.
13. At the end of these procedures you have the setpoint target position value, the LDT values with time and speed or position data from either the scope or oscilloscope functions of either software.

Exact procedures for use of the inverters and their software are available in SEW Eurodrive manuals (SEW Eurodrive, 2006a, and Bosch Rexroth, undated).

5.4.5 Configuration 2 position control observations

The following is a typical displacement – time graph which captures the motion of the moving carriage. The little bump at point A on the graph indicates the overshoot in positioning, while the region between B and C indicates its final rest position which should correspond to the target position. The difference between values in this region and the target position gives the absolute error in positioning.

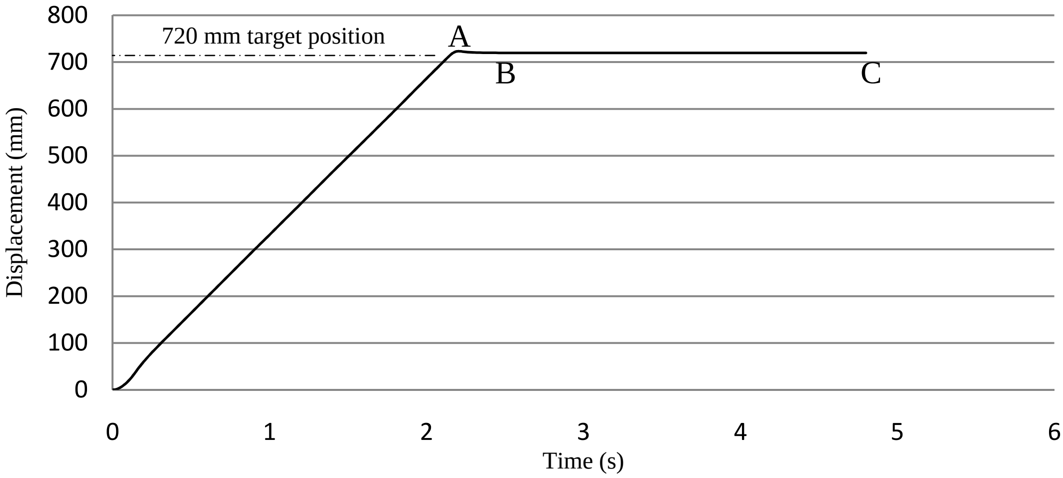


Figure 5-4 Typical displacement time graph

Table 5-2 is a summary of data obtained from the position control experiments for configuration 2 loaded with 40 kg. It provides absolute error and overshoot readings for varied ramp times (ramp up equals ramp down time).

Table 5-2 VFC – ACIM position control summary data

Ramp time (s)	Absolute error (ε_p) (mm)	Overshoot(mm)
0.03	1	7.5
0.50	1	4
1.00	1	2.5
2.40	1	1
4.00	1	1

5.4.6 Configuration 3 position control observations

The displacement – time graph (Figure 5-4) above is also representative of that encountered with the servo drive. Table 5-3 gives a summary of the resulting positioning data for a 40 kg loaded condition.

Table 5-3 CFC – Servo position control summary data

Ramp time (s)	Absolute error (ε_p) (mm)	Overshoot (mm)
0.02	< 0.5*	3.5
0.50	< 0.5*	< 0.5*
1.00	< 0.5*	< 0.5*
2.40	< 0.5*	0
3.30	< 0.5*	0

*Note: Absolute error was less than LDT measurement resolution (LDT resolution ≈ 0.5 mm)
The zero values for the overshoot simply means the carriage never reached the target position.

5.5 Speed control experiments

5.5.1 Objectives

The objective of these experiments was the determination of the speed accuracies achievable with ACIM and VFC inverters and servo and CFC inverters under varying conditions. It basically entails the determination of the conformity of actual speeds to setpoint speeds defined in the drive control software. Speed control data obtained was expressed as percentage speed deviation.

Speed control experiments involve executing speed profiles defined by ramps in the form of accelerations and decelerations, speed and positions. A speed profile is simply a combination of at least two continuous positioning operations, each with the same or different speeds and ramps.

These speed profiles were executed for the configurations to determine conformity of output speeds with command speeds. Just as with the positional tasks, feedback encoder information is available on the Movitools and Drivetop software interfaces. These speed profiles are monitored using the mentioned control software scope functions. The feedback on the speed profile is captured and saved and may be used afterwards in analysis. For these experiments the required speed profile is essentially kept constant for the servo and ACIM configurations, however, loads were introduced to check conformity to set speed commands under the resulting load conditions. In summary these experiments involve:

- Determination of average speed value for any one fixed setpoint speed value within a speed profile
- Determination of speed absolute error (ε_s) (|average running speed value – setpoint speed|) in rev/min or mm/min. This is the speed equivalent of eq. (5.3)
- Determination of the percentage speed deviation from the setpoint speed value

$$\text{Speed deviation} = \frac{\varepsilon_s}{\text{Setpoint speed}} \tag{5.5}$$

Linear speeds imposed in these experiments are the same as those used in the positioning experiments.

5.5.2 Configuration 1 speed control observations

The speed control provided by this configuration is dependent on loading conditions. Although setpoint speeds are set on the inverter and translated to the motor, effects of loads greater than 150% the rated torque (SEW Eurodrive, 2006b) cause significant disturbances which are undetected by the inverter. The inability of the drive to compensate for disturbance in the system results in significant load dependent deviation of actual speeds from setpoint speeds required by an application. The unloaded configuration was however found to maintain a speed deviation of about 0.07% for command setpoint speeds values.

5.5.3 Configurations 2 and 3 speed control experiment procedures

Speed control experiment procedures for configurations 2 and 3 are similar, with exceptions in certain control software terms specified in the procedures below.

1. On the Movitools interface, “VFC n-control & IPOS” must be selected as the operation mode of the ACIM, this enables definition of the speed profile in a tabular format in the “Table positioning application module” as travel distances with required speeds and ramps. Similarly “Process block mode” must be selected as the primary operation mode for the servo on the Drivetop interface. This also enables definition of the required speed profile.
2. For the Movidrive, a maximum of 32 positions and corresponding speeds and ramps can be set for VFC n-control & IPOS on Movitools. “Process block mode” on Drivetop can be configured for up to 63 distinct or continuous blocks of commands on the Ecodrive, however “continuous block” commands are used in this experiment to provide the required speed profiles. The required position, speed and acceleration are set, with other values left as their default values.
3. Load (40 kg) and move the carriage to the zero point of travel range along linear shafts. This should correspond to speed profile the start position on the software and must fit within software limit switches.
4. Ensure that the encoder has been reset to zero for either the servo or the ACIM. The procedure for this is the same as that for the position control experiments.
5. Configure the scope or oscilloscope functions for the Movitools or Drivetop respectively.
6. Select the speed profile to be executed.
7. Start the scope or oscilloscope functions and then start positioning command for the ACIM or execute position strobe command for the servo.

8. After a speed profile has been executed and the carriage is at rest, stop the scope and load the data to view the speed – time graph on Movitools. For the Drivetop, the oscilloscope function is terminated at the end of record time and is loaded automatically with its graph displayed.
9. The graphs and data resulting from the scope and oscilloscope functions can then be analyzed to determine conformity with set speed profile values.

Exact procedures for use of the inverters and their software are available in SEW Eurodrive and Bosch Rexroth documentation (SEW Eurodrive, 2005, and Bosch Rexroth, undated). The combined closed loop feedback on the speed profile executed is captured by the graph and actual data can be saved and utilized afterwards in data analysis. For this sets of experiments the speed profile was kept constant for both ACIM and servo configurations with loads.

5.5.4 Configuration 2 speed control observations

The curve between Points A and D in the graph below (Figure 5-5) represents the forward speed trajectory of the carriage. Points B, B1 and B2 are the maximum overshoots with respect to speed, which are typically encountered with PID control. The curve between C and D (and similar regions) is the region of interest in checking conformity to setpoint speeds. In the graph below, the setpoint speed for forward and backward motions is 100 rpm. The negative speed values indicate motion in the backward direction.

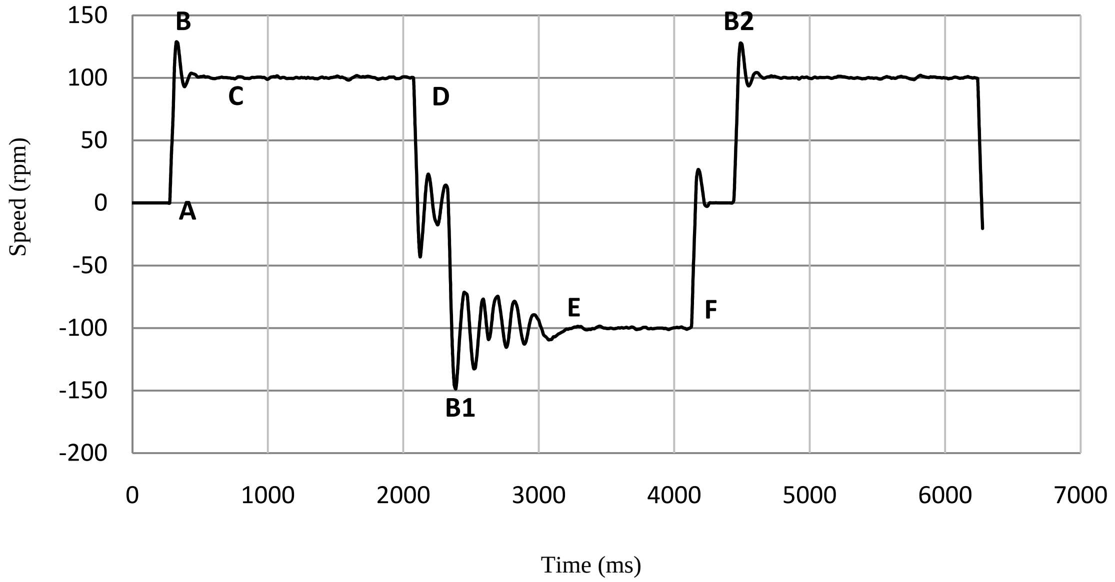


Figure 5-5 VFC - ACIM with encoder speed profile for CW and CCW

The spikes at the transition regions in Figure 5-5 are attributed to overshoots during a change in direction from clock wise to counter clock wise and vice-versa rotation of the motor shaft.

Table 5-4 is a summary of data obtained from the ACIM speed control experiment for unloaded conditions.

Table 5-4 Speed deviation values for unloaded configuration 2 at 146rpm

Ramp time (s)	% Speed deviation
0.03	0.15
0.10	0.15
0.50	0.15
1.00	0.09
2.40	0.09

The above experiment was also conducted under loaded conditions. Table 5-5 gives percentage speed deviation values for three different speeds and ramp times for the loaded configuration.

Table 5-5 Speed deviation for varying ramps and ACIM speeds with 40 kg load

Ramp time (s)	% Speed deviation at		
	100 rpm	146 rpm	160 rpm
0.03	0.42	0.73	1.19
0.50	0.31	0.71	1.15
4.00	0.12	0.05	0.57

The speed deviation ranges in Table 5-5 all fall within 0.04% to 1.5%, indicating the fairly good speed control capability of the VFC and encoder configuration. It should be noted, however, that the above data has been obtained for rather low speeds in comparison to the rated ACIM motor speed of 1500 rpm due to limitations of the experimental set up and resource constraints. Furthermore the speed data herein is believed to represent accuracies obtainable within the lower spectrum of the SEW drive properties for speed (SEW Eurodrive, 2006a).

5.5.5 Configuration 3 speed control observations

The curves from A to B, C to D, and E to F in Figure 5-6 where analyzed for conformity to the setpoint speed of 1600 rpm (8000 mm/min). Curve B1 to D1 represents a forward motion of the carriage. The accelerations (ramp times) for the trajectory were varied from 0.07 s to 0.1 s to 0.13 s, hence the increasing slope left to right from B to C, D to E and F to F1.

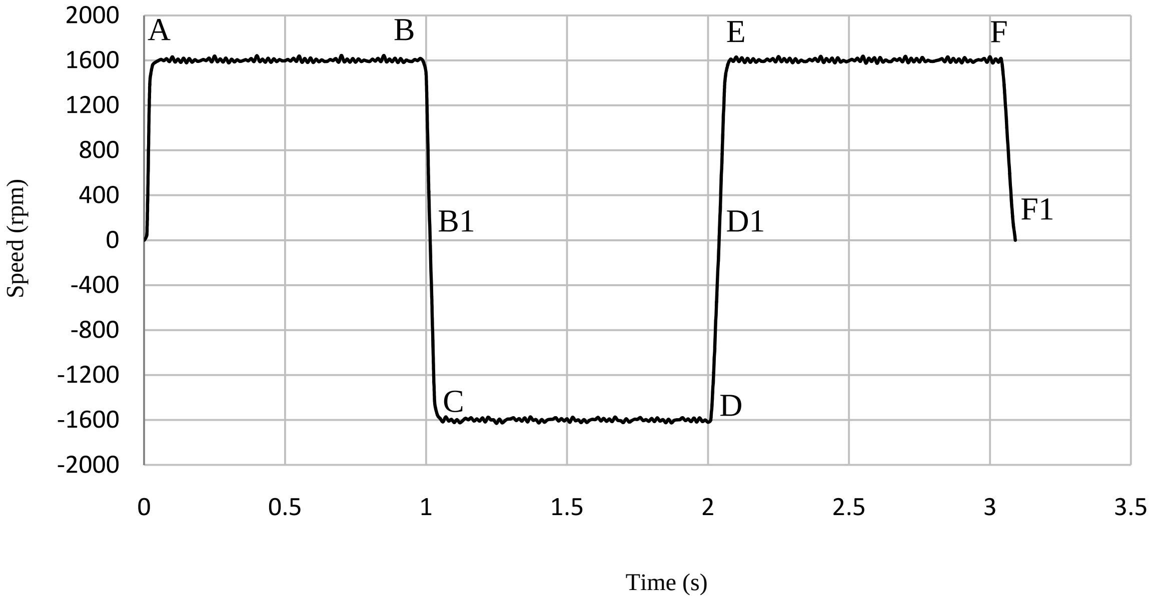


Figure 5-6 CFC - Servo speed profile for CW and CCW motion at 1600rpm

Tables 5-6 provides a summary of speed control experiment data for configuration 3 at 1600 rpm and varying ramp times/accelerations.

Table 5-6 Speed deviation values for unloaded CFC – Servo application at 1600rpm

Ramp times (s)	% Speed deviation
0.01	0.19
0.03	0.15
0.07	0.08
0.10	0.03
0.13	0.08

Table 5-7 provides percentage speed deviation values for loaded conditions of the same configuration for varying accelerations and speeds.

Table 5-7 Speed deviation for varying accelerations and servo speeds with 40 kg load

Accelerations (mm/s^2)	% Speed deviation at			
	4000 rpm	2800 rpm	1600 rpm	400 rpm
10000	0.07	0.08	0.08	0.07
6800	0.09	0.04	0.09	0.10
3600	0.03	0.02	0.06	0.02
400	0.03	0.09	0.02	0.06

5.6 Torque control

Experiments in torque control were not conducted due to constraints in resources and equipment. However discussion with SEW representatives (Strzalkowski, 2007) and review of commercial literature, establish that torque control for AC drives is only possible with CFC type inverters (SEW Eurodrive, 2006a). More sophisticated absolute encoders are also a requirement if torque control is to be implemented. The decision on what control type to use when torque control is an application requirement is straight forward, in other words if torque control is a requirement, then CFC type inverters must be used.

5.7 Comparison and significance of experimental and SEW data

Drive systems as a whole have an effect on the overall accuracy of applications. As such less rigid systems are more likely to have errors equal in magnitude to its loosely fitting parts (e.g. a belt and pulley set up). The rigidity of the ACIM configuration was improved by maximizing tensions in the belt and changing inertia settings in the drive software to improve “stiffness” in the motor rotor. Running ACIM’s at speeds far lower than their rated speed (as in our case above – where the rated speed is 1500 rpm and it was run at 145 – 200 rpm), is not recommended. To do so, a proper knowledge of the drive software is necessary. Inertia settings must be calculated to avoid an inertia mismatch. For the SEW drive system, the operation was optimized for the particular application. These issues are of significant importance when considering control information.

SEW data presented in the following section, provides recommendation based strictly on SEW products. Having used SEW products (ACIM, Movidrive and Movitrac inverters) for some of the experimentation, it is important to make a comparison between the experimentally obtained data and those provided by SEW manuals (SEW Eurodrive, 2006a). This comparison serves to validate results for both SEW and Bosch drive (servomotor and Ecodrive inverter) data experimentally obtained. Recommendations based on quantitative data with respect to these different drive configurations can then be made with some degree of assurance and reliability.

5.7.1 SEW recommendations

Tables 5-8 and 5-9 give a summary of the data given by SEW Eurodrive manuals (2006a) used for the VFC/CFC type inverters (MDX60B/61B Drive inverters). Their data as such has been used in corroborating results obtain from experimentation.

Table 5-8 SEW Eurodrive drive properties [SEW Eurodrive, 2006a]

Voltage flux control (VFC) without encoder	Position control error	< ±360°
	Speed settings range	1:200
	Torque control	No
Voltage flux control (VFC) with encoder	Position control error	< ±5° to ±45°
	Speed settings range	1:800
	Torque control	No
Current flux vector control (CFC) with encoder or resolver	Position control error	<±1°
	Speed settings range	>1:800
	Torque control	Yes

Position control values refer to angular error of motor shaft.
Settings range values are in reference to 3000 rpm.

The settings range figures shown in Table 5-8 indicates ratios in reference to 3000 rpm. This means that for the VFC inverters without encoders, optimum speed control is achievable from 3000 rpm down to 15 rpm (1/200th of 3000). Similarly for VFC inverters with encoders, speed can be controlled efficiently from 3000 rpm down to 3.75 rpm (1/800th of 3000). CFC inverters with encoders provide speed control better that the later VFC configuration (i.e. better than 1/800th of 3000). Table 5-9 provides more information with respect to the speed settings range in the Table 5-8.

Table 5-9 SEW Speed control characteristics [SEW Eurodrive, 2006a]

Inverter configuration	Max. speed deviation at $\Delta M = 80\%$. based on $n_{max} = 3000$ rpm	Speed deviation at constant torque. based on $n_{max} = 3000$ rpm
VFC without Encoder	1.8%	≤ 0.20%
VFC with Encoder	1.5%	≤ 0.17%
CFC with Encoder	1.0%	≤ 0.07%

Setpoint speed = 1000 rpm
Step change in load ΔM = 80% of rated motor torque
The defined control characteristics are maintained in the specified speed range.

In setting up the ACIM for position control, parameters must be supplied to the control software such as the diameter of the driving wheel, which are utilized in determining actual position. Due to inaccuracies in the drive wheel (pulley pitch diameter) as well as others in the test bed, errors may have been introduced into the positioning accuracy results for the ACIM. To assess its influence, the error due to the pulley pitch diameter was varied about its specified and calculated value. This showed that errors introduced in this way are of the order of microns, and therefore does not significantly affect the overall determined positional accuracy. As such the experimental results give a good representation of the positioning capabilities of the ACIM configuration when compared to corresponding SEW data.

Tables 5-10 and 5-11 present a comparison of experimental data and SEW data for position and speed respectively. In order to make the necessary comparison between SEW and experimental position control data, the SEW data had to be converted from angular error (positioning error in motor shaft) to linear error. The following equation was used in conversion for the ACIM and servo motor configurations.

$$\text{Linear error (mm)} = \frac{\text{SEW angular error}}{360^\circ} \times \text{Reference displacment (mm)} \qquad (5.6)$$

where, reference displacement refers to the linear travel for each revolution of the motor shaft.

For the ACIM, this equals the pulley circumference.

$$= \pi \times 76.42\,\text{mm} = 240.081\text{ mm}$$

For the servo motor, this equals the ball screw pitch.

$$= 5\text{ mm}$$

Table 5-10 Experimental and SEW position control error comparison

Drive configurations	Position control error	
	Experimental data	SEW data
Voltage flux control (VFC) and ACIM without encoder	< 1.5 mm to 4 mm (with external feedback)	-
	-	< ± 360° (without external feedback)
Voltage flux control (VFC) and ACIM with encoder	< 1 mm to 7.5 mm	< ± 3 mm to ±30 mm
Current flux vector control (CFC) with servomotor (internal encoder)	< 0.5* mm to 3.5 mm	< ± 0.014 mm

*Note: Absolute error was less than LDT measurement resolution (LDT resolution ≈ 0.5 mm)

Table 5-11 Experimental and SEW percentage speed deviation comparison

Drive configurations	Percentage speed deviation	
	Experimental data	SEW data
Voltage flux control (VFC) and ACIM without encoder	> 0.1% (load dependent)	≤ 0.2% to 1.8%
Voltage flux control (VFC) and ACIM with encoder	< 0.1% to 1.5%	≤ 0.17% to 1.5%
Current flux vector control (CFC) with servomotor (internal encoder)	< 0.02% to 0.6%	≤ 0.07% to 1.0%

5.7.2 AC drive position control recommendations

5.7.2.1 VFC and ACIM without encoder

Due to inability to provide programmatically controlled position and its entire dependence on external sensing for feedback, experimental position control data for this configuration given by SEW Eurodrive (2006a) is less than 360° angular error of motor shaft. This value corresponds to about 240 mm, which is the distance travelled for each revolution of the ACIM shaft, and is intuitively a range within which position may be controlled even by visual means.

With proximity sensors and limit switches providing feedback on position, a positioning error range of less than 1.5 mm to 4 mm was obtained. The upper limit (4 mm) corresponds to the maximum displacement above which the limit switch lever will bend. Bending of the limit switch lever defeats its positioning purpose. It is important to note that for such an application as implemented in the experiment, the creep speed plays the major role in the eventual positioning accuracy. For creep speeds less than those implemented in the experiments, positioning may be further improved.

5.7.2.2 VFC and ACIM with encoder

The minimum and maximum absolute errors obtained for this configuration are 1 mm and 7.5 mm respectively (Table 5-10). These values represent data for both loaded and unloaded conditions. This error range (1 mm to 7.5 mm) falls within the lower limits of equivalent positioning data from the SEW project planning manual (SEW Eurodrive, 2006a), and stated in Table 5-10 as 3 mm to 30 mm. A logical explanation for this is that the speeds adopted for these experiments were low (100 to 200 rpm ≈ 35,000 mm/min) in comparison to the rated ACIM speed (1,500 rpm ≈ 360,000 mm/min). The adopted speeds were so chosen to ensure comparable maximum linear speeds of the servomotor (7,000 rpm ≈ 35,000 mm/min). The experimental ACIM speeds were also limited by the length of the test bed. It can therefore be inferred that the experimental positioning data for implemented low speeds should correlate to those obtainable about the 3 mm lower limit of position accuracy data specified by SEW.

5.7.2.3 CFC with servomotor

For loaded and unloaded conditions, the minimum and maximum absolute positioning errors for this configuration are less than 0.5 mm and 3.5 mm respectively (Table 5-10). Position control data from these experiments were better representative of the drive configuration because they were performed at high as well as low servo speeds. Due to the resolution of the LDT (approximately 0.5 mm), the minimum error measurable is 0.5 mm. Table 5-3 indicates positioning data less than 0.5 mm for majority of the readings. Although these experiments were conducted using a Bosch drive, data obtained is in conformity with those specified by SEW system manuals as < ± 0.014 mm for SEW servo drives. This range (< 0.5 mm to 3.5 mm) provides a lot better performance than with the VFC with ACIM configurations.

5.7.3 AC drive speed control recommendations

5.7.3.1 VFC and ACIM without encoder

As already explained, this drive has no speed feedback, as such it provides load dependent speed deviations of about 0.1% for loads within 150 % of the rated torque of the attached motor (SEW Eurodrive, 2006b, p.37). This value corresponds to the specified SEW data of ≤ 0.2% to 1.8% (SEW Eurodrive, 2006a).

Due to a lack of feedback speed information, disturbances in the system as a result of loads are not compensated for, causing the actual running speed value to be less than the setpoint speed. In order for this drive configuration to be used for efficient speed control, the motor must be properly matched to the driven loads. The experimental speed deviation range (> 0.1%) obtained for this configuration is unbounded by an upper limit because it was tested only under unloaded conditions. An upper speed deviation limit can only be obtained under loaded conditions. The lower speed deviation limit, as expected, coincides with that achievable with an encoder and is evident from VFC with encoder experimental data.

5.7.3.2 VFC and ACIM with encoder

For loaded and unloaded conditions the percentage speed deviation range is 0.1% to 1.5%. With reference to the speed profile graph (Figure 5-4) for this configuration, it should be noted that a longer period of travel would provide the drive with enough time to stabilize from its disturbed state of acceleration to setpoint speeds. As such the average speeds obtained from between points C and D and other similar regions are expected to conform more to setpoint speeds with time. The above mentioned issue is important in describing the speed control capabilities of these drives. However, SEW data specifies a percentage speed deviation range of ≤ 0.17% to 1.5% for this configuration (Table 5-10) and is in entire agreement with the obtained experimental data.

5.7.3.3 CFC with servomotor

The minimum and maximum speed deviations obtained for this configuration are 0.02% and 0.6%. In comparison to SEW data indicating a ≤ 0.03% to 0.7% deviation (Table 5-8), experimental data show a remarkable likeness. This speed deviation range (0.02% to 0.6%) is much tighter than those obtainable with VFC configurations, and indicates a speed control performance niche for CFC and servo configurations.

5.8 Control evaluation conclusion

Figures 5-7 and 5-8 provide a summary of the operating niches and accuracy ranges for speed and position of servo and ACIM drives. In conclusion, these figures could quite easily be used in determining drive alternatives depending on the speed and position control requirements of any application. Torque control, even though not specified on a graph has been stated as possible only with CFC type inverters in combination with ACIMs or servomotors (Strzalkowski, 2007). Other drive alternatives such as DC and stepper drives may be capable of providing position, speed and torque control of similar performance as determined above. However, quantitative data for these drives are similarly difficult to obtain. Experimentation on these drives could form part of subsequent work on electric motor selection.

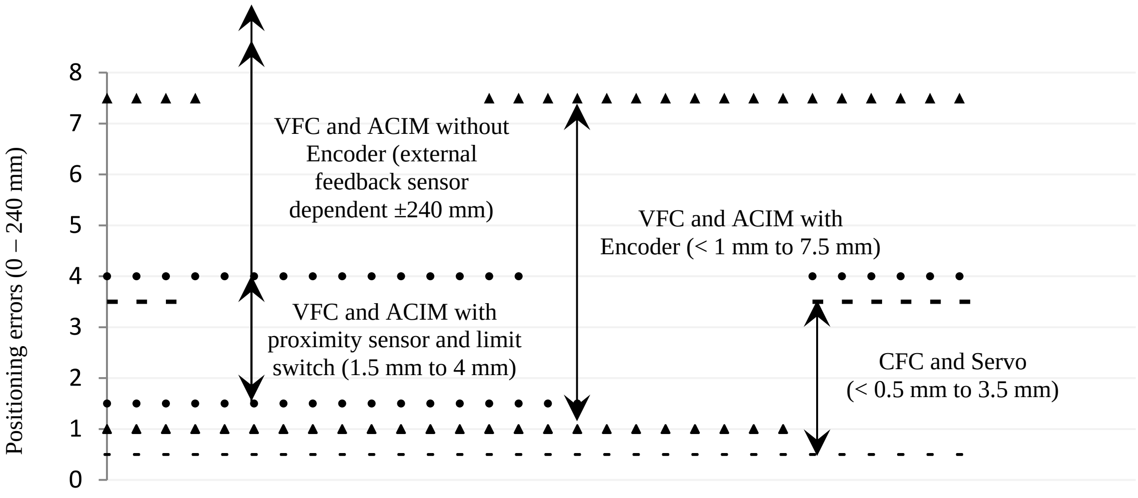


Figure 5-7 Positioning error ranges for the different drive configurations

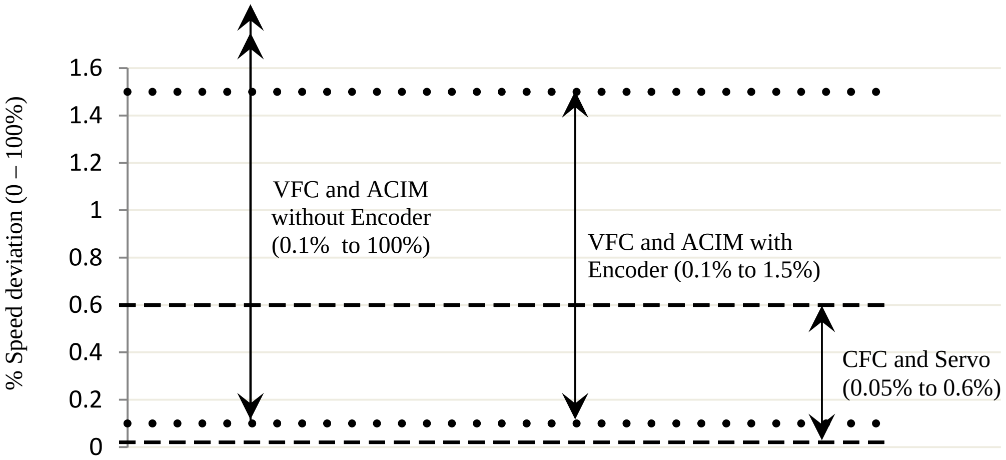


Figure 5-8 Speed deviation ranges for the different drive configurations

These experiments contribute directly to obtaining quantitative data on control and controllability requirements in the selection aid already discussed. The obtained data serve as validation of the controllability requirements rules implemented in the software which helps in providing more information in fully describing a given application.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

An objective of this thesis was to formulate a generally applicable and easy to use actuator selection procedure oriented towards LCA, with primary focus on electric motors and their interfacing with inverters. This objective was achieved by the formulation of rules and involved the correlation of inherent and driver acquired motor properties to application requirements. In so doing all commonly available drive alternatives could be considered as technically viable solutions for any application depending only on the application requirements.

The mentioned rules were also formulated having in mind the need for the procedure to be expandable to other actuator types, hence a guideline being the definition of a list of generic actuator properties. This satisfied the objective for the developed software program to be expandable to more actuator types.

The software was developed using Visual C++ programming language and incorporated the rules to reflect application requirement choices made by any user as technically viable motor and driver solutions.

The actuator selection aid was designed to strike a balance between two extremes: on the one hand, the aid should give information that is as precise as possible to enable clear design decisions, but on the other hand the aid should not require too highly detailed inputs, so that it can be applied earlier in the design phases when design details may not have been finalized. In the formulation of the overall strategy, priority is given to the aid being used earlier in the design process, rather than giving more precise results, since the impact of early design decisions on the final cost are usually greater.

Experiments to determine some quantitative operational information on AC drives were also performed. This was done to further improve content of the selection procedure while augmenting scarce published quantitative data. Position and speed accuracy for three drive configurations were determined with results presented in Tables 5-10 and 5-11.

Though the developed selection procedure and software have been prioritized for early design phases, and especially where selection of particular drives or technologies could potentially alter the design concept, the software could be very helpful in selection of actuators for systems being redesigned.

In conclusion, having successfully developed the selection procedure, the ability to make cost effective, unbiased and experience independent actuator selection decisions for Low Cost Automation has been satisfied.

6.2 Recommendations

The following paragraphs outline some areas where further work is required and other areas where the research objectives may be improved.

Experimenting at speeds closer to the rated speed for the ACIM drive configuration may provide more accurate control data. This, and experimentation on DC and stepper drives to determine similar quantitative control data, is expected to be the next step to this research.

The database containing drive solution must however be built up and improved to reflect more properties of applications, drives and actuators as a whole. Upgrading the selection procedure to include other actuators is proposed work for future research. This would involve work similar to that done here, but with focus on another actuator technology (hydraulics and pneumatics).

The CES selector (Granta Material Intelligence, 2007) is a materials and process selection software developed by renowned authorities at Cambridge University. This software has been designed to allow creation and editing of reference data. An investigation into its use as a possible shell for actuator selection is also proposed future work.

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APPENDIX A INPUT RULES AND SEARCH MODE CONTENTS

Group box:

Used to group application requirements under the same selection criteria

Radio button:

Used to implement mutual exclusivity amongst requirement under the same selection criteria

Combo box:

Used to implement mutual exclusivity for directional requirements only

Check box:

Used to implement Yes or No conditions for the application requirements

Table A-1 Search mode 1 input rules and contents

Selection criteria	**Microsoft Visual C++ features**	**Application requirements**
Tab page 1: Power supply, speed and torque		
Power supply	Mutually exclusive	Unknown Power supply
		Three phase (AC)
		Single phase (AC)
		DC power supply
Speed	Quantitative value	
Torque	Quantitative value	
Tab page 2: Load characteristics and control type		
Application load characteristics	Mutually exclusive	Unknown load characteristics
		Constant torque, variable speed loads
		Variable torque, variable speed loads
		Constant power loads
		Constant power, constant torque loads
		High starting/breakaway torque followed by constant torque loads
Control type	Mutually exclusive	Unknown control type
		Closed loop control
		Open loop control
Tab page 3: Position control, torque control and response		
Position control requirements (Position accuracy)	Mutually exclusive	Position control – No
		$< \pm 360^{o}$
		$< \pm 5^{o}$ - 45^{o}
		$< \pm 1^{o}$
Torque control	True/False	Yes/No
Rapid response	True/False	Yes/No

Tab page 4: Speed control and drive configuration		
Speed control requirements (Speed deviation)	Mutually exclusive	Speed control - No
		0.20% - 1.8%
		0.17% - 1.5%
		0.03% - 1.0%
Drive configuration	Mutually exclusive	Indirect drive application
		Direct drive application
Tab page 5: Overshoot restrictions and directional requirements		
Overshoot restrictions	Mutually exclusive	Overshoot restrictions – No
		$< \pm 360^{o}$
		$< \pm 5^{o}$ - 45^{o}
		$< \pm 1^{o}$
Directional requirements	Mutually exclusive	Unidirectional
		Bidirectional
Tab page 6: Environmental considerations		
Quiet running requirements	True/False	Yes/No
Temperature sensitive application	True/False	Yes/No
Environmental operating conditions	Mutually exclusive	Normal conditions
		Vacuum conditions
		Corrosive/harsh environments
Tab page 7: Speed variation and starting current		
Operating speed variation	Mutually exclusive	Constant speed operation, known and maintained
		Constant but slight variations (default actuator speeds acceptable)
		Significant speed variation (may need driver)
		Constant and adjustable
Starting current requirements	Mutually exclusive	Unknown starting current requirements
		Approximately less than or equal to operating or rated full load current
		Greater than operating or rated full load current
Tab page 8: Start duty and duty cycle		
Start duty	Mutually exclusive	Unknown start duty
		Less than nominal loads with infrequent starting
		Nominal loads with infrequent starting
		Greater than nominal loads with frequent starting
Duty cycle	Mutually exclusive	Unknown operating duty
		Continuous duty requirements
		Intermittent duty requirements

Table A-2 Search mode 2 contents

Radio button No.	Mutually exclusive predefined actuation scenarios
1	Unknown actuation scenario
2	Constant - speed service where starting torque is not excessive
3	Constant – speed where fairly high starting torque is required infrequently with starting current about 550% of full load
4	Constant – speed and high starting torque, if starting is not too frequent, and for high peak loads with or without flywheels
5	Constant – speed service where starting duty is light
6	High starting torque with low starting current, where limited speed control is required
7	Constant – speed service, direct connection to slow speed machines and where power factor correction is required
8	High starting torque and fairly constant speed
9	Constant – speed service where starting is easy, and where polyphase is not available
10	Constant – speed service for any starting duty and quiet operation and where poly - phase current cannot be used
11	Constant – speed service for any starting duty, where speed control is required and polyphase current cannot be used
12	High starting torque is required and speed can be regulated
13	Constant or adjustable speed is required and starting conditions are not severe
14	Constant or adjustable speed service with positioning accuracy requirements (point to point and incremental motion control)
15	Constant or adjustable speed service with rapid start - stop response requirements (short, rapid repetitive moves) as well as positioning accuracy is required
16	Bidirectional and adjustable speed service operation with fairly high starting torques
17	Constant/adjustable speed service in Harsh/Temperature sensitive operating conditions requiring light weight and or positioning accuracy

APPENDIX B GLOSSARY OF MOTOR TERMS

The following is a glossary of terms, most of which were sourced from Rockwell Automation (2007).

A

AC MOTOR
A motor operating on AC current that flows in either direction. There are two general types: induction and synchronous.

ADJUSTABLE SPEED
Adjustable speed property of a motor is the ability of motor speed to be manipulated by the user when necessary

B

BASE SPEED, RPM
The speed in revolutions per minute (RPM) which a DC motor develops at rated armature and field voltage with rated load applied.

BREAK AWAY TORQUE
The torque required to start a machine in motion. Almost always greater than the running torque.

BREAKDOWN or MAXIMUM TORQUE (developed during acceleration)
The maximum torque a motor will develop at rated voltage without a relatively abrupt drop or loss in speed.

C

CE: This designation shows that a product such as a motor or control meets European Standards for safety and environmental protection. A CE mark is required for products used in most European countries.

CANADIAN STANDARDS ASSOCIATION (CSA)
Canadian Standards Association like U.L., sets specific standards for products used in Canada.

CAPACITOR MOTOR
A single-phase induction motor with a main winding arranged for direct connection to the power source, and an auxiliary winding connected in series with a capacitor. There are three types of capacitor motors: capacitor start, in which the capacitor phase is in the circuit only during starting; permanent-split capacitor, which has the same capacitor and capacitor phase in the circuit for both starting and running; two-value capacitor motor, in which there are different values of capacitance for starting and running.

CLOSED LOOP
A broadly applied term, relating to any system in which the output is measured and compared to the input. The output is then adjusted to reach the desired condition. In

motion control, the term typically describes a system utilizing a velocity and/or position transducer to generate correction signals in relation to desired parameters.

COMPOUND WOUND DC MOTORS
Designed with both a series and shunt field winding, the compound motor is used where the primary load requirement is heavy starting torque and variable speed is not required. Also used for parallel operation. The load must tolerate a speed variation from full load to no-load.

CONSTANT TORQUE
Refers to loads with horsepower requirements that change linearly at different speeds. Horsepower varies with the speed, i.e., 2/1 HP at 1800/900 RPM (seen on some two-speed motors). Applications include conveyors, some crushers and constant-displacement pumps.

CONSTANT SPEED
A DC motor which changes speed only slightly from a no-load to a full-load condition. For AC motors, these are synchronous motors.

CONTROLLER
A device or group of devices, that governs in a predetermined manner the electric power delivered to the apparatus to which it is connected

CONVERTER/FREQUENCY CONVERTER
Frequency changer or frequency converter refers to an electronic device that converts alternating current (AC) of one frequency to alternating current of another frequency. The device may also change the voltage, but if it does, that is incidental to its principal purpose.

CURRENT, RATED
The maximum allowable continuous current a motor can handle without exceeding motor temperature limits.

D

DC MOTOR
A motor using either generated or rectified DC power. A DC motor is often used when variable-speed operation is required.

DESIGN A, B, C, D - FOR AC MOTORS
NEMA has standard motor designs with various torque characteristics to meet specific requirements posed by different application loads. The design "B" is the most common design

Table B-1 NEMA motor design characteristics

NEMA DESIGN	STARTING TORQUE	STARTING CURRENT	BREAKDOWN TORQUE	FULL LOAD SLIP	TYPICAL APPLICATIONS
A	Normal	High	High	Low	Machine Tools, Fans
B	Normal	Normal	Normal	Normal	Same as Design "A"
C	High	Normal	Low	Normal	Loaded compressor Loaded conveyor
D	Very High	Low		High	Punch Press

DRIVE
An actuator subsystem consisting of a motor and driver, it may also include other accessories such as tachometers and encoders.

DRIVER
An electronic device that controls torque, speed and/or position of an electric motor. Typically a feedback device is mounted on the motor for closed-loop control of current, velocity and position. It can however also be used for open-loop control.

DUTY CYCLE
The relationship between the operating and rest times or repeatable operation at different loads. A motor which can continue to operate within the temperature limits of its insulation system after it has reached normal operating (equilibrium) temperature is considered to have a continuous duty (CONT.) rating. A motor which never reaches equilibrium temperature but is permitted to cool down between operations, is operating under intermittent (INT) duty. Conditions such as a crane and hoist motor are often rated 15 or 30 minute intermittent duty. Repetitive cycles refer to loads for various intervals of time which are well defined and repeating and are given by the ratio of on-time to total cycle time.

$$\text{Duty cycle (\%)} = \left[\frac{On\,time}{On\,time + Off\ time}\right] \times 100\,\%$$

Duty cycles are, however, different. Where NEMA commonly designates either continuous, intermittent, or special duty (typically expressed in minutes), IEC uses eight duty cycle designations.

S1 - Continuous duty: The motor works at a constant load for enough time to reach temperature equilibrium.

S2 - Short-time duty: The motor works at a constant load, but not long enough to reach temperature equilibrium, and the rest periods are long enough for the motor to reach ambient temperature.

S3 - Intermittent periodic duty: Sequential, identical run and rest cycles with constant load. Temperature equilibrium is never reached. Starting current has little effect on temperature rise.
S4 - Intermittent periodic duty with starting: Sequential, identical start, run and rest cycles with constant load. Temperature equilibrium is not reached, but starting current affects temperature rise.
S5 - Intermittent periodic duty with electric braking: Sequential, identical cycles of starting, running at constant load and running with no load. No rest periods.
S6 - Continuous operation with intermittent load: Sequential, identical cycles of running with constant load and running with no load. No rest periods.
S7 - Continuous operation with electric braking: Sequential identical cycles of starting, running at constant load and electric braking. No rest periods.
S8 - Continuous operation with periodic changes in load and speed: Sequential, identical duty cycles run at constant load and given speed, and then run at other constant loads and speeds. No rest periods.

E

ELECTRONIC CONTROL
Term applied to definite electronic, static, precision, and associated electronic control equipment.

ENCLOSURE
The housing or frame of the motor.

ODG	Open Drip-Prof, Guarded
ODG-FV	Open Drip-Proof, Force Ventilated
ODG-SV	Open Drip-Proof, Separately Ventilated
ODP	Open Drip-Proof
HP	Vertical P-Base, Normal Thrust
LP	Vertical P-Base, Medium Thrust, Extended Thrust
Prot.	Protected
TEAO	Totally-Enclosed, Air-Over
TEBC	Totally-Enclosed, Blower-Cooled
TECACA	Totally-Enclosed, Closed Circuit, Air to Air
TEDC-A/A	Totally-Enclosed, Dual Cooled, Air to Air
TEDC-Q/W	Totally-Enclosed, Dual Cooled, Air to Water
TEFC	Totally-Enclosed, Fan-Cooled
TENV	Totally-Enclosed, Non-Ventilated
TETC	Totally-Enclosed, Tube Cooled
TEWAC	Totally-Enclosed, Water/Air Cooled
TEXP	Totally-Enclosed, Explosion-Proof

IP-22	Open Drip-Proof (IEC Standard)
IP-44	Totally-Enclosed (IEC Standard)
IP-54	Splash Proof (IEC Standard)
IP-55	Washdown (IEC Standard)
WPI	Weather Protected, Type I
WPII	Weather Protected, Type II
XE	Premium Efficient
XL	Extra Life
XP	Explosion-Proof
XT	Extra Tough

ENCODER
A device that converts a linear or rotary displacement into digital representation

F

FEEDBACK
A signal which is transferred from the output back to the input for use in a closed loop system.

FULL-LOAD TORQUE
That torque of a motor necessary to produce its rated horsepower at full-load speed, sometimes referred to as running torque.

FULL-LOAD/RATED MOTOR SPEED
The speed of the motor at full-load torque or the motor speed at which rated horse power is developed.

H

HYBRID STEP MOTOR
A motor designed to move in discrete increments of steps. The motor has a permanent magnet rotor and a wound stator. Such motors are brushless. Phase currents are commutated as a function of time to produce motion

I

IEEE Standards (AIEE)
Is an organization concerned with fundamentals such as basic standards for temperature rise, rating methods, classification of insulating materials and test codes.

INDUCTION MOTOR
An induction motor is an alternating current motor in which the primary winding on one member (usually the stator) is connected to the power source and a secondary winding or a squirrel-cage secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding, its current is induced.

INERTIAL LOAD
A load (flywheel, fan, etc.) which tends to cause the motor shaft to continue to rotate after the power has been removed (stored kinetic energy). If this continued rotation cannot be tolerated, some mechanical or electrical braking means must be applied. This application may require a special motor due to the energy required to accelerate the inertia.

INERTIA MATCH
For most efficient operation, the system coupling ratio should be selected so that the reflected inertia of the load is equal to the rotor inertia of the motor.

INTERMITTENT DUTY
A requirement of service that demands operation for alternate intervals of (1) load and no load; or (2) load and rest; (3) load, no load and rest; such alternative intervals being definitely specified.

INVERTER
An electronic device that converts fixed frequency and fixed voltages to variable frequency and voltage. It enables the user to electrically adjust the speed of an AC motor.

J

JOGGING/INCHING
The intermittent operation of a motor at low speeds. Speed may be limited by armature series resistance or reduced armature voltage.

L

LIMIT SWITCH
A device that translates a mechanical position or physical position into an electric control signal.

LOAD
The burden imposed on a motor by the driven machine. It is often stated as the torque required to overcome the resistance of the machine it drives. Sometimes "load" is synonymous with "required power"

M

MOTOR CONTROL CIRCUIT
The circuit that carries the electric signal directing controller performance but does not carry the main power current. Control circuits tapped from the load side of motor branch circuits’ short-circuit protective devices are not considered to be branch circuits and are permitted to be protected by either supplementary or branch-circuit overcurrent protective devices.

MULTI-SPEED MOTORS
A motor wound in such a way that varying connections at the starter can change the speed to a predetermined speed. The most common multi-speed motor is a two-speed although three- and four-speeds are sometimes available. Multi-speed motors can be

wound with two sets of windings or one winding. They are also available with constant torque, variable torque or constant horsepower.

N

NAMEPLATE

The plate on the outside of the motor describing the motor horsepower, voltage, speed efficiency, design, enclosure, etc.

N.E.C. TEMPERATURE CODE ("T" CODE)

A National Electrical Code index for describing maximum allowable "skin" (surface) temperature of a motor under any normal or abnormal operating conditions. The "T" codes are applicable to U.L. listed explosion-proof motors. The skin temperature shall not exceed the minimum ignition temperature of the substances to be found in the hazardous location. The "T" code designations apply to motors and other types of electrical equipment subject to hazardous location classification.

NEMA

The National Electrical Manufacturers Association is a non- profit organization organized and supported by manufacturers of electric equipment and supplies. NEMA has set standards for:

- Horsepower ratings
- Speeds
- Frame sizes and dimensions
- Standard voltages and frequencies with allowable variations
- Service factors
- Torque
- Starting current & KVA
- Enclosures

NO-LOAD SPEED

Motor speed when allowed to run freely with no load coupled.

NOISE

Any unwanted disturbance within a dynamic electrical or mechanical system. This can include electrical, electromagnetic, or acoustical energy.

NONREVERSING

A control function that provides for motor operation in one direction only.

O

OPEN-LOOP

A system in which there is no feedback. Motor motion is expected to faithfully follow the input command. Stepping motor systems are an example of open-loop control.

P

PEAK TORQUE (Tpk) (lb-in.)

The maximum torque a brushless motor can deliver for short periods of time. Operating Peak Torque motors above the maximum torque value can cause demagnetization of the rare-earth magnets. This is an irreversible effect that will alter the motor characteristics and degrade performance. This is also known as peak current.

Not to be confused with system peak torque, which is often determined by amplifier peak current limitations, where peak current is typically two times continuous current.

POLYPHASE MOTOR

Two- or three-phase induction motors have their windings, one for each phase, evenly divided by the same number of electrical degrees. Reversal of the two-phase motor is accomplished by reversing the current through either winding. Reversal of a three-phase motor is accomplished by interchanging any two of its connections to the line. Polyphase motors are used where a polyphase (three-phase) power supply is available and is limited primarily to industrial applications.

POWER FACTOR

A measurement of the time phase difference between the voltage and current in an AC circuit. It is represented by the cosine of the angle of this phase difference. For an angle of 0 degrees, the power factor is 100% and the volt/amperes of the circuit are equal to the watts (this is the ideal and an unrealistic situation). Power factor is the ratio of Real Power-KW to total KVA or the ratio of active power (watts) to apparent power (volt amperes). It can also be defined as

$$\text{Power factor} = \frac{\sum watts\ per\ phase}{\sum RMS\, volt - amperes\ per\ phase} = \frac{Real\ power}{Apparent\ power}$$

PROGRAMMED CONTROL

A control system in which operations are directed by a predetermined input program consisting of cards, tapes, plug boards, cams etc.

PULL-IN TORQUE

The maximum constant torque, which a synchronous motor will accelerate into synchronism at, rated voltage and frequency (there is no corresponding term for induction motors).

PULL-OUT TORQUE

Is the maximum torque which the motor will develop at synchronous speed.

PULL-OVER TORQUE (Stepper motors)

Refers to the amount of torque the motor can exert from one position to the next

PULL-UP TORQUE (minimum accelerating torque)

The minimum torque developed by a motor while it is accelerating from rest to the speed at which breakdown occurs. For motors, which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed during the process of achieving rated speed.

R

RATED (CONTINUOUS) TORQUE
The maximum torque, at rated speed, the motor can produce on a continuous basis, without exceeding the thermal rating of the motor.

RATED SPEED
The approximate motor speed at its rated torque point.

RATED POWER
The maximum output power the motor can produce without exceeding its thermal rating. (output power is a function of speed and torque)

REGENERATIVE BREAKING
In ac motors, it results from the motors inherent tendency (through a negative slip) to resist being driven above synchronous speed by an overhauling load. In shunt-wound dc motors, it occurs when driven by an overhauling load, when shunt field strength is increased, or when armature voltage is decreased (in adjustable voltage drives).

REVERSING
Changing the operation of a drive from one direction to another.

REGENERATIVE DRIVE
Regenerative drives, often used interchangeably with four quadrant drives, and applies to the regeneration of energy from the motor and drive, back to the power source. A motor generates when the load forces the motor to go faster than the drive has set. Four quadrant drives can prevent motors from over speeding. A four quadrant drive is regenerative when it puts the generated energy back into the source, like a battery or the AC line. Also, the energy could be dumped across a dynamic brake resistor or a dump resistor, as is the case in a non-regenerative, four quadrant drive.

RELUCTANCE SYNCHRONOUS MOTOR
A synchronous motor with a special rotor design which directly lines the rotor up with the rotating magnetic field of the stator, allowing for no slip under load. Reluctance motors have lower efficiencies, power factors and torques than their permanent magnet counterparts.

RESOLVER
An electromagnetic feedback device which converts angular shaft position into analogue signals. These signals can be processed in various ways, such as with an RDC (resolver-to-digital converter) to produce digital position information. There are two basic types of resolvers; transmitter and receiver. A transmitter-type is designed for rotor primary excitation and stator secondary outputs. Position is determined by the ratio of the sine output amplitude to cosine output amplitude. A receiver-type is designed for stator primary excitations and rotor secondary output. Position is determined by the phase shift between the rotor output signal and one of the primary excitation signals.

RESOLUTION
Resolution refers to the smallest change in the measured variable that can be detected by a sensor.

REPEATABILITY
Repeatability refers to the ability of a measurement system to indicate the same value upon repeated but independent application of the same input.

REVERSING
Unless otherwise specified, a general-purpose DC motor is reversible. A DC motor can be reversed by changing the polarity of the field or the armature, but not both. When rapid reversing is necessary, the armature circuit is reversed. In some cases, it is advantageous to reverse the field connections of shunt motors, since the controls have to handle much less current, especially on large motors, than do armature-circuit contactors. An AC motor is reversed by reversing the connections of one leg on three-phase power or by reversing the leads on single phase.

ROTOR
The rotating member of an induction motor made up of stacked laminations. A shaft running through the centre and a squirrel cage made in most cases of aluminium, which holds the laminations together, and act as a conductor for the induced magnetic field. The squirrel cage is made by casting molten aluminium into the slots cut into each lamination.

S

SERVO
A Servo is a small device that has an output shaft. This shaft can be positioned to specific angular positions by sending the servo a coded signal. As long as the coded signal exists on the input line, the servo will maintain the angular position of the shaft. As the coded signal changes, the angular position of the shaft changes. In practice, servos are used in radio controlled airplanes to position control surfaces like the elevators and rudders. They are also used in radio controlled cars, puppets & of course robots. Servo is a system consisting of an amplifier, actuator & feedback elements. Servos tend to control one or combination of the following variables: position, velocity and Torque.

SHAFT
The rotating member of the motor which protrudes past the bearings for attachment to the driven apparatus.

SLIP
The difference between the speed of the rotating magnetic field (which is always synchronous) and the rotor in a non- synchronous induction motor is known as slip. It is expressed as a percentage of synchronous speed. Slip generally increases with an increase in torque.

$$s = \frac{n_s - n}{n_s}$$

where, s = slip
n_s = synchronous speed [r/min]

n = rotor speed [r/min]

SOFT START & STOP

When starting, an AC Induction motor develops more torque than is required at full speed. This stress is transferred to the mechanical transmission system resulting in excessive wear and premature failure of chains, belts, gears, mechanical seals, etc. Additionally, rapid acceleration also has a massive impact on electricity supply charges with high inrush currents drawing +600% of the normal run current. The use of Star Delta provides a partial solution to the problem.

SPLASH-PROOF MOTOR

An open motor in which the ventilating openings are so constructed that drops of liquid or solid particles falling on it, or coming toward it in a straight line at any angle not greater than 100 degrees from the vertical, cannot enter either directly or by striking and running along a surface of the motor.

SPEED

The speed of the motor refers to the RPM (revolutions per minute) of the shaft.

SQUIRREL CAGE (ROTOR)

They are composed of bare copper bars, slightly longer than the rotor, which are pushed into the slots. The opposite ends are welded to two copper end-rings, so that all the bars are short-circuited together.

STANDARDS ORGANIZATIONS

ANSI	American National Standards Institute
API	American Petroleum Institute
BASEEFA	British Approval Service for Electrical Equipment in Flammable Atmospheres
CE	Compliance to European Standards
CSA	Canadian Standards Association
EPACT	1997 U.S. Energy Policy Act
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association
UL	Underwriters Laboratories
UR	Underwriters Laboratories Recognized

STARTER

A starter is an electric controller for accelerating the motor from rest to normal speed. Note: a device designed for starting a motor in either direction includes the additional function of reversing and should be designated a reversing controller.

STATIC TORQUE

The maximum torque available at zero speed.

STATOR

That part of an AC induction motor's magnetic structure which does not rotate. It usually contains the primary winding. The stator is made up of laminations with a large hole in the centre in which the rotor can turn; there are slots in the stator in which the windings for the coils are inserted.

STIFFNESS

The ability to resist movement induced by an applied torque. Stiffness is often specified as a torque displacement curve, indicating the amount a motor shaft will rotate upon application of a known external force when stopped.

SYNCHRONOUS MOTOR

A motor which operates at a constant speed up to full load. The rotor speed is equal to the speed of the rotating magnetic field of the stator - there is no slip. There are two major synchronous motor types: reluctance and permanent magnet. A synchronous motor is often used where the exact speed of a motor must be maintained.

SYNCHRONOUS SPEED

The speed of the rotating magnetic field set up by the stator winding of an induction motor. In a synchronous motor, the rotor locks into step with the rotating magnetic field and the motor is said to run at synchronous speed. Approximately the speed of the motor with no load on it.

$$\text{Synchronous speed } (n_s) = \frac{frequency \times 120}{number\, of\ poles}$$

T

TACHOMETER

A small generator normally used as a rotational speed sensing device. Tachometers are typically attached to the output shaft of DC or AC variable-speed motors requiring close speed regulation. The tachometer feeds its signal to a control which adjusts its output to the DC or AC motor accordingly (called "closed loop feedback" control).

THREE PHASE POWER & SINGLE PHASE POWER

3 phase power is typically 150% more efficient than single phase in the same power range. In a single phase unit the power falls to zero three times during each cycle, in 3 phase it never drops to zero. The power delivered to the load is the same at any instant.

U

UNIDIRECTIONAL
Rotates in one direction only and stops every 90 degrees until signalled to move again.

U.L. (UNDERWRITER'S LABORATORY)
An independent testing organization, which examines and tests devices, systems and materials with particular reference to life, fire and casualty hazards. It develops standards for motors and controls used in hazardous locations through cooperation with manufacturers. U.L. has standards and tests for explosion- proof and dust ignition-proof motors, which must be met and passed before application of the U.L. label.

V

VARIABLE FREQUENCY/VOLTAGE ELECTRONIC DRIVES
Drives for motors through which frequency and voltage may be changed, allowing an independent change of speed and torque

VARIABLE TORQUE
A multi-speed motor used on loads with torque requirements, which vary with speed as with some centrifugal pumps and blowers. The horsepower varies as the square of the speed.

VARIABLE SPEED
Variable speed is an inherent property of a motor characterized by speed fluctuation about the mean synchronous speed and is dependent on loading conditions. For applications where constant speed is absolutely necessary an asynchronous motor without an inverter will be a wrong choice because of its variable speed property. A more appropriate choice would be a synchronous motor, servo motor or even an asynchronous motor with an inverter for speed control.

VECTOR CONTROL
Vector or field orientated control in AC motors involves adjusting the magnitude and phase alignment of the vector quantities of the motor. It is used to produce high performance servomechanisms by predicting the location of internal flux and then injecting current to interact optimally with that flux.

W

WOUND ROTOR INDUCTION MOTOR
A wound rotor induction motor is an induction motor in which the secondary circuit consists of polyphase winding or coils with terminals that are either short circuited or closed through suitable circuits. A wound rotor motor is sometimes used when high breakdown torque and soft start or variable-speed operation are required.

WORLD Standards
Standards similar to our NEMA Standards have been established in other countries.
The most significant are
a. IEC (International Electrochemical Commission) Standard 72–1, Part 1
b. German Standard DIN 42673
c. British Standard BSI-2960, Part 2

APPENDIX C EQUIPMENT SPECIFICATIONS

C.1 *Hardware specifications*

1. Encoder specifications (SEW Eurodrive):

   Incremental encoder (OG 71) – Optoelectronic precision speed measurement device

   Temperature class: T4

   Group of equipment: II

   IP 66

   Resolution: 1024

2. Inverter specifications (SEW Eurodrive):

   2.1 Movidrive Inverter MDX61B0008 – 5A3 – 4 – 00

   kW: 0.75

   3 phase 380V

   Multifunctional programmable drive

   2.2 Movitrac B MC07B0005 – 2B1 – 4 – 00 (SEW): IP 20

3. Inverters specifications (Bosch Rexroth): Ecodrive03 (FGP 01VRS)

4. AC Induction motor specifications (SEW Eurodrive): Nameplate details

Type: DT90S4/ES1T			I-KI: F
V: 230/400	Con: Δ/Y	Cos: 0.81	Hz: 50
A: 2.80	M/Pos: B3	T/Box: 0	IP 55
kW: 1.1	R/min: 1400		m: 16 kg

5. Servomotor specifications (Bosch Rexroth): Nameplate details

Type: MKD041B – 144 – KG1 – KN		
S/N: MKD041 – OV574		m: 4.4 kg
Natural convection		
MdN: 2.7 Nm		I.CI: F
IdN: 7.5 A	IP 65	nMax: 7500 min^{-1}
KE (eff): 36.3	V/1000 min^{-1}	Km: 0.40 Nm/A
Brake: 2.2 Nm	DC: 24 V ± 10%	0.34 A
Motor encoder resolution: 32768		

Other equipment used includes a ball screw, linear bearing shafts, micro switches, position sensors and coupling. Their specifications are given below.

6. SKF precision shafts: SKF LRC 25
   SKF ball screw: SKF BSFB 25 FBUF 25

7. HRC spider coupling
   Size 70
   Angular misalignment capacity of up to 1o
   Standard element -40^{o}C / +100^{o}C

8. ASM Linear displacement transducer:
   2000 mm/10 V Range

9. HBM PC measurement electronics
   Spider8 (Catman Easy DAQ software)
   4.8 kHz carrier frequency technology
   12 bit resolution

10. Rhomberg Brasler Proximity sensor:
    R14-9020F NO-PBC
    Detechtor intelligent can line sensor

11. RS components Micro switches:
    D45X 125-250 VAC

12. Aluminium toothed pulleys
    Type T5
    Number of teeth: 48
    Pitch diameter: 76.42 mm

13. Polymer ribbed with steel wires toothed belt
    Pitch: 5 mm
    Width: 25 mm

C.2 *Software specifications*

MOVITOOLS - MOTIONSTUDIO 5.30 (5.3.0.6) SEW-EURODRIVE GmbH & CoKG:

> This SEW software was used in conjunction with Type 1 Movitrac inverter for open loop control of the AC induction motor without an encoder. It provides a means to parameterize and the motor, as well as an oscilloscope function (SCOPE) to diagnose faults and to monitor drive properties. For the experiments it also served in data acquisition for speed control.

MT Manager MOVITOOLS SEW-EURODRIVE GmbH & CoKG, Version 4.40:

> This SEW software was used in conjunction with Type 2 Movidrive inverter for closed loop control of the AC induction motor and encoder. Functions of interest within this software are: SHELL for parameterization and start up of the motor, and SCOPE for drive diagnosis and monitoring. This software also served in obtaining speed control data.

DriveTop INDRAMAT Bosch Rexroth AG 2004, Version SWD-DTOP^{xx} - INB - 16V09 - MS:

> This Bosch Rexroth software was used in conjunction with Type 3 Ecodrive inverter for closed loop control of the servomotor. It provides a means to parameterize and start up the motor, as well as an oscilloscope function to monitor (speed control data acquisition) and diagnose the drive.

HBM Catman Easy Version 2.0:

> The HBM Spider8 PC measurement electronics with this software were used in conjunction with the linear displacement transducer (LDT) for independent displacement data acquisition. It was used in calibrate the LDT for measurement using data acquisition (DAQ) projects. The conversion resolution of the Spider8 PC measurement electronics is 4096 (2^{12}) and the range of the LDT is 2000 mm/10 V.