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An Electromechanical Actuation System for an Expendable Launch Vehicle

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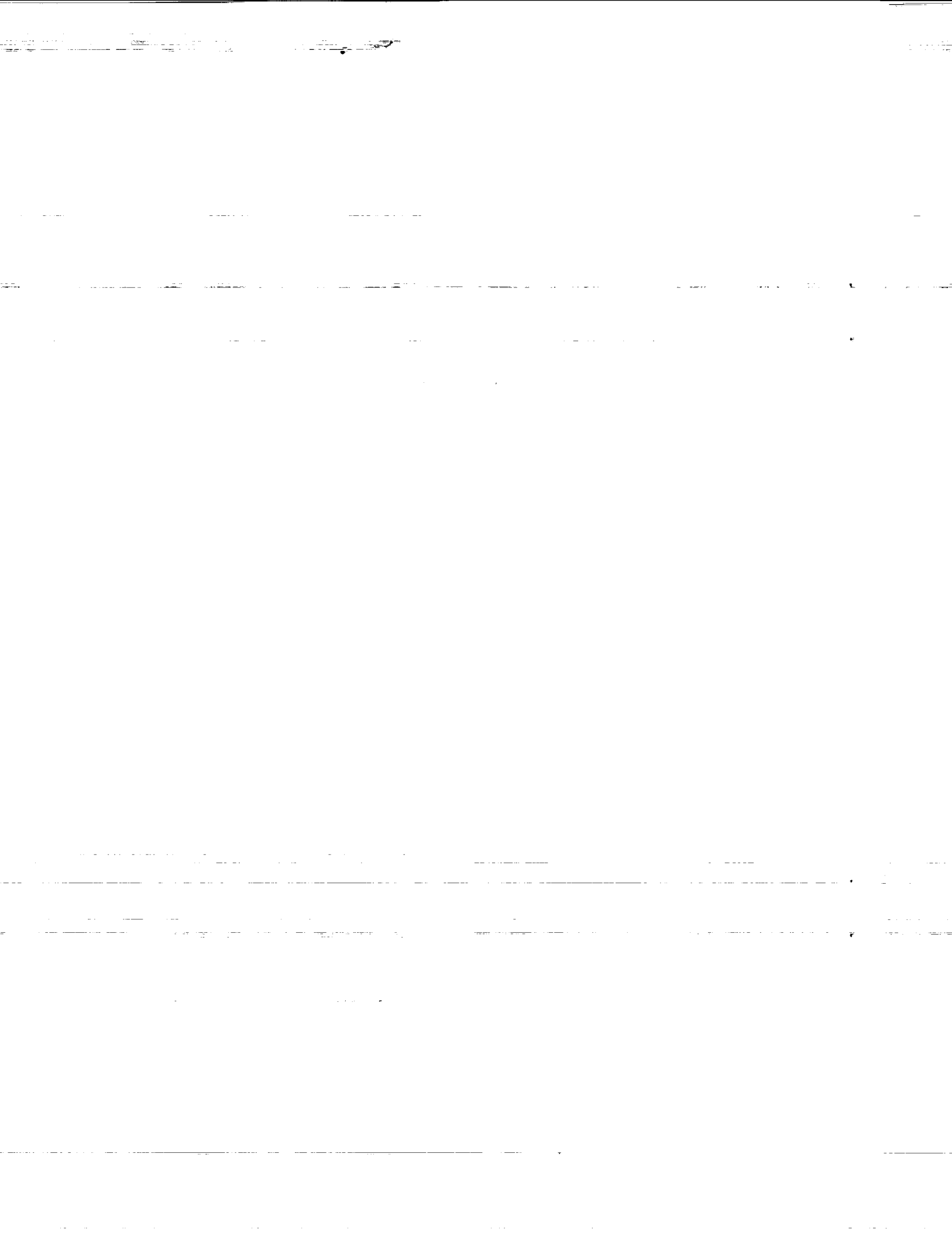


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An Electromechanical Actuation System for an Expendable Launch Vehicle

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Abstract

A major effort at the NASA Lewis Research Center in recent years has been to develop electro-mechanical actuators (EMA's) to replace the hydraulic systems used for thrust vector control (TVC) on launch vehicles. This is an attempt to overcome the inherent inefficiencies and costs associated with the existing hydraulic structures. General Dynamics Space Systems Division, under contract to NASA Lewis, is developing 18.6 kW (25 hp), 29.8 kW (40 hp), and 52.2 kW (70 hp) peak EMA systems to meet the power demands for TVC on a family of vehicles developed for the National Launch System. These systems utilize a pulse population modulated converter and field-oriented control scheme to obtain independent control of both the voltage and frequency. These techniques allow an induction motor to be operated at its maximum torque at all times. At NASA Lewis, we are building on this technology to develop our own in-house system capable of meeting the peak power requirements for an expendable launch vehicle (ELV) such as the Atlas. Our EMA will be capable of delivering 22.4 kW (30 hp) peak power with a nominal of 6.0 kW (8 hp). This system differs from the previous ones in two areas: 1) the use of advanced control methods, and 2) the incorporation of built-in-test. The advanced controls are essential for minimizing the controller size, while the built-in-test is necessary to enhance the system reliability and vehicle health monitoring.

The ultimate goal of this program is to demonstrate an EMA which will be capable of self-test and easy integration into other projects. This paper will describe the effort underway at NASA Lewis to develop an EMA for an Atlas class ELV. An explanation will be given for each major technology block, and the status of the overall program will be reported.

Introduction

Most launch vehicles currently utilize hydraulics for their thrust vector control (TVC) actuation systems. Due to operational problems associated with the hydraulics, an improved means of control is essential. The Space Shuttle Solid Rocket Booster, for example, requires over 5,000 man hours per flight for hydraulic TVC processing. A Kennedy Space Center study showed that by replacing the hydraulics with an all-electric configuration, a savings of approximately 2/3 of these man hours could be realized [1]. NASA Lewis is investigating the application of electromechanical actuators (EMA's) to eliminate these hydraulic systems.

There have been a number of technologies developed for NASA Lewis by General Dynamics Space Systems Division (GDSS) and the University of Wisconsin in the areas of resonant converters and field oriented controllers [2,3]. While GDSS has begun work on a 52.2 kW (70 hp) peak power EMA system to meet the TVC requirements for the National Launch System (NLS), NASA Lewis has begun a corresponding effort to produce a 22.4 kW (30 hp) peak power system to satisfy the TVC requirements of an expendable launch vehicle (ELV). The main objective of the NASA program is to demonstrate technology readiness to meet the ELV hydraulic TVC requirements with a more reliable electrical scheme. The Atlas has been chosen as the target vehicle, since this is a cooperative effort and GDSS would like EMA's incorporated into their 1995 Atlas line.

NASA is working closely with GDSS to develop these two systems independently, but with common components. Advanced control techniques will be used in both, with the NASA ELV system differing by the incorporation of built-in-test. The main goal of the NASA Lewis program is to develop and

demonstrate, by means of the Atlas ELV project, in-house expertise in the area of EMA systems for launch vehicles. These abilities will then allow us to effectively participate in technology advancements for both government and industry. This paper will describe the NASA Lewis Atlas EMA program and the progress to date.

Background

REQUIREMENTS - This project began with the definition of the Atlas TVC requirements. These specifications were generated at GDSS for both the Atlas sustainer and booster and then reviewed for acceptance by NASA Lewis. Some results of the simulation are shown in Table 1. We have designed our system to meet the booster requirements with a 150% capability so that it can accommodate up to 22.4 kW (30 hp) peak loads.

Table 1-Atlas ELV Requirements

	VELOCITY	POWER
SUSTAINER	4.7 cm/s	5.5 kW
BOOSTER	22.0 cm/s	13.9 kW

PRESENT TECHNOLOGIES - The existing technologies implemented in this EMA system are an AC resonant power converter, 20 khz link, pulse population modulated (PPM) converter, field oriented controller and an induction motor. A basic block diagram of the system is shown in Figure 1. The resonant power converter, developed for the Space Station [4], utilizes zero current switching to minimize the stress and power loss in the switching devices. The converter produces a single phase high frequency sine wave, in this case 20 khz, although higher frequencies may be used. The converter may be powered by either a DC or low frequency AC source.

The PPM motor driver selects individual pulses of the link voltage to produce a variable voltage, variable frequency waveform to drive the induction motor. The population of the pulses determines the amplitude of the voltage, while the pulse pattern determines the frequency. Figure 2 shows a typical PPM waveform. The 20 khz link allows all the power conversion to be done at this high frequency instead of the machine frequency, thereby reducing the size and mass of the electronic controls. Both the AC resonant converter and the PPM motor driver are inherently

bi-directional, which is important since an actuation system such as this one will return energy (the motor will generate) to the power source during a typical flight. The system must be able to accept this returned energy.

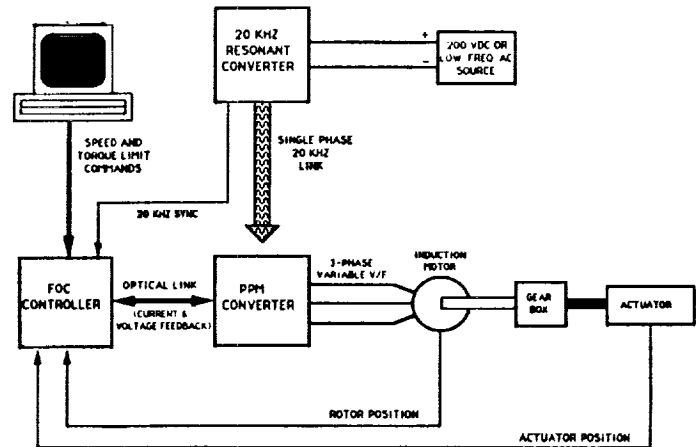


Figure 1-System block diagram

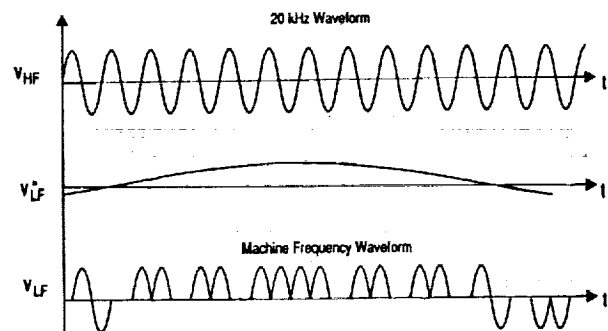


Figure 2-PPM Waveforms

Control of the induction motor is accomplished through a technique called field oriented control (FOC). FOC permits servo control of an induction motor in much the same manner as a DC motor. The stator current is broken down into two orthogonal components, I_{qb} , the torque producing component and I_{db} , the flux producing component. These two currents are controlled by managing the applied voltage and frequency to the motor through the PPM technique described above. By controlling these two currents (i.e. controlling the slip), the machine can be operated at any point on the torque speed curve, including full torque at zero speed, with minimum loss. This allows maximum utilization of the electronics within their current limits, as shown in Figure 3. A more detailed FOC description will follow.

The induction motor was selected due to its rugged construction and high temperature operation. More importantly, it has high torque to inertia and high torque to current ratios. It is necessary to get the most out of the motor for a

given current since the limits of the actuation system are directly related to the current and voltage limits of the electronics. Another advantage of the induction motor is its benign failure mechanism due to the absence of a permanent magnetic field. An advanced induction motor is being developed to incorporate a high power capability with a low inertia rotor for rapid motor response.

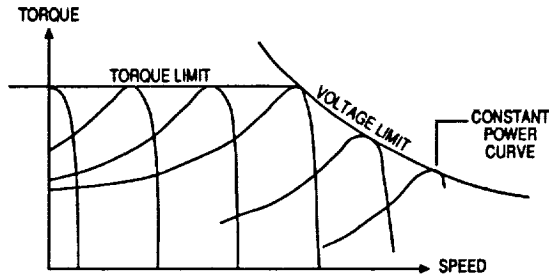


Figure 3-Electronic Limitations

Advanced System Concepts

The ELV EMA system employs a Space Station developed 20 khz converter as the source. The majority of the program effort, however, centers on the motor control and power stages.

POWER STAGE - The power stage is based on a design by GDSS modified for our specific application. It is housed in an aluminum chassis with dimensions of 50.8 cm x 38.1 cm. Insulated gate, bipolar transistors (IGBT's) are used as the switching devices. They are rated for 1200 v and 50 amp continuous (100 peak) operation. An advanced field oriented control provides the required switching decisions every 25 us. A diagram of the ELV power stage is shown in Figure 4.

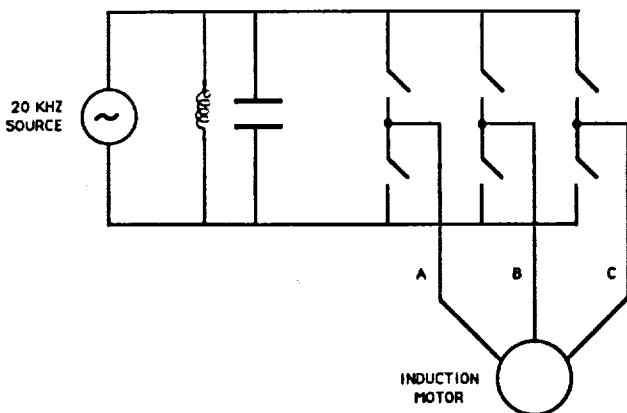


Figure 4-Power Stage Diagram

Several concerns dealing with the power stage have become evident as a result of previous power stage testing at GDSS. The incorporation of IGBT modules is necessary for shorter inductance paths

which are critical for minimizing parasitics associated with high frequency operation. It is also necessary to design the power stage to allow for easier access to the components in order to reduce trouble-shooting time. At NASA Lewis, we are taking steps to incorporate these advantages by using a simple layout which utilizes IGBT modules. These modules will be connected via a power plane to reduce stray inductances in the system. The communication between the power and control stages will be through a fiber optic link to reduce noise into the system.

CONTROL STAGE - The block diagram for the system controller, based on a field-oriented control (FOC) design, is shown in Figure 5. The main feedbacks in the system are the actuator and rotor position. The actuator position command and feedback are summed to produce a position error signal. This signal, along with the rotor velocity and I_{ds} command produces the I_{qs} command. The I_{ds} and I_{qs} commands are then processed by the FOC block and the Slip Gain Calculator to produce the three phase current reference waveforms.

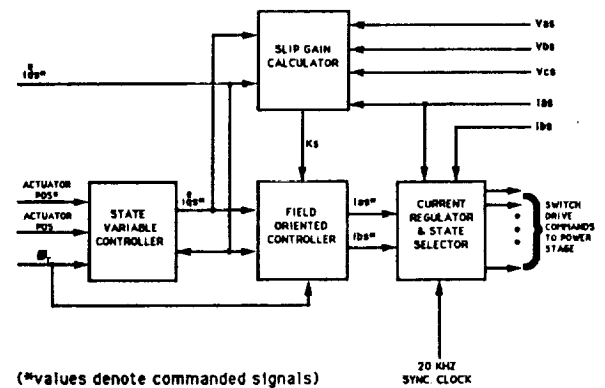


Figure 5-System controller block diagram

Measuring the slip angle accurately is fundamental for correct control of the motor. The slip speed calculation is shown in Equation 1.

$$(1) \omega_s = (R_r L_m I_{qs}^e) / (L_r \epsilon_{dr})$$

One of the parameters the slip angle depends on is the rotor resistance, R_r . Since R_r varies with temperature, this parameter error can produce an incorrect value of rotor flux, which in turn produces an incorrect slip angle. An adaptive controller developed at the University of Wisconsin allows for parameter correction in the slip gain calculator [6]. Using the air gap flux and rotor speed, which may be obtained from the third harmonic voltage, a correction to the rotor flux is made. The corrected slip angle is then fed to the FOC block.

The FOC section of the code executes the two

phase to three phase transformation, shown in equations 2-4, to produce the current reference waveforms.

$$(2) I_a^* = I_{qs}^* \cos \phi + I_{ds}^* \sin \phi$$

$$(3) I_b^* = [-1/2 I_{qs}^* - 3/2 I_{ds}^*] \cos \phi + [3/2 I_{qs}^* - 1/2 I_{ds}^*] \sin \phi$$

$$(4) I_c^* = -I_a^* - I_b^*$$

These references are compared with the actual current feedbacks to produce error signals which are fed to the state selector. By using these errors, the state selector picks the allowable states for the switching, as shown in Figure 6. Only adjacent states or a zero state are permitted as the next switching state. If the motor current vector is within a certain hysteresis band around the commanded current, a zero state (0,0,0 or 1,1,1) is selected. Likewise, if the current vector is not adjacent to the present vector state, the zero vector is again selected. The state selector algorithms will reside on a Programmable Logic Device (PLD). All other control software will be written in 'C' and will reside on a Digital Signal Processor (DSP).

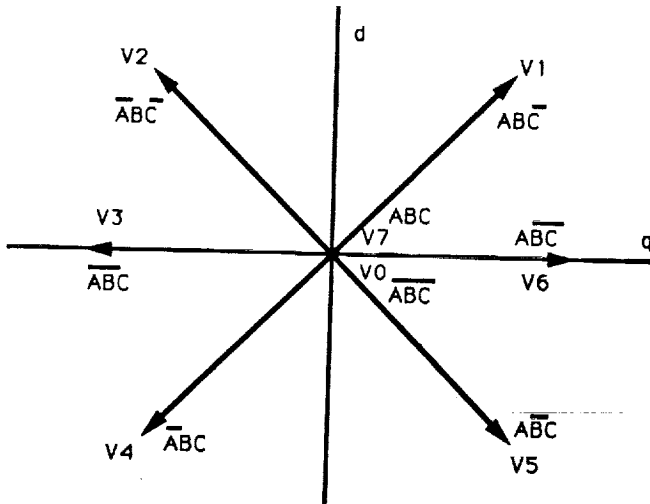


Figure 6-Possible voltage vectors

Initial FOC designs were developed using analog parts which caused drifts in the electronics. A second generation of controls were developed using part analog and part micro control, since the micro was not fast enough to evaluate the entire FOC scheme. For the third generation, a DSP has been chosen due to its highly pipelined architecture and ability to rapidly evaluate additions and multiplications, which are the basis of FOC [7]. Along with rapid speed, the DSP greatly reduces the overall size of the controller by eliminating the analog components. The control stage is based on

the described FOC scheme programmed into a VME bus based Texas Instruments 320C30 DSP system. A '386 micro is used for communication to the DSP module via the VME backplane. Data is transferred to and from the DSP by a high speed I/O board which directly accesses the DSP.

NASA Lewis is also investigating a hybrid control system that combines the advantages of both the FOC method and a maximum torque per ampere method. Acceleration requirements drive the peak power rating of the system. To meet the acceleration requirements, it is necessary to determine the most efficient way to produce maximum torque. P.C. Krause and Associates is investigating several control options in this area.

Built-in-Test

An advanced technique to be used in this ELV project is Built-in-Test (BIT). BIT uses local intelligence to determine when and where a problem arises in a system. At NASA Lewis, we will use BIT to decide whether an electrical actuation system is functioning properly prior to lift off. This will be a non-intrusive method which will aid in determining launch readiness. Currently on the Space Shuttle, the hydraulic TVC actuators need to be checked out 21 seconds prior to launch and if a problem occurs, the flight is aborted for at least 24 hours [1]. Using EMA's with BIT, pre-launch testing could be completed enough in advance to replace any problem units and still launch within the allotted time window. The same advantage could be realized for the Atlas or any other launch vehicle.

NASA Lewis is in the process of defining which control parameters will give the best indication of a system malfunction. Initially, we will be focussing on the actuator position error and motor current. Evaluations will be made to determine the validity of these choices. Once the final parameters are designated, a fuzzy logic approach will be used to analyze them and make a determination of system readiness. For this program, the user will be alerted to the status of the ELV EMA by either a 'run', 'caution', or 'stop' flag. Eventually we expect to develop BIT not only for system status, but also to show where a problem occurred. This is the step required for vehicle health monitoring and redundancy management. Figure 7 shows an example membership function for a potential fuzzy logic element. The position error is displayed with its possible groupings from very small (VS), medium small (MS), small (S), normal (N), large (L), medium large (ML), to very large (VL). The value of the error in relation to normal operating conditions will help to determine if the EMA is functioning properly.

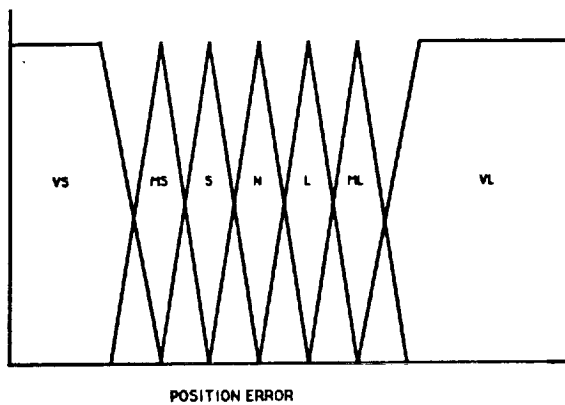


Figure 7-Possible Fuzzy Logic Element

Status

The control and power stages are scheduled to be connected by early fall. Once this is accomplished, an advanced induction motor and actuator will be integrated into the system to begin complete operational testing. The high power analysis will be done on a test stand which is being designed and built at NASA Lewis. Once performance testing is concluded, we will begin the incorporation and evaluation of BIT.

Conclusion

This ELV program has given NASA Lewis the opportunity to work directly with industry in transferring technologies. The experience and skill developed by both will prove beneficial not only for this effort, but also for other programs as well, such as the National Launch System, Electrical Actuation/Power Bridging, and Power By Wire Aircraft. The BIT capability alone will greatly benefit a number of vehicles. This program has enhanced the Lewis in-house capability necessary to effectively transfer the technologies required for advanced vehicles.

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