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Electrodynamic Tether System Study
Extended Study Final Report

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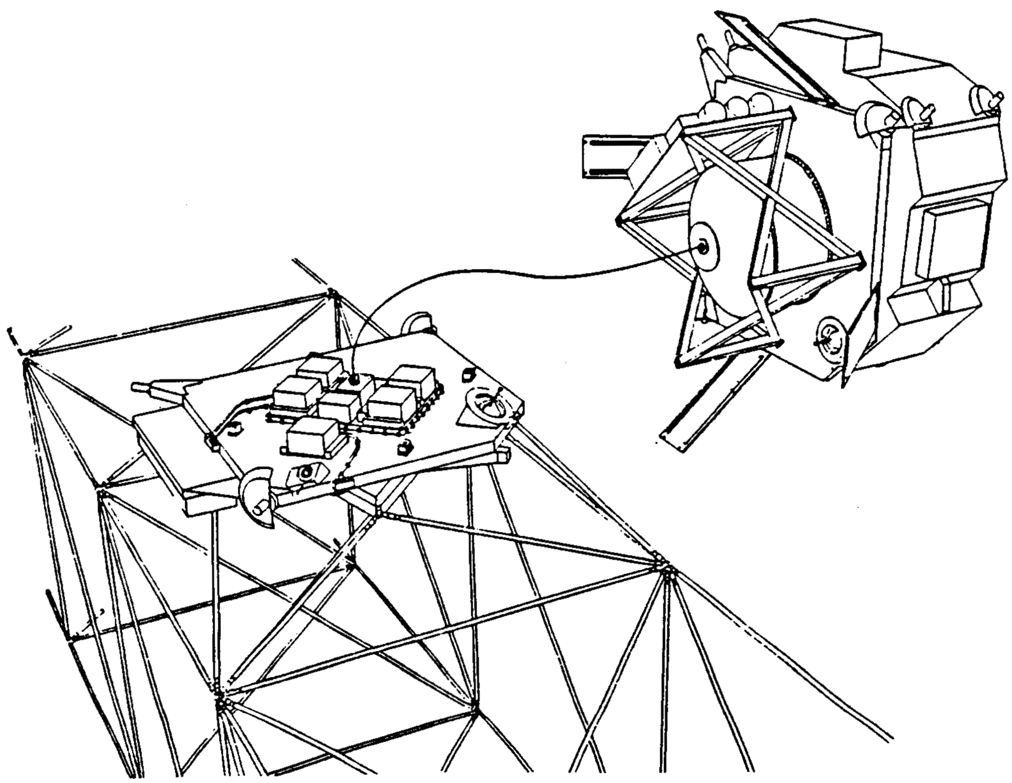

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Acronyms

AC	Alternating Current
AO	Atomic Oxygen
AWG	American Wire Gauge
BSSD	Ball Space Systems Division
DC	Direct Current
EMC	Electro Magnetic Cleanliness
EMI	Electro Magnetic Interference
EPS	Electrical Power System
ET	Electrodynamic Tether
ETS	Electrodynamic Tether System
GTOSS	Generalized Tethered Object Simulation System
HVDC	High Voltage Direct Current
ICA	Integrated Carrier Assembly
IGRF	International Geophysical Reference Field
JSC	Johnson Space Center
LRM	Line Replaceable Module
LVAC	Low Voltage Alternating Current
MBSA	Main Bus Switching Assembly
NASA	National Aeronautics and Space Administration
OMV	Orbital Maneuvering Vehicle
PDCA	Power Distribution and Control Assembly
PMAD	Power Management and Distribution
PMC	Power Management Controller
PMG	Plasma Motor Generator
PSC	Power Source Controller
PV	Photovoltaic
RBI	Remote Bus Isolator
SDP	Standard Data Processor
SS	Space Station
STS	Shuttle Transportation System
TSS-1	Tethered Satellite System 1

Introduction

This document represents the final report for a study performed by Ball Space Systems Division (BSSD) for the NASA Johnson Space Center under an extension to contract NAS9-17666. The results of the original study tasks have already been described in the final report for that phase (reference 1) and will not be repeated here.

The tasks for the extended study were;

> Define an interface between the Electrodynamic Tether System (ETS) and the Space Station (SS).
>
> Identify growth paths for the 100 kW ETS defined in the original study to a 200 kW level of performance.
>
> Quantify orbit perturbations caused by cyclic day/night operations of a Plasma Motor/Generator (PMG) on the SS and explore methods of minimizing these effects.
>
> Define the analyses, precursor technology, ground tests, and precursor demonstrations leading up to a demonstration mission for an electrodynamic tether system that would be capable of producing maneuvering thrust levels of 25 newtons.
>
> Propose a development schedule for the demonstration mission and preliminary cost estimates.

and the results are documented in this report.

This report begins by defining the mission objectives for a 25 newton Plasma Motor and the necessary analyses, precursor technology, ground tests, and precursor demonstrations that will lead up to a full scale demonstration. A preliminary development schedule and cost estimates are also included.

A simplified interface between a PMG and the SS is presented in the next section. This concept is based on the latest design information for the Space Station Electrical Power System (EPS) and replaces the concept developed in the first phase of this study.

The last sections present discussions of the orbit perturbation analysis results and preliminary concepts for IxB phasing libration control approaches for electrodynamic tethers.

Members of the BSSD study team were:

Study Manager	Dan McMann
Mechanical Configurations	Jim Byrnes
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Electrical Packaging	John Tarpley Jr.
EMI/EMC Evaluation	Terry Mize
GTOSS Simulations	Dan McMann
IxB Control Concept	Rich Pluim

This study also received valuable inputs from Mr. Irv Hansen of NASA LeRC regarding the operation of the Space Station PMAD system. Dr. James E. McCoy of NASA JSC was the Technical Officer for this contract and provided valuable guidance and assistance during the study.

1 Demonstration Mission Objectives

The proof-of-concept demonstration mission, outlined in this report, is based on several assumptions about available hardware and mission scenarios. These assumptions were made to allow the definition of mission objectives, establishment of a tentative development schedule, and preliminary cost estimates.

The tether system is assumed to be attached to a low earth orbit (LEO) platform or satellite that will be referred to as the "test bed" in this report. The test bed has a power system capable of providing at least 200 kilowatts of energy to the tether for maximum thrust. In addition, a means of dissipating tether generated energy during libration control cycles, if required, is assumed to be available. The LeRC Spacecraft 2000 concept[2] might be ideal as a tether thruster test bed, if sufficient power capability is available.

The demonstration mission must be capable of fulfilling all mission objectives which include: an OMV-assisted tether deployment, libration control of a massive tether, production of 25 newtons maximum thrust, orbital maneuvers using the tether thrust generation capabilities, and long-term tether operations.

Considerations in the definition of the development mission were simplicity, low cost, maximum use of available hardware with minimum modifications, and minimum development time consistent with low cost.

1.1 OMV-assisted Tether Deployment Demonstration

The tether deployment is one of the more challenging portions of the mission. The electrodynamic tether's metallic conductor will make the tether much harder to maneuver during the deployment than lighter weight tethers. Tether packaging and construction is critical to minimize tether preset and twisting during deployment.

Deployment of a high power electrodynamic tether (ET) with a reeling mechanism would complicate the design and add significant weight penalty to the entire system. Therefore, an OMV assisted deployment of the tether, or tethers, is assumed as the baseline approach. The details of this approach are covered in an earlier report[1]. The OMV is also assumed to provide servicing, if required, for the end-mass consumables (i.e. plasma contactor gas supply) and orbital replacement units (ORU's).

1.2 Dual Tether Operation

The demonstration flight could be accomplished as a dual or single tether mission. However, many proposed tether applications would require the disturbing torques, applied by the tether to the spacecraft or platform, to be minimized. Consequently, a dual tether demonstration mission would provide more data and is assumed as the baseline. The dual tether approach complicates the mission, increases costs, and lengthens the development schedule. Therefore, the cost/benefit trades of this choice should be further evaluated in the Phase A studies for this project.

A phased approach to the demonstration may be desireable from a funding viewpoint. In this approach a single tether would be demonstrated first, and a second tether would be added to the system after preliminary testing was completed with the single tether. This would allow characterization of the ETS under both single and dual tether operation. The major design impact would be the addition of hollow cathodes and their support subsystem to the test bed end of each tether. This approach also assumes in orbit installation of the ETS on the test bed.

The baseline approach will allow the operation of dual tethers to be explored over the entire LOE operation regime. The combined effects on the test bed, tethers, and end masses can be fully explored with this configuration.

1.3 Twenty-Five Newton Thrust Level

The primary purpose of this demonstration of electrodynamic tethers is to provide a long-term reliable source of maneuvering thrust for platforms and/or satellites to a peak of 25 newtons (5.6 lbf).

1.4 Orbit Maneuvers Using Plasma Motor

Thrust levels and timing will be varied during the flight to evaluate the orbital maneuvering capabilities of the ETS. The orbit maneuvers will be designed to verify the capability of this system throughout its operating envelope. The types of maneuvers that can be demonstrated include: changes in semi-major axis, orbit phasing, eccentricity, line of apsides, inclination, and ascending node. Thrust/drag control algorithms will be developed to simultaneously control orbit maneuvers and tether librations. The controller hardware will be designed to allow control system software modifications after launch. This is necessary to permit on-obit testing of distinct current control schemes that are a function of the type of maneuver being attempted.

1.5 Extended High Power Tether Operations

The effects of extended orbital operations on tether materials and operating efficiency are important since the advantage of using this system for propulsion accrues over prolonged periods of time. In addition, this information will allow a better assessment of the repair and maintenance requirements for the tether and related hardware. Initial selection of tether materials will be based on results from ground simulations of the orbital environments on candidate tether materials. However, the full evaluation of synergistic effects and orbital debris damage will only be possible by studying the prolonged operations of tethers in orbit.

Measurements of EMI/EMC levels at the test bed, over time, will help evaluate the effectiveness of design measures taken to limit this potential problem.

2 Hardware/Software Requirements

A project the size of a 25N Electrodynamic Tether Plasma Motor will require a variety of precursor tasks and developments in the areas of analysis, technology, ground testing, and proof-of-concept demonstrations leading up to the actual demonstration mission. Table 2-1 is a preliminary listing of some major items that must be included in this precursory work. Many of these items would be included in the Phase A/B portions of the demonstration mission definition, and others would be the result of technology fall out from other NASA and industry R&D projects. For instance, many of the items listed under "Electrical Components/Hardware" will be covered by R&D efforts related to development of the electrical power system for Space Station. The purpose of Table 2-1 is to highlight those areas were current technology needs to be augmented with further study and or development.

Figure 1-1 illustrates how many current and proposed NASA projects will benefit the ETS development. This figure also provides a tentative time line for those areas where specific developments are required prior to starting the Phase C/D project for the 25N thruster demonstration mission.

2.1 Tether

The tether is the primary component of the electrodynamic tether system (ETS) and represents a single point failure in most designs. Therefore, careful analysis, design and testing will be required for this component.

Analysis	Technology	Ground Tests	Demonstrations
TETHER			
Upgrades to GTOSS analysis pgm. PC based design software Broken tether dynamics analysis Insulation damage analysis	- Tether construction techniques	- EMI/EMC testing of ET - Materials testing for insulation mat. - Robotic repair devices - Tether thermal cycling	- On-orbit inspection/repair
ELECTRICAL COMPONENTS/HARDWARE			
Circuit simulations of converters	- Hollow cathode characterization	- Hollow cathodes - Converter stack operation - EMI/EMC testing	- Converter operations - Hollow cathode ops in space
SYSTEM MEASUREMENTS AND MONITORS			
Sensor analysis for ET state vector determination Combined control/dynamics sim.	- None for sensors	- None for sensors	- Orbital demonstration of devices and techniques for determining end-mass state vector
SOFTWARE			
- Development of control laws - Integration of current control algorithms and converter control software with dynamics simulation software	- None for Software	- Testing of converter control software	- Small-scale series converter operations demonstration
DEPLOYMENT			
OMV-assisted deployments Failure modes analysis Ground test feasibility analysis	- Packaging techniques - Pre-twisting tether	- Initial deployment simulation - End-of-deploy. simulation	- SEDS-type deployers - OMV operations
MAINTENANCE			
Orbital debris assessment	- Robotic inspection/repair - OMV capabilities	- Environmental effects on insulation - OMV servicing simulations - OMV docking to tethered end-mass	- Tether crawlers - OMV docking, servicing - OMV docking with tetherd object
RETIREMENT			
- Tether lifetime predictions - Orbit mechanics of tether - Recovery by STS	- None for retirement	- Retreival devices and techniques	- None for retirement

Table 2-1 Precursor Development Activity for 25 Newton ETS

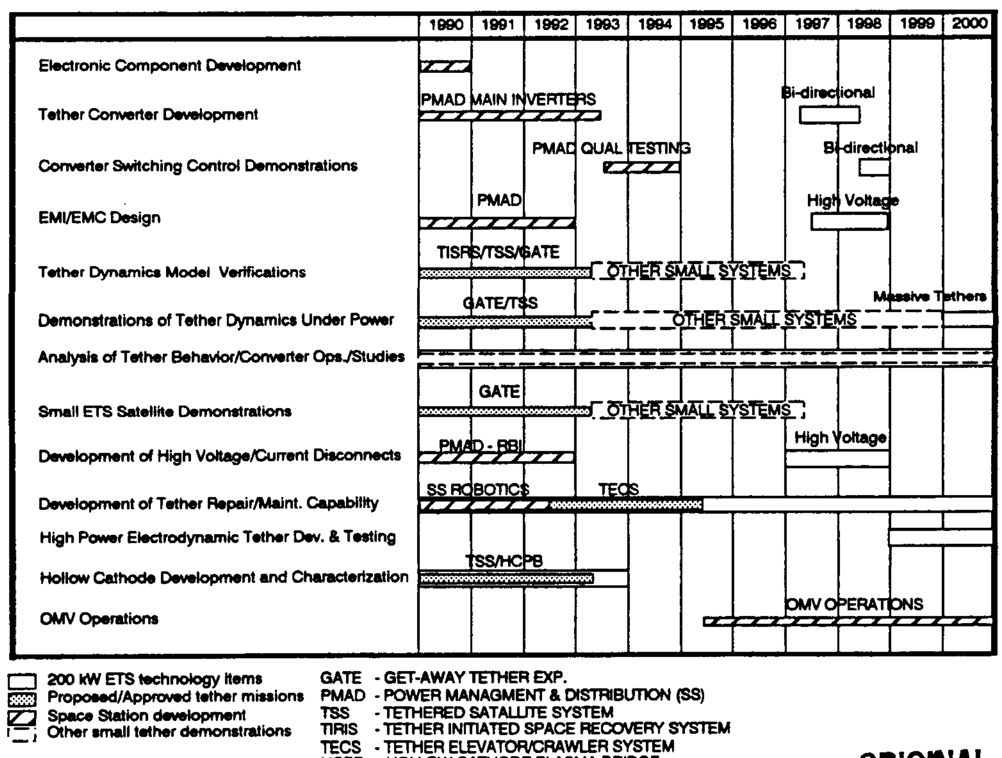

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Figure 2-1 Schedule of Precursor R&D Activities

2.1.1 Analysis

Tether dynamics analysis will be a continuing requirement in the future. Current analysis tools do not allow cost effective long-term simulations of the tether motion under the influence of all external forces and disturbances. In addition, these tools will have to be upgraded to allow the modeling of thrust and libration control algorithms.

Many of the orbit manuevers that a low thrust ET could perform occur over a period of several days or weeks. These maneuvers will be simulated many times during the design and operational phases of the program to facilitate control algorithm development and mission planning operations. It is recommended that an engineering design software tool be developed to allow rapid evaluation of variations in tether current on orbital motion. This computer program would be used in the preliminary design phase, possibly on a personal computer, and allow rapid evaluation of current control algorithms. The larger analysis programs would then be used to do detailed evaluation of the tether and system orbital motion based on the preliminary control algorithms developed. This detailed analysis would then be used to "tune" the algorithms as necessary.

The safety issues surrounding the use of a tether involve the presence of high voltages and the recoil from a broken tether. Analysis of failure modes for the tether will be required during the definition and preliminary design phases. This will include failures in the tether insulation as well as complete mechanical failure of the tether due to impact or fatigue. Analysis of the broken tether will require many simulations to completely envelope the possible initial and boundary conditions for the failure.

The high voltages and currents developed in the tether and operation of the plasma contactors could present EMI/EMC problems for electronic equipment on the primary vehicle. Electrical simulations to assess the magnitude of these effects should be carried out early in the preliminary design phase.

2.1.2 Precursor Technology

No precursor technology developments are necessary since several viable tether designs have been proposed[3,4,5] based on current materials and technology. However, continued developments in materials technology in the areas of insulators, conductors, and coatings should be monitored for application to the tether design.

Methods of fabricating electrodynamic tethers will have to be developed. Commercial cable fabrication techniques may need to be modified to accommodate space quality construction. Methods will be developed to apply the appropriate thermal control and environmental protection coatings to the cable insulation.

On orbit failure of a tether will require either a complete replacement of the tether or repair of the tether to restore complete functionality. Replacement of the tether is not a cost effective alternative if robotic servicing and maintenance facilities are available.

Preliminary on-orbit repair devices and procedures will have to be developed to assure extended life operation for the tether. Some of this technology may be developed and tested as a result of the demonstration flight. However, basic repair and maintenance concepts should already be in place when this system flies. Smaller systems can be used to develope and demonstrate the repair techniques and devices. It is anticipated that repair, inspection, and maintenance of the tether will need to be accomplished using robotic devices that can perform their tasks without significant human intervention. This type of technology is currently being pursued by the US and Italians under a letter of agreement with NASA[6].

2.1.3 Ground Tests

EMI/EMC testing will be accomplished on the tether components in combination with the converters and control electronics to verify and improve on analytical results. This testing will involve high power levels and can make use of the new test facilities at LeRc that are being developed for Space Station. Evaluation of the EMI/EMC impact of the tether itself will be a goal of the demonstration flight.

Materials testing for UV, AO, and high energy particle degradation can be accomplished in ground facilities. These tests will be completed under the Space Station Advanced Development Program[7] and should not have to be repeated for the tether development.

Thermal cycling of the tether will be accomplished to evaluate the effect of differential expansion between the insulation and the conductor on tether performance and life. A means of thermal cycling a 10 to 20 kilometer long tether over its expected operating temperature range will have to be devised.

Ground tests of robotic devices to repair and maintain the tether insulation and conductor can be accomplished prior to the need for flight testing. Tether crawlers are a candidate for the tether inspection and repair tasks and should be initially tested using ground facilities.

2.1.4 Precursor Demonstrations

On-orbit inspection and repair of electrodynamic tethers will be demonstrated prior to this flight. Work in this area is being pursued by the US and Italy. It is anticipated that a crawler-type device will be developed and demonstrated that will affect autonomous on-orbit inspection and repair of electrodynamic tethers. The Tether Elevator/Crawler System (TECS) is a joint US/Italian demonstration that is being proposed[6] as a possible new start in the next 4 to 7 years.

2.2 Electrical Components/Hardware

The electrical devices to regulate, convert, and conduct the ET current will need a greater power handling capacity than present space qualified equipment provides. Most of the electrical components needed to assemble the ET control devices are currently under development in support of the Space Station power system (see Figure 2-1). These components and the associated design methodology should be very mature by the time it is needed for constructing an ETS.

The primary component that is unique to the tether application is the hollow cathode plasma contactor and it is the subject of current research and development activities by NASA and others[8,9,10,11].

2.2.1 Analysis

Circuit simulations of the tether converter stack, control electronics, and safety devices will be required. These computer simulations will evaluate the performance of the system under various operating load profiles and control procedures. The simulations should be performed before actual construction of the converters to assure the feasibility of the design approach. This type of simulation is currently being performed at NASA LeRC in support of the Space Station Power Management and Distribution System performance and design in the EASY5 modeling project[12]. LeRC is using EASY5 to develop a library of component simulation models that will be applicable to the ETS converter and controller designs with little or no modification. Analysis of system response to various failure modes will also be accomplished using this simulation methodology.

The purpose of these simulations would be to improve the design and assure long-term operation of the system without extensive maintenance requirements. Secondary benefits of the analysis would include development of better control algorithms and improved knowledge about the expected performance of individual components, which will be needed in other design areas such as thermal control, packaging and EMI/EMC.

2.2.2 Precursor Technology

Component technology developments will be necessary to support the high power and voltage requirements of the ETS. Commercial and DOD interests in this technology promises to produce many of the solid-state components required for the ETS under other programs. Advanced development is also proceeding in the areas of magnetics and capacitor capabilities. Therefore, precursor technology programs for these components that are specific to the ETS should not be necessary.

Hollow cathodes are used to complete the circuit between the tether and the space plasma. Development in this area will need to continue in order to reach reliable operation at the current levels needed for high power tether systems.

2.2.3 Ground Tests

Preliminary testing of the hollow cathode devices is being accomplished in ground facilities. However, testing of the higher power devices, at full power, will probably not be possible in ground facilities. Full power characterization and extended operation of the hollow cathodes will need to be accomplished in space.

The converter stack design and operation can be tested using ground facilities, although operation at full power (200 kW) may not be feasible. Reduced power testing of the stack will still provide valuable performance information on the control electronics, control algorithms, and configuration of the converter stack during normal and simulated failure conditions. The LeRC test facilities will be required for most of the converter and controller testing activities.

EMI/EMC testing of the individual converters, complete converter stack, and the tether itself can be completed, possibly at reduced power levels, in ground test facilities.

2.2.4 Precursor Demonstrations

Demonstration of the converters, both individually and in series, will be a demonstration milestone during the early development phase. The converters proposed for the ETS are identical to the ones being used in the Space Station Power System. The development test demonstrations of these systems will be a milestone for further ETS development activities. If the Space

Station design is changed the ETS design should be re-evaluated. If the resonant converter technology is retained for the ETS, then a separate demonstration of the converter operation would have to be made part of the development cycle.

Successful operation of the hollow cathodes is required before proceeding with the demonstration flight. Hollow cathode operation, at a low power level, will be demonstrated during the Tethered Satellite (TSS-1) mission with the Hollow Cathode Plasma Bridge (HCPB) experiment. Another experiment in development is the Plasma Motor/Generator-Proof Of Function (PMG-POF) Hitch-Hiker G payload that will fly on the STS in a few years. Dr. Jim McCoy of NASA JSC is the principal investigator for both of these experiments. Several other demonstrations of these devices have either been completed[9] or are in the advanced development phase[8,10]. Results of these experiments will help in the characterization of the hollow cathode performance.

2.3 System Measurements and Monitors

Requirements for ETS measurements and monitors have not been clearly defined yet, but they will at least include current, voltage, magnetic field vector, and tether position. During the deployment phase a means of monitoring the position of the tether and end-mass will be required for safety reasons and to implement IxB phasing libration control algorithms. It is not anticipated that advances in the state-of-the-art will be required to implement ETS measurement and monitoring requirements.

2.3.1 Analysis

Definition of the measurement accuracies, ranges, and bandwidths need to be established by detailed analysis of the ETS requirements. These requirements will be driven by the libration control system, current control specifications, and any constraints of the test bed. The main focus of the analysis should be a technology trade that will result in the performance requirements being met at the lowest cost.

Control and dynamic simulations of the deployed tether will refine the requirements for equipment to determine the end-mass state vector and tether position. This analysis could be performed with a version of GTOSS that has been updated to include the control algorithm simulation.

2.3.2 Precursor Technology

Technology development is not anticipated for the sensor and measurement hardware since all required measurements can be made with currently available equipment (i.e. radar, magnetometers, voltage and current sensors, etc...). However, software simulation and analysis improvements will be needed to fully define the requirements for the state vector and tether position determination hardware.

2.3.3 Ground Tests

Ground testing and evaluation of the sensor and measurement hardware is possible, but on-orbit evaluation of the end-mass state vector determination system will be required.

2.3.4 Precursor Demonstrations

An orbital demonstration of the ability to monitor, sense, and predict tether position and end-mass state vector is recommended. This demonstration could probably be combined with other experiments that are being planned for STS or ELV launch over the next few years. TSS-1 will provide valuable information about tether dynamics and sensing end-mass state vector.

2.4 Software

Software requirements for the ETS will be concentrated in three areas: libration control, orbit maneuvers, and converter operation and sequencing. The libration control and orbit maneuver algorithms will need to be closely coupled and, therefore, developed simultaneously. The control of the resonant converter operation is a separate task and much of the algorithm development will be identical to the Space Station system. Maximum use will be made of the software and hardware from this advanced development work.

2.4.1 Analysis

Equations of motion for the tether system will be developed and a set of control laws established. The highly complex and non-linear behavior of the tether system will require considerable simplification in the equations of motion for control law development. Therefore, extensive coupled non-linear computer simulations of the tethers under the control laws will be needed to verify performance. The attitude control and converter control software will be coupled to the tether dynamics software (possibly GTOSS) to perform fully coupled simulations of the ETS system.

2.4.2 Precursor Technology

None.

2.4.3 Ground Tests

Ground testing will not be possible for the libration and maneuver software. However, the resonant converter control software and its interface with the control software can be tested in facilities at LeRC.

2.4.4 Precursor Demonstrations

A small scale demonstration of the converter and control techniques would be feasible. A low power (1 to 5 kW) system could be placed in operation very quickly using available hardware and technology. Possibly, the TSS-1 hardware could be modified to perform a demonstration of series resonant converter operation and tether libration control using IxB techniques. A lower cost approach may be to develop a dedicated tether payload for ELV launch that could demonstrate operation of the converters and all software.

2.5 Logistics

The design areas that need the greatest effort over the next few years will be in the repair, maintenance, and retirement of tethers. The deployed tether presents a large area to orbital debris and is constantly exposed to the near earth space environment. In order for the benefits of tether systems to be realized and to meet the expected mission requirements of many host vehicles the tether must have a relatively long operational lifetime. A broken tether presents a potential safety problem for the host vehicle and for other orbiting objects. An obsolete tether system must be removed from orbit or "safed" in some other manner or it will become a source of orbital debris.

NASA and Italy are both studying the problem of tether repair and maintenance and have suggested designs and concepts for devices to repair and maintain orbiting tethers. A broken or severed tether will be very difficult to repair and additional study will be needed in this area.

The hollow cathodes require a gas supply, so a means of servicing these supplies must be developed for long-term applications. The OMV fluid servicing facility is a likely candidate for this task, but methods of docking the OMV with the moving end-mass must be developed.

2.5.1 Deployment

One of the most technically challenging aspects of the ETS is the design and development of a system to deploy the tether. The deployment will require the use of automated systems and procedures. The techniques and designs arrived at during this study need additional analytical evaluation and precursor demonstrations before development can proceed on the baseline 25 newton plasma thruster.

2.5.1.1 Analysis

Three methods of deploying tethers are currently being evaluated for various tether applications. These methods are reel[5], SEDS-type[8], and OMV-assisted[2]. Extensive analysis has been completed and is in progress for the first two methods. The reel and SEDS-type deployments can be simulated using a variety of currently available software tools. However, the OMV-assisted deployments will require additional capabilities in the analysis tools to simulate the control algorithm for the OMV thrusters. If reel and SEDS-type deployments are determined to be inappropriate for the ETS system, then additional enhancements to the tether simulation software will be required. It is possible that the tether deployment simulation tools used for the TSS-1 mission analysis may be able to handle this type of deployment with minor modifications.

Analysis of an OMV-assisted deployment should include evaluation of normal deployment and failure modes. Failure modes will include tether binding, OMV attitude control failure, and tether mechanical failure. Appropriate procedures will have to be developed for each of these failure modes and any others identified during the design phase.

The baseline design arrived at during this study assumes that the OMV will be capable of servicing the plasma cathode gas supply on the end-mass. Therefore, analysis of and procedures for an OMV rendezvous with the tether tip mass will be required. Preliminary control algorithms and analysis of this scenario has been published[13] for an actively controlled end-mass. This analysis should be extended to evaluate the performance with a passive end-mass.

2.5.1.2 Precursor Technology

Packaging techniques for a massive tether will have to be developed. The deployment forces and rates will have to be kept low so any preset or permanent warping of the tether must be avoided. Gravitational and acceleration forces could cause settling of the tether during ground and launch operations. This settling could lead to binding of the tether during the deployment stage. Methods of packing the tether to avoid this must be developed.

It may be necessary to pre-twist the tether during the process of putting the tether in its container for launch. The pre-twist will keep the tether from twisting during the deployment phase. Pre-twisting a tether of this size may require the development of new hardware.

2.5.1.3 Ground Tests

Ground testing and simulation of a tether deployment is very desirable. However, it may not be practical for a tether of this size. A study to determine the feasibility and cost benefit of ground testing versus the risk of flying the mission without a test should be accomplished.

The ground tests that are possible for the tether deployment system will be quite limited. This is because of the system size, gravitational effects, and complexity a full-up simulated tether deployment test. It may be possible to simulated portions of the deployment, like start up, with simplified test procedures and fixtures. The range of ground tests that are possible and useful should be the subject of early system trades.

2.5.1.4 Precursor Demonstrations

Flights of SEDS-type deployers are currently planned for early in the 1990's. These demonstration missions will provide valuable data for the OMV-assisted deployments. One possible scenario for the OMV-assisted deployment is for the OMV to simply provide the initial separation and attitude control. At a certain point the deployment would transition to a SEDS-type deployment with the OMV simply providing velocity and attitude control. Near the end of the deployment the OMV would arrest the excess velocity of the end-mass. The early demonstrations of SEDS-type deployments will provide needed information to refine the ET deployment scenario.

The OMV should be operational for several years before the ETS demonstration so its abilities to assist in deployments will already have been established. The response of the OMV, while attached to other payloads, will provide valuable input to the overall deployment strategy for the ETS. It is likely that the OMV can be used to deliver the ETS to the test bed, install it on the test bed, and then deploy the tether.

2.5.2 Maintenance

Short duration (one year or less) ETS missions would probably not require servicing and maintenance requirements should be minimal. However, for the longer duration missions a number of maintenance and servicing items have been identified including; hollow cathode gas re-supply, converter replacement, end-mass servicing, and tether repair. Many of these maintenance tasks can be accomplished by the OMV using planned servicing facility attachments. Others may require the development of ETS unique robotic devices, procedures, and materials.

2.5.2.1 Analysis

The tether maintenance requirements will be a function of the orbital environment. Orbital debris will be the greatest threat to a deployed tether. Preliminary assessment of this threat has already been completed[14]. However, detailed analysis of the debris environment will be required to determine the appropriate maintenance scheduling for the tether. This analysis will also yield information on the configuration of the tethers. For instance, if the debris hazard is too great, a multiple tether approach may have to be re-evaluated to meet minimum lifetime and reliability requirements.

2.5.2.2 Precursor Technology

Maintenance for the tether system will require the development of advanced robotic technology. The OMV and tether crawler technology will be required for ETS maintenance functions. The OMV technology is being developed to support other NASA programs and the tether crawler technology is being pursued by current and planned future technology development efforts.

2.5.2.3 Ground Tests

Environmental effects on candidate tether material can be tested in ground facilities. These effects include UV, AO, high energy particles, contamination and temperature. It will also be possible to do impact studies on samples of tether construction to quantify impact damage from orbital debris.

Simulated OMV servicing missions will probably be accomplished in ground simulators that will be available for OMV mission planning. These simulated mission will be used to verify interfaces and procedures before the maintenance mission is flown by the OMV.

Development testing on the hollow cathodes will yield information about gas flow rates that can be used to size the gas supply and predict the required servicing interval. Servicing of the end-mass gas supply may require the OMV to dock with a librating tethered object. Hopefully, the procedures and algorithms required for this function can be developed and tested using ground simulators.

2.5.2.4 Precursor Demonstrations

Demonstrations of tether crawlers, OMV remote docking operations, and OMV servicing functions will be required prior to the ETS demonstration mission. If a short term demonstration mission is decided on the crawler and OMV servicing demonstration would not be necessary. Docking of the OMV with a tethered end-mass could either be a precursor demonstration requirement, or be made a part of the ETS demonstration mission.

2.5.3 Retirement

When the demonstration ETS system has fulfilled its mission objectives or otherwise becomes unproductive the system will have to be "retired". This will mean stowing the tether and probably removing the ETS from the test bed. Since the baseline design provides for no reel-in capability an alternate means of stowing the tether needs to be developed.

2.5.3.1 Analysis

Planning for the retirement of the ETS will require an analysis of mission requirements and a prediction of the expected lifetime of the tether system. At least two different retirement scenarios need to be investigated. One involves normal retirement due to completion of mission objectives or deteriorated ETS performance. The second type of retirement is for an ETS that has suffered irreparable damage or failure. This second type could be the result of a broken tether, in which case the recovery of the end-mass and attached tether segment needs to be considered.

Analysis of the orbital behavior of the end-mass will be required to predict its orbital decay rate or to facilitate a rendezvous with the OMV for recovery.

Final disposal of the ETS could be by forced re-entry and burn up in the atmosphere, STS recovery to earth, or simply wound onto a container that would remain in orbit on the test bed. Each of these scenarios will need to be analyzed to determine the most cost effective alternative. There may also be other alternatives to be considered, such as using the ETS equipment as raw material for orbital construction.

2.5.3.2 Precursor Technology

None.

2.5.3.3 Ground Tests

Ground testing of tether retrieval devices will be required. It is anticipated that these devices will be simplified reelers to temporarily store the tether until it can be de-orbited or permanently stored on orbit. Existing facilities used for the ETS construction and test should be sufficient for these tests.

2.5.3.4 Precursor Demonstrations

None.

3 Preliminary Development Schedule & Costs

A development schedule for a 25 Newton Plasma Motor is presented in Figure 3-1. This schedule is based on the design presented in reference 1 with the electrical interface modifications presented latter in this report (see section 4). The physical description of the system is presented in Figure 3-2. It basically consists of two Integrated Carrier Assemblies (ICA) that are connected together, on orbit, to form the Plasma Motor.

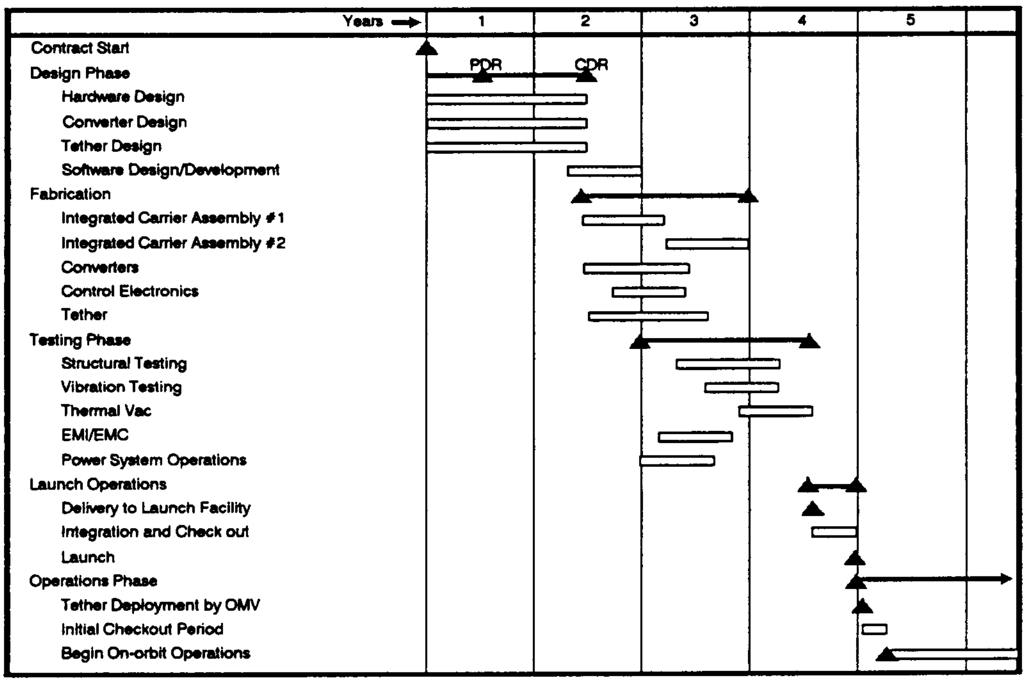

Figure 3-1 Preliminary Development Schedule

Each of the ICA's consist of a Fixed Carrier Assembly (FCA) and a Deployed Carrier Assembly (DCA). The FCA is joined to the DCA during launch by a Deck-to-Deck Interface Structure (DDIS). The FCA remains attached to the test bed after the tether is deployed, and the DCA is deployed with the tether. The tether provides the physical connection between the FCA and DCA after tether deployment. This design has no reeling mechanism since the tether is deployed by the OMV off a specially designed spool. Both carrier assemblies are constructed of honeycomb decks with trunnions for attachment to the STS for launch and/or recovery. A standard grapple fixture is attached to each ICA to allow the STS Remote Manipulator System to be used for moving the ICA's out of the STS Bay for attachment to either an OMV or directly to the test bed vehicle. The ICA's are designed so that they can be brought to orbit and deployed individually.

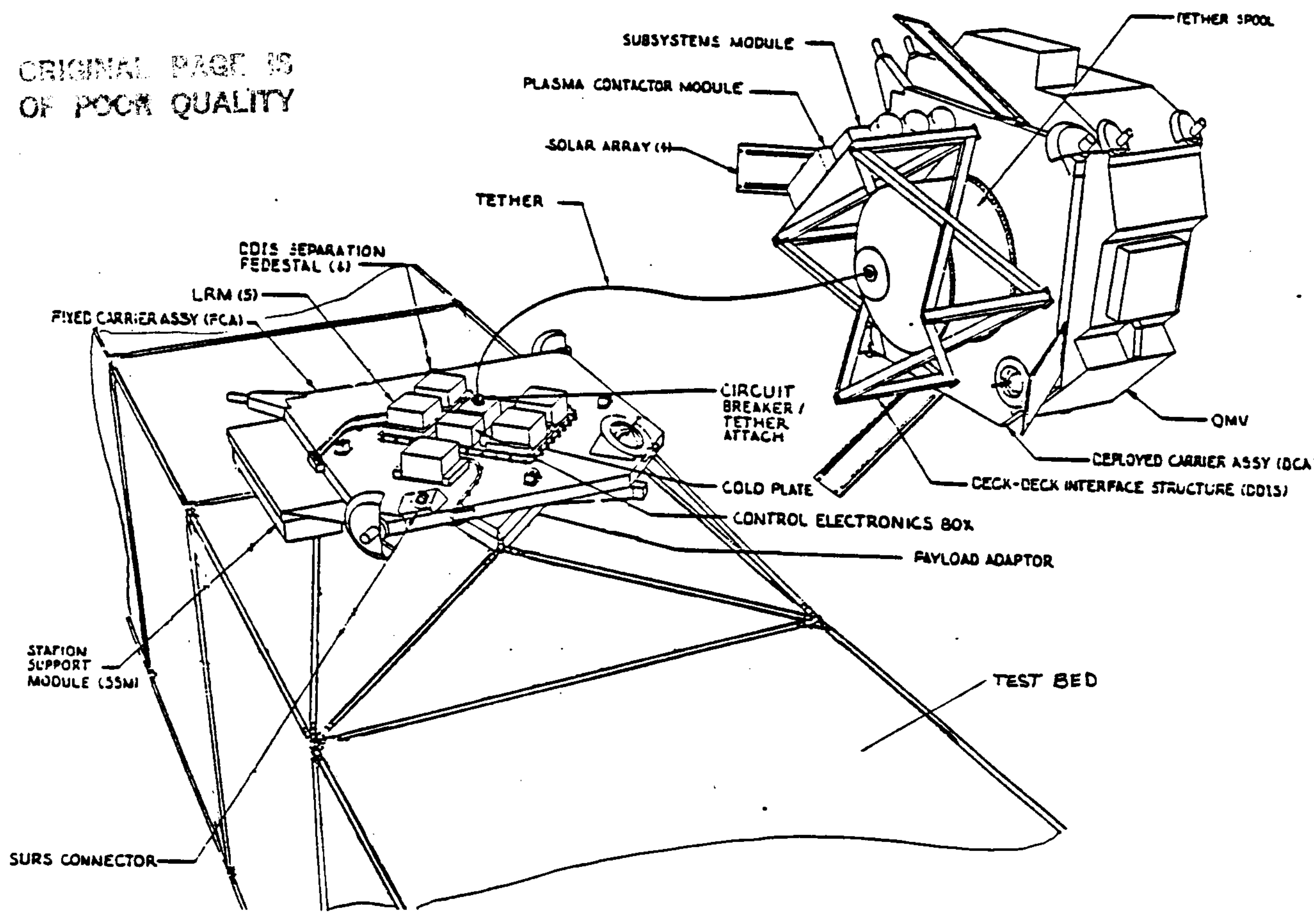

Figure 3-2 Electrodynamic Tether Design Concept

The FCA provides support for the equipment that remains with the test bed. This includes the converter modules, transformers, converter controllers, tether communications and state vector determination equipment, tether guillotine, and converter thermal control coldplates. The DCA becomes the end mass for the electrodynamic tether and provides a structural support for the end-mass equipment including; gas supply, hollow cathodes, power supply, batteries, solar arrays, control electronics, and equipment for communicating with the FCA. The FCA and DCA both have interface devices to allow attachment to the test bed and OMV respectively. The FCA is designed to have a Space Station type electrical, data and thermal interface to the test bed. The DCA needs only a mechanical interface and possibly a high pressure gas interface if the end-mass requires servicing of its hollow cathode gas supply over the mission lifetime.

The development schedule for this system is shown in Figure 3-1. The three main phases - design, fabrication, and testing - each last approximately 18 months. However, the fabrication and test phases overlap because the construction of the converters and one ICA is completed while the production of the second ICA and its converters continue. The converters and first ICA will be started through their test programs while work continues on the second ICA. This scheduling results in a duration of about four years from contract start to launch. This schedule assumes that both ICA's will be launched on the same STS flight. If they are launched on separate flights the first ICA could be ready for launch three to six months before the second ICA.

A test bed with 200 kW power capacity will probably not be available until early in the 21st century. At that time significant progress will have been made in many of the technology areas (see Figure 2-1) important to the development of this system. Each phase of the demonstartion mission has some key technology issues that will be pacing items. In the design phase it will be the converters, and deployment spool. In the fabrication phase it will be the tether. During the testing phase the full scale testing of the converters and tether for operating characteristics and EMI/EMC will be pacing items. In the orbital operations phase the remote deployments, servicing, and repair will be key technology requirements.

A preliminary cost estimate of this program from Phase C/D contract award through launch has been completed. This cost estimate is based on work completed earlier (reference 1) that was modified to include the results of the extended study tasks. The primary impact of the extended study was in the converter costs (increased to 6 per ICA) and the addition of an interface transformer between the test bed electrical power system (assumed to be identical to the proposed Space Station EPS) and the tether converter modules (see Figure 4-2). Table 3-1 summarizes the preliminary cost estimates for the hardware to support a demonstration mission of this size.

The converter estimates are based on a bi-directional design suitable for a Plasma Motor/Generator (PMG) system. Technically the Plasma Motor design only needs to operate in one direction (thrust). However, it is very likely that even a system whose primary function is thrust generation will require bi-directional operation for libration control and possibly, to allow for reduction in orbit altitude. Also, the technology that is being used for their design is based on the Space Station PMAD system which is bi-directional. Therefore, the converter design was assumed to be bi-directional.

The non-recurring engineering costs are estimated to be \$25M and the recurring costs are \$9.8M per Integrated Carrier Assembly. The total hardware costs for the 25 newton demonstration mission are estimated at \$45M.

The precursor technology, analysis, ground tests, and demonstrations, described in section 2 of this report, are not costed since many of these items will be funded under other NASA programs irrespective of the tether program.

Cost Item	Eng.($K)	Mfg($K)	Tot.($K)
Honeycomb Decks	3084	720	3804
Grapple Fixture	**	336	336
Trunnions	313	116	429
Test Bed SS-type Interface	5998	1760	7758
Deck-to-Deck Interface	1015	240	1255
DCA/OMV/SS Interface	1242	410	1652
Gas Supply Tanks	**	660	660
Current Converters (6 units)	2012	1212	3224
Interface Transformers (3 units)	755	228	983
DCA Power System	**	690	690
Command, Comm. & Data Handling	683	238	921
Electrical Harness	160	40	200
Spool and Enclosure	745	276	1021
Tether	**	350	350
Mechanical Circuit Breaker	243	85	328
Thermal Coldplate	622	134	756
Thermal Control	152	181	333
Converter Control Electronics	550	250	800
Tether Guillotine	62	53	115
Software	2500	---	2500
GSE	2000	500	2500
Integration and Test	2975	1275	4250
Cost of 1st Integrated Carrier Assy.	**25,111**	**9,754**	**34,865**
Cost of 2nd Integrated Carrier Assy.	**-**	**9,754**	**9,754**
Total Cost			**44,619***

* Excludes costs for plasma contactors and control electronics, state vector determination hardware, STS integration and launch, SS integration and support, all servicing and repair items, Phase A/B studies and OMV usage for deployment.

** Purchased Items

Table 3-1 Preliminary Hardware Cost Estimates

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4 Electrodynamic Tether Electrical Interfaces

4.1 Space Station Interfaces and Equipment Commonality

Based on information contained in Rockwell International, Rocketdyne Division report RI/RD87-201 P-2, Section 4.1 "PMAD Systems Design"[12], none of the standard PMAD assemblies appear to be usable for the tether interface. However, many of the orbit replaceable units (ORU's) will be usable either as is or with minor modifications. These ORU's include the standard ORU package housing, selected portions of the RBI (Remote Bus Isolator), power distribution cabling, a modified version of the Main Inverter Units (MIU), and a modified version of the TU (Transformer Unit). In addition the PMAD control bus will be utilized for control and switching of the tether converter (CV) units. Figure 4-1 shows a simplified overview of one-half of the PMAD system.

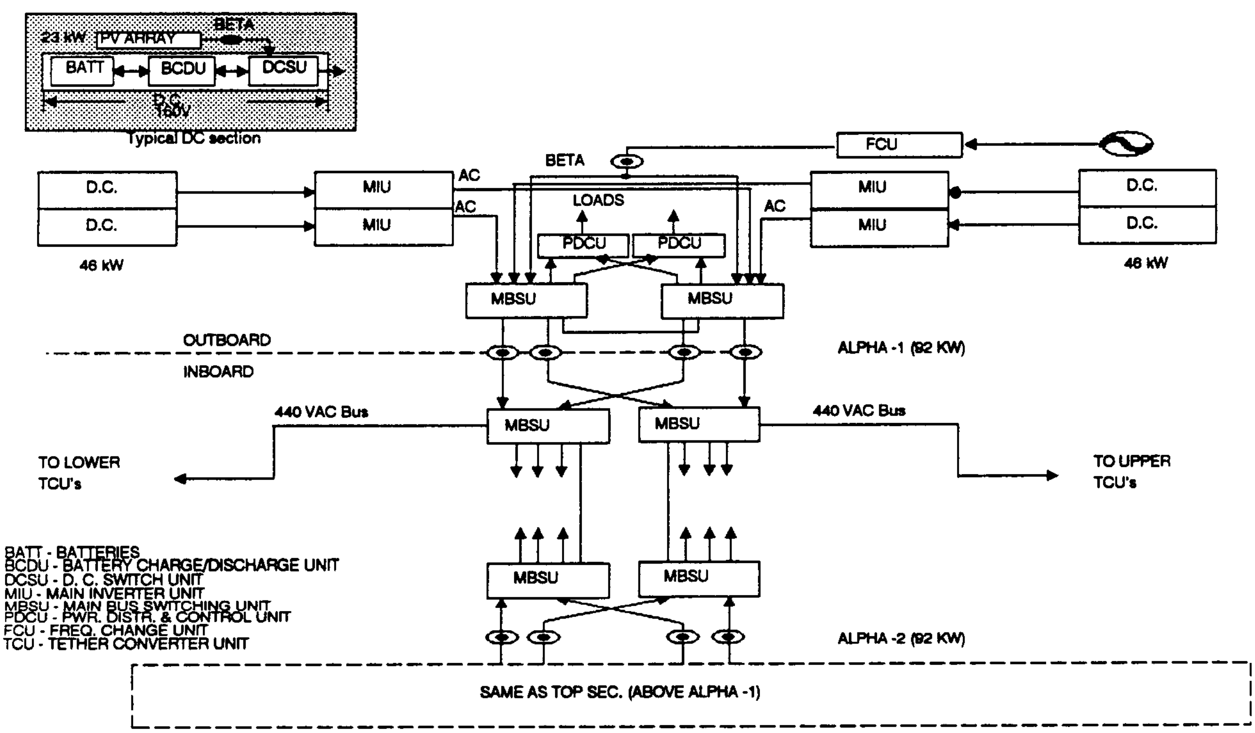


Figure 4-1 Space Station PMAD System

Figure 4-2 shows the basic Tether/PMAD interface, for both generator and motor modes of operation.

In the generator mode, DC from the tether is converted to 20 kHz, 440 volt sinewave AC in each CV. Two CV's are electrically and mechanically combined into a single ORU referred to as a Tether Converter Unit (TCU). The AC outputs of each CV pair in a TCU are connected in series, and feed a transformer (XFMR), coupling power directly to the 440VAC PMAD bus. Since the tether induced voltage can vary widely, the corresponding

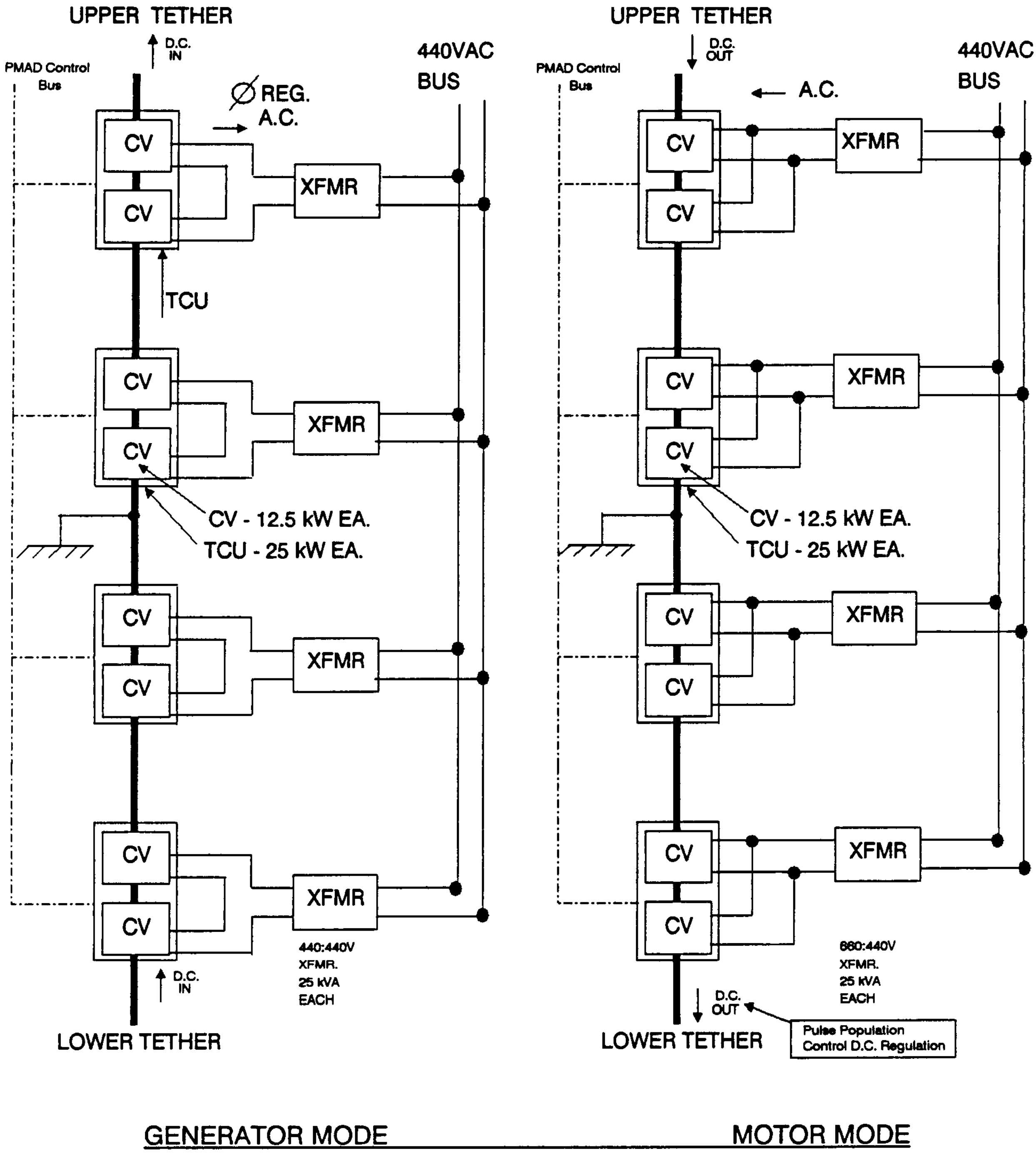


Figure 4-2 Interface for Original 100 kW System (Simplified)

converter AC outputs will vary accordingly, and require regulation to match the PMAD bus voltage. This is accomplished by means of phasor control (as used in the PMAD MIU's) - the vector sum of the two CV outputs in each TCU is matched in phase and magnitude with the PMAD system 440VAC bus and fed to each XFMR coupled to the bus.

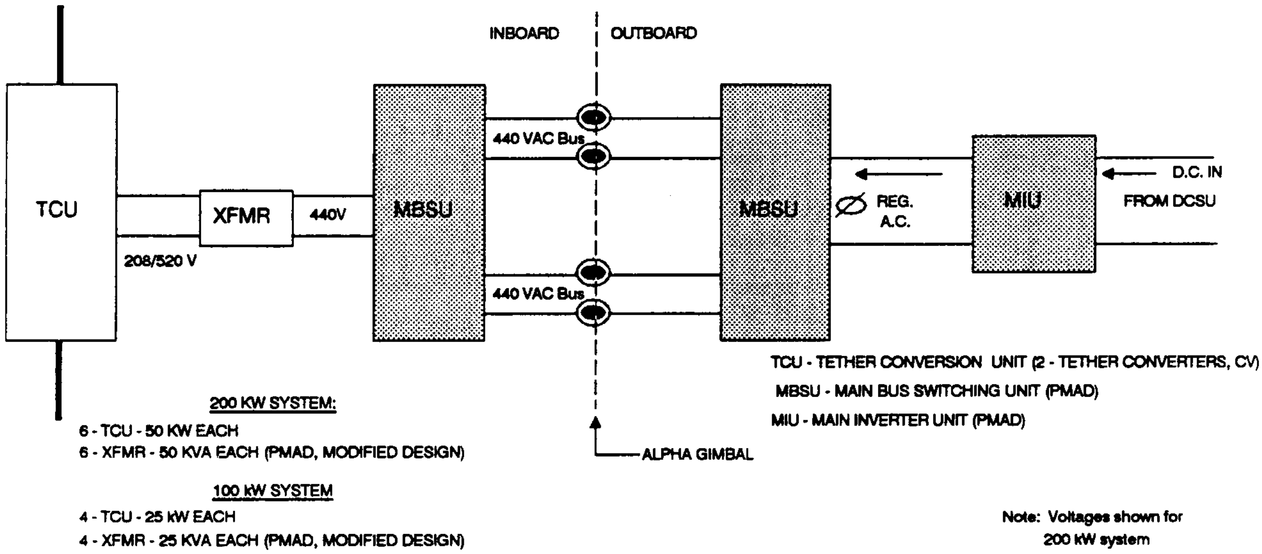
In the motor mode, each TCU has AC fed through the bus coupling XFMR to each CV in parallel, and in phase. Now, each CV acts as a full-wave rectifier providing DC to the tether. Since regulation by phasor control is not possible in this mode of operation, a method known as "pulse population control"[15] will be used. This technique simply provides more or less of the half-sine rectified AC pulses to the tether (through an averaging filter) to give the desired DC output. The "pulse population control" is achieved by using reverse-connected thyristors (instead of the usual rectifiers) in the resonant converter circuit and gating these on and off using an algorithm designed to achieve the desired DC output level. Not shown are any PMAD bus disconnects which may be required to satisfy SS safety requirements.

Figure 4-3 shows the basic power flow between one TCU and the prime power source for the PMAD system, together with the basic switching required for generator/motor transition. The bus coupling transformer is a modified version of the TU in the PMAD system. The tether transformer is modified to have a tapped winding on the tether side in order to supply a motor mode AC voltage higher than the generator mode AC (this is required to overcome the tether back EMF). Load switching uses hybrid switches consisting of double-pole, double-throw (DPDT) contacts shunted by bi-directional thyristors. The bi-directional thyristors provide arc-free switching, and minimum conduction loss with the mechanical contacts. Transformer ratios and power ratings for both a 100kW and a 200kW system are shown.

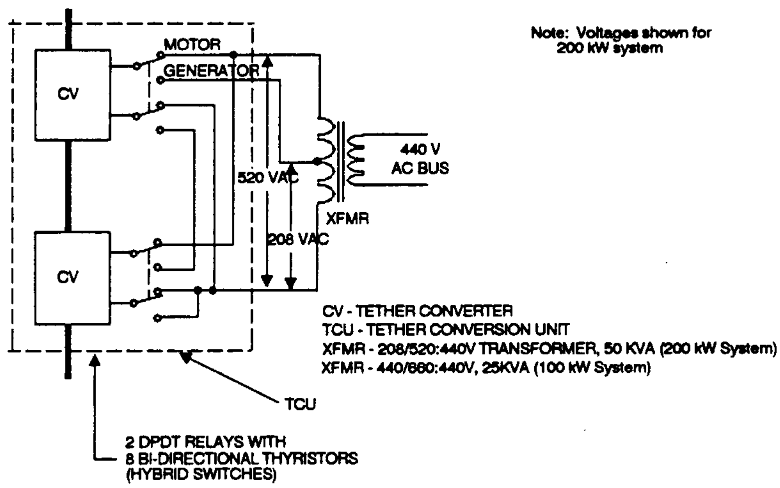
Figure 4-4 shows the voltage ratios required in each transformer for both generator and motor modes. The 208V and 520V windings are combined into a single 520V winding with a tap at 208V, as shown in Figure 4-3.

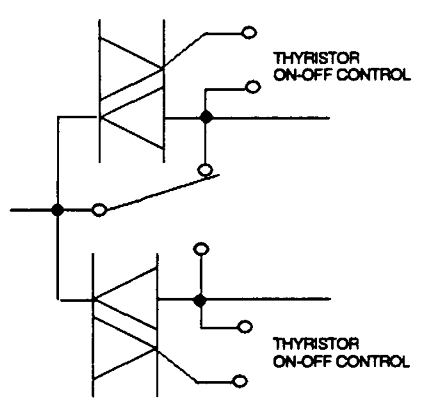
Figure 4-5 shows the basic CV unit having the identical topology as those used in the PMAD MIU's. This is basically a bi-directional H-bridge 20 kHz resonant converter as shown in the original design. However, the circuit has now been coupled with appropriate filtering (shown as a basic filter), and includes provisions to optimize the filter for each mode of operation.

The basic filter circuit requires either an inboard or an outboard storage capacitor depending on the mode of operation. In the generator mode a storage capacitor on the inboard side of the filter inductor is required, however in the motor mode an outboard capacitor is required. By placing an isolation resistor in series with the inboard storage capacitor, it can effectively be removed from the circuit in the motor mode. For generator mode operation the relay shorts out the resistor and allows the inboard storage capacitor to operate properly. The outboard capacitor does not effect generator mode operation.



LOAD SWITCHING FOR MOTOR/GENERATOR OPERATION





RELAY CONTACT DETAIL

Figure 4-3 Details of Converter Switching and Control

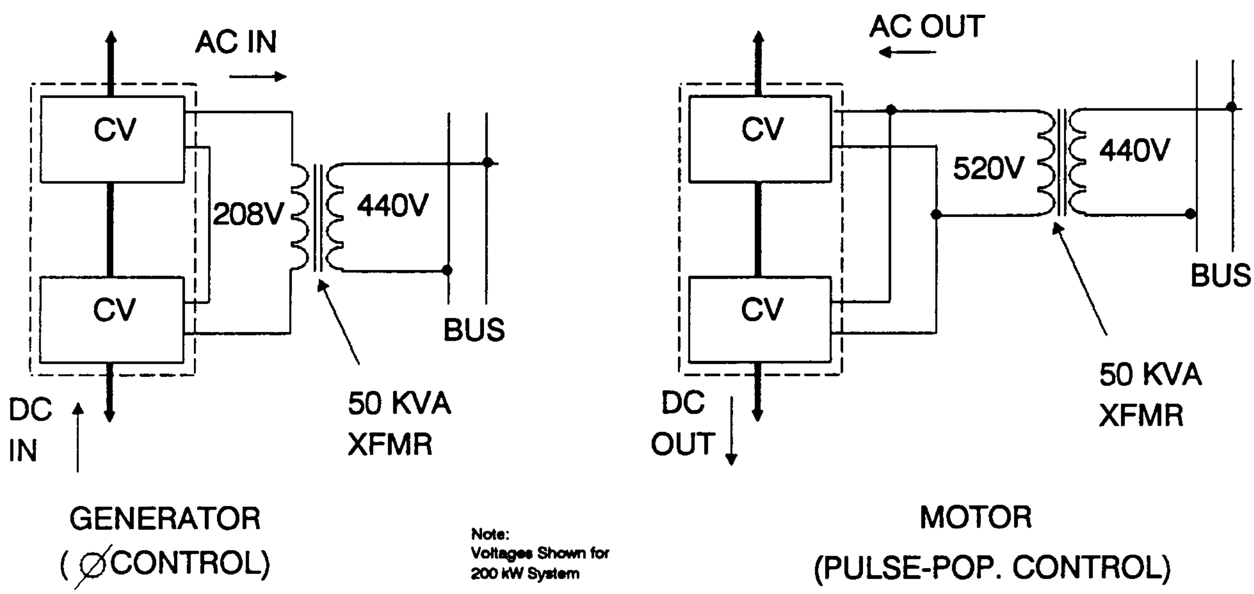


Figure 4-4 Phase and Pulse Population Control Schematics

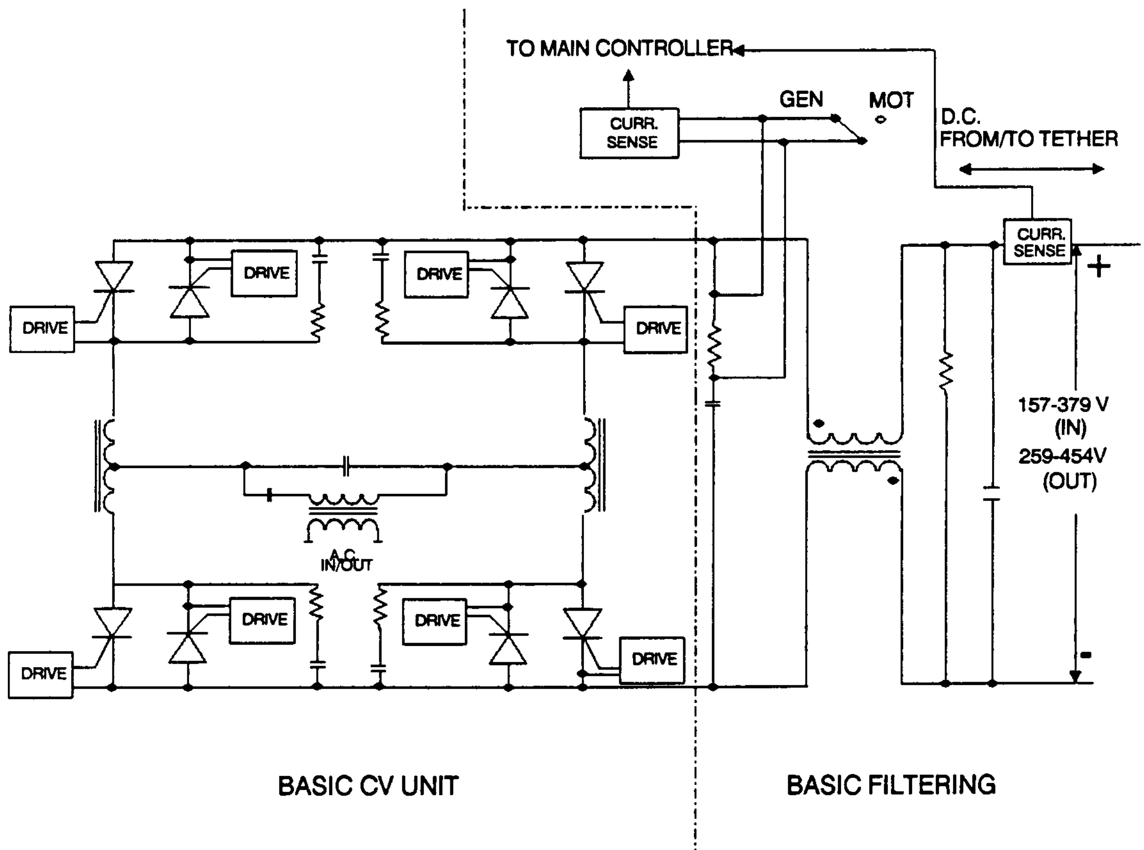


Figure 4-5 Converter and Filter Circuits

4.2 Revised Estimates of System Parameters

The revised weight estimate for the original 100kW system using information contained in the referenced Space Station PMAD proposal is:

CV	120 lb. x 8	=	960 lb.
XFMR	8 lb. x 4	=	32 lb.
BREAKERS & SWITCHES		=	50 lb.
FILTER UNITS	16 lb. x 8	=	128 lb.

The revised thermal estimate for the original 100kW system is:

CV	800W x 8	=	6400W
XFMR	300W x 4	=	1200W
BREAKERS & SWITCHES		=	50W

4.4 Outline for Growth to 200 kW

Growth from the 100kW to 200kW level based on the originally proposed converter design would be somewhat impractical, since adding components in parallel for example, would seriously impact both weight and system complexity. Therefore, it is recommended that the system be designed with 25kW CV units, rather than trying to parallel two of the original 12.5kW units. This results in only about a 25% increase in weight vs. double the weight of two 12.5kW units.

Due to the higher motor mode voltages (compared to the 100kW system) necessary to overcome the increased tether power losses, the total number of CV's has been increased from 8 to 12 in order that individual CV voltage levels stay within reasonable limits. Twelve converters also allow for a 300kW peak power capability for short times.

Figure 4-6 shows a simplified 200kW interface which is identical in concept to the original 100kW interface. Only the number of TCU's and voltages are different. Refer to Figure 4-3 for the appropriate transformer voltages in the 200 kW design concept.

Figure 4-7 shows the electrical equivalent of the 200kW tether system operating in the generator mode. Data identified in Figure 4-7 by an asterisk were obtained from reference 11. Figure 4-8 shows the electrical equivalent of the 200kW tether system operating in the motor mode.

Figure 4-9 shows a type of transformer which could be used to provide the simple transition between generator and motor modes: a servo controlled variable auto-transformer. A smooth transition between motor and generator modes would be made by simply moving the slider contact. The zero current flow point change would be sensed to provide a signal to alter the CV drive mode from converter to rectifier and vice

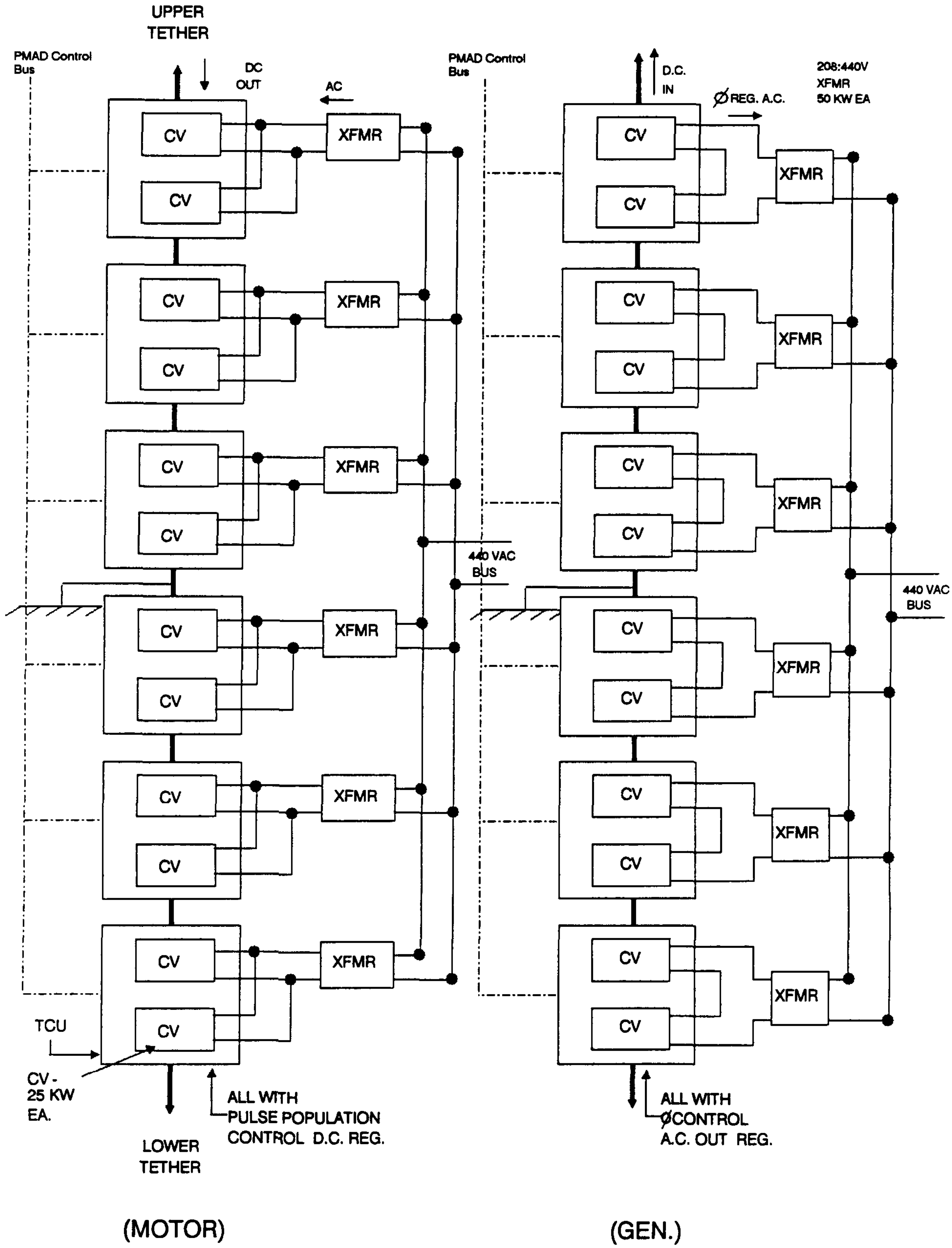
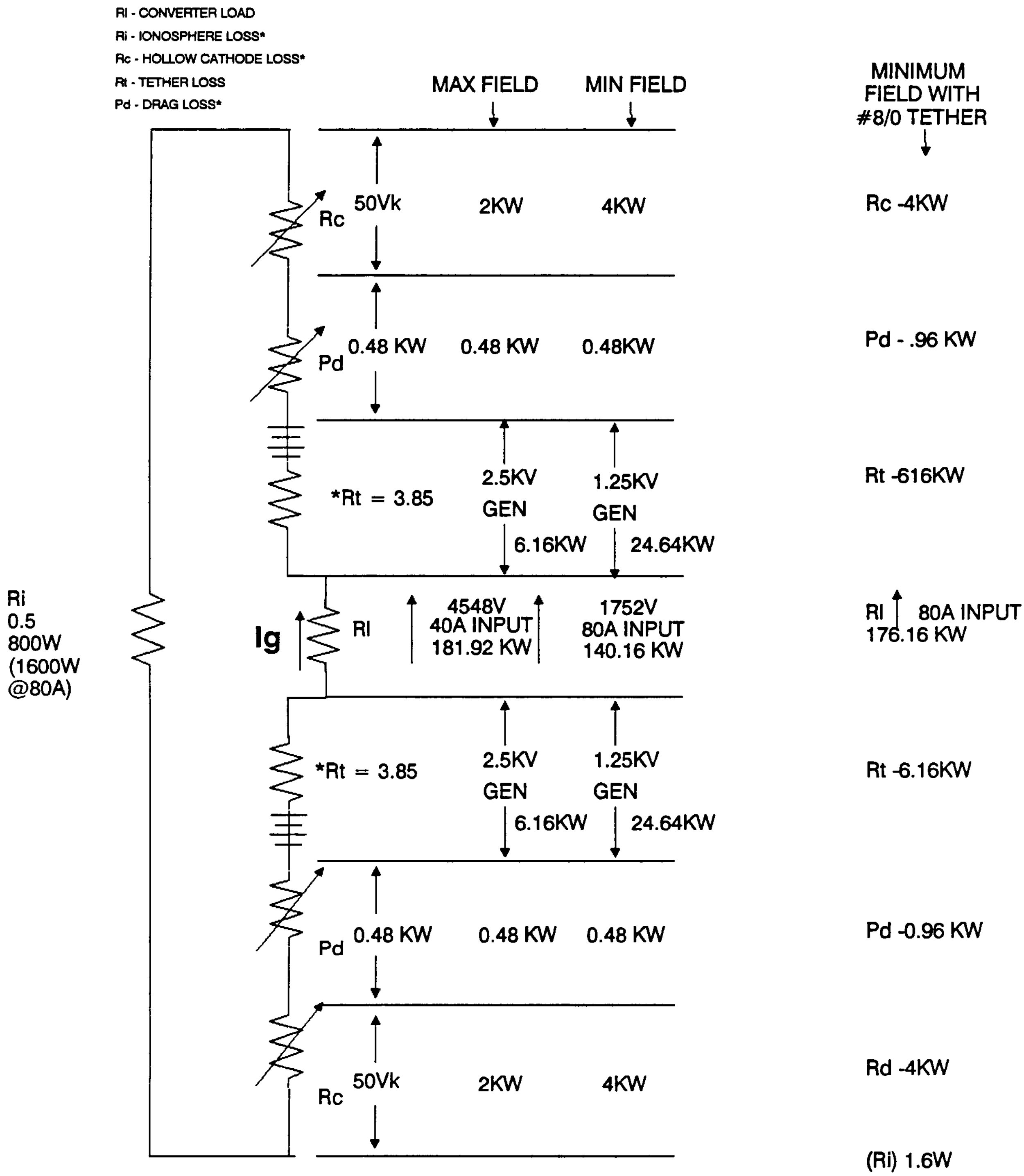


Figure 4-6 Interface for 200 kW System (Simplified)



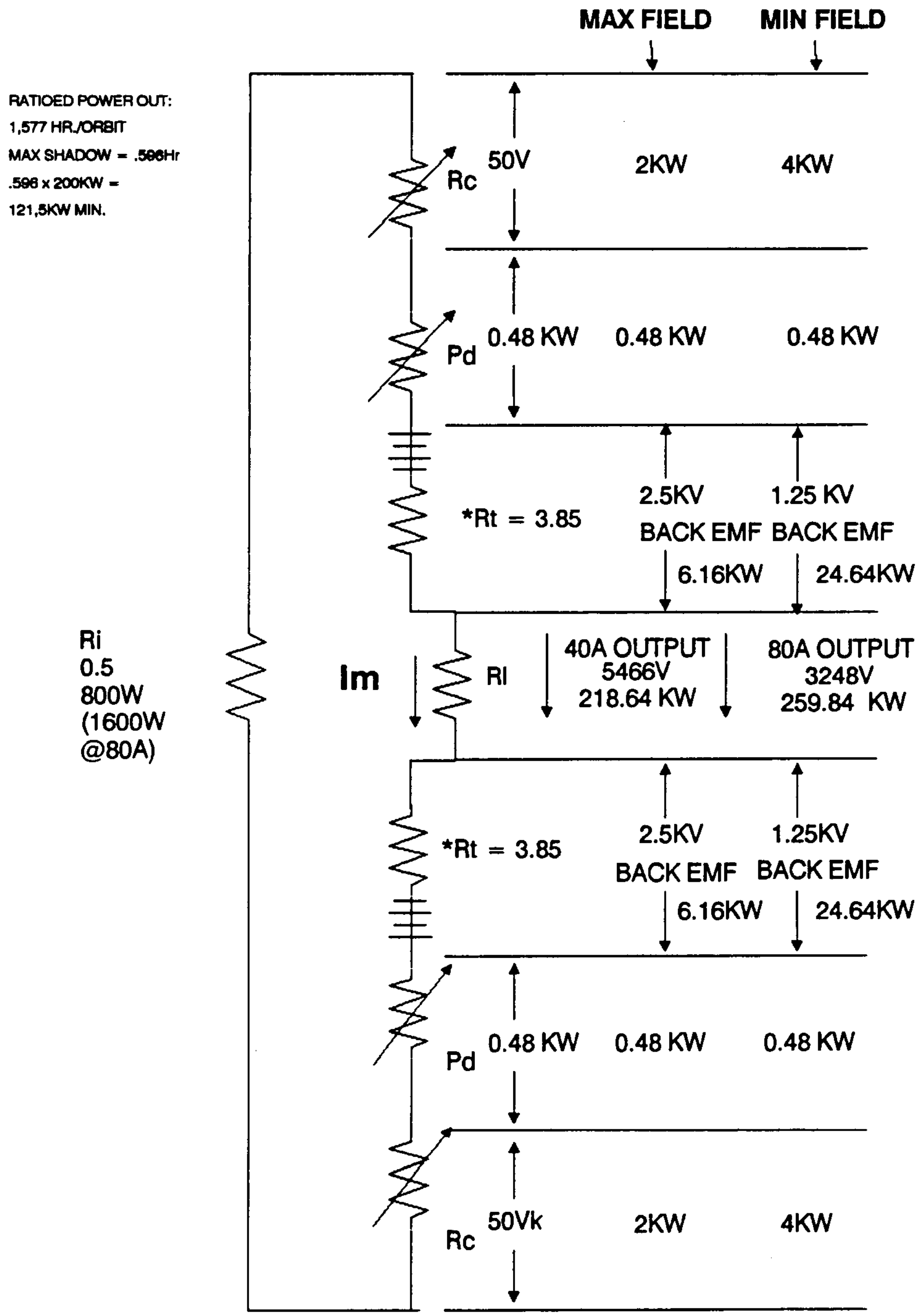
MAX FIELD: (5000 VDC @ 40A)
18.08 KW TOTAL LOSSES @40A
182.92KW TO CONVERTERS (Rl)
= 90.96% 4548V INPUT, Rl = 113.7

MIN. FIELD: (2500 VDC @ 80A)
59.84 KW TOTAL LOSSES @ 80A
140.16 KW TO CONVERTERS (Rl)
= 70.08% 1752V INPUT, Rl = 21.9

MIN. FIELD: (2500 VDC @50a)
28.46 kW LOSSES @ 50A
98.54 kW TO CONVERTERS (Rl)
= 78% 1971V INPUT, Rl = 39.4

23.84 KW TOTAL LOSSES WITH #8/0
TETHER 176.16 KW TO Rl
= 88.1%
2202 V INPUT Rl = 27.5
#8/0 WIRE APPROX. 0.73 IN. DIA.

Figure 4-7 200 kW Tether System - Generator Mode



MAX FIELD: (5452 V @ 40A)
18.08 KW TOTAL LOSSES @40A
218.08 KW TO TETHER
= 91.7% 5452 V OUTPUT

MIN. FIELD: (3248 V @ 80A)
59.84 KW TOTAL LOSSES @ 80A
259.84 KW TO TETHER
76.9% 3248 OUTPUT

MIN. FIELD
36.48 KW LOSS @ 60A
186.48 KW TO TETHER
= 80.4% 3108 V OUT.
AND
26.46 KW LOSS @50A
151.46 KW TO TETHER
= 82.5% 3029 V OUT.

Figure 4-8 200 kW Tether System - Motor Mode

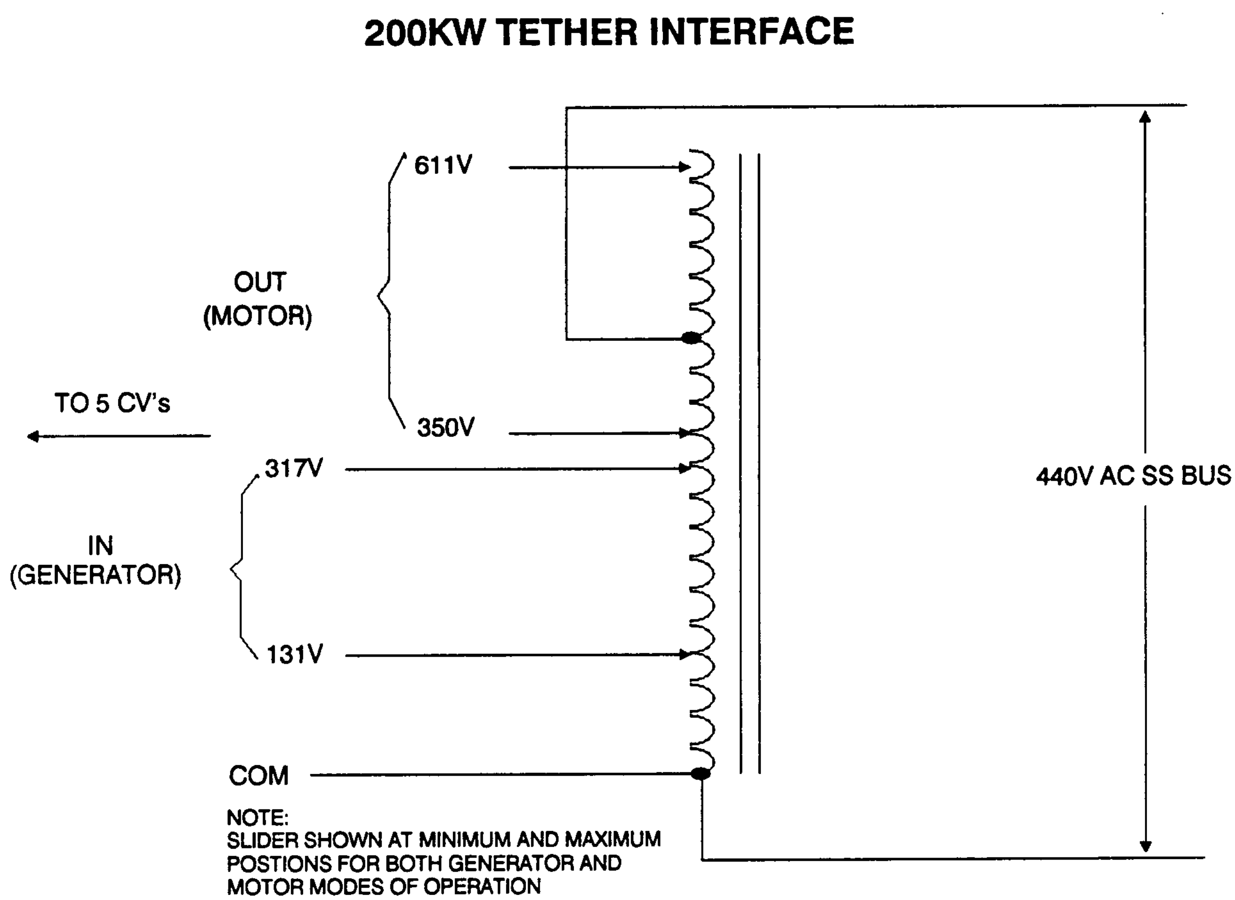


Figure 4-9 Peschel Variable Transformer Interface Concept

versa. All CV's are controlled through the PMAD control bus and therefore will operate in phase with the PMAD bus. Phasor and pulse-population control will no longer be necessary since the auto-transformer takes care of all voltage matching. No switching to re-configure when going from motor it generator mode is required. The CV stack could be reduced to 10, as shown in Figure 4-10.

The variable transformer illustrated in Figure 4-9 could possibly be a 20 kHz version of the presently available Peschel Variable Transformer, manufactured by Hipotronics, Inc., Power Products Div. in Millerton, N.Y. They have built units up to half a megawatt utilizing an exclusive non-shorting (between turns) slider assembly. The qualification status of this transformer is unknown and special control algorithms would have to be developed, but this approach would significantly reduce the complexity of the design.

4.3 Motor/Generator Performance at 50 Amperes

Figures 4-7 and 4-8 include operational efficiency estimates for the ETS at various operating currents. These efficiencies do not account for changes in the tether resistance due to internal heating caused by the higher currents. In the generator mode (Figure 4-7) the system efficiency is estimated to be 78% exclusive of the converter efficiency (94%). In the motor mode (Figure 4-8) the efficiency is 82.5% up to the converter input.

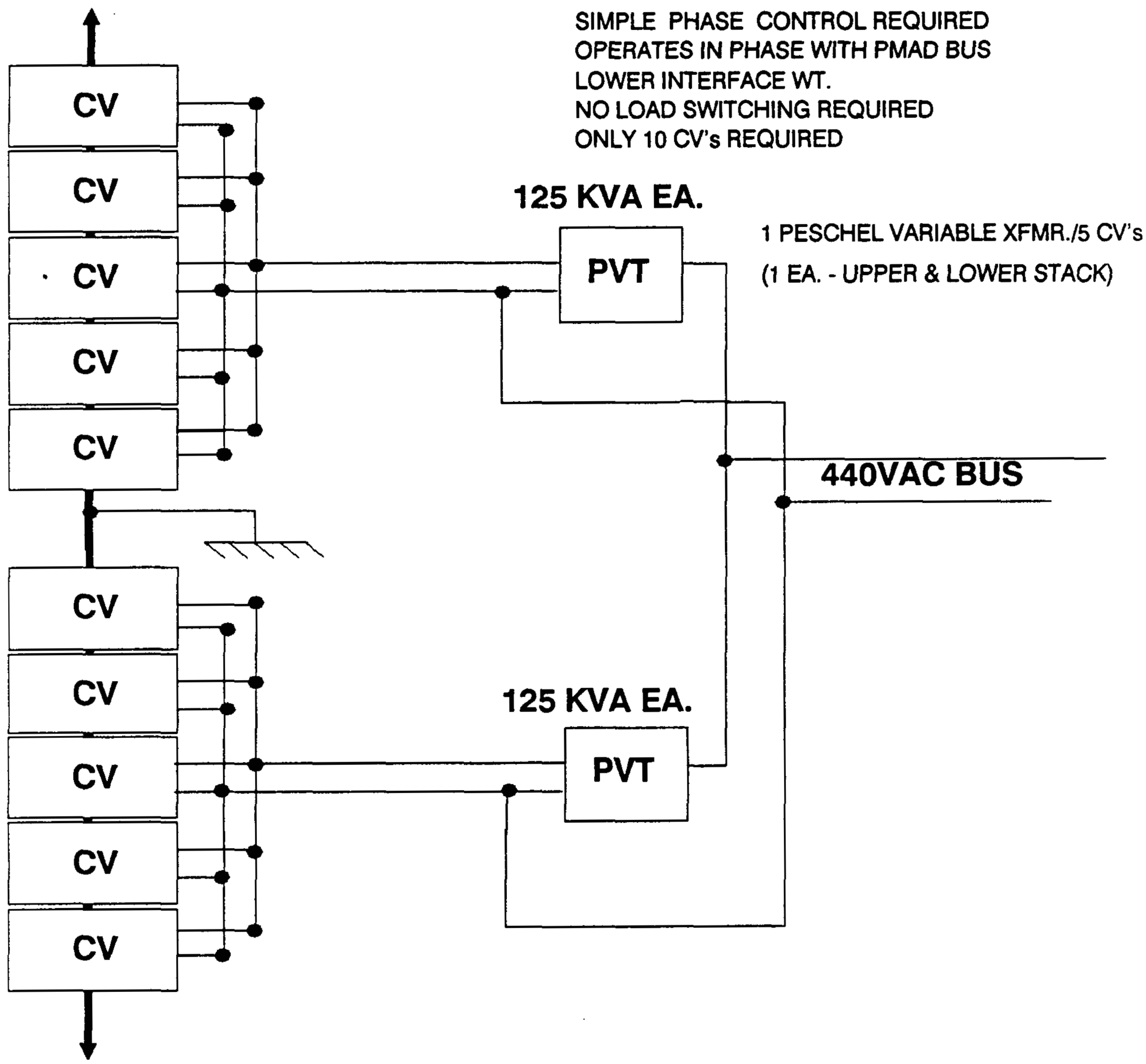


Figure 4-10 Peschel Transformer Could Simplify SS Interface

5 Orbit Perturbation Analysis

5.1 GTOSS Program Modifications

To facilitate the analysis of orbital perturbations caused by electrodynamic tether generator/motor operations several changes were made to the **GTOSS** program code.

The evaluation of various operations schemes required that the day/night power generation scenarios be made more general. For instance, the duration of the daytime thrusting scenario had to be made variable in duration and start time. It was also necessary to add an "energy monitor" to assure that the various operations schemes did not significantly alter the orbital average system energy and introduce orbital perturbations in excess of those attributable to the basic electrodynamic tether operation.

A change was also made to **DTOSS**. The parameters of interest for orbit perturbation analysis were not available on any of the standard page formats supplied (version D1). Therefore, an additional page format was added to output only the information considered critical to evaluating solution stability and orbit perturbation effects.

The following routines were effected by these changes:

Program	Module	Modification
GTOSS	TOSSFQ	Changed
GTOSS	TOSSH3	Added
DTOSS	XPGDEF	Changed
DTOSS	XPGHD	Changed
DTOSS	XPGLN	Changed
DTOSS	YPDF55	Added
DTOSS	YPDFEL1	Added
DTOSS	YPHD55	Added
DTOSS	YPLN55	Added

The modification to the standard day/night power generation option was made by allowing a third type of power generation scenario. The type "3" scenario was implemented by making code changes to routine **TOSSFQ** and adding routine **TOSSH3.** This latter routine is modeled after the standard **TOSS** routine **TOSSH2.** The major changes involve the interpretation of the scenario input blocks and the addition of orbital state monitors for energy and time from orbital sunrise.

The scenario input for type "3" day/night operations are just like the standard type "2" inputs except the "Ending Power Level" parameter is used to specify how many seconds to delay after orbit sunrise before starting motor mode operations. Motor operations are terminated when the energy monitor (explained below) crosses zero or orbit sunset is reached.

The energy monitor is zeroed at the beginning of a run and constantly updates the changes in orbital energy during the generator/motor operations. The change in orbital energy is approximated by the trapezoidal integration of power (in or out of tether) with respect to time. The monitor is programmed to stop motor operations when the system energy crosses zero. Motor/generator operations are inhibited until the first orbital sunset. This guarantees that the first changes in orbital energy will be due to generator operation and eliminates the need to account for partial orbit effects in the energy monitor.

In order to establish the proper time in the orbit to start motor operations a special "event timer" was programmed into the system. This event timer is reset to the current integration time at each orbit sunrise. It is then used in the motor operations code to determine if the proper delay time has been reached to start operations. The delay time, as specified in the type "3" scenario input, is compared to the difference between the current **GTOSS** integration time and the time stored in the event timer. When the proper delay time is reached motor operations begin.

5.2 Analysis Results

Using the modified **GTOSS/DTOSS** programs several different simulations were run. The purpose of these simulations was to assess the relationship between day/night cycling periods and the perturbations introduced into the SS orbit. It was hoped that this information would provide insight into generator/motor scenarios that would minimize orbit perturbations while still allowing efficient use of the electrodynamic tether system for energy storage functions.

Figure 5-1 illustrates how the generator/motor simulations were setup. The generator mode was always assumed to last throughout the shadowed portion of the orbit at a constant 200 kW level. The power level, duration, and start time of the motor operations were allowed to vary in each run. The time between orbital sunrise and the beginning of motor operations is referred to as "delay". The delay is input to the program through the type "3" generation options added to **GTOSS.**

The initial orbital scenarios analyzed have served to bracket the expected response of other possible scenarios for day/night operations. That is all other motor/generator scenarios that are strictly dependent on day/night operation should fall within the performance envelope of the scenarios analyzed. This envelope does not include those scenarios that allow power generation during daylight periods or motor mode operations during shadowed conditions. The assumed electrodynamic tether system configuration consists of two 10 km tethers attached to a 100,000 kg SS. One tether is deployed upward and one downward from the SS. Each tether has an end-mass of 1200 kg. The initial SS orbit is assumed to be 500 km in altitude at an inclination of 28.5 degrees.

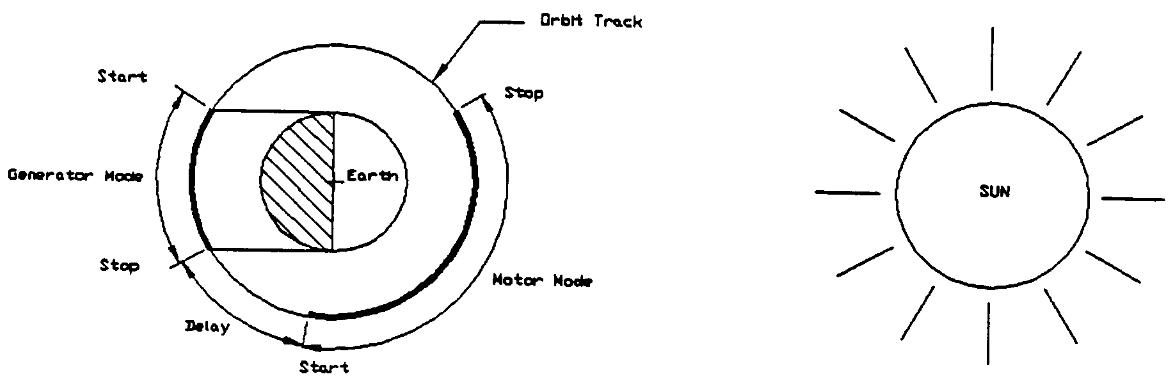


Figure 5-1 Day/Night Scenario for Orbit Analysis

The standard **GTOSS**-type day/night cycle is used as the reference operation scenario. The motor mode power level is set just high enough to allow the recovery of all the energy "lost" in generator mode operation in the available daylight portion of one orbit. This configuration will allow the SS power system to be sized for minimum "excess" power. Excess power is defined as that power available during daylight periods after all SS load requirements and conversion losses have been met. The current through the electrodynamic tether system is limited to 40 amperes for all cases.

Comparison analyses were then done using orbits that allowed the motor mode tether currents to run at maximum levels (40 amperes) to regain the "lost" energy in a minimum time. After the energy is regained the system is shutdown until the start of the next eclipse period. Variations on this theme were analyzed by delaying the start of the motor mode operations after orbit sunrise.

Figures 5-2 and 5-3 present a summary of eccentricity and apogee/perigee perturbations produced by the various day/night scenarios. Three delay simulations plus the reference scenario are presented. The three delay times are zero, 500, 1500 seconds. This represents maximum thrusting (limited by the 40 ampere maximum current) starting at orbit dawn, 500 seconds after orbit dawn, and 1500 seconds after dawn. This latter delay results in maximum thrusting occurring as late in the orbit as possible to allow all energy to be recovered just prior to entering the Earth's shadow for the next generator cycle.

These figures indicate that the minimum level of orbit perturbations correspond to the continuous daylight thrusting mode. The maximum perturbation roughly corresponds to thrusting opposite the generator drag cycle, and the dawn/dusk thrusting modes produce approximately the same level of variations in the orbit parameters.

It should be noted that while these simulations only cover 10 hours, longer simulations have produced similar results[16]. One possible long term effect that is not considered in

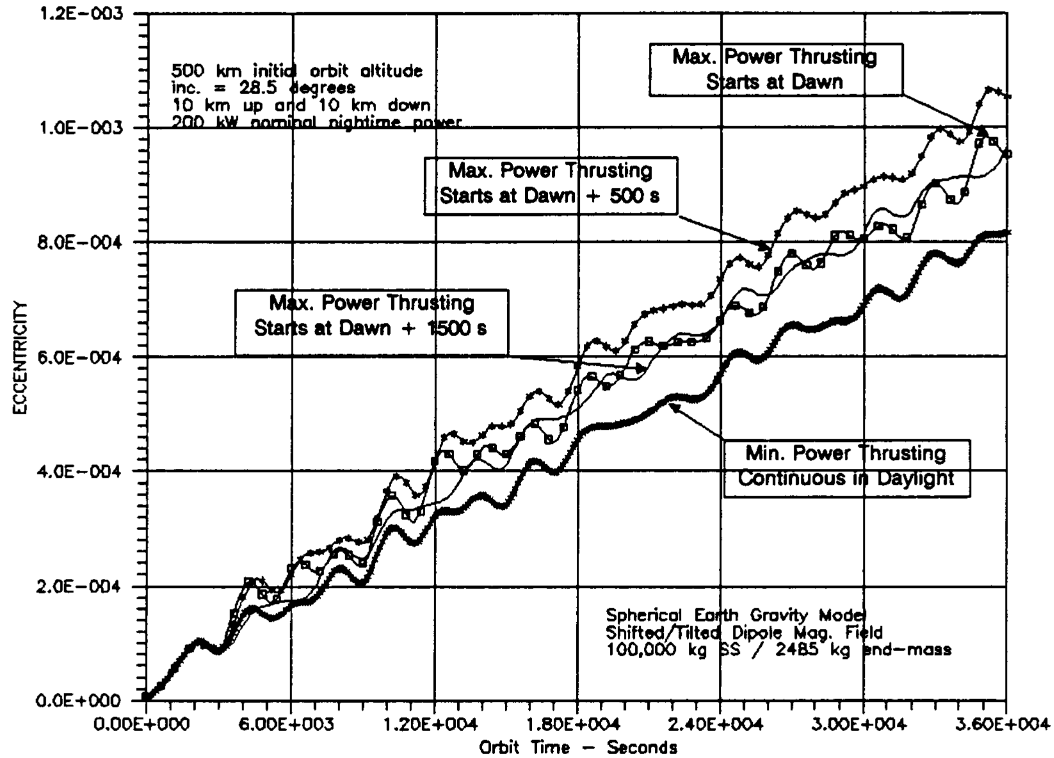


Figure 5-2 Eccentricity Perturbation Results

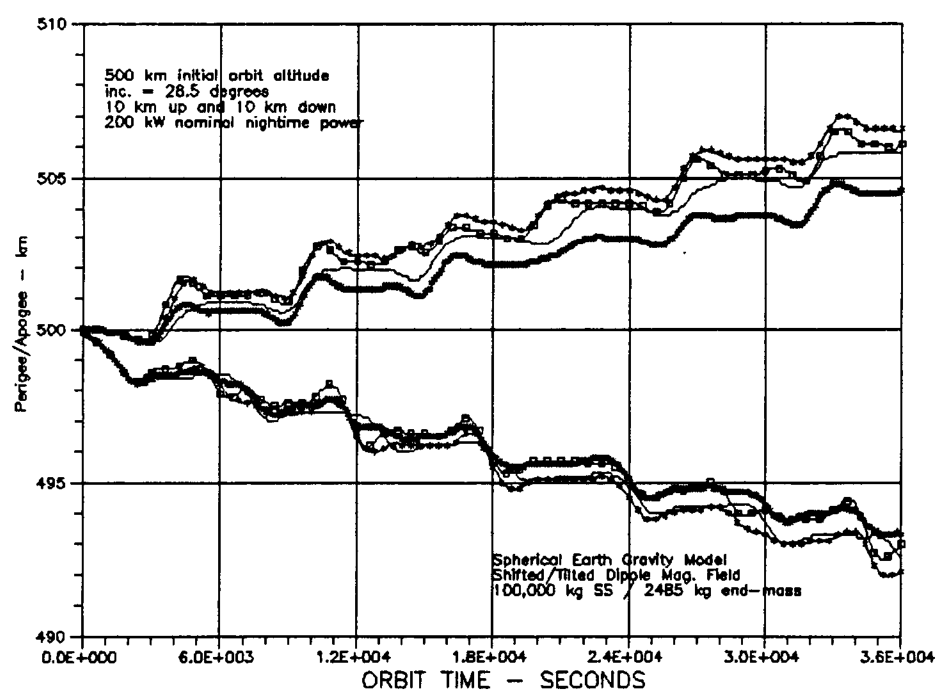


Figure 5-3 Apogee/Perigee Perturbation Results

these simulations is an oblate earth model for gravity. This type of gravity model will produce rotation in the line-of-apsides and over an extended period (several weeks) the orbit geometry should change enough to start returning the orbit to its original shape. However, the orbit may be severely distorted before this can happen.

5.3 Discussion of Perturbation Control Techniques

The analysis results discussed above allow some conclusions to be drawn about control strategies for electrodynamic tether systems (ETS) being employed as energy storage devices on the Space Station.

The basic problem with the generator/motor mode operations is that drag is produced at apogee (which lowers perigee) and thrust is produced at perigee (which raises apogee) for many orbits, at least to a first approximation. This results in an orbit with a constantly increasing eccentricity, decreasing perigee altitude, and increasing apogee altitude. The rotation of the line-of-apsides should eventually moderate this condition, but not until significant orbital perturbations have occurred.

Modifications to the standard, constant power, scenario will produce even larger perturbations if the ETS is limited to generator modes during eclipses and motor modes at other times (this limitation seems reasonable from an efficiency standpoint).

One approach to controlling the orbit parameters would be to introduce a generation period into the normal motor (daylight) operation time line. This would produce a drag force at perigee and lower the apogee. The solar arrays would have to provide the required additional energy for this maneuver, and the tether converters may need to be redesigned to handle larger current flows during motor operations.

5.4 Needed Modifications to GTOSS

Early attempts to simulate various orbit operations scenarios with GTOSS pointed out several limitations in the current version (D1) that will need to be eliminated if this program is to be used for this type of analysis in the future. This program is amazingly versatile and well documented, so the changes should be relatively easy to incorporate. The following is a brief list of the recommended modifications and added features.

- Allow the environment models (gravity,magnetic fields...) to be updated at a frequency other than the integration interval. It is very desireable to use the highest fidelity models available, but the values may not needed to be updated every integration step.

- Long term simulations of day/night operations will require the position of the Sun to be updated as a function of time.

- A useful utility for use with GTOSS would be a program to return appropriate initial conditions for the reference point based on the input of classical orbital parameters. Another possibility would be to change GTOSS to accept classical orbital parameters (i.e. inclination, altitude...) for initializing the reference point.

- The power generation scenarios need to be made much more general. Real orbital operations simulation will need the ability to input system power requirements as a function of time and/or specific events. Event flag and/or timers will be required to record specific happenings such as; entering the Earths shadow, exiting the Earth's shadow, passing a certain longitude and/or latitude on the Earth, passing a certain orbit altitude, etc... The motor mode scenarios need to allow for non-continuous operation, and their duration needs to be coupled to orbital energy changes. The power available for motor operations needs to be related to subsystem power requirements and solar array operational parameters.

6 IxB Phasing for Libration Control

6.1 IxB Control Overview

The IxB control problem involves the position control of an electrodynamic tether by varying the current in a conducting tether. Controlling the magnitude and polarity of the current in the tether makes the system act as a generator or a motor, as illustrated in Figure 6-1. This means that the tether system can be made to alternately thrust or drag. The amount of

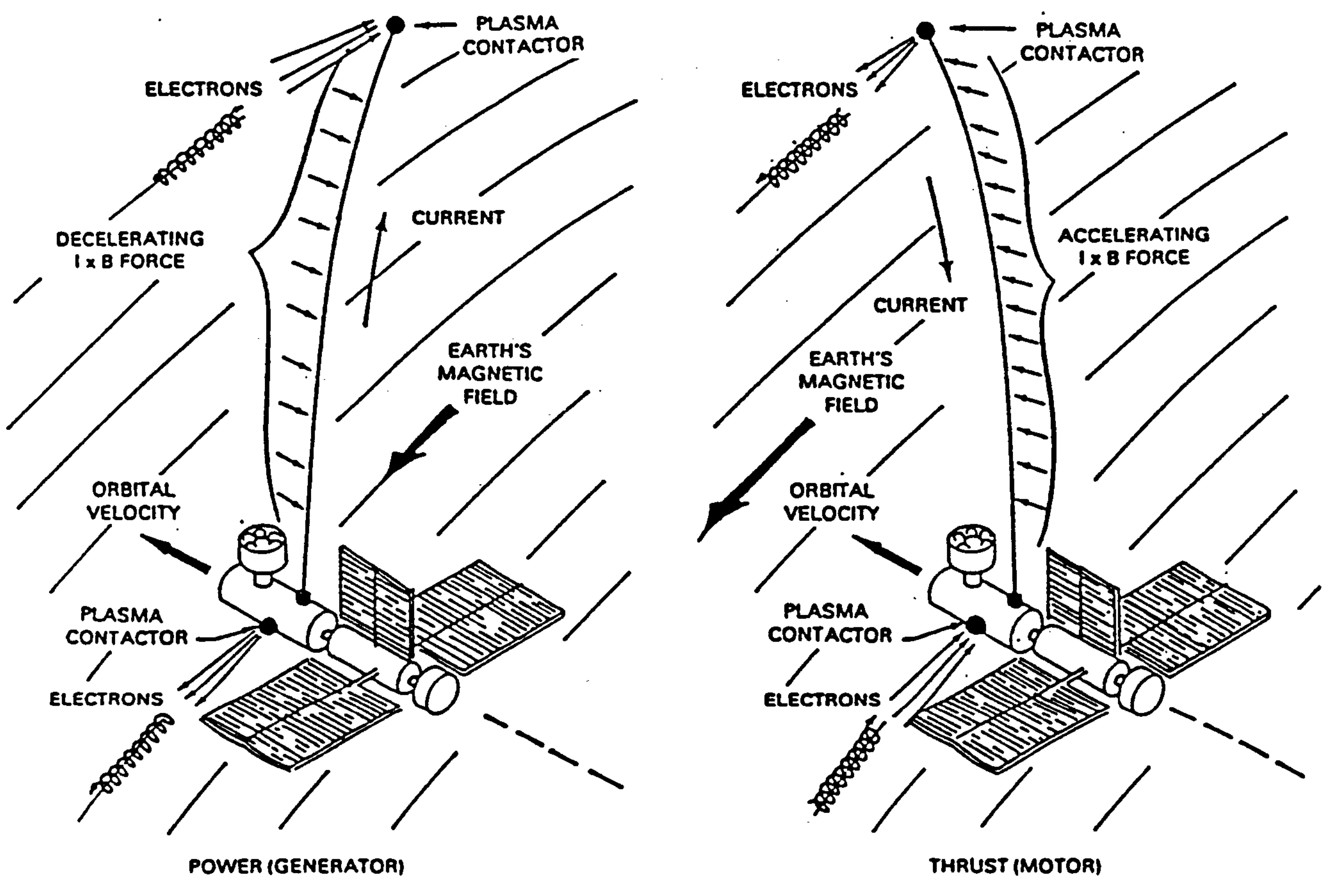


Figure 6-1 Electrodynamic Tether in Thrust/Generator Modes

thrust/drag depends on the orbital position and rate, the magnetic field strength, the tether length and the current flowing in the tether. For the purpose of discussing the control system it is assumed that the tether is already deployed in a nominal position about local vertical. The primary purpose of the control is to confine the tether motion about the local vertical within some pre-defined conical limits. The conical limits are based on the desired limitations of the in-plane and out-of-plane libration angles and, possibly, the mission phase. For instance, it may be desireable to completely arrest the tether libration during rendezvous with the OMV for end-mass servicing. It is desired to develop an optimal controller that minimizes the impact on any desired thrusting which may be needed for orbit maneuvering of the host vehicle. Figure 6-2 illustrates the tether control concept.

6.2 Tether Satellite System Modeling Approach

The equations of motion for the in-plane and out-of-plane librations of a tether-satellite system are rather complex[17]. The equations of motion are very non-linear and the in-plane and out-of-plane libration angles are highly coupled. Because the angular excursions of interest about the local vertical are normally small (within 10 degrees), small angle approximations are appropriate. Also, it is desireable to linearize the equations of motion about some operating point in order to utilize available computer aided control system design tools. The effect of any significant non-linearities can be later investigated by employing time simulations. A basic tether/satellite system model must include at least the following:

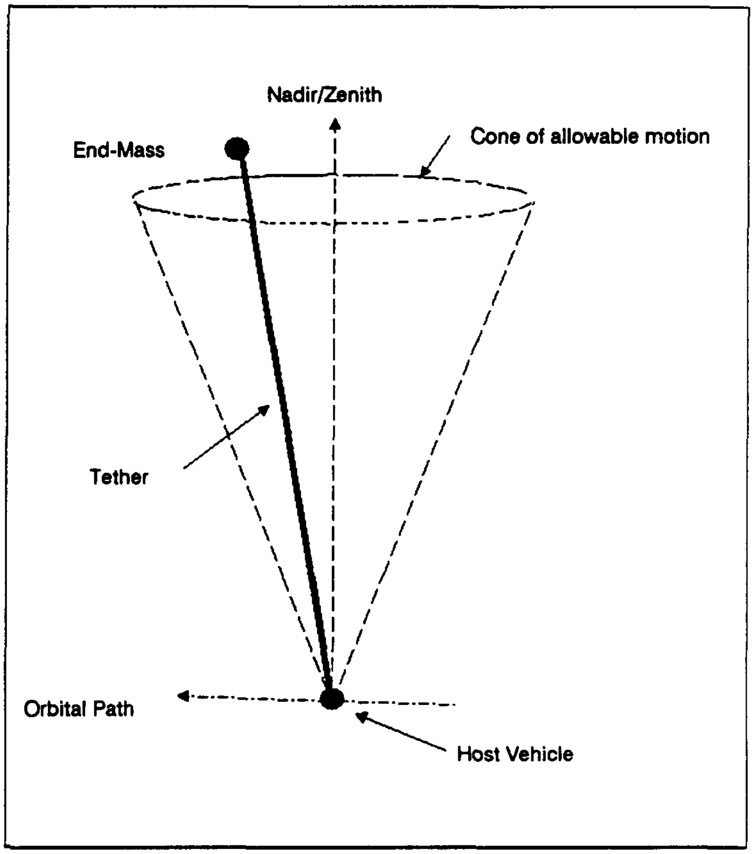


Figure 6-2 Tether Control Concept

(1) Orbit motion of system center of mass about earth.

(2) Tether and end mass connected by a simple rigid massless tether.

(3) Tether thrust force model.

(4) Magnetic field strength model.

The above model description is adequate for initial test studies and additional complexity and detail can be added if desired.

6.3 Control System Design Approach.

The general complexity of the tether satellite system makes analysis using classical control methods (PID controllers, lead-lag networks, etc.) difficult. A more fruitful approach is to use a state variable (modern control) formulation since it permits easier examination of multi-variable (multi-input, multi-output) control systems. The state vector should include the following variables which represent sensor measurements:

(1) In-plane libration position.

(2) In-plane libration velocity.

(3) Out-of-plane libration position.

(4) Out-of-plane libration velocity.

(5) In-orbit position of satellite.

(6) Magnetic field strength.

A candidate control system approach is to use a Kalman filter which provides both closed loop and adaptive processor compensation. The adaptive processor involves the comparison of the error signal of a process model of the tether dynamics and the actual system measured parameters in order to adjust the control system parameters.

6.4 Kalman Filter Description.

A Kalman filter is a reasonable choice since it can be employed in a number of different modes. It can perform prediction, filtering, and smoothing of data as well as being used to solve the estimation, identification, and optimization control system problems. A Kalman filter produces the best estimate ("best" in a minimum variance sense) of the state vector by using sensor measurement information. A "mean" state estimate is obtained by using "a-priori" (prior to available measurement) and "a- posteriori" (after a measurement is available) state covariances to produce a Kalman gain. This gain is then used to weight the subsequent state estimates so that the difference of the predicted measurement of the process model and the actual system measurement data is reduced. In other words, the model begins to accurately predict the output measurement. In this fashion the Kalman filter permits estimation prediction) based upon measured data resulting in an optimal control strategy. Figure 6-3 illustrates the basic Kalman control process.

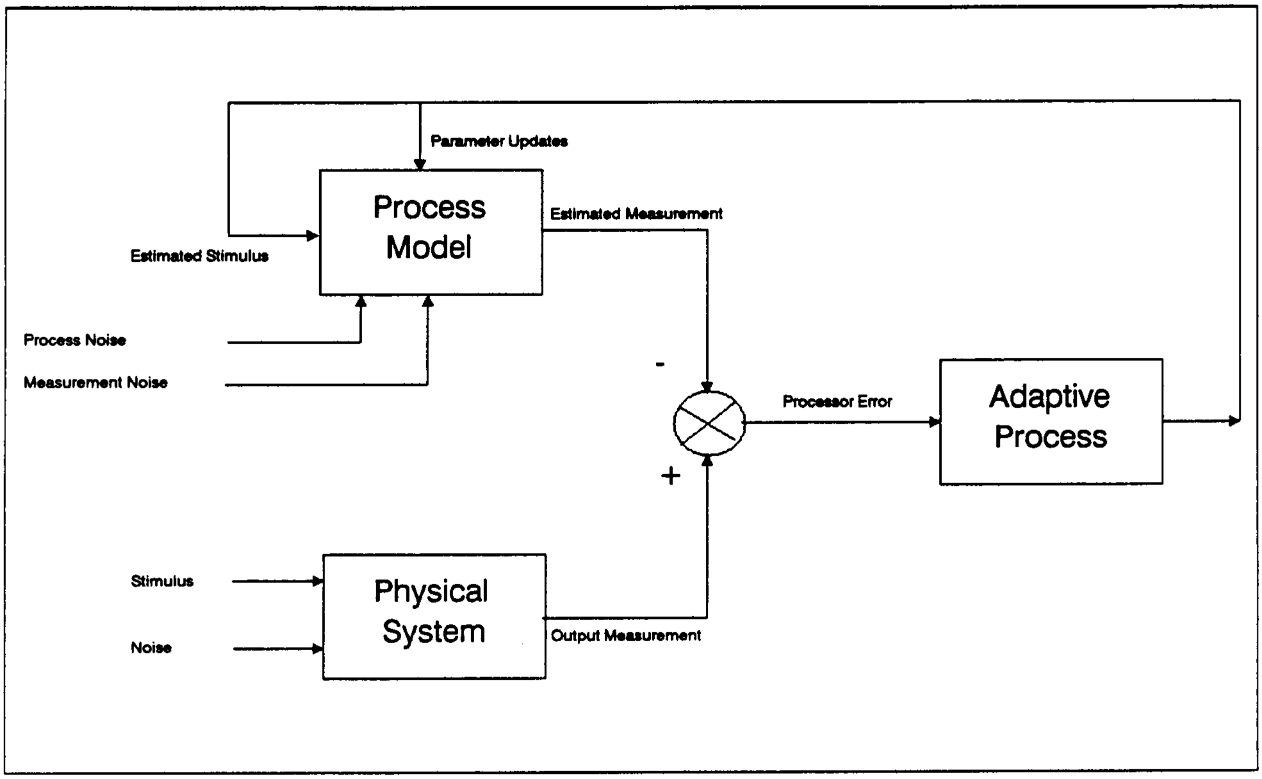


Figure 6-3 Overview of Adaptive Control Process

Some desirable features of the Kalman filter are:

(1) Stochastic state equation - This permits the state equation to include a random part that allows for modeling uncertainties.

(2) Stochastic measurement equation - This permits the measurement equation to include a random part that allows for measurement accuracies or uncertainties.

(3) Easily implemented into software - This permits flexibility to change algorithms and allows easy incorporation into other computer software, e.g. GTOSS, RTOSS.

6.5 An Approach to IxB Control Studies

When the control system and the tether satellite system dynamics have been incorporated into a mathematical simulation, there are two main aspects to be studied; stability of the controlled tether system, and the efficiency of the controlled tether system.

Stability is always of concern in the development of a control system as it is an essential requirement. Because some of the dynamics of the tether system are at low frequency it may be difficult to ascertain slow growing instabilities from short computer simulation runs. Longer computer runs may be necessary which are both time consuming and costly.

One alternative would be to use Lyapunov function analysis to examine the energy of the system for stability. However, there is always the possibility that the Lyapunov analysis may be inconclusive if a Lyapunov function cannot be found.

The effect of the control system on the useful maneuvering thrust produced by the system is also of concern. An analysis needs to be performed to see how much degradation (if any) of thrusting results from the inclusion of a control system. The "efficiency" of the controlled system could be defined in any number of ways. One useful definition would be the ratio of the power used to accomplish a given maneuver using the Kalman controller and the power used by an uncontrolled tether.

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