DK-2215-2 to TIC

Contract No. DE-AC02-81RA50292
with Westinghouse Electric Corporation
Conference Report: 1, September 1982

MASTER

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COVER

DISCLAIMER

DOE/RA/50292--T1

AGENDA
DOUBLY FED MACHINE REVIEW
1 SEPTEMBER 1982

DOE/RA/50292--T1

DE83 002492

Westinghouse Conference Room
9th Floor, 1801 K St. N.W.
Washington, D.C.
(Metro Station - Farragut West)

TIME	SPEAKER	INTRODUCTION
9:30	DOE	Introduction
9:45	ANDERSEN	Project Outline and Status
		TASKS 1 & 2 - SYSTEMS INVESTIGATION & TRADE-OFFs
9:55	ANDERSEN	Overview and Summary
10:15	MUTONE	Performance Update
		TASK 3 - EXPERIMENTAL VERIFICATION
10:40	ANDERSEN	Objective and Introduction
10:55	MUTONE	Supervisory Control Description
11:30	HUGHES	Cycloconverter Control Description
12:00		--- LUNCH ---
1:00	HUGHES	Controls Verification Approach
1:30	HUGHES	Machine/System Verification Approach
2:00	ANDERSEN	Summary
2:20	DOE	Identification of Action Items
2:30		--- ADJOURN ---

CONTRACT No. DE-AC02-81RA50292
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TASK 1 - SYSTEM INVESTIGATIONS

- 1.1 Review of Technical Papers
- 1.2 Machine Concept Investigation
- 1.3 Simulation of the Overall System
- 1.4 Conceptual System Design

TASK 2 - TRADE-OFF EVALUATION AND APPROVAL

- 2.1 Trade-Off Evaluation
- 2.2 Approval of Continuation

TASK 3 - EXPERIMENTAL CONCEPT VERIFICATION

- 3.1 Verification Plan
- 3.2 Controls Verification
- 3.3 Machine and System Verification
- 3.4 Evaluation

TASK 4 - FINDINGS AND REPORTING

- 4.1 Findings
- 4.2 Reporting

Figure 1.4-1. Work Breakdown Structure

DOE Form CR-535
(1-78)

U.S. DEPARTMENT OF ENERGY

MILESTONE SCHEDULE AND STATUS REPORT

1. Contract Identification: INVESTIGATION OF DOUBLY-FED MACHINE FOR VARIABLE SPEED APPLICATIONS	2. Reporting Period: March 1982 through July 1983	3. Contract Number: DE-AC02-81RA50292
4. Contractor (name, address): Westinghouse Electric Corporation, Advanced Energy Systems Division, Post Office Box 10864, Pittsburgh, PA 15236		5. Contract Start Date: September 1, 1981 6. Contract Completion Date: October 31, 1981

9. Fiscal Years and Months: FY 83

7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	10. Percent Complete a) Planned	b) Actual
	PHASE II																									
	Task 3																									
3.1	Verification Plan																									
3.2	Controls Verification																									
3.3.1	Machine & Sys. Ver.-design																									
3.4	Evaluation																									
	PHASE III																									
3.3.2	Machine & Sys. Ver.-test																									
3.4	Evaluation																									
	Task 4																									
4.1	Findings																									
4.2	Technical Reporting																									

11. Remarks: Schedule Revised 2/17/82

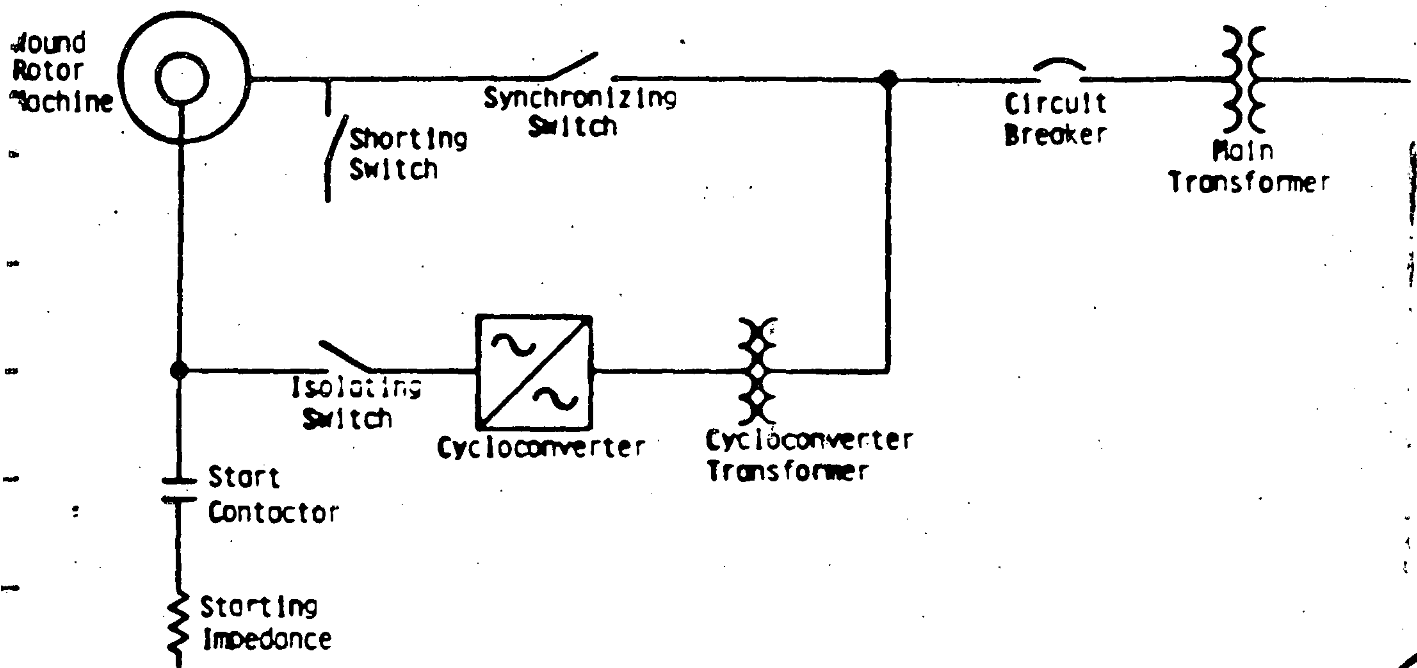
12. Signature of Contractor's Project Manager and Date	13. Signature of Government Technical Representative and Date

1.1 LITERATURE REVIEW

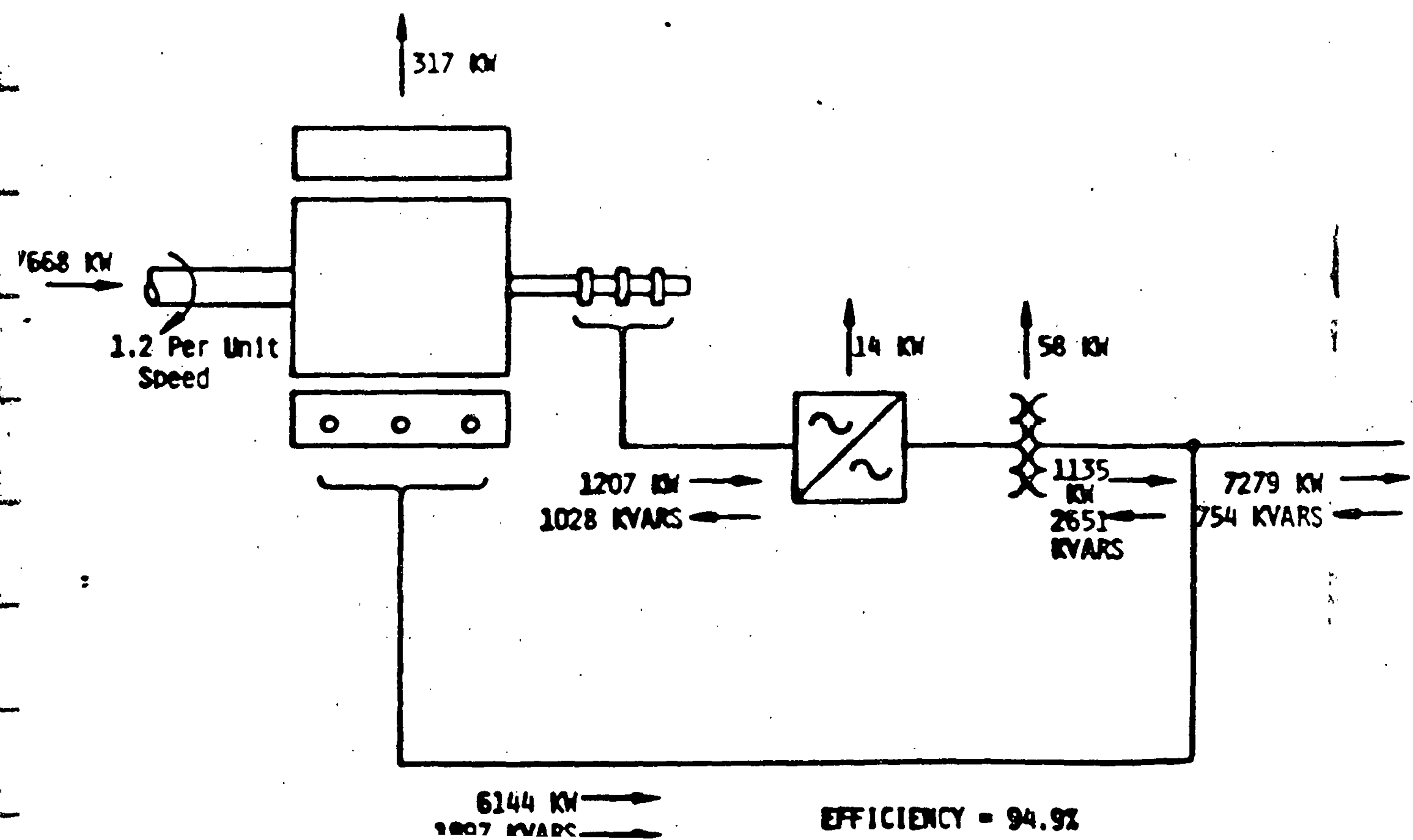
OBJECTIVES: Determine Current State-of-the-Art in the Following Areas:

- Doubly-Fed Machine
  - Design
  - Analysis
- Power Electronics;Rotor Circuit Control
  - Design
  - Stability
  - Analysis
- Applications
  - Wind-Vertical Axis
  - Wind-Horizontal Axis
  - Hydro
  - Other

DOUBLY-FED MACHINE BASELINE CONFIGURATION



DOUBLY-FED MACHINE, BASELINE KW/KVAR DISTRIBUTION EXAMPLE



CONCEPTUAL STUDIES OF VARIABLE SPEED GENERATION SYSTEMS

RESPONSIBLE ORGANIZATION	TARGET APPLICATIONS	FAVORED CONFIGURATION	COMMENTS
BuRec of Reclamation	Hydro	DFM/Cycloconverter	0.5 hp demo 197_ 30 hp demo 1982
Westinghouse for DOE	Wind/Hydro	DFM/Cycloconverter	500 hp demo 1983
NASA LeRC for DOE	Wind	DFM/Cycloconverter	300 kW demo 1982
Bogue for NASA	Wind	DFM/Proprietary	Status Uncertain
T.A. Lipo - Purdue for DOE	Wind	DFM/Cycloconverter	Study Only
Jayadev/Ramakumar Oklahoma State Univ. for DOE	Wind	Field Modulated Generator/Rect/Inverter	Study Only Requires triple tandem machines
Hian Lauw Oregon State Univ. for BPA	Hydro	DFM/ Schwarz Converter	Study only Complex 10 khz link in AC-DC Conversion
Siemens for FRG	Wind	DFM/Cycloconverter Cycloconverter	3 MW Growian I application
PTI	Wind	-	Key benefit for wind turbines found to be dynamic isolation of turbine/electrical network interface
BPA	Hydro	-	Underway

ACTIVE LARGE VARIABLE SPEED WIND TURBINE PROJECTS

PROJECT FIRST OP.	RESP. ORG.	SIZE	RATING	TYPE	COMMENTS
SWT-3 1980	Schachle/ Bendix	165 ft	3 MW	Hydraulic/ Synchronous	Now being converted to single speed - poor hydraulics relibility performance
Growian II 1981 1985?	MBB (FRG)	48m 145m	350 KW 5 MW	Synchronous/ Full Conversion	Single bladed turbine
Growian I 1982	MAN (FRG)	100m	3 MW	DFM/ Cycloconverter	Variable speed for gust absorption, allow slow speed full span pitch control
Orkney ~1982 ~1985	WEG (UK)	20m 60m	250 kW 3 MW	Synchronous/ Full Conversion	2:1 operating speed ratio on prototype
MOD-0 1983	NASA(LeRC)	125 ft	300 kW	DFM/ Cycloconverter	3:1 operational speed ratio
MOD-5B 1984	Boeing	420 ft	7.2 MW	DFM/ Cycloconverter	1.67:1 operating speed ratio

MAJOR FACTORS CITED IN SELECTION OF VARIABLE SPEED GENERATION FOR LARGE WIND TURBINES

1. Dynamic smoothing of "np" torque pulsations
2. Dynamic absorption and smoothing of wind gust transients
3. Relief of requirements for high speed/precise pitch control
4. Reduction in transient torque margin for costly drive train components
5. Enables consideration of single bladed rotor
6. Enables consideration of reduction or elimination of active blade lift/drag control
7. Improved energy capture over a range of wind speeds

2.1 TRADE-OFF EVALUATION

OBJECTIVE: Compare DFM based system with actual constant speed system in following respects

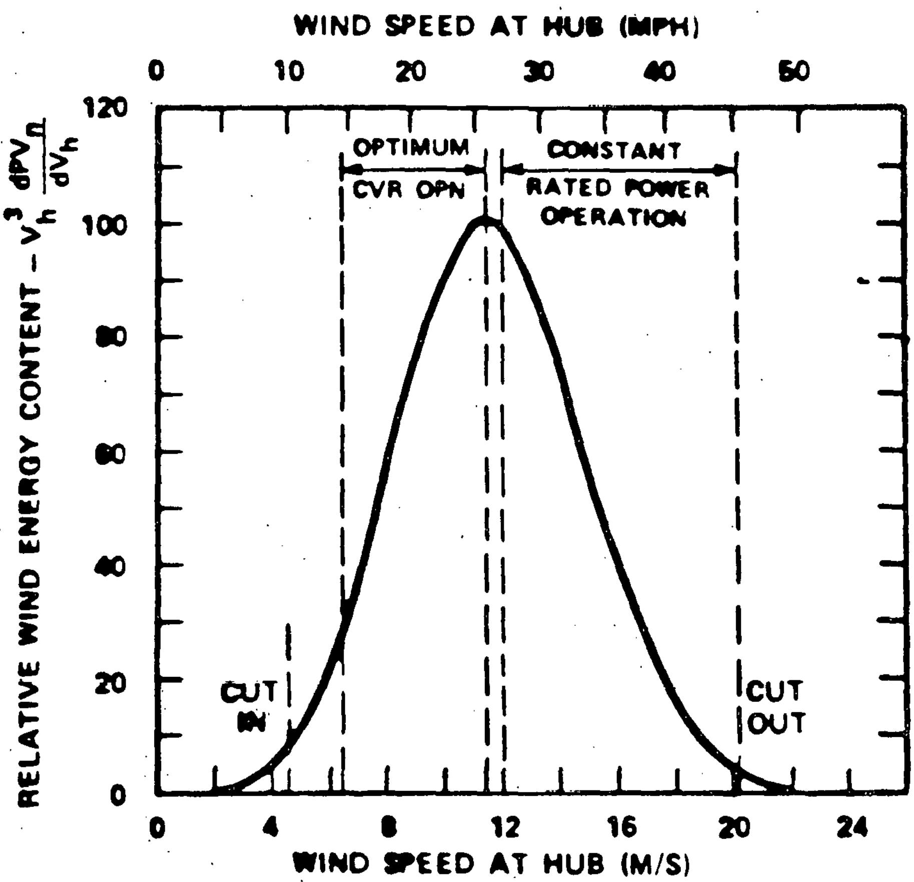
- 1. Energy Capture
- 2. Electrical and Drive Train Efficiency
- 3. Operational Considerations
- 4. Performance
- 5. Cost

2.1 TRADE-OFF EVALUATION

1. ENERGY CAPTURE

- Wind Systems
  - Velocity Duration Curves
  - Aerodynamic Efficiency
    - Horizontal Axis
    - Vertical Axis Darrieus

- HYDRO SYSTEMS
  - Flow Duration Curves
  - System Head/Flow Characteristics
  - Hydrodynamic Efficiency
    - Propellor type turbine
    - Full Francis turbine
    - Fixed vane turbine
    - Pelton wheel


WIND SPEED AT HUB (MPH)
0
10
20
30
40
50
120
100
80
60
40
20
0
OPTIMUM
CVR OPN
CONSTANT
RATED POWER
OPERATION
CUT
IN
CUT
OUT
RELATIVE WIND ENERGY CONTENT – $V_h^3 \frac{dPV_n}{dV_h}$
0
4
8
12
16
20
24
WIND SPEED AT HUB (M/S)

WIND SPEED RAMP FROM 5 MPH TO 40 MPH, PITCH CONTROL

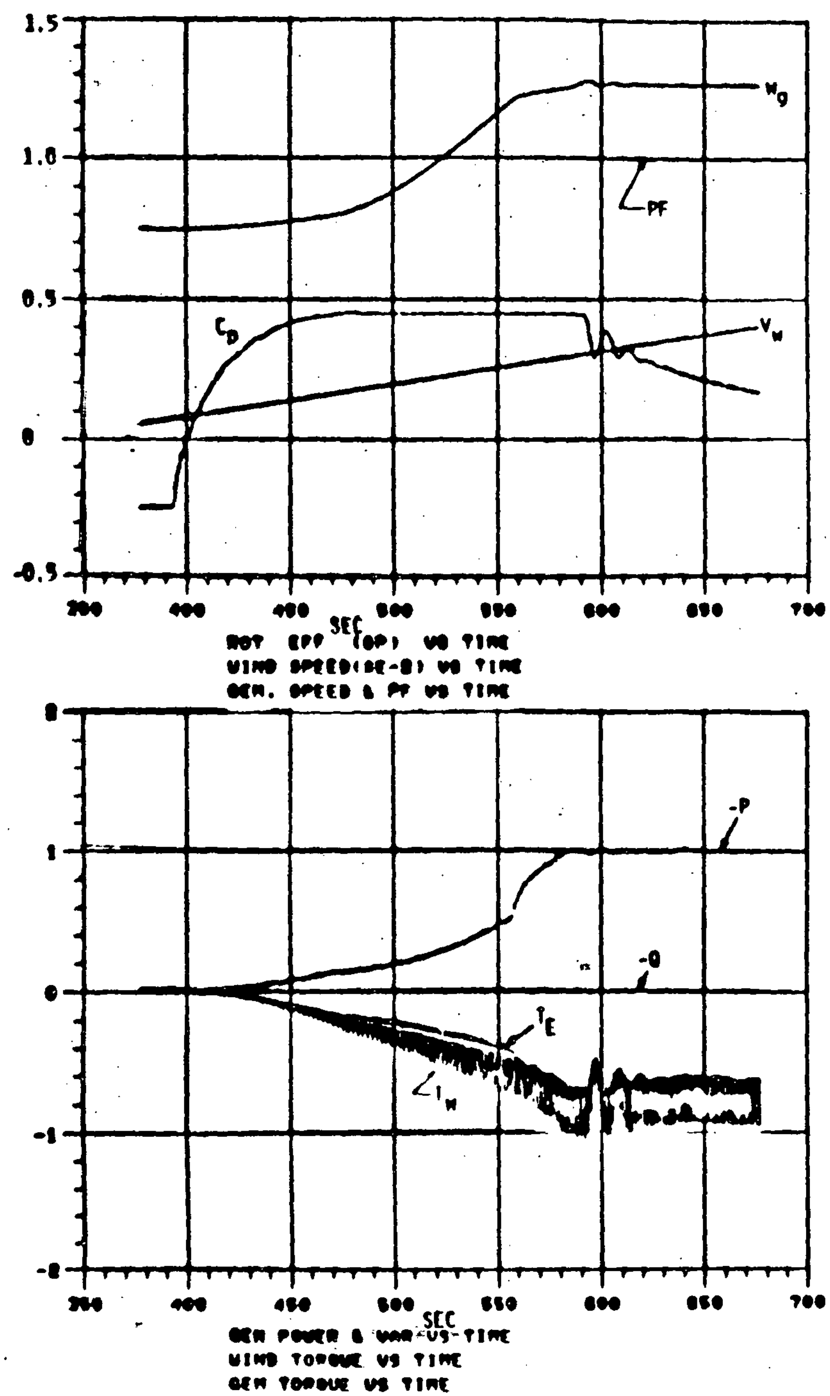
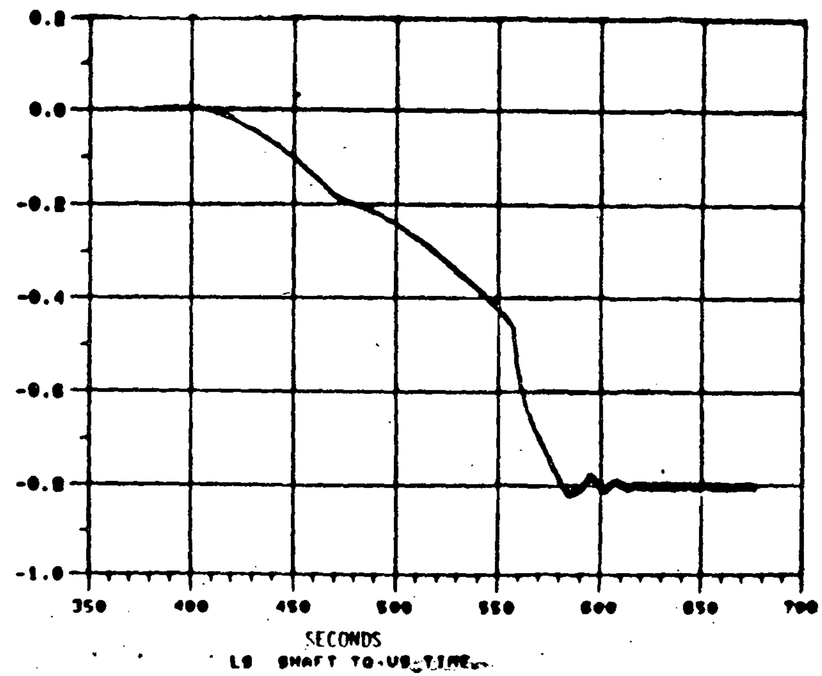


Figure 3.1.4.2-11. Power, VAR, Electrical and Wind Torque Behavior During a 5 to 40 mph Wind Speed Ramp

GENERATOR SYSTEMS STUDIES

WIND SPEED RAMP FROM 5 MPH TO 40 MPH, PITCH CONTROL



3.1.4.2-12. Low Speed Shaft Torque Behavior During a 5 to 40 mph Wind Speed Ramp

ANNUAL ENERGY CAPTURE FOR FIXED AND VARIABLE SPEED HYDRO

Fixed Speed, Fixed Pitch

Flow ratio = $\frac{665.5}{509}$ = 1.307

Ave power = .54 x 2500 = 1350 kW
hrs = (.277 - .210) x 8760 = 586.9 hrs

1350 x 586.9 =	792,340 hrs
at rated or above =	3,725,190
	4,517,530

Variable Speed

FLOW RATIO

Range	% Time	Hours	$\bar{P}$	kW Hrs
At rated or above 1.4	21	1,839.6	.81 x 2500	3,725,190
1.4 to 1.2	4	350.4	.81 x 2500	709,560
1.2 to 1.0	5	438.0	.47 x 2500	514,650
1.0 to 0.8	6	525.6	.23 x 2500	302,220
0.8 to 0.63	7	613.2	.11 x 2500	168,630
Total Output	43			5,420,250

1.2 x fixed speed

2.1 TRADE-OFF EVALUATION

3. OPERATIONAL CONSIDERATIONS

Consideration	Doubly Fed Machine Characteristic	Fixed Speed Machine Characteristic
Motorized Start	Good-external resistor or variable frequency	Poor-amortiseur winding
Synchronization and operational mechanical speed/torque control needed	Accommodate "rough" control.	Requires precise control
Drive train perturbation absorption	Excellent	None-mechanical Damping required
Complexity and Reliability	Slip rings and power electronics add complexity	Normal electrical gear
Maintenance	More but acceptable	Minimal

2.1 TRADE-OFF EVALUATION

4. PERFORMANCE

TYPE	MOD-OA	MOD-X	MOD-2	PROPELLER HYDRO
SIZE (Diameter-Ft)	125′	125′	300	5.76
FIXED SPEED OPERATION				
Speed	40	40	17.5	131.5 (specific) @ 90%
Rating	200	500	2500	2500
Energy Capture	.83	1.3	9	4.5
VARIABLE SPEED OPERATION				
Speed	28-40		10-28	60-130
Ratio	1.43		2.8	2.25
Rating	500		3800	2500
Energy Capture	1.49		10.8	5.4
VARIABLE /FIXED ENERGY RATIO	1.8	1.15	1.2	1.2

CONCLUSION: Variable speed ratios from 1:15 to 1:2.5 yield energy capture improvements at from 10 to 20% relative to fixed speed operation.

2.1 TRADE-OFF EVALUATION

5. PRODUCTION HARDWARE COST ESTIMATES 1981 $'s

Power Rating	Speed Range		Variable Speed System Cost/ $/kW	Less Single Speed System Cost $/kW	Marginal Cost as % of $1-3 k/kW System Cost	Expected Performance Benefit	Benefit/ Cost Ratio $1-3 k/kW System Cost
500	1.5:1		294	~110	18-6%	10%	0.56-1.6
	2.3:1		~400	110	29-9.7%	20%	0.65-2.1
2500	1.5:1		106	~50	5.6-1.9%	10%	1.8-5.3
	2.3:1		300	50	25-8.3%	20%	0.8-2.4
7200	1.5:1	production	73	~50	2.3-0.8%	10%	4.3-12.5
		prototype	120	50	7-2.3%	10%	1.5-4.3
	2.3:1		101	50	5.1-1.7%	20%	1.9-5.9

CONCLUSIONS:

- Preliminary benefit/cost ratio's indicate good potential application of doubly fed machines
- Larger sizes show better benefit/cost than smaller sizes
- At 7200 kW, even a prototype installation could be cost cost effective (not considering design costs)
- These figures are preliminary only, especially for hydro applications

CONCEPTUAL DESIGN/TRADE STUDY UPDATE

NON-CIRCULATING CURRENT

- Chosen for NASA (LeRC) and Bureau of Reclamation studies for 300 kW and 30 hp investigations respectively
- Minimizes passive components but a 12 pulse (72 thyristor) configuration required to achieve ±50% speed variation
- To preclude current circulation from forward to reverse bridges, controls must enforce a time delay between commutations, increasing output distortion
- No demonstration is known of application to large doubly fed machines which could require smooth dc operation

CIRCULATING CURRENT

- Chosen by Westinghouse for large scale applications
- Provides tolerance to control variation, smooth transition thru dc during phase reversals, and increased protection for thyristors
- A recent paper by Tamura, Tanaka, and Tadakuma at the 1982 IEEE/IAS International Semiconductor Power Converter Conference quantified some comparisons in an application of a cycloconverter to a 10 kW synchronous motor drive; they claim circulation current can be controlled to achieve the following:
  - operation of 6 pulse (36 thyristor) cycloconverters beyond ±50% frequency with distortion and torque ripple equal to or less than non-circulating current 12 pulse configurations
  - improvement in cyclo-converter power factor to near unity.
- If confirmed these additional circulating current benefits would further strengthen trade study conclusions favoring DFM's in variable speed applications

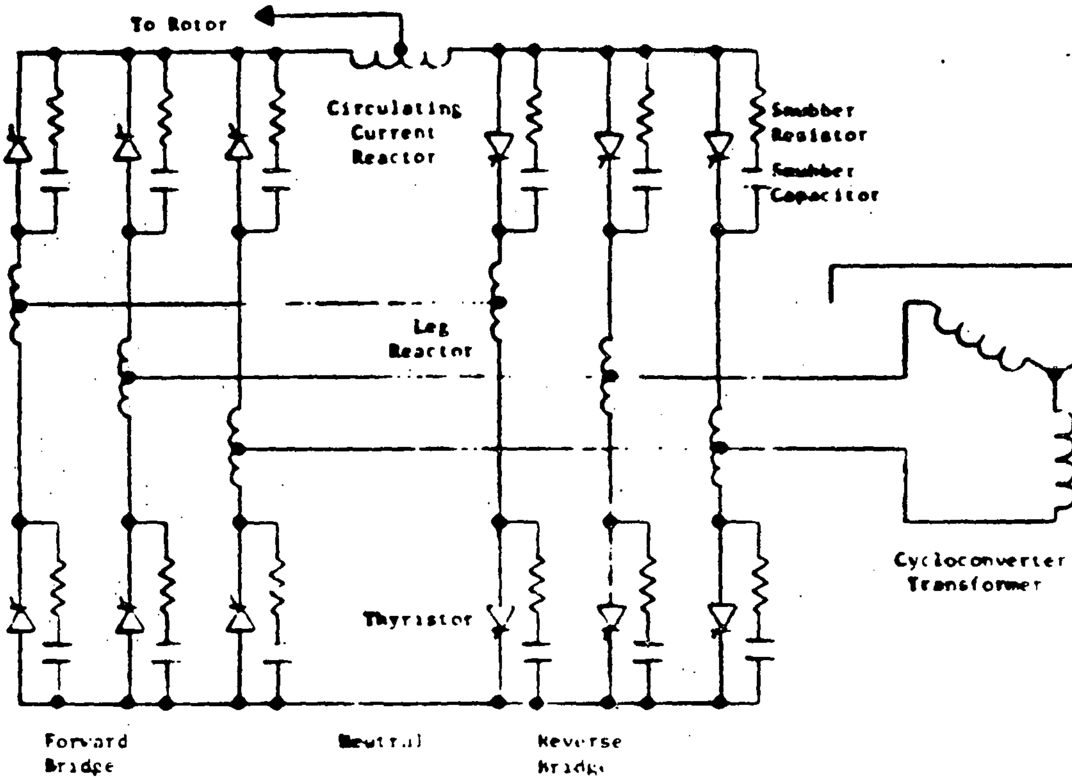
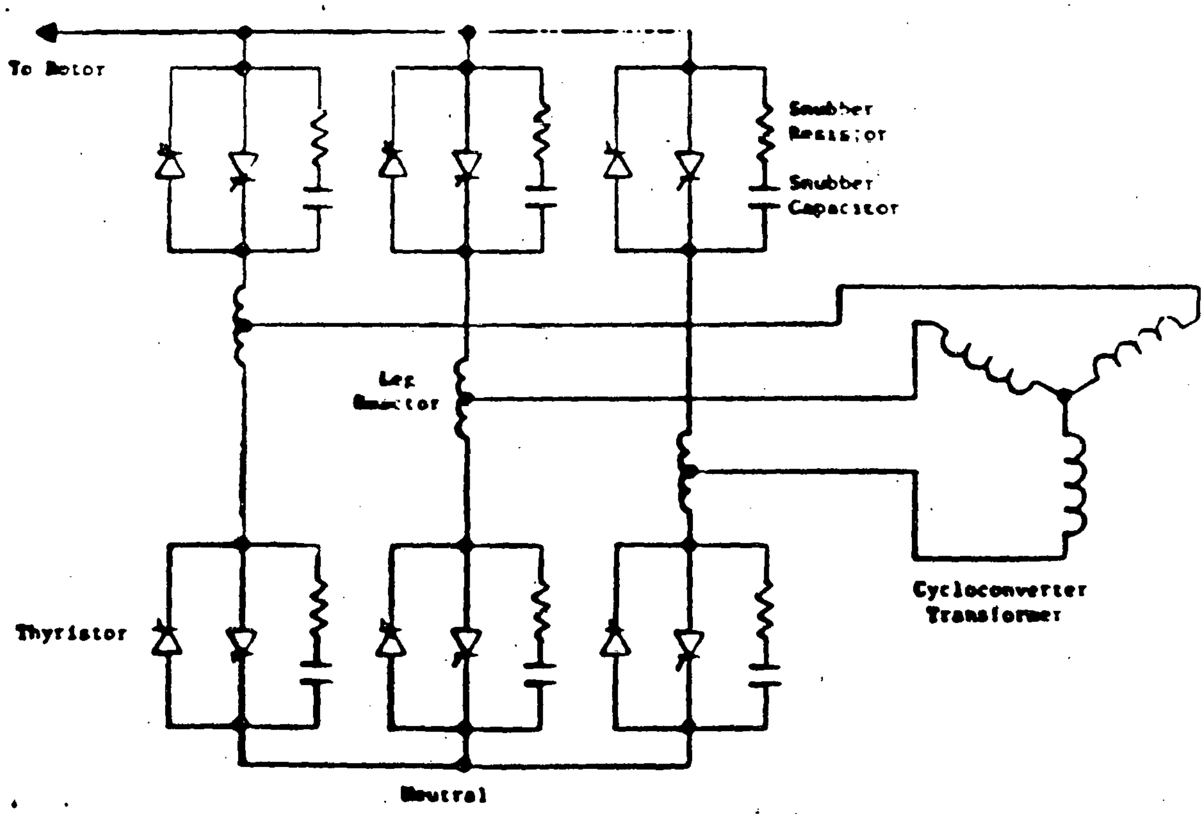


Figure 3.1.2.1-1. Bridge Schematic; Circulating Current Configuration



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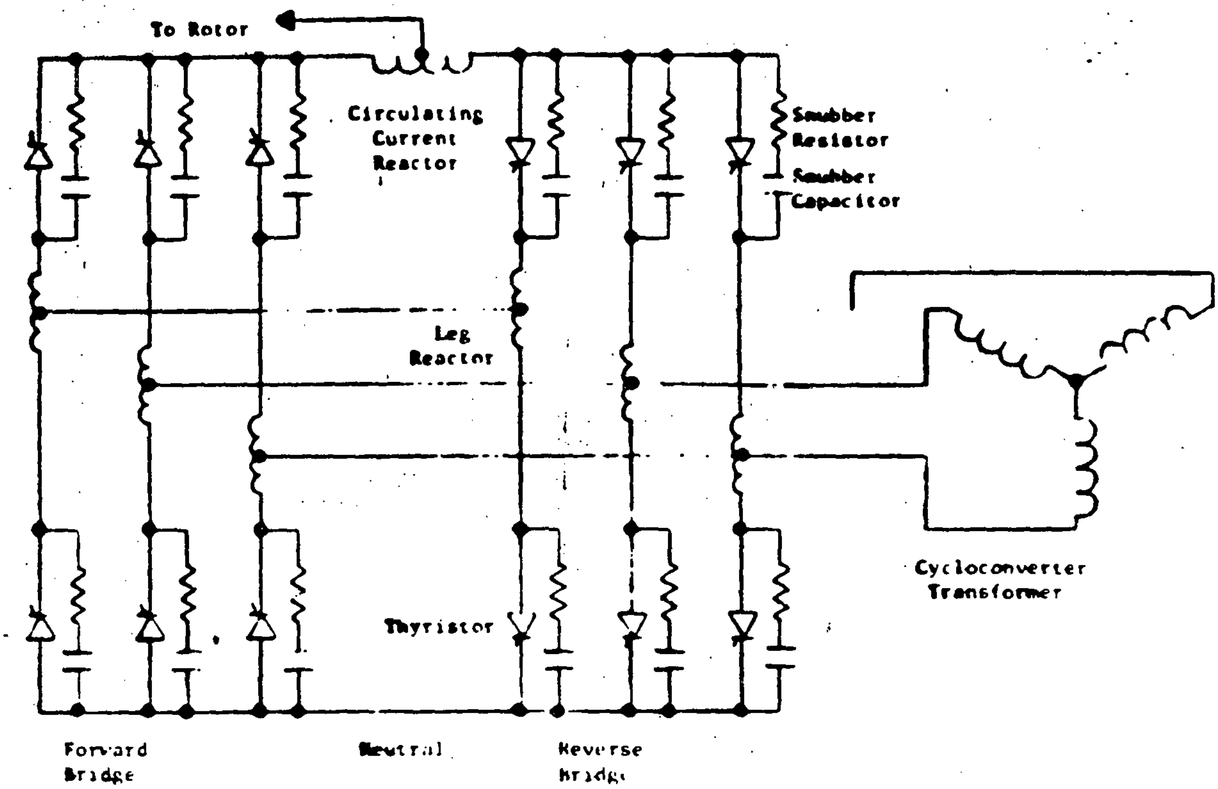
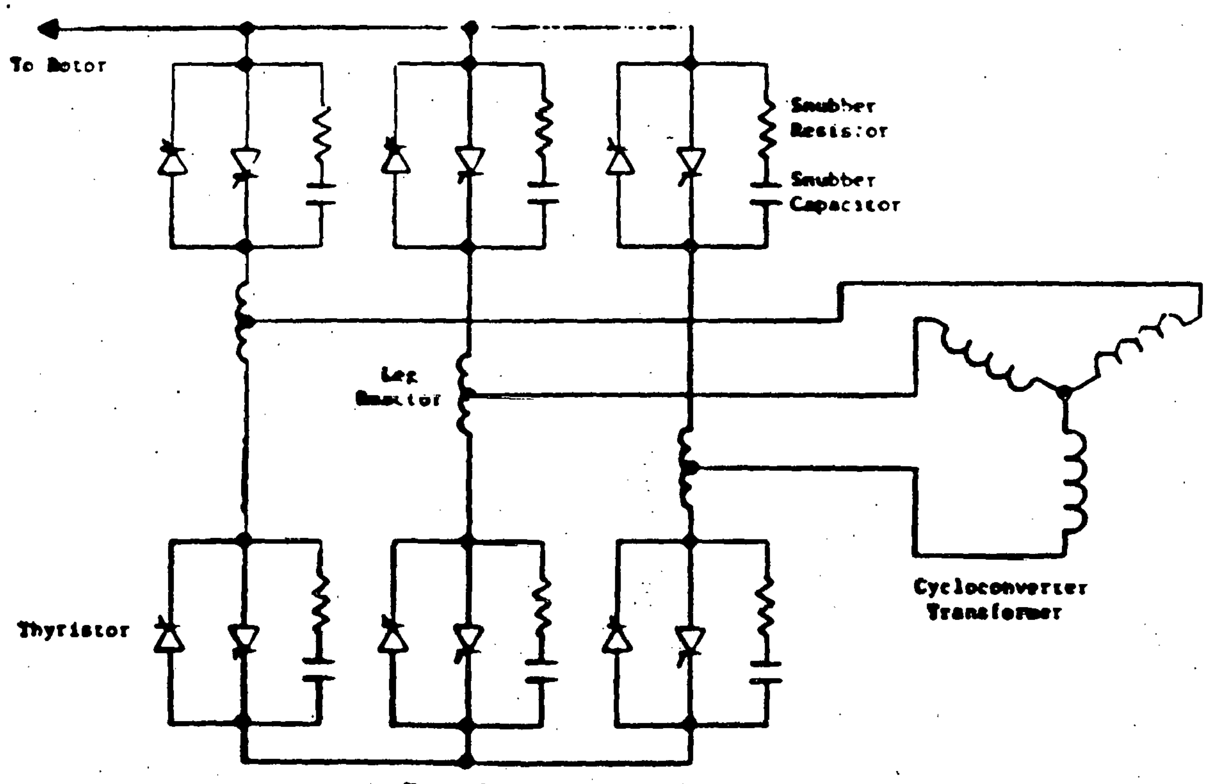
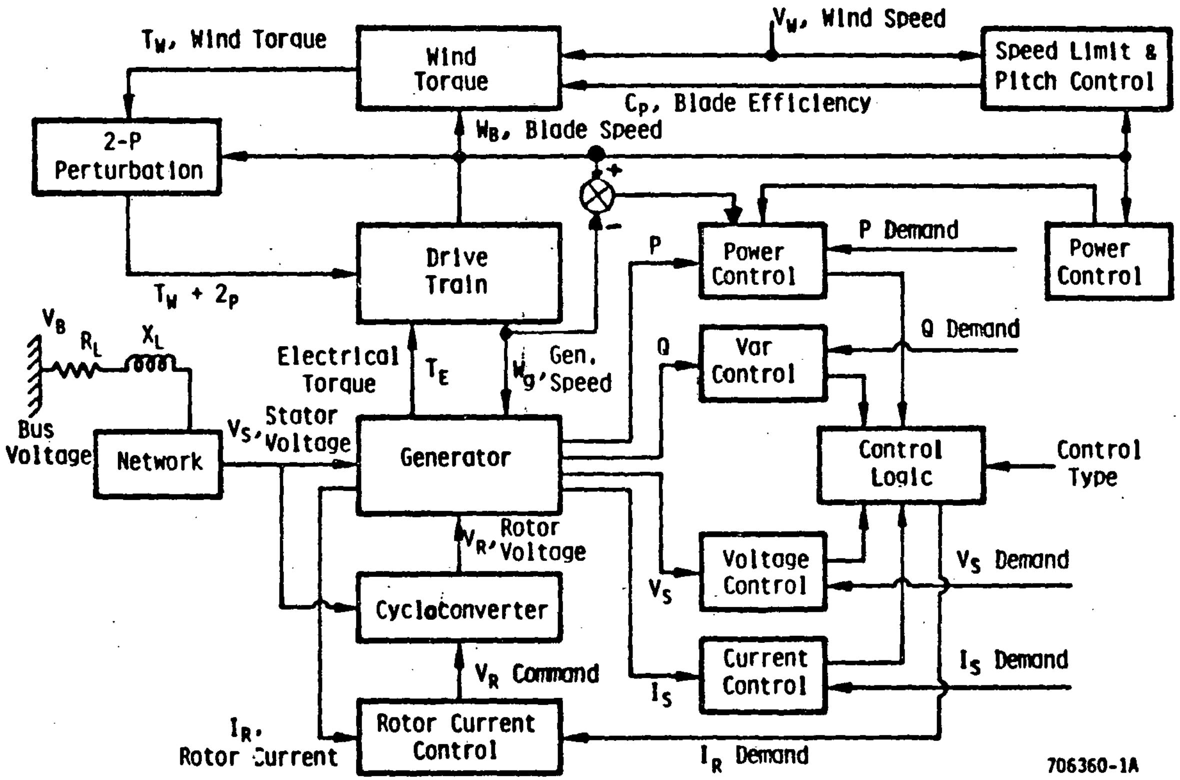
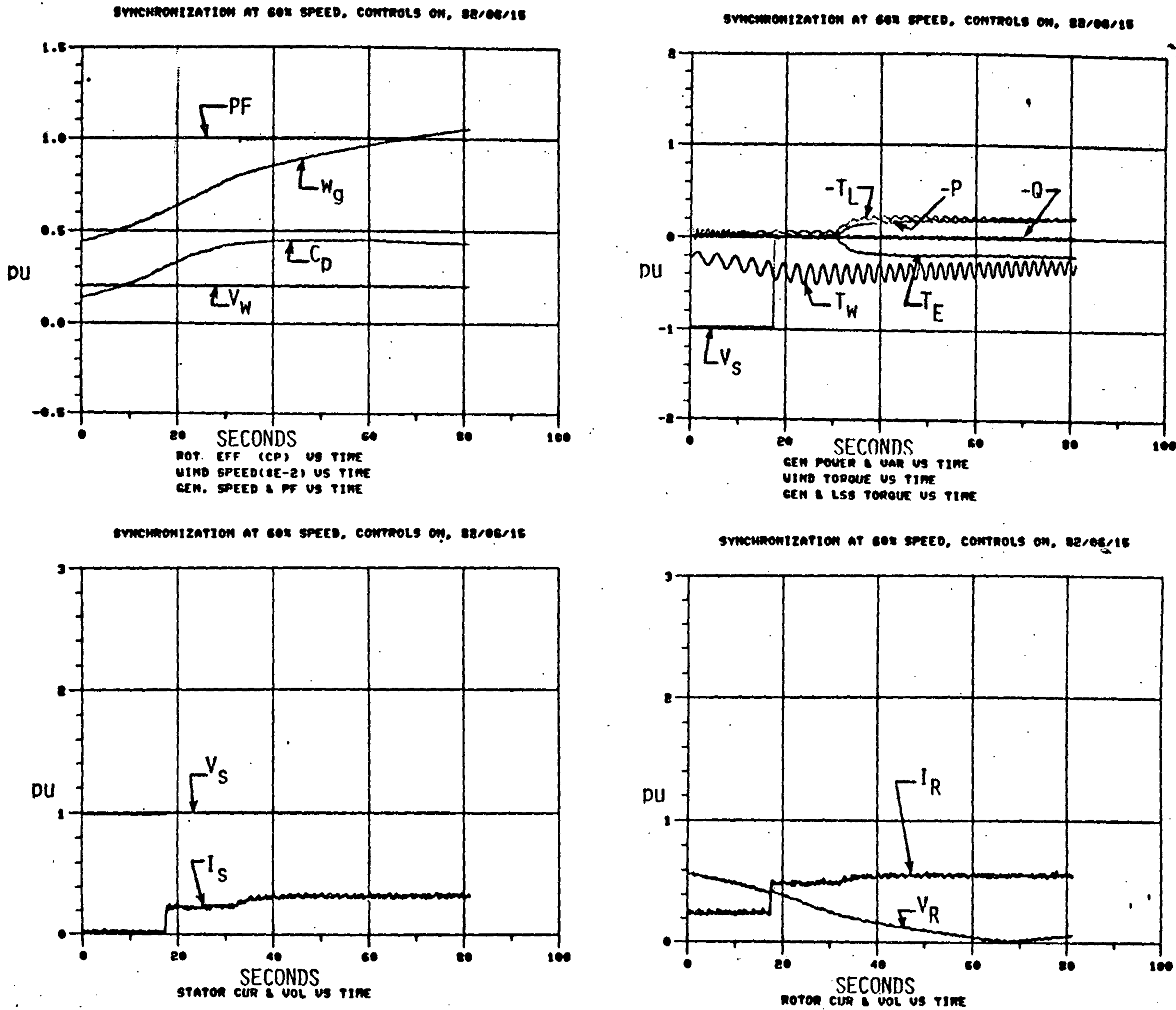


Figure 3.1.2.1-1. Bridge Schematic; Circulating Current Configuration

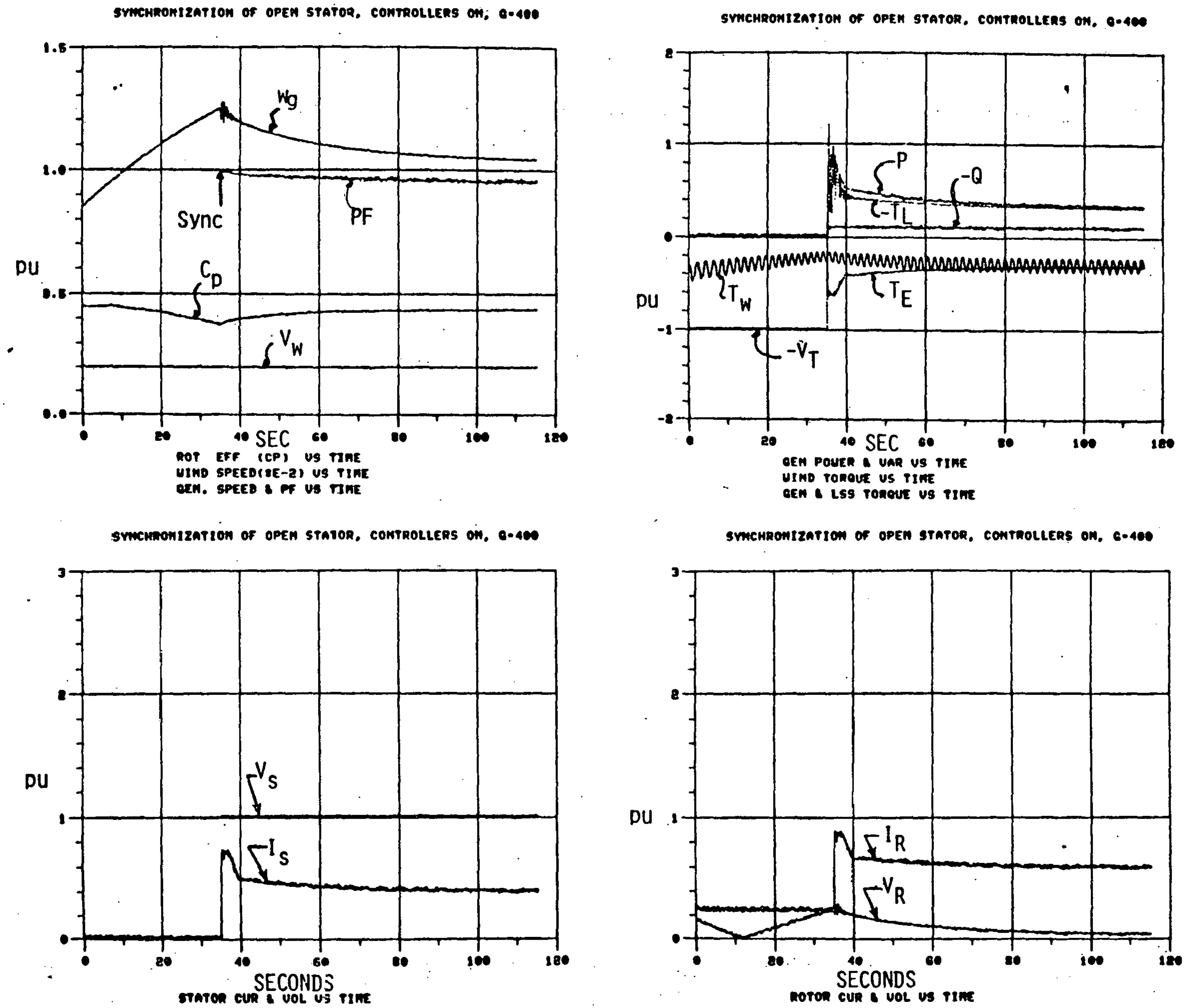


HYBRID COMPUTER SIMULATION OF GENERATOR DYNAMICS AND CONTROL SIMPLIFIED BLOCK DIAGRAM

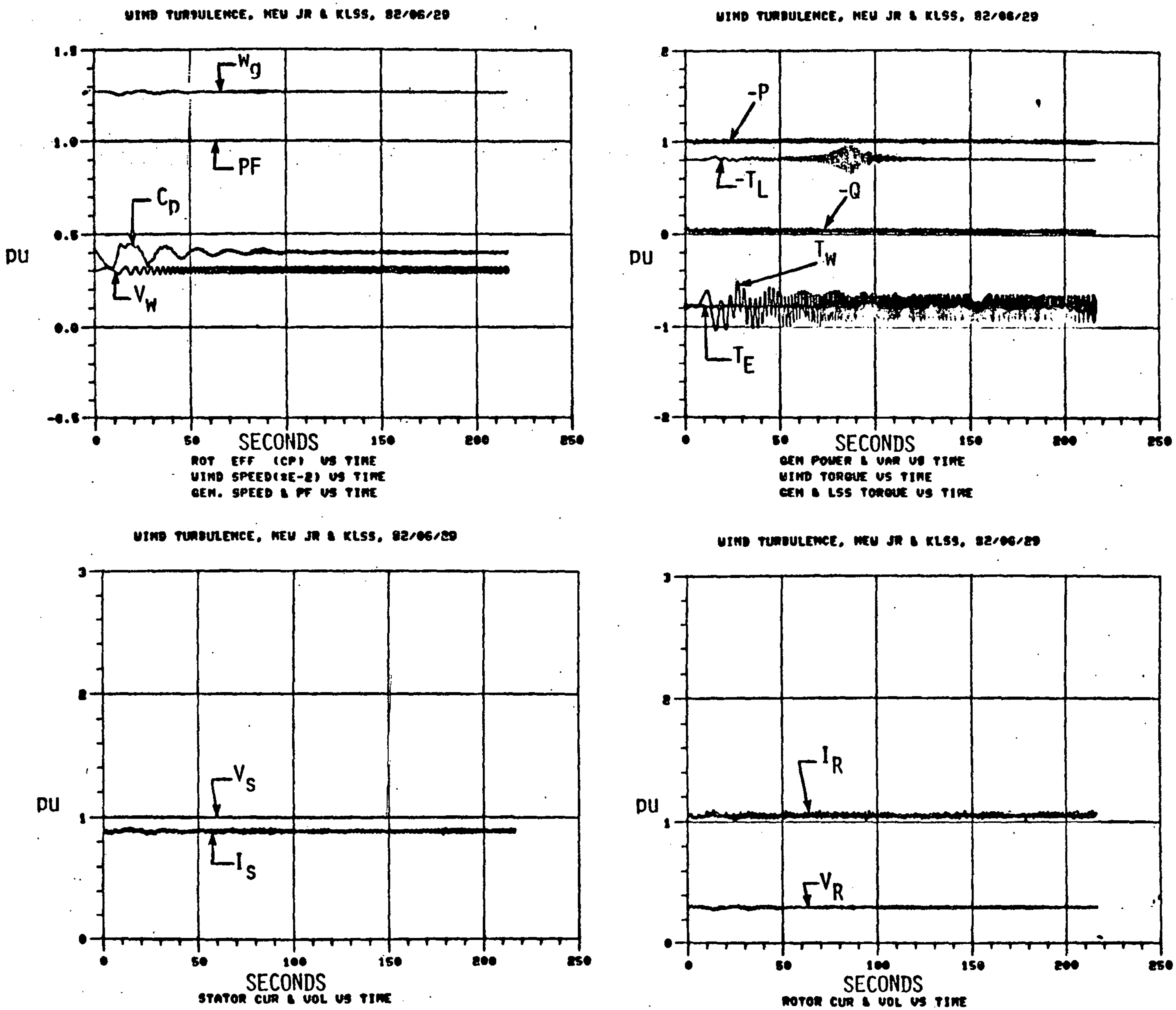




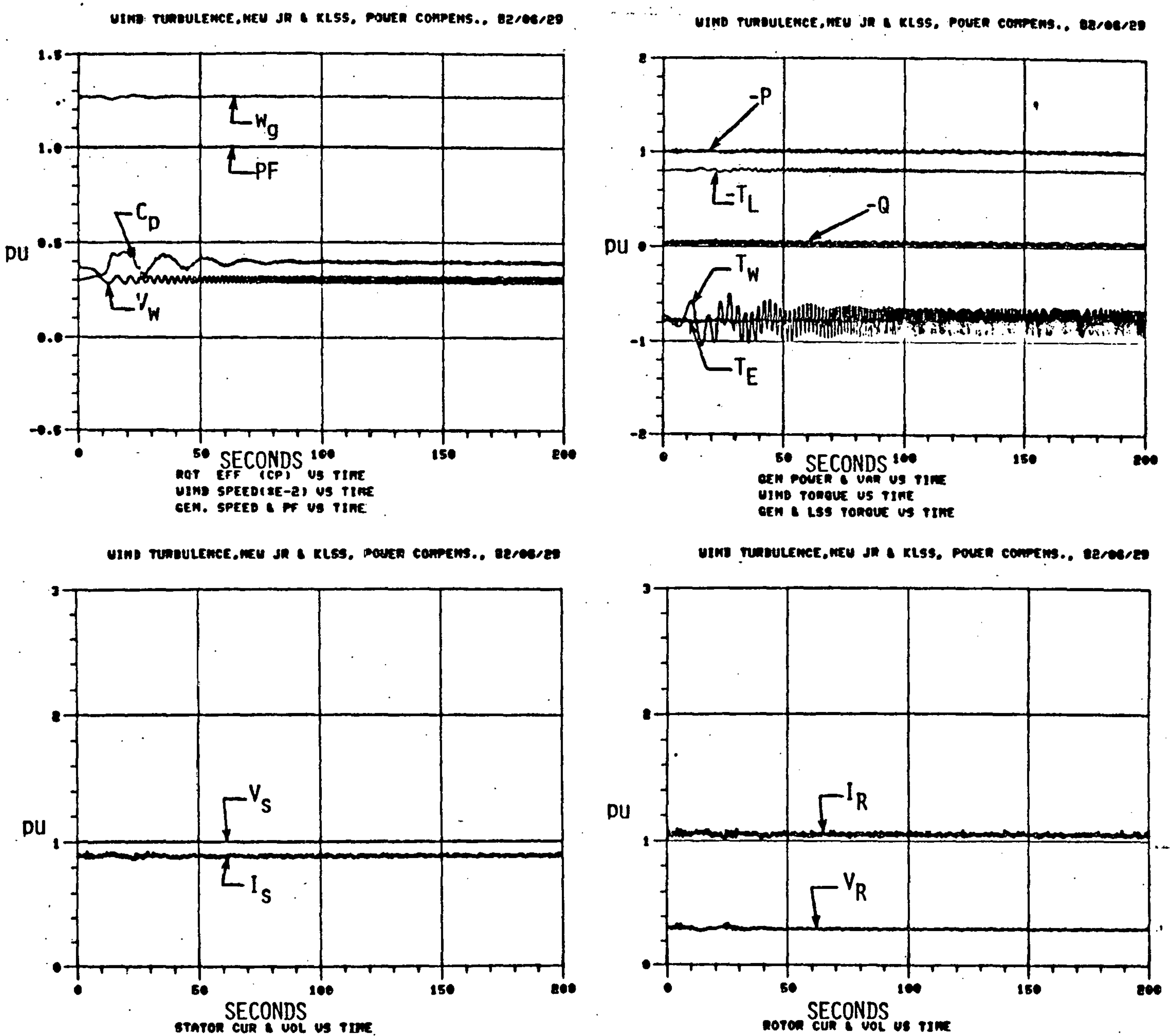
Power, Reactive Power, Wind Torque, Generator Torque, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Wind Speed, Stator and Rotor Parameters During Synchronization at 60% Speed. Power and Pitch Controls Active.



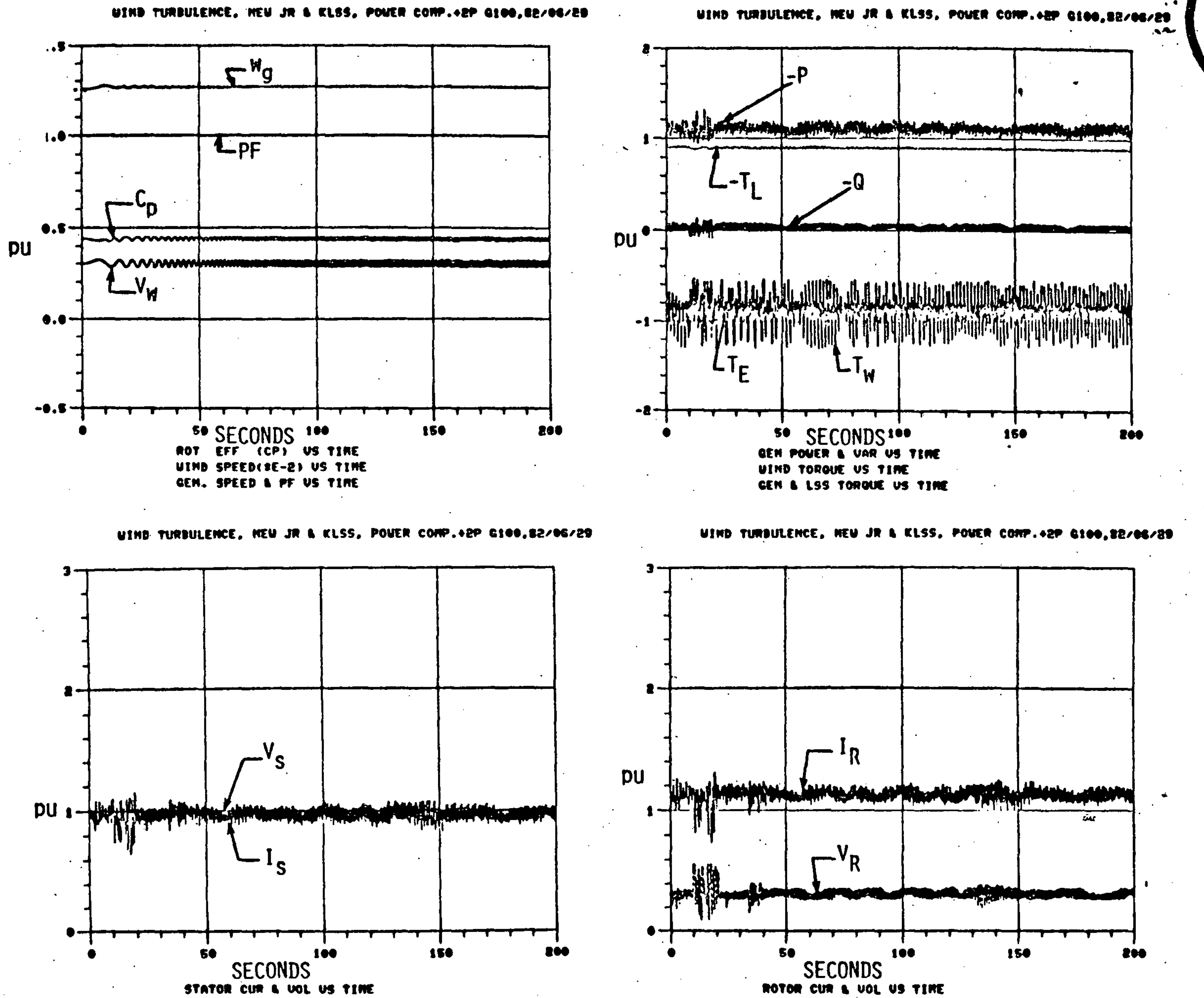
Power, Reactive Power, Wind Torque, Generator Torque, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Wind Speed, Stator and Rotor Parameters During Synchronization Above Synchronous Speed. Power and Pitch Controls Active.



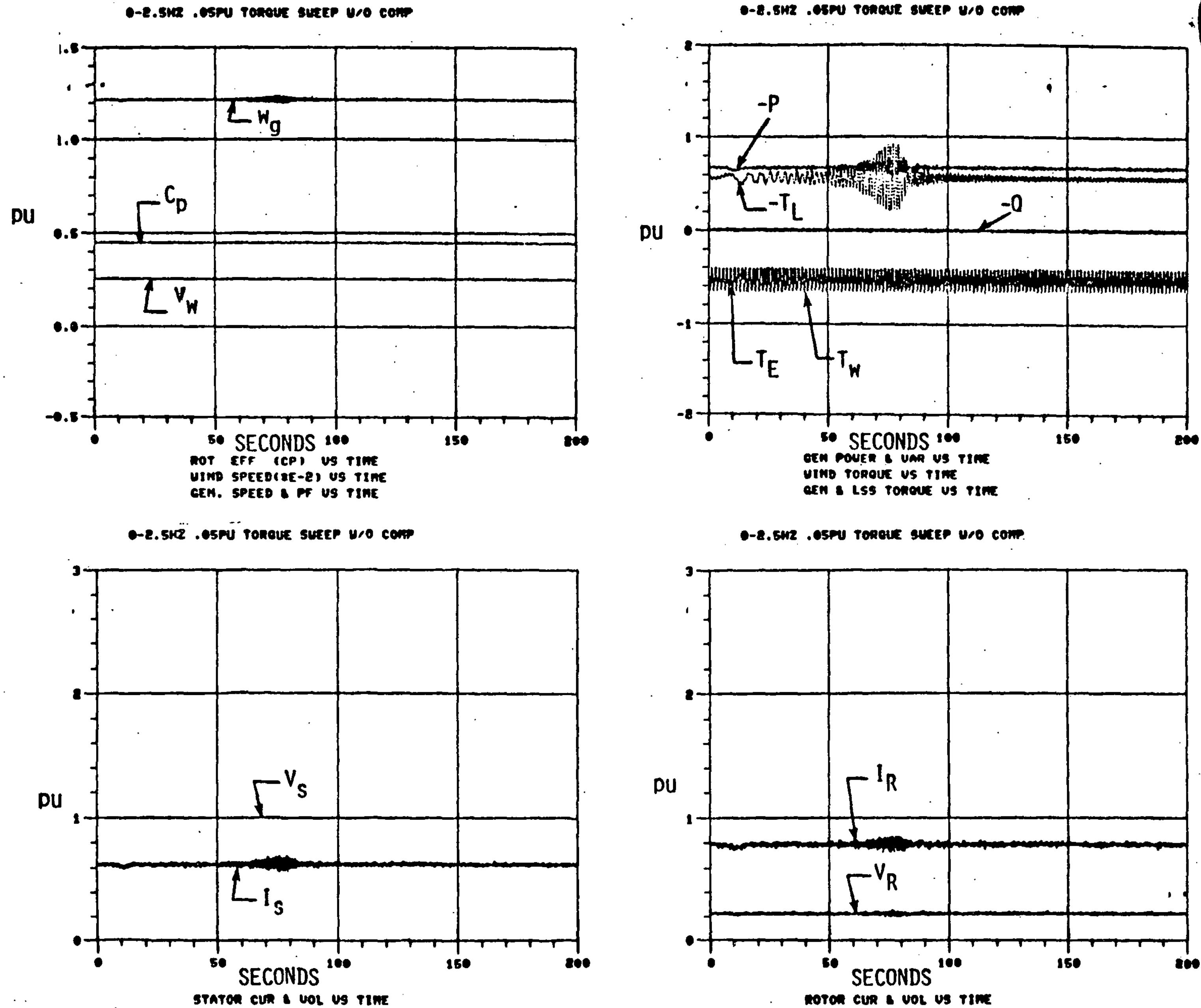
Power, Reactive Power, Wind Torque, Low Speed Shaft Torque, Generator Torque, Generator Speed, Blade Efficiency, Power Factor, Stator and Rotor Parameters During a ± 2 mph Wind Perturbation From 0 to 2 Hz. Power and Pitch Controls Active. 2p Perturbation Not Included.



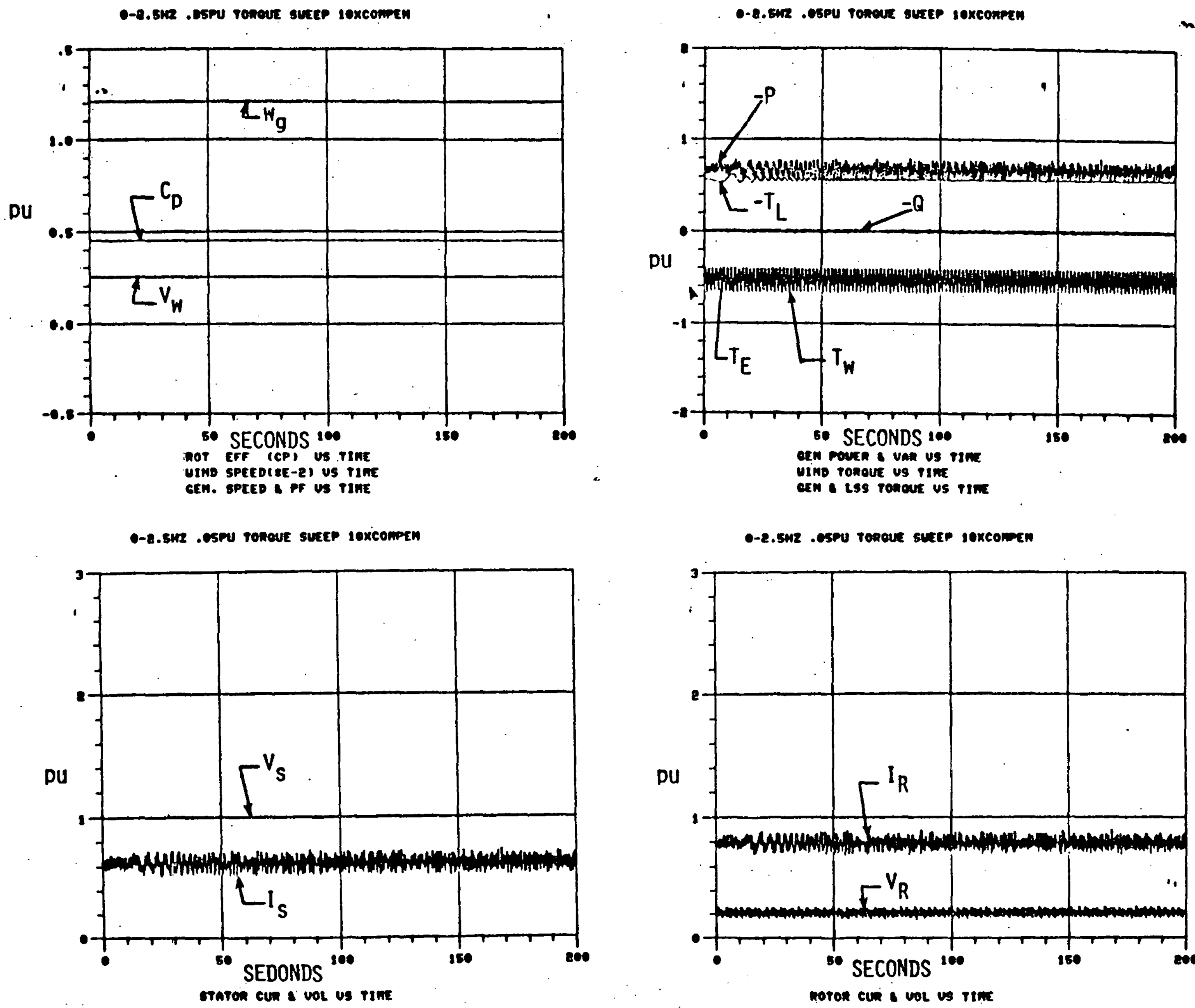
Power, Reactive Power, Wind Torque, Generator Torque, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power-Factor, Stator and Rotor Parameters During a ± 2 mph Wind Perturbation from 0 to 2 Hz. Speed Differential Compensation on Power Demand with Low Gain. 2p Perturbation Not Included. Power and Pitch Controls Active.



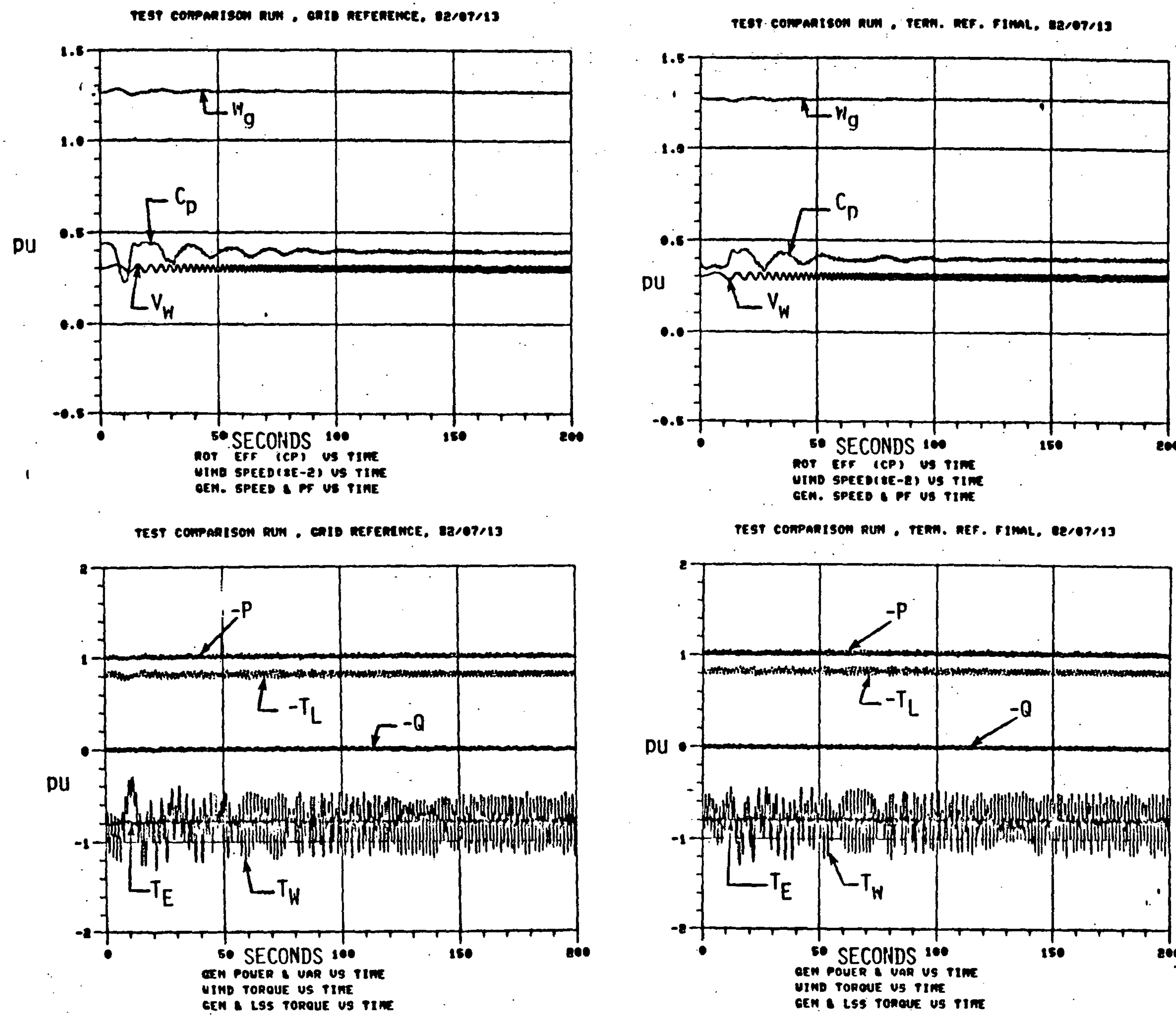
Power, Reactive Power, Wind Torque, Generator Torque, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Stator and Rotor Parameters During ±2 mph Wind Perturbation from 0 to 2 Hz. Speed Differential Compensation on Power Demand with High Gain. 2p Perturbation Included. Power and Pitch Controls Active.



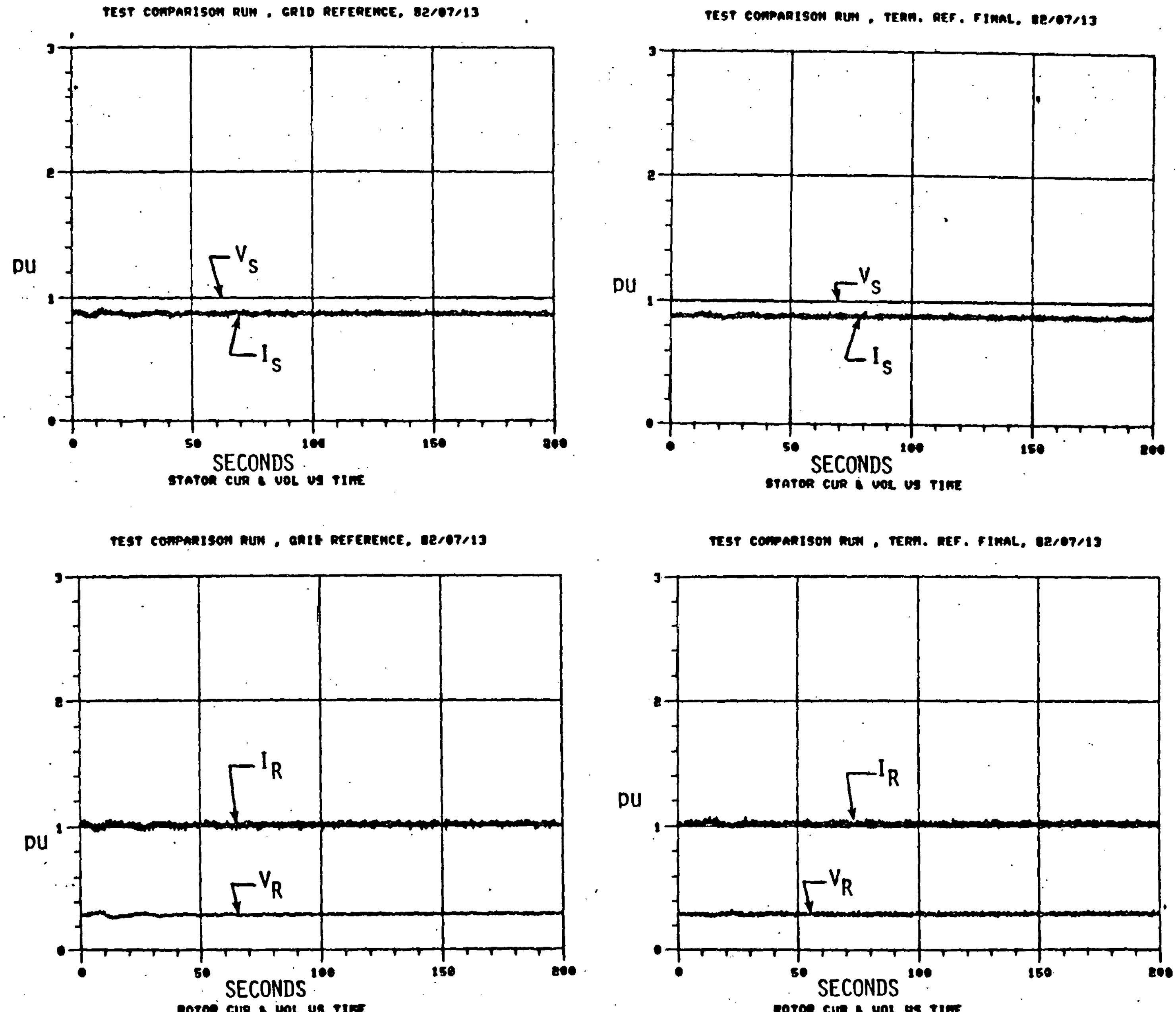
Power, Reactive Power, Wind Torque, Generator Torque, Wind Speed, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Stator and Rotor Parameters During a ±0.05 pu Air Gap Torque Perturbation from 0 to 2.5 Hz. No Compensation. Power and Pitch Controls Active.



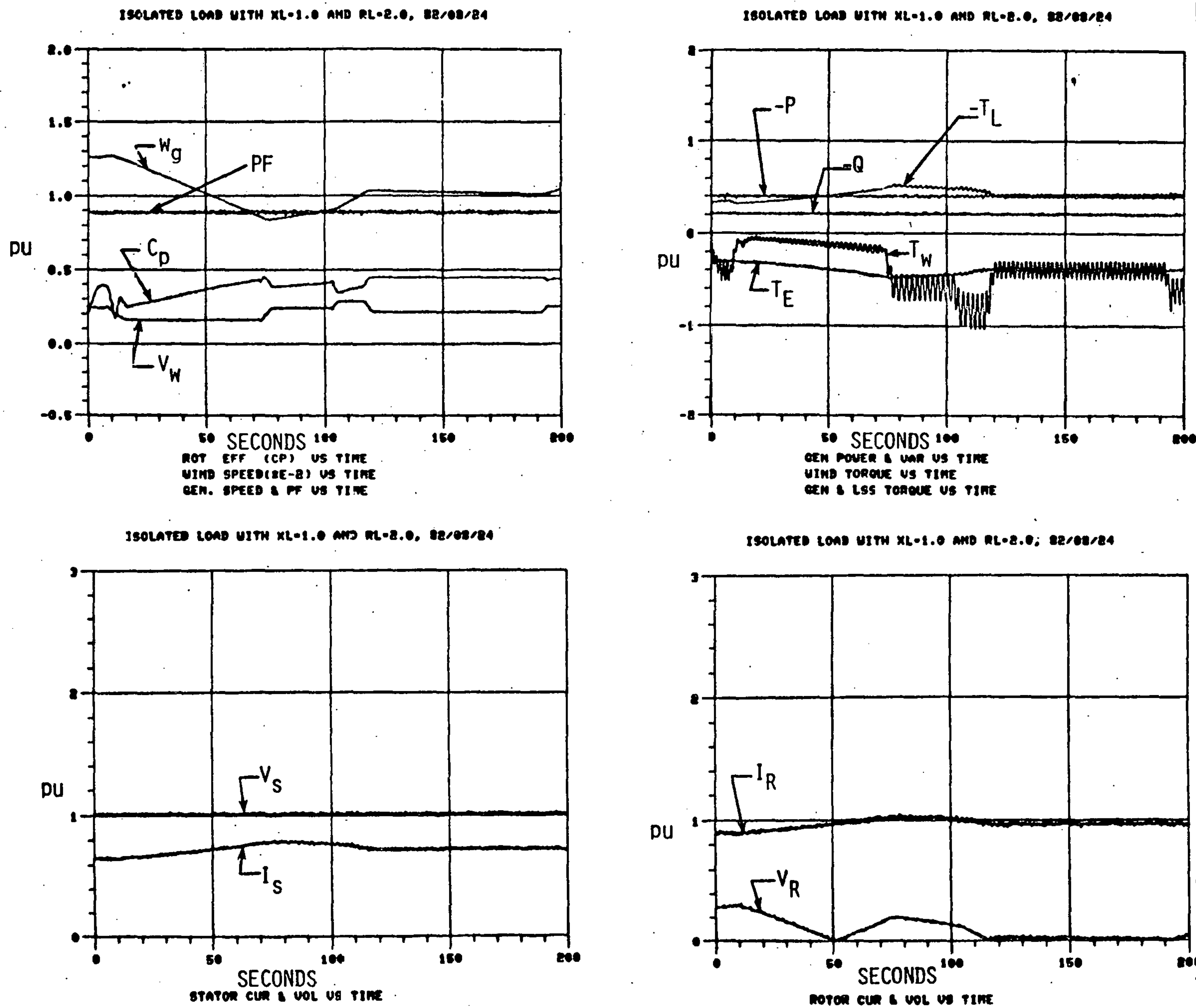
Power, Reactive Power, Wind Torque, Generator Torque, Wind Speed, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Stator and Rotor Parameters During a ±0.05 pu Perturbation on Air Gap Torque from 0 to 2.5 Hz. Speed Differential Compensation on Power Demand with High Gain. Power and Pitch Controls Active.



Comparison of Generator Speed, Power, Reactive Power, Low Speed Shaft Torque, Wind Speed, Generator Torque, Power Factor, Blade Efficiency, Wind Torque Evaluated for Two Identical Typical Runs Obtained with Grid Reference and Terminal Reference, Respectively.



Comparison of Total Stator and Rotor Parameters Evaluated for Two Identical Typical Runs Obtained with Grid Reference and Terminal Reference, Respectively

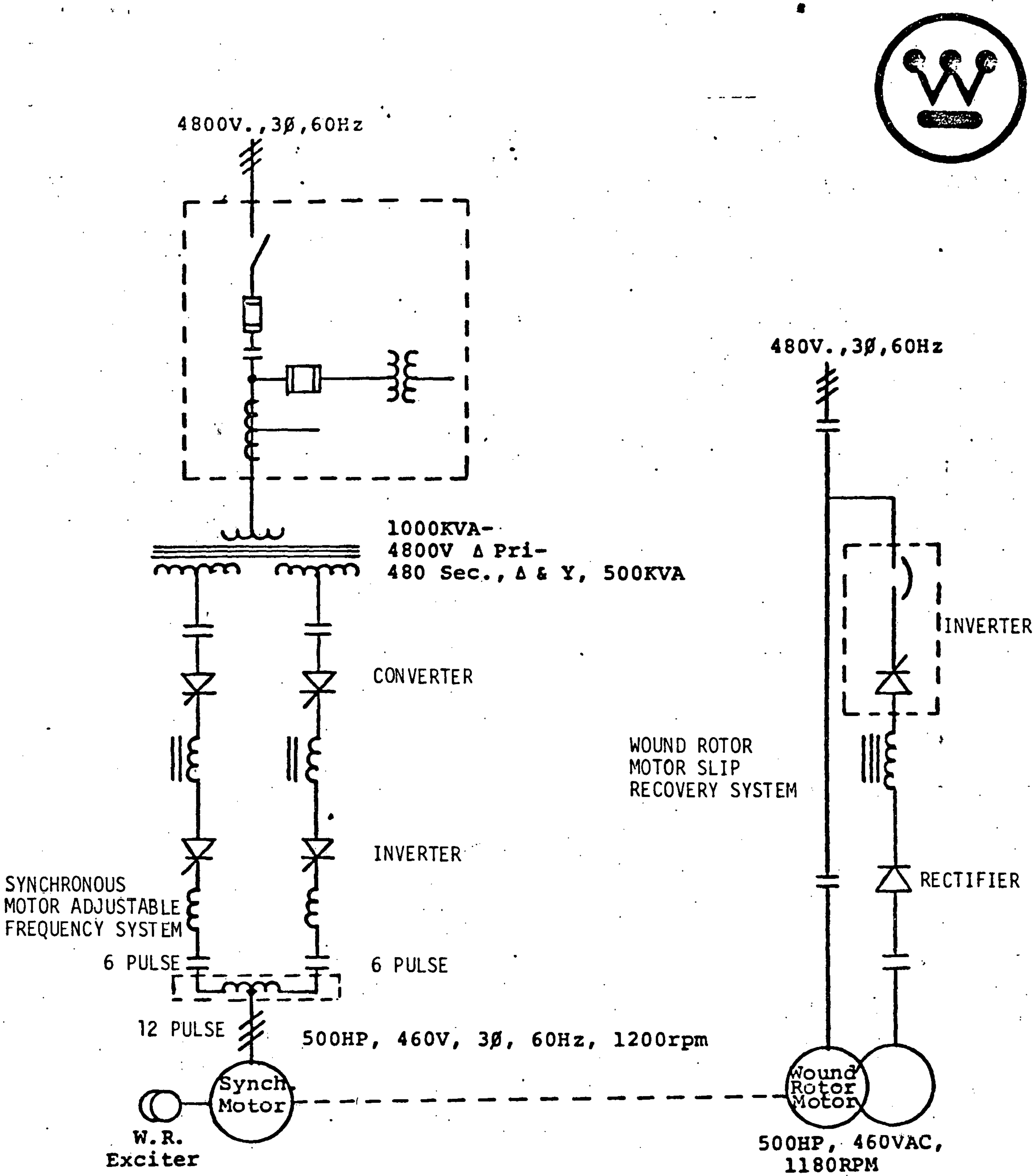


Power, Reactive Power, Wind Torque, Generator Torque, Low Speed Shaft Torque, Generator Speed, Blade Efficiency, Power Factor, Wind Speed, Stator and Rotor Parameters During Isolated Load Operation.

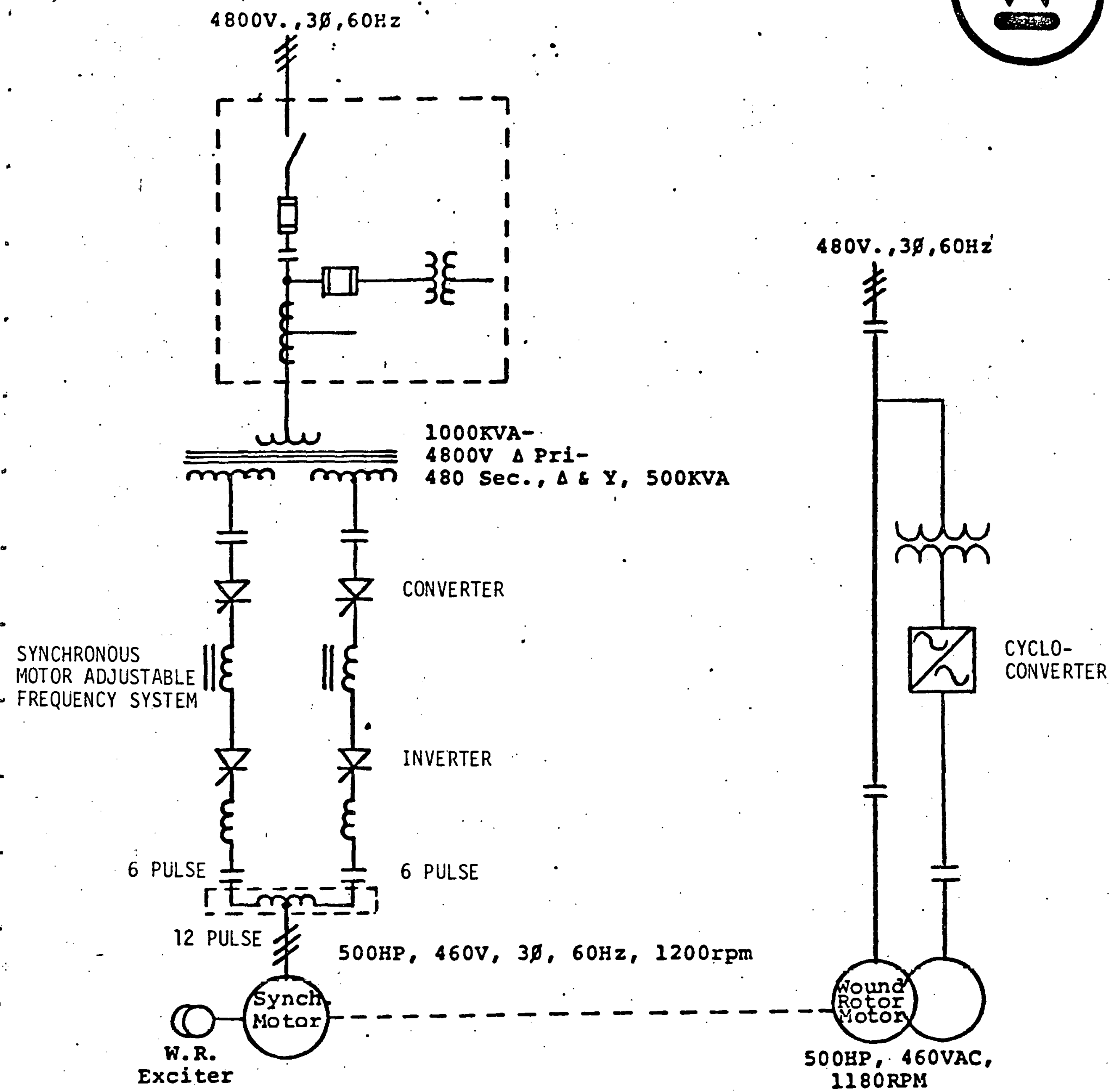
DOUBLY FED MACHINE

MACHINE/SYSTEM VERIFICATION APPROACH

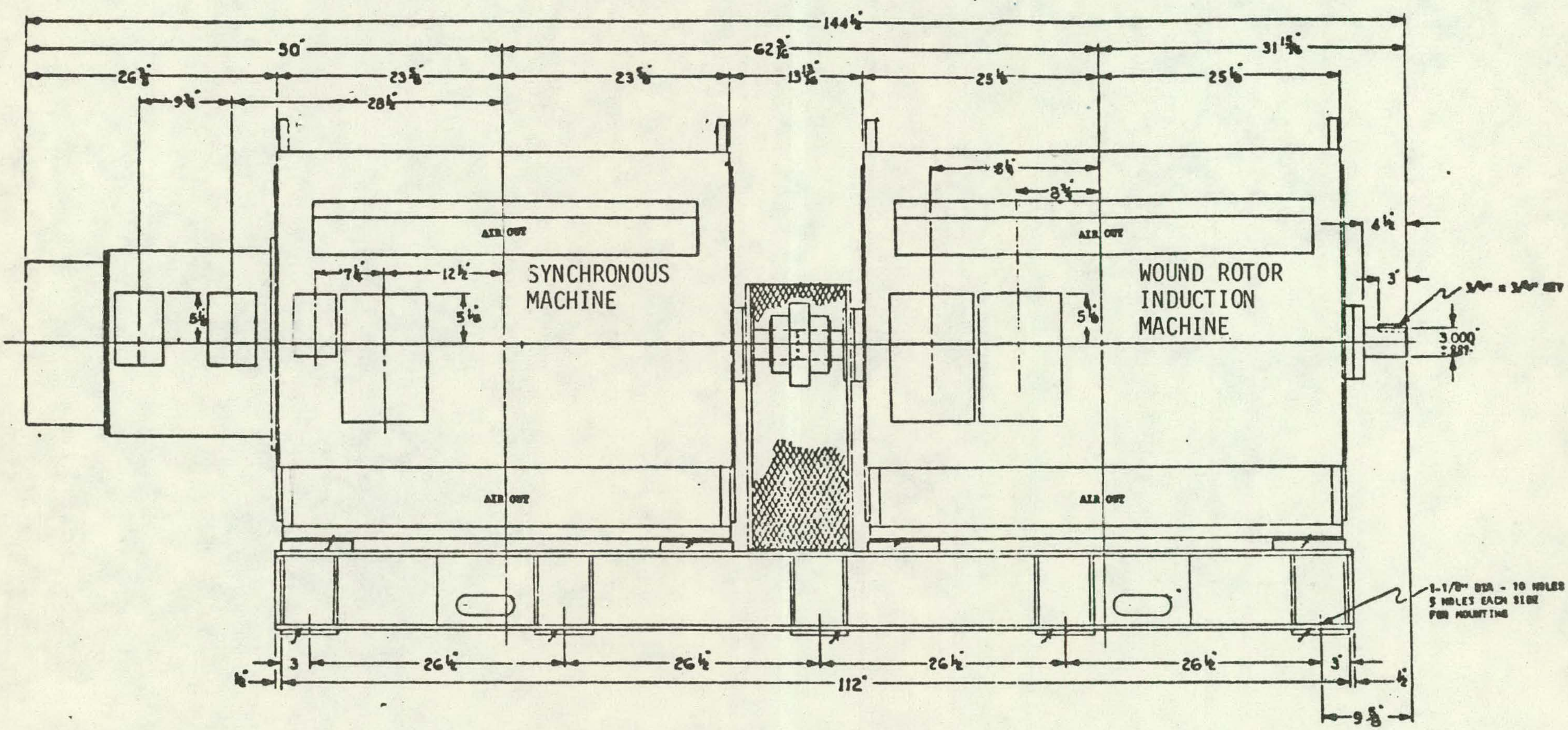
SEPTEMBER, 1982



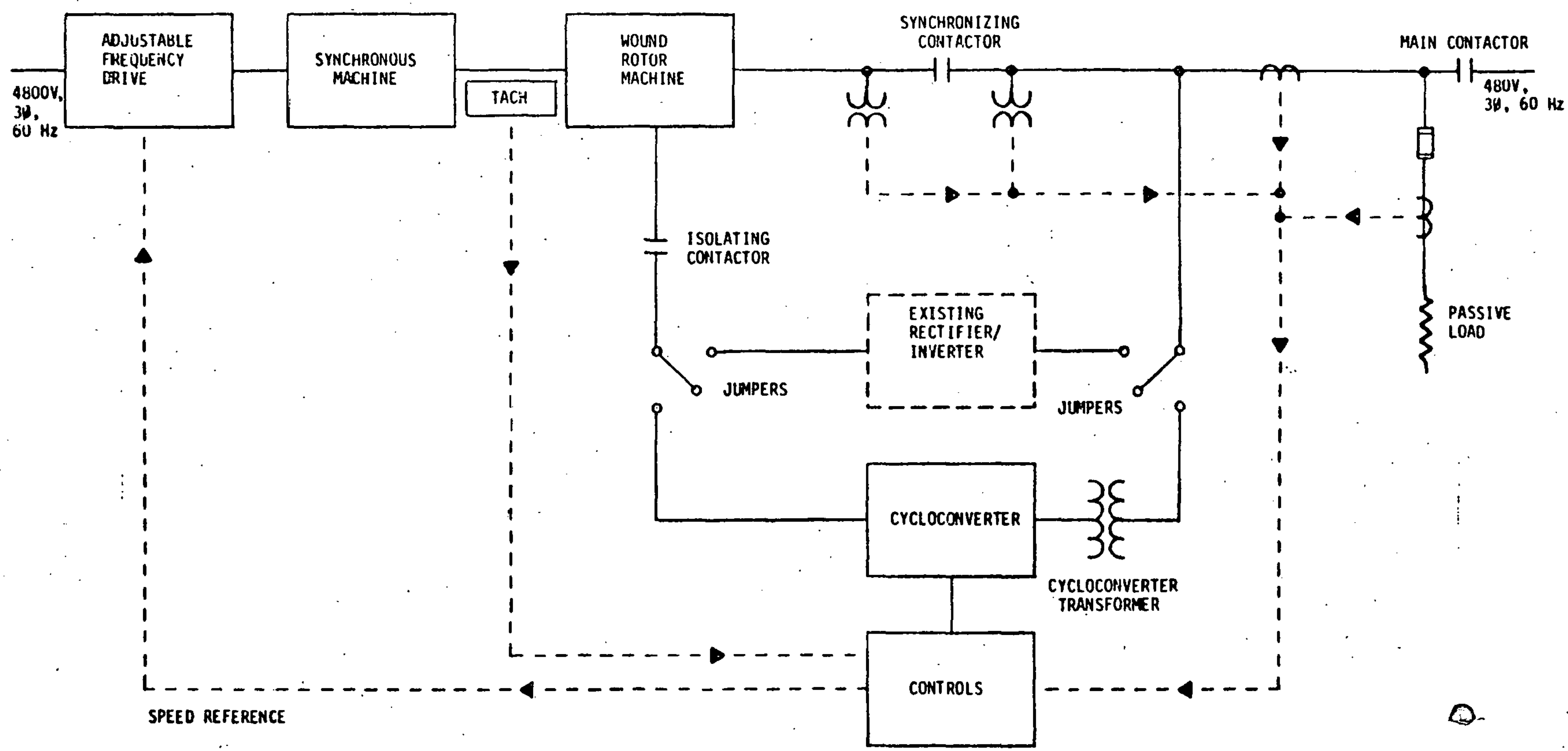
EXISTING TEST TRAIN CONFIGURATION



MODIFIED TEST TRAIN CONFIGURATION
TO ACCOMMODATE DFM VERIFICATION



PHYSICAL ARRANGEMENT OF EXISTING TEST TRAIN



DRIVE TRAIN/CYCLOCONVERTER TEST CONFIGURATION

HARDWARE CHANGES TO EXISTING TEST CONFIGURATION

- Disconnect rectifier/inverter from the rotor circuit.
- Connect cycloconverter and transformer to the rotor circuit.
- Provide speed reference to the adjustable frequency drive.
- Provide passive load.
- Provide current and potential transformers.

EXISTING HARDWARE UTILIZED

- Adjustable frequency drive 0 to 69 Hz design range.
- Synchronous machine as a motor in accordance with design load/speed limits.
- Wound rotor induction machine.
- Synchronizing, isolating and main contactors.

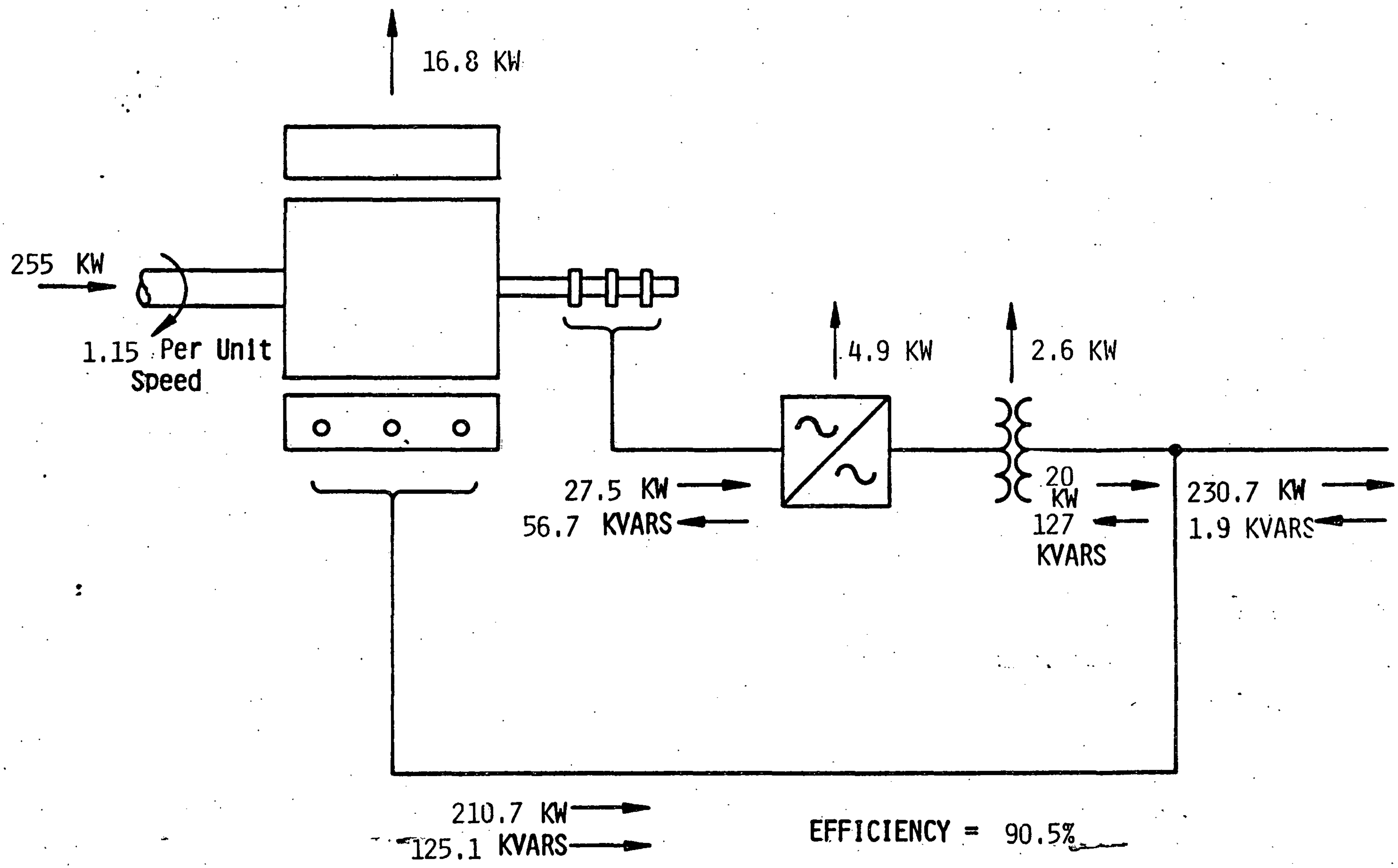
ADDITIONAL TEST HARDWARE REQUIRED

- Generator system supervisory controller (GSSC).
- Cycloconverter gate drive controls.
- CRT Terminal and disk drive.
- Cycloconverter power circuit.
- Potential transformers.
- Current transformers.
- KW transducers.
- KVAR transducer.
- Passive load.
- Tachometer.
- Harmonic analyzer.

WOUND ROTOR MACHINE CHARACTERISTICS

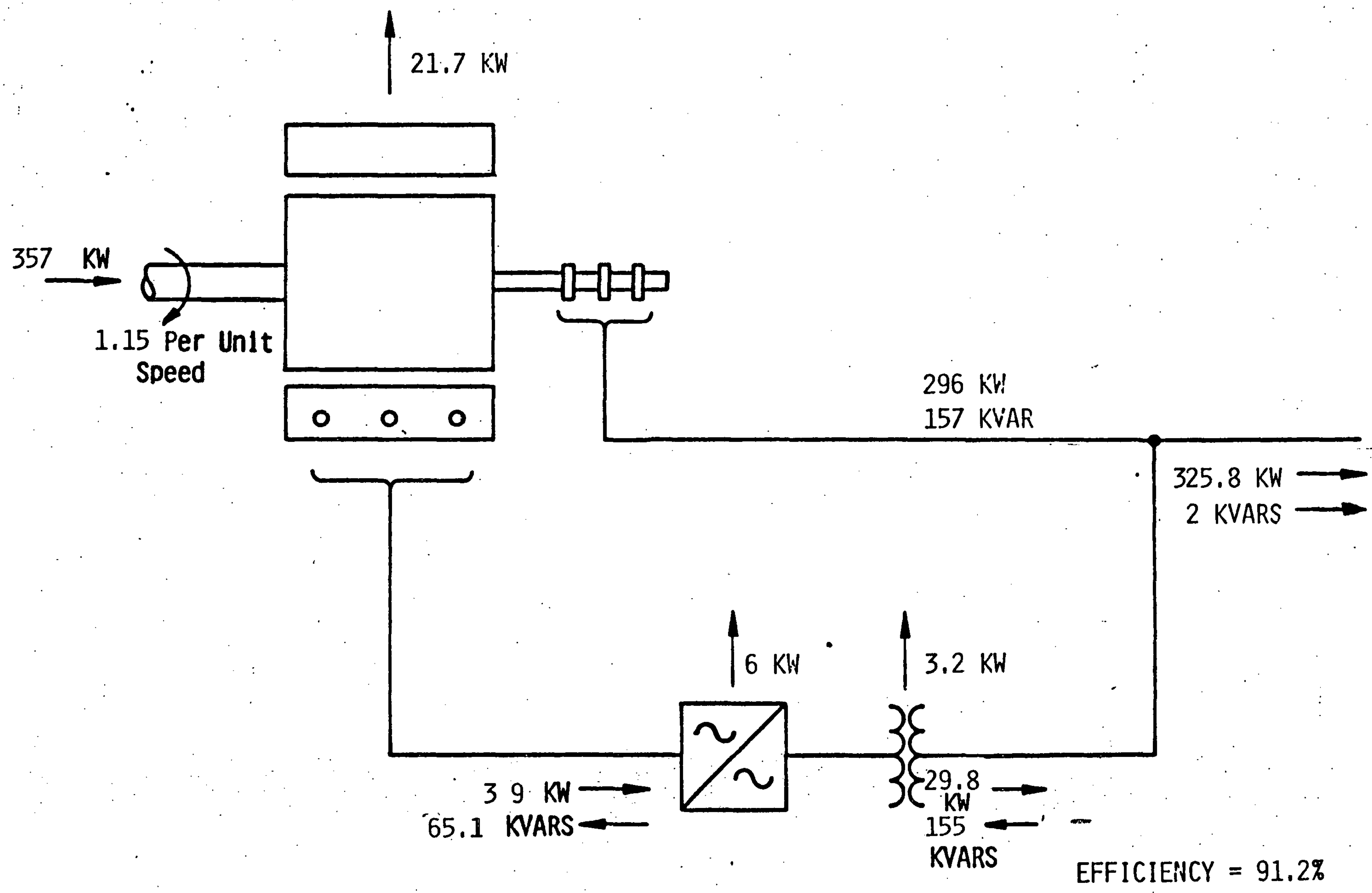
- 500 HP, 1182 RPM
- 460V, 601A STATOR
- 468V, 478A ROTOR
- Class B Insulation, 105°C, Temperature rise by resistance 40°C.
- 3 Phase, 60 Hz, Service Factor 1.0
- WYE connected stator, Wye connected rotor.
- Base KVA; 373
- Xm; 1.9639 p.u.
- X1; 0.0678 p.u.
- X2; 0.0997 p.u.
- R1; 0.0109 p.u.
- R2; 0.0123 p.u.

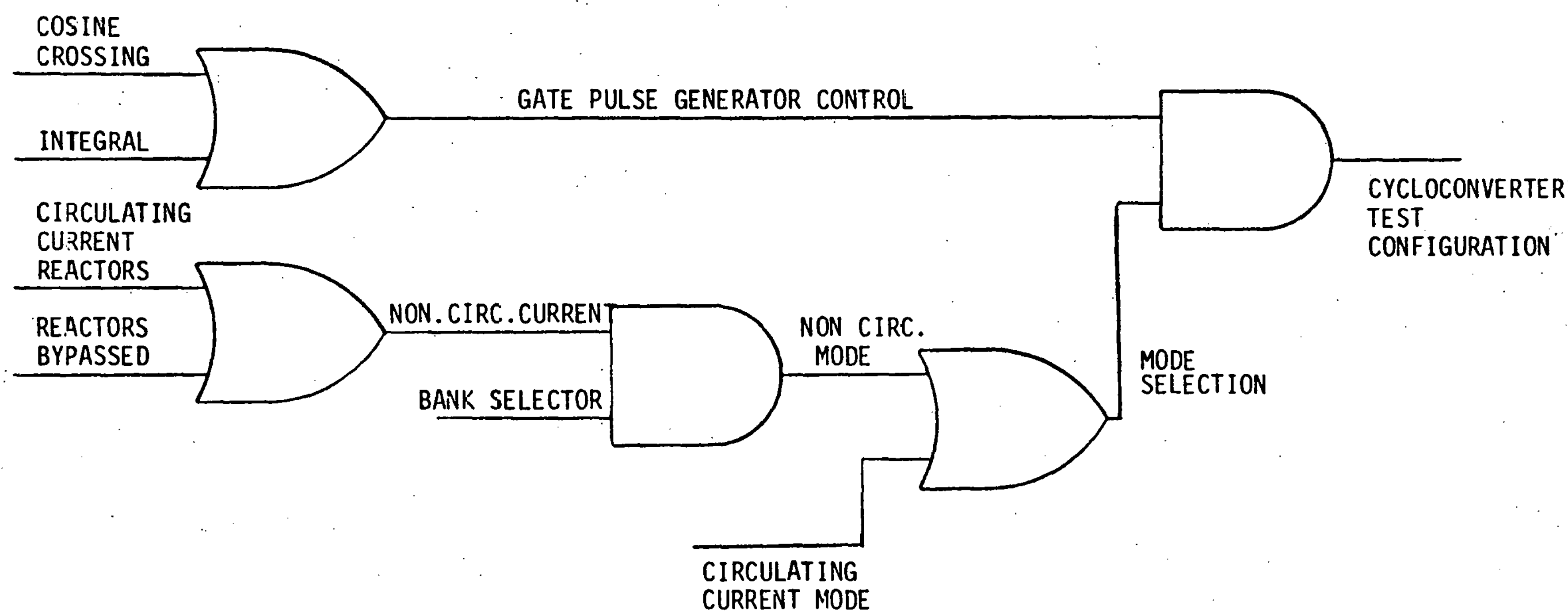
TEST TRAIN, NORMALLY CONFIGURED, OPERATING AT ROTOR CURRENT LIMIT OF 478A



EFFICIENCY = 90.5%

TEST TRAIN, INSIDE OUT CONFIGURATION, OPERATING AT STATOR LIMIT OF 601A





CONTROL MODE LOGIC DIAGRAM

TYPICAL TEST SEQUENCE

- Check Synchronizing contactor open.
- Close high voltage contactor to adjustable frequency drive.
- Close input contactors to both converter sections.
- Close main contactor on 480V distribution system.
- Close isolating contactor in rotor circuit.
- Close output contactor in both inverter sections.
- Soft start the synchronous machine.
- At 80 percent speed activate cycloconverter controls.
- Adjust cycloconverter controls to permit synchronization.
- Close synchronizing contactor at zero power.
- Increase synchronous drive speed demand to 115 percent of synchronous speed.
- Return to 80 percent speed.
- Superimpose 2 per revolution torque perturbations on the drive shaft, through synchronous drive speed demand.
- Rerun speed excursion.
- Return to 80 percent speed.
- Open synchronizing contactor at zero power.
- Deactivate cycloconverter controls.
- Decrease adjustable frequency drive to full stop.
- Open output contactor in both inverter sections.
- Open isolating contractor in rotor circuit.
- Open main contactor on 480V distribution system.
- Open input contactors to both converter sections.
- Open high voltage contactor to adjustable frequency drive.

ADDITIONAL TESTS

- Cosine crossing versus integral control.
- Circulating current versus noncirculating current.
- VAR control.
- Simulate anticipated wind gusts at $\leq$ 2 percent speed per second.
- Cycloconverter capabilities in 50 to 80 percent speed range.
- Power quality.
- Harmonics.
- Soft starting wound rotor machine as a motor by shorting the stator and utilizing the cycloconverter to excite the rotor.
- Generation into passive load.

OPTIONAL ADDITIONAL TEST

- Simulate wind and hydroturbine drive train dynamics utilizing analog simulation circuits as input to adjustable frequency drive control.

2.1 TRADE-OFF EVALUATION

5. PRODUCTION HARDWARE COST ESTIMATES 1981 $'s

Power Rating	Speed Range		Variable Speed System Cost/ $/kW	Less Single Speed System Cost $/kW	Marginal Cost as % of $1-3 k/kW System Cost	Expected Performance Benefit	Benefit/ Cost Ratio $1-3 k/kW System Cost
500	1.5:1		294	—110	18-6%	10%	0.56-1.6
	2.3:1		—400	110	29-9.7%	20%	0.65-2.1
2500	1.5:1		106	—50	5.6-1.9%	10%	1.8-5.3
	2.3:1		300	50	25-8.3%	20%	0.8-2.4
7200	1.5:1	production	73	—50	2.3-0.8%	10%	4.3-12.5
		prototype	120	50	7-2.3%	10%	1.5-4.3
	2.3:1		101	50	5.1-1.7%	20%	1.9-5.9

CONCLUSIONS:

- Preliminary benefit/cost ratio's indicate good potential application of doubly fed machines
- Larger sizes show better benefit/cost than smaller sizes
- At 7200 kW, even a prototype installation could be cost cost effective (not considering design costs)
- These figures are preliminary only, especially for hydro applications