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Final Report

Induction and Synchronous Machines for Vertical Axis Wind Turbines

E. N. Hinrichsen

Power Technologies, Inc.

Prepared by Sandia Laboratories, Albuquerque, NM 87185
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INDUCTION AND SYNCHRONOUS MACHINES FOR VERTICAL AXIS WIND TURBINES

FINAL REPORT

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Sandia Laboratories
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Prepared by
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Power Technologies, Inc.
Schenectady, New York
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ABSTRACT

This report describes the behavior of synchronous and induction generators driven by vertical axis wind turbines and assesses the merits of the two types of machines. Major advantages of the synchronous generator are reactive power control and general acceptance by utility companies. The major advantage of the induction generator is excellent damping of torque pulsations. There is no significant difference in starting ability, efficiency, or voltage ripple.

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1.0 INTRODUCTION AND SUMMARY

1.1 Objective

This study has been conducted to determine the behavior of synchronous and induction generators driven by vertical axis wind turbines (VAWT), and to assess the relative merits of the two types of machines.

1.2 Approach

The complete electromechanical system of VAWT's connected to electric utility networks was modeled in the environment of PTI Power System Simulator (PSS/E). Principal model components are:

- Wind turbine
- Induction generator
- Synchronous generator
- Exciter (synchronous generator only)
- Turbine/Generator drive train
- Electrical system from generator terminals to terminals of equivalent utility source
- Equivalent utility source

The simulated VAWT system was operated at steady state near rated load and subjected to a number of disturbances.

A separate system for the investigation of electrical starting was modeled in the environment of PTI Dynamic System Simulator (IDAP). Model components are:

- Salient pole machine (starting) - including autotransformer for reduced voltage starting
- Turbine/Generator drive train

The reason for a separate simulation system for starting is the small integration time step required for representing salient pole torque pulsations at twice slip frequency (120 Hz at standstill).

Each of the two simulation systems was executed for four turbine sizes (60, 200, 500 and 1600 kW), with either a synchronous or an induction generator.

Equipment lists, estimated costs, and conceptual layouts of wind turbine stations were also prepared.

1.3 Summary

Major advantages of the synchronous generator are reactive power control and general acceptance by utility companies. The major advantage of the induction generator is excellent damping of torque pulsations. In terms of starting ability, efficiency and voltage ripple, there is no significant difference.

The lack of damping in VAWT systems with synchronous generators requires greater care in mechanical design. Induction generators appear to be the likely choice for small VAWT's, synchronous generators for the larger sizes. In most cases, characteristics of the utility grid at the connection point are not expected to influence wind turbine design.

There appear to be no problems peculiar to wind turbine clusters unless automatic generation control and spinning reserve in a large service area are considered. Mechanical excitation of the electromechanical system with turbine torque pulsations and thermal limitations of the generator during starting are two areas requiring particular attention in VAWT design.

2.0 TERMINOLOGY, PROCEDURES AND CONVENTIONS

The per-unit system is used throughout this investigation. Terms are, therefore, dimensionless and must be multiplied with the proper base quantity to obtain absolute values. Voltage, current and frequency bases are set independently:

Voltage Base = Rated Voltage

Current Base = Rated Current

Frequency Base = Synchronous Speed = $2\pi*60$ = 377 rad/sec

All other bases are automatically set by physical relationships; e.g.,

$$\text{Impedance Base} = \frac{\text{Voltage Base}}{\text{Current Base}}$$

For the four machine sizes investigated in this study, the following system base values were used:

Turbine Rating (kW)	System Base (kVA)
60	75
200	250
500	625
1600	2000

The inertia constant H is defined as:

$$H = \frac{1/2\ J\ \omega^2}{\text{Rated Machine Power}}$$

i.e., the ratio of kinetic energy over rated power. The units are seconds.

The torsional spring constant K is defined as:

$$K = \frac{\text{p.u. torque}}{\text{electrical radians}}$$

Since the simulation contains both mechanical and electrical elements, care was taken to differentiate between electrical and mechanical radians. The 1800 rpm generators used for this application have two pairs of poles; i.e., 180 mechanical degrees are equivalent to 360 electrical degrees or 1 mechanical radian is equivalent to 2 electrical radians.

The parameters shown in the simulation results are:

V-SYSTEM	Utility system voltage
DUM TORQ	"Dumbbell" torque, shaft torque between turbine halves
TORQTT	Same as DUM TORQ
GEN ANGL	VAWT generator rotor angle (synchronous machine only)
GEN POWR	Electrical power from generator
TER VOLT	Generator terminal volts
TUR SLIP	Generator speed variation
TUR POWR	Mechanical power from turbine
SLIP	Same as TUR SLIP
ETERM	Same as TER VOLT
TORQTG	Shaft torque between turbine and generator
EFD	Exciter field voltage

The time scales of the simulation results are calibrated in seconds.

3.0 MODEL DESCRIPTION

3.1 Wind Turbine

Mechanical power delivered by the turbine is:

$$P = cp \cdot 1/2 \cdot \delta \cdot A \cdot V^3$$

where

P = mechanical power

cp = power coefficient

δ = air density

A = area of wind turbine rotor

V = wind velocity

The power coefficient cp is a function of the tip speed ratio λ

$$\lambda = r\omega/V$$

where

r = radius of wind turbine rotor

ω = angular velocity

V = wind speed

Figures 1-4 show the relationship between tip speed ratio λ and power coefficient cp for the four turbine sizes. The wind turbine model calculates tip speed ratio λ and extracts the power coefficient cp from a look-up table which contains the relationship $cp = f(\lambda)$.

Power delivered by the wind turbine pulsates at a frequency of 2 cycles per revolution as the two blades turn into and out of the wind. In the wind turbine model, the pulsating torque output is simulated by superposition of steady state and oscillating torque. The oscillating torque varies sinusoidally with a frequency of 2 cycles per revolution and a magnitude determined by drive train characteristics and tip speed ratio.

3.2 Drive Train

The drive train is represented by three rotating discs connected by two torsional springs (Figure 5). Inertias and torsional stiffnesses are referenced to the speed of the generator. Figure 5 shows inertias and torsional stiffnesses for the four turbine sizes. Of the four speeds available on the 60 kW (17 meter) turbine, 52.5 rpm has been used throughout this study. For the 60 kW turbine, a second, lower value of torsional stiffness between generator and turbine has been included in the simulation studies.

3.3 Induction Generator

Typical single cage induction machines with standard characteristics were used. Figures 6 and 7 show equivalent circuit, machine constants and characteristic curves. Contrary to the synchronous machine, induction machines draw excitation volt-amperes from the line; i.e., they represent an inductive load to the electrical system. In this study, fixed capacitors have been connected to the induction generator bus to provide excitation volt-amperes. Without capacitors, the generator bus voltage would be less than rated under steady state conditions. Capacitive kVAR used in the simulation and resulting generator bus voltages for the four turbine sizes are:

Turbine Size (kW)	Capacitive kVAR (kVA)	Bus Voltage (p.u.)
60	31.7	0.9990
200	105.7	1.0026
500	264.0	1.0016
1600	686.0	1.0025

Fixed capacitors can only provide static voltage support. Dynamic voltage support with variable reactance has not been investigated. Dynamic voltage support would raise equipment complexity and cost. It would practically eliminate voltage variations at the generator terminals.

In an actual installation, the capacitors would be chosen to give induction machine and capacitors together an inductive power factor of approximately 0.95. Slight undercompensation is necessary to avoid self-excitation and the resulting overvoltage. Self-excitation would occur if induction machine and capacitors became separated from the utility system and the capacitors could provide all the excitation volt-amperes required by the generator.

3.4 Synchronous Generator

Typical salient pole machines with standard characteristics were used. The generator model includes a detailed representation of operational impedances of the rotor, saturation effects and effective rotor resistance. Figure 8 is a block diagram of the generator model. The excitation model represents a static excitation system using SCR bridges to produce main field voltage. Figure 9 is a block diagram of the excitation model. Generator and excitation constants are tabulated in Figure 10. Figure 11 shows the results of a response test of the SCR exciter for the 60 kW turbine. At time t=0, the exciter reference is increased by 10%. The responses of generator field voltage (EFD) and generator terminal voltage (ETERM) are shown.

3.5 Electrical System

For single wind turbine configurations, the electrical system is described in Figure 12. The electrical system for wind turbine clusters is shown in Figure 13. The components are:

- Wind turbine generator
- Transformer (generator to distribution level)
- Transmission line
- Transformer (distribution to subtransmission level)
- Equivalent utility source

Single wind turbine systems have been investigated for all four sizes. Per unit resistances and impedances used for the different turbine sizes are tabulated in Figure 12. It has been assumed that the step-up transformer from generator voltage to distribution voltage has the same rating as the generator and that the step-up transformer from distribution voltage to subtransmission voltage has 10.0 times the rating of the generator. The line characteristics represent 0.2 miles at 4.16 kV, 1.5 miles at 13.2 kV, or 11 miles at 34.5 kV. The relationship between per unit line characteristics at the kVA bases chosen and the three most probable voltage levels is shown in Figures 14 and 15. The investigation of wind turbine clusters has been limited to two machines of the 200 kW size. The main difference between a single machine and a cluster is the interaction between machines. The worst case for interaction are two machines with asynchronous torque ripple and asynchronous disturbances. Since the rotors of a VAWT cluster will rarely be in synchronism with each other, the effect of a cluster on the utility system will be less than that at an equivalent single unit.

Two configurations of the equivalent utility source have been used. In most cases, the source is infinite with respect to the wind turbine generator. An infinite source maintains a generator rotor angle of zero and has constant bus voltage at all times.

For the 200 kW wind turbine, an equivalent utility source with a short circuit rating of 15 MVA has been included in the investigation. This represents a weak utility connection. While the "infinite" source is comparable to a generator 1000 times the size of the VAWT, the "weak" source is equivalent to a generator 50 times the size of the VAWT.

4.0 SYSTEM SCENARIOS

The individual equipment models are combined into several simulation packages representing the complete electromechanical system of one or two VAWT's. For investigations at full speed, the simulation systems are initialized at approximately rated conditions and then perturbed by a change in wind speed or a three-phase short circuit at the high side of the VAWT step-up transformer. The change in wind speed is the same in all cases: A decrease to 20 MPH from the initial value, constant wind speed (20 MPH) for several seconds followed by an increase to 25 MPH.

For investigations of starting behavior, the simulation systems are initialized at a slip frequency of 15 Hz. This corresponds to a speed of 1350 rpm. Electrical

torque pulsations during startup occur at twice slip frequency. After the circuit breaker is closed, the drive accelerates to the vicinity of 1800 rpm, while slip frequency approaches zero. Since the significant natural frequencies of the drive exist below 10 Hz, any resonances appear between 1350 and 1800 rpm. Reduced voltage starting has been used throughout. During starting, the generators are connected to the 50% tap of an autotransformer.

The scenarios investigated during the simulation runs and the corresponding case numbers are:

Single Turbine at Rated Condition	Case Number	Page Number
Induction Generator		
60 kW	I11	39-40
60 kW (reduced torsional stiffness)	I12	41-43
200 kW	I13	44-46
200 kW (weak system connection)	I14	47-49
200 kW (without voltage support)	I17	56-58
500 kW	I15	51-52
1600 kW	I16	53-55
Synchronous Generator		
60 kW	S11	60-61
60 kW (reduced torsional stiffness)	S12	62-64
200 kW	S13	66-67
200 kW (weak system connection)	S14	68-69
500 kW	S15	71-72
1600 kW	S16	74-75
60 kW (without torque ripple)	S17	76-77
200 kW (without torque ripple)	S18	78-79
500 kW (without torque ripple)	S19	80-81
1600 kW (without torque ripple)	S110	82-83
Turbine Cluster at Rated Condition		
Induction Generator		
200 kW	I21	85-86
200 kW (weak system connection)	I22	88-91
Synchronous Generator		
200 kW	S21	93-94
200 kW (weak system connection)	S22	96-99
Single Turbine Starting		
Induction Generator		
60 kW	IS1	100
200 kW	IS2	101
500 kW	IS3	102
1600 kW	IS4	103
Synchronous Generator		
60 kW	SS1	104
200 kW	SS2	105-106
500 kW	SS3	107-108
1600 kW	SS4	109

Before a dynamic simulation at rated conditions can be initialized, a load flow calculation must determine real and reactive power flow in the electrical network. The following load flow cases are included:

Single Turbine at Rated Condition	Case Number	Page Number
Induction Generator		
60 kW	I11	39-40
200 kW	I13	41-43
200 kW (weak system connection)	I14	44-46
500 kW	I15	51-52
1600 kW	I16	53-55
Synchronous Generator		
60 kW	S11	60-61
200 kW	S13	66-67
200 kW (weak system connection)	S14	68-69
500 kW	S15	71-72
1600 kW	S16	74-75
Turbine Cluster at Rated Condition		
Induction Generator		
200 kW	I21	85-86
200 kW (weak system connection)	I22	88-91
Synchronous Generator		
200 kW	S21	93-94
200 kW (weak system connection)	S22	96-99

5.0 DISCUSSION AND EVALUATION OF RESULTS

5.1 Differences Between Induction and Synchronous Generators

In an induction machine, average rotor speed changes with load; i.e., a speed change caused by a load change is inherently damped. In a synchronous machine, only instantaneous speed changes occur while the rotor seeks a new position. Since average rotor speed remains constant, there is little damping.

This effect is quite apparent in the simulation results; e.g., Cases I11 and S11 or I13 and S13. Torque pulsations at the generator shaft and voltage ripple at the generator bus are lower with induction generators than with synchronous generators.

Excitation for synchronous machines is provided by a separate excitation system. Excitation for induction machines is provided by the electrical system in the form of inductive volt-amperes. It is common practice to provide inductive volt-amperes with capacitors at the induction machine bus to eliminate most of the voltage drop. Case I17 is the same as I13, except that the capacitors have been removed to show the effect of capacitive voltage support.

5.2 Electromechanical Resonances

The two frequencies of concern are the predominant natural frequency of the electromechanical system and the forcing frequency of the torque ripple. The former is found by executing the simulation systems for synchronous generators with the pulsating torque component set to zero (cases S17, S18, S19, S110). The first two rows of Fig. 16 contain a tabulation of both frequencies for the four turbine sizes.

Figure 16 indicates that the 500 kW VAWT is the most likely candidate for excitation by blade pulsating torque. The 1600, 200, and 60 kW turbines follow in descending order of likelihood. This is corroborated by cases S15, S16, S13, and S11. Case S15 shows considerable amplification of pulsating torque from turbine power to generator power. A milder form of the same phenomenon can be seen in case S16.

The last two rows of the frequencies tabulated in Figure 16 demonstrate that the predominant natural frequency is primarily determined by the inertia of the turbine rotor and the torsional stiffness of the shaft between turbine and generator. The estimated drive train frequency in the third row is based on a single inertia representing the turbine rotor and a torsional spring representing the shaft between the turbine and the generator. The torsional spring connects the turbine rotor to an infinite inertia. These estimates are a reasonable approximation of the natural frequencies obtained from a simulation of the complete system. The fourth row of frequencies in Figure 16 is based on a single mass connected to an infinite electrical system through a synchronous machine. The resulting frequencies are much higher and apparently do not play a significant role in this system.

5.3 Wind Turbine Torque Pulsations

The ratio of torque ripple amplitude in induction generator power over torque ripple amplitude at the turbine shaft is approximately 0.17 for the 60 kW turbine (Case I11). This agrees reasonably well with the data shown in Figure 4 of Reuter and Worstell's paper, "Torque Ripple in a Vertical Axis Wind Turbine," where the same ratio is approximately 0.20 for $\lambda = 5$.

Torque ripple amplitude in induction generator power is further reduced by a lower value of torsional stiffness between turbine and generator (K2 of Figure 5). In Case I12, the above ratio drops to 0.10 when K2 is reduced to 57% of the value used in Case I11.

Torque ripple amplitude in synchronous generator power is not significantly reduced by reducing K2 (Case S11 and S12). The only noticeable change is a reduction in frequency of the generator power pulsations.

Cases I12 and S12 include plots of generator torque to show the close agreement between generator power and torque at essentially constant speed operation.

5.4 Wind Turbine Starting

During starting, both induction and synchronous generators function as induction motors. The only significant difference is the rotor structure of the synchronous generator which gives rise to torque pulsations at twice slip frequency. Cases IS1 through IS4 and SS1 through SS4 show the behavior of both types of machines in the four sizes. There are no significant resonances in the region of interest, i.e. in the range of slip frequency between 15 Hz and 0 Hz.

5.5 Electrical Interaction Between Wind Turbines

There is little evidence of significant electrical interaction between wind turbines connected to the same system. In cases I21 and S21, the wind speed transient occurs at turbine 1 and the torque ripple of the two machines is out of phase by approximately 180°. The same condition exists in cases I22 and S22 except that the equivalent utility source has a higher impedance to represent a short circuit rating of 15 MVA at the point of interconnection. In cases I22 and S22 the systems are also subjected to a three phase short circuit on bus 4.

5.6 Utility System Parameters

The change from an equivalent utility source which is electrically and mechanically infinite to a "weak" utility connection with 15 MVA short circuit capability does not change results appreciably. Voltage fluctuations caused by torque ripple increase slightly (cases I14 and S14).

It is apparent that within the expected range of equivalent utility sources, there will be little effect on the operation of wind turbines.

6 .0 WIND TURBINE STATION DESIGN AND COST

Figures 17 and 18 are conceptual layouts of wind turbine stations. The cost estimates are based on standard, commercial equipment.

6.1 Electrical Equipment for 60 kW VAWT:

	INDUCTION	SYNCHRONOUS
Incoming line	3000	3000
Transformer	1500	1500
Secondary equipment	1000	1400
Cable line-transformer, transformer-starter and starter to motor	2000	2000
Capacitors 20 kVAC @ 480 v	400	
Motor 1800 rpm, 480 v, 60 hp vertical	1000	1000
	8900	8900
Installation (50% of equipment cost)	4450	4450
TOTAL	$13350	$13350

6.2 Electrical Equipment for 200 kW VAWT:

	INDUCTION	SYNCHRONOUS
2.4 to 13.8 kV incoming line via underground cable: fuses, switch, lightning arrester, pothead, all on distribution line pole	4000	4000
Transformer - 3ø 300 kVA pole-mount type, but placed in station yard, stress cone/ pothead, taped cable on 600 volt side.	3500	3500
Secondary equipment: (same description as 500 kW)	4500	7000
Cable distribution line to transformer Cable transformer to starter Cable starter to turbine	2500	2500
Capacitors 480 v, 75 kVAC, 1800 rpm	500	0
Motor: Vertical 250 hp, 480 v	5000	5000
	20000	22000
Installation (50% of equipment cost)	10000	11000
TOTAL	$30000	$33000

6.3 Electrical Equipment for 500 kW VAWT:

4.16 to 13.8 kV incoming line via underground cable: fuses, switch, lightning arrester, pothead on distribuiton line pole.	4000	4000
Transformer - 3ø 750 kVA pothead incoming, 480 v cable outgoing (junction box with CT's)	9500	9500
Secondary equipment at 480 v, motor controller (contactor), protection, current transformers, synchronizing control, static exciter, etc.	6000	8500
Cable MV line to transformer (15 kV)	1000	1000
Cable transformer to starter	500	500
Cable starter to motor	1000	1000
Capacitors 480 v, 175 kVAC	600	0
Motor - vertical, 460 v, 600 hp, 1800 rpm	16000	16000
	38600	40500
Installation (50% of equipment cost)	19300	20250
TOTAL	$57900	$60750

6.4 Electrical Equipment for 1600 kW VAWT:

	INDUCTION	SYNCHRONOUS
34.5 kV incoming structure, fuses, switches, terminations on structure	4000 3000	4000 3000
Transformer - 2000 kVA with lightning arrester on transformer	14000	14000
Secondary equipment at 2400 v: motor contactor (starter), current transformers, relays (protective), synchronizing panel, etc.	12000	20000
Cable, power and control to turbine	2000	2000
Capacitors (mounted at controller) 2400 v, 357 kVAC	2000	0
Motor - vertical, 2400 v, separate exciter (static) included, 1750 hp, 1800 rpm	48000	48000
	85000	91000
Installation (50% of equipment cost)	42500	45500
TOTAL	$127500	$136500

6.5 Design Considerations:

Repetitive Starting

The turbine represents a high inertia load. There are two considerations:

- duty on the motor
- duty on the transformer

The motor must be capable of bringing the turbine up to operating speed with a specified repetition rate.

The transformer thermal duty due to starting will not be a problem. However, if the motor starting current is five times full load current and the transformer rating equals motor (generator) full load capability, then the transformer will also see five times its rated current each start. This situation contrasts with the more typical situation where a transformer serves several motors and starting current of the largest motor is one or two times transformer rating or less.

Protection

Due to ΔY transformer connection, three phase over current devices should be used.

Type of Motor

Type K of NEMA design B.

Indoor/Outdoor

The incoming line equipment and transformer will be outdoor equipment. However, the secondary equipment should be enclosed in a weather-tight housing. Outdoor equipment is available, but the quantity of secondary equipment (starter, synchronous control, capacitors, etc.) will probably justify a building. Also, the cost of outdoor equipment is high and may make a building an economic alternative.

Standard Equipment

The cost estimates presented here are for standard equipment. That is, it has been assumed that some of the equipment such as the vertical motor and the synchronous control panel for operation in the motor and generator modes, which may not presently be standard items, will become standard due to demand. The early installations may be more costly than indicated in these estimates.

Starting Voltage Drop

The starting of the motor/generator will cause a large voltage drop in the transformer.

The primary system may also see some voltage drop during the start.

For a 1750 kVA motor (5 x inrush) connected to a 1750 kVA transformer (Z=6%) on a 50000 kVA system, start voltage will be 67.7% of initial voltage.

The motor starter contactor and other controls must be capable of operating properly at this voltage.

Motor start time etc. must be adequate at this voltage.

Quality of Estimates

The estimates are necessarily imprecise. There will be considerable variation in cost depending on a number of factors including:

- aesthetic requirements - undergrounding, transformer camouflage, etc.
- short-circuit level at tap point
- utility practices as to sectionalizing of lines, transformer protection, etc.

The estimates include a multiplier of 1.5 to provide for shipping and installation. This includes primarily labor and materials for pads, ground mat, etc.

The estimate for a 1500 kW unit is based solely on connection at 34.5 kV. There would be some cost reduction for this unit size at lower voltages. The reduction would be on the order of 5% for application at voltages in the range 4 kV to 15 kV.

Motor Starter (contactor)

The secondary circuit need not have a circuit breaker for protection. The short-circuit level will be well within the interrupting capability of conventional motor starter contactors.

Motor control such as GE "Limitamp" is rated as high as 50 MVA interrupting without current limiting fuses (2400 v application).

For 480 volt systems, starters which include a fused switch or circuit breaker are readily available for the 480 volt fault levels which will be encountered with transformer sizes of 750 kVA and below.

Generator Considerations

The estimates show costs for induction and synchronous generators. In the case of induction type, the power factor is assumed to be rated .85, but corrected to .95 by capacitors. This means the induction generator must draw some reactive current from the system (19 kvar for 50 kW, 78 kvar for 2000 kW, 187 kvar for 500 kW, and 468 kvar for 1600 kW). This will be a very important consideration in selection of the generator type. Correction to unity power factor by capacitors is not possible due to self-excitation.

The estimates for synchronous generator are based on a unity power factor machine. It would draw no reactive current from the system.

An .8 power factor synchronous generator would be advantageous where the turbine is to be installed on a relatively weak system. Reactive power support of the system within the capability of the machine would be quite practical.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation do not make the induction generator a clear favorite over the synchronous generator or vice versa. They do show that the induction generator is a strong contender.

Major advantages of the synchronous generator for wind turbine applications are:

- No reactive power demands
- Contribution to reactive power requirements possible
- General acceptance by utility companies.

Major advantages of the induction generator for wind turbine applications are:

- Excellent damping of torque pulsations

In a number of areas, the two machines do not differ significantly:

- Starting

  No appreciable difference exists between synchronous and induction generator starting for comparable machines. Torque pulsations resulting from rotor saliency in the synchronous machine do not play an important role.
- Efficiency
- Voltage Variations

  An induction generator with capacitive voltage support does not have greater voltage variations due to turbine torque pulsations than a synchronous generator.

The advantages of the synchronous machine are more significant in the large sizes and the engineering care required to avoid resonances in synchronous machine VAWT's is easier to justify for large turbines (> 1 MW). It is therefore likely that synchronous generators are the best choice for large turbines and induction generators for small turbines.

Characteristics of the utility grid at the interconnection point will probably not influence wind turbine system design significantly. Even for a wide range of utility system parameters, the utility grid is essentially an infinitely large system when viewed from the wind turbine.

There are no inherent problems in multiple wind turbine applications. The only question which could arise in connection with large, concentrated blocks of wind power is area generation control (AGC) and spinning (stand-bye) reserve maintained by the utility company to regulate effects of changing wind velocity. Present AGC systems are designed for a spectrum of random load fluctuations which might not be suitable for regulating a system with a large wind power component. This question is beyond the scope of this study.

This investigation indicates that the two major electrical engineering challenges in VAWT design are:

- Amplification of natural frequency of electromechanical system by turbine torque pulsations. Since the natural frequency appears to depend primarily on drive train characteristics, the solution has to be mechanical. If an induction generator is used, it is unlikely that amplification will occur. If a synchronous generator is used, the torque ripple frequency should be substantially higher than the first natural frequency of the drive train.
- Excessive generator heating during starting. Turbine inertias viewed from the generator shaft are high. Starting times vary between 15 and 25 seconds for the three smaller sizes and are in excess of 25 seconds for the 1600 kW size. Permissible starting times for infrequent starts of predominantly inertia type loads are between 10 and 15 seconds. The only cost-effective electrical solutions are oversize generators or forced cooling.

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17.	Conceptual Layout of Wind Turbine Station (60,200,500 kW)	36
18.	Conceptual Layout of Wind Turbine Station (1600 kW)	37

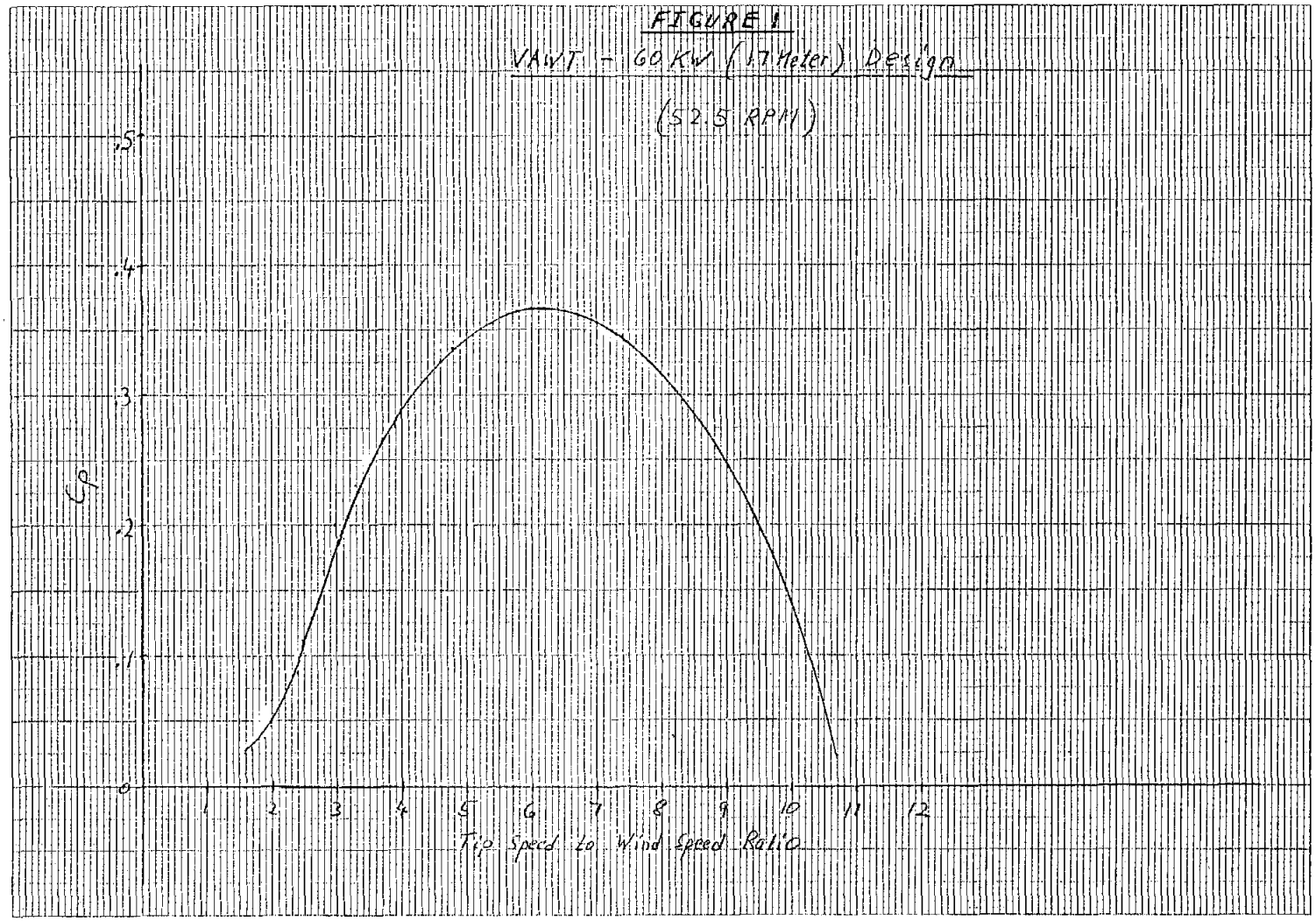


FIGURE 1
VAWT - 60 KW (17 Meter) Design
(52.5 RPM)
Cp
.5
.4
.3
.2
.1
0
1
2
3
4
5
6
7
8
9
10
11
12
Tip Speed to Wind Speed Ratio

[redacted]

FIGURE 2

VAWT - 200 KW Design

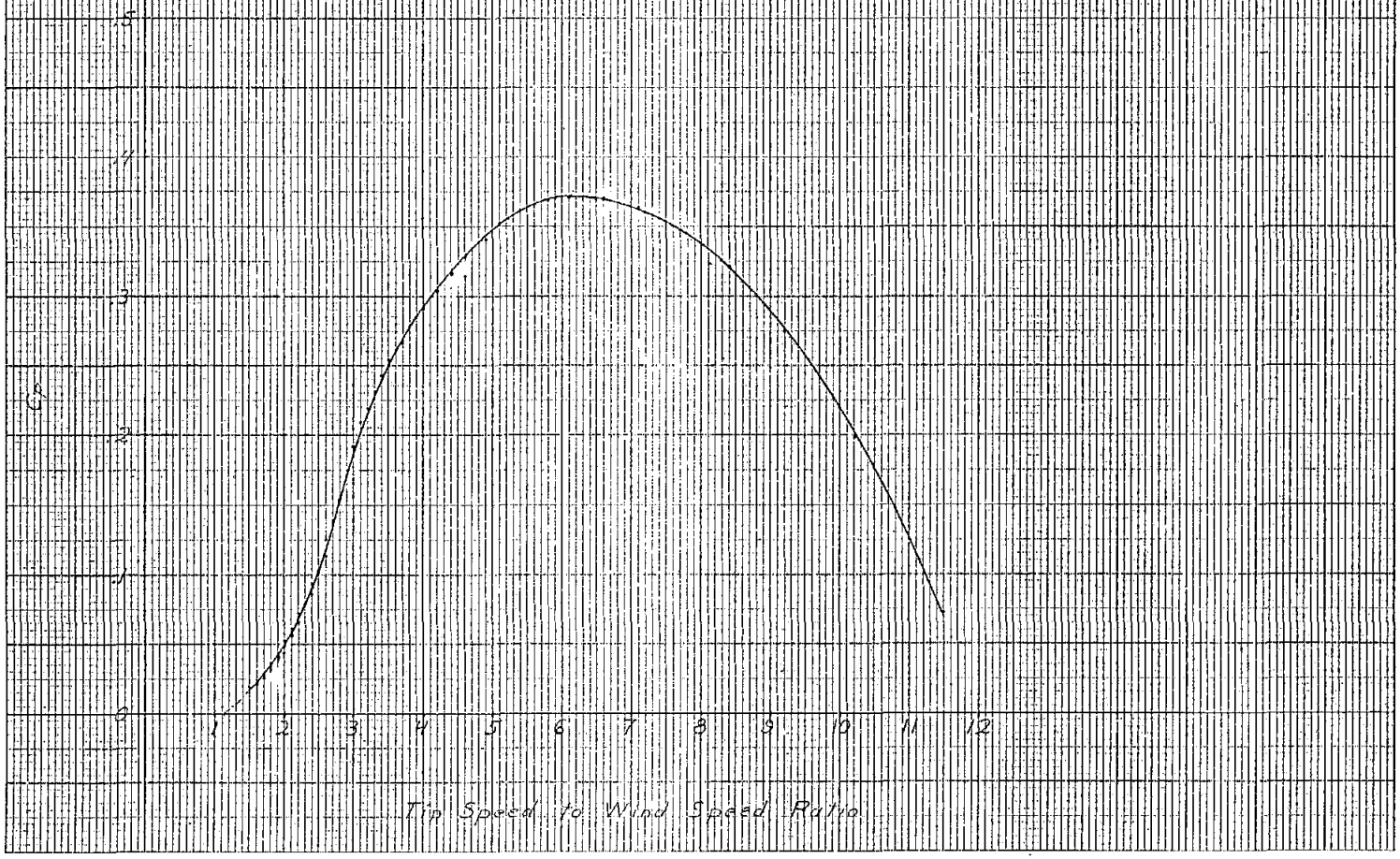


FIGURE 3

VAWT – 500 KW Design

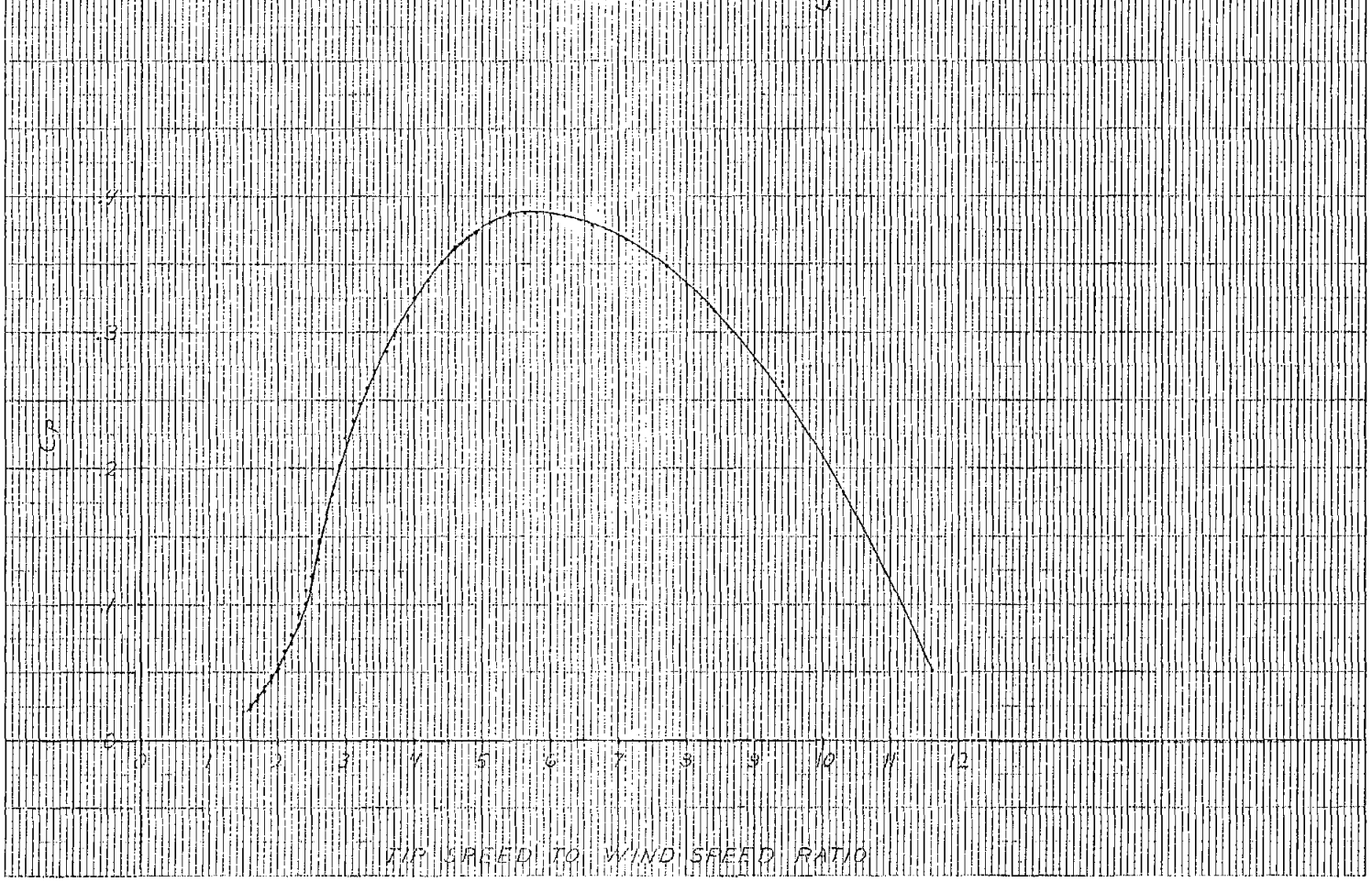


FIGURE 4

VAWT - 1600 KW Design

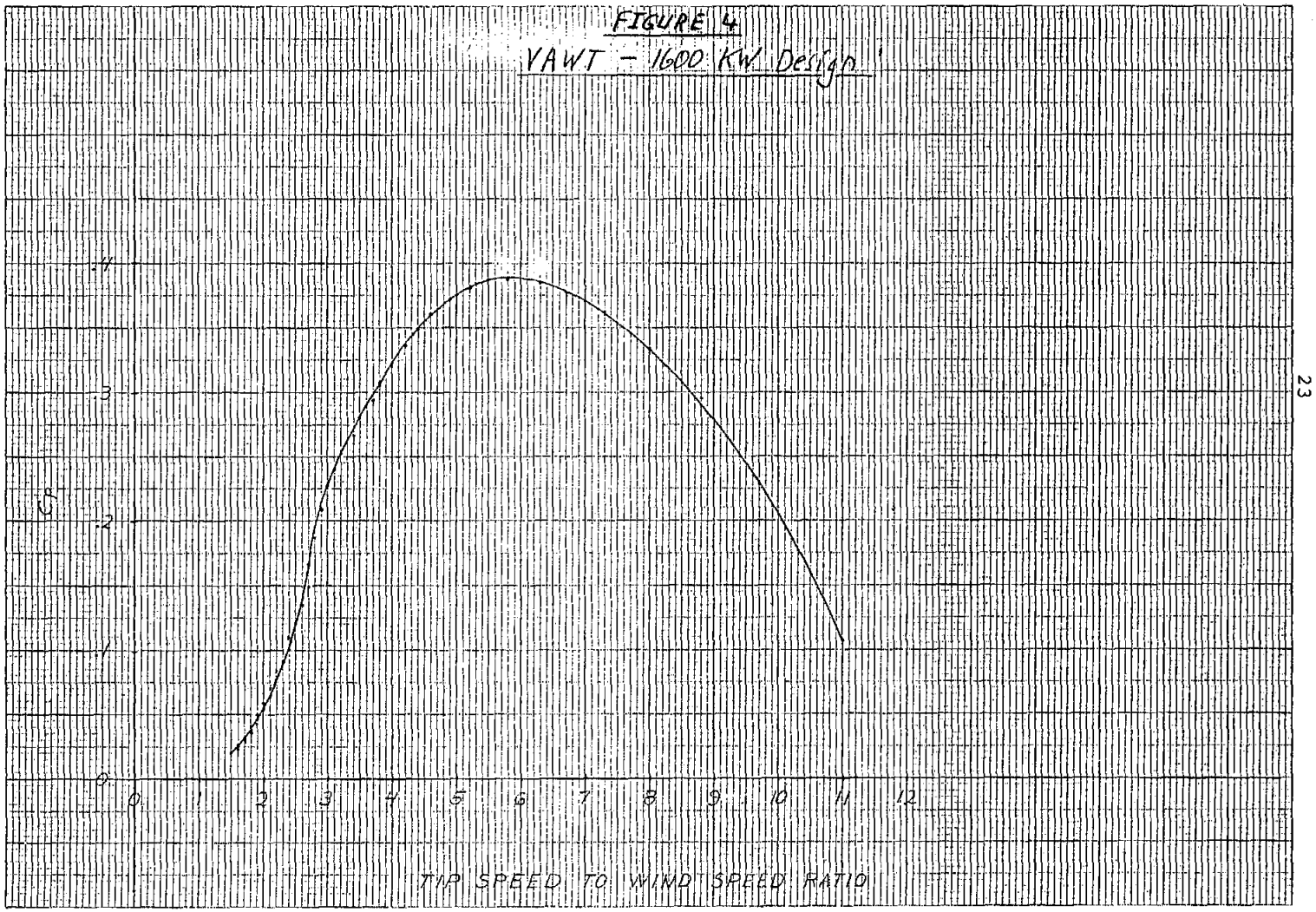
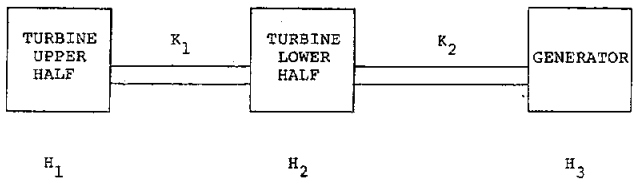


FIGURE 5

WIND TURBINE

MECHANICAL SYSTEM



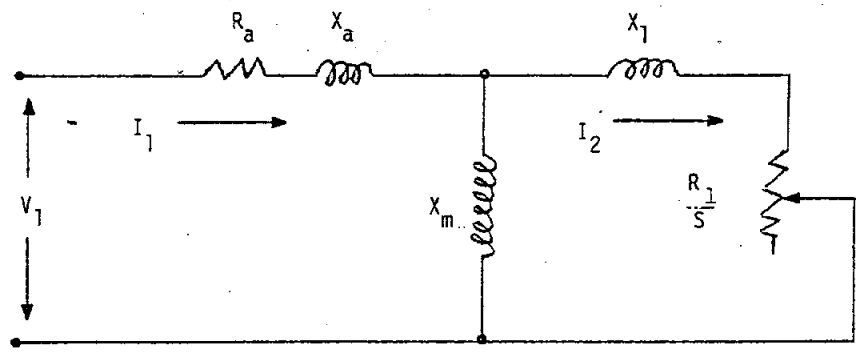
TURBINE SIZE (kW)	H_1 (SEC)	H_2 (SEC)	H_3 (SEC)	K_1 PUT/RADE	K_2 PUT/RADE	SPEED RATIO	SPEED [RPM]
60	2.24	2.24	0.687	11.85	0.435**	42.87*	*
200	2.94	2.94	0.496	2.38	1.65	44.89	40.1
500	2.71	2.71	0.693	1.77	1.57	57.7	31.2
1600	4.08	4.08	1.39	0.69	0.65	88.0	20.5

* multiply with additional speed ratio to obtain total ratio

** alternate K_2 for 60 kW turbine: 0.248 PUT/RADE

RPM	29.6	27.0	45.5	52.5
RATIO	1.416	1.134	0.923	0.800

INDUCTION GENERATOR



X_a	0.12	Stator Leakage Reactance
R_a	0.02	Stator Resistance
X_m	3.00	Magnetizing Reactance
X_1	0.12	Rotor Leakage Reactance
R_1	0.03	Rotor Resistance
S		Slip
I_1		Stator Current
I_2		Rotor Current
V_1		Terminal Voltage

FIGURE 6

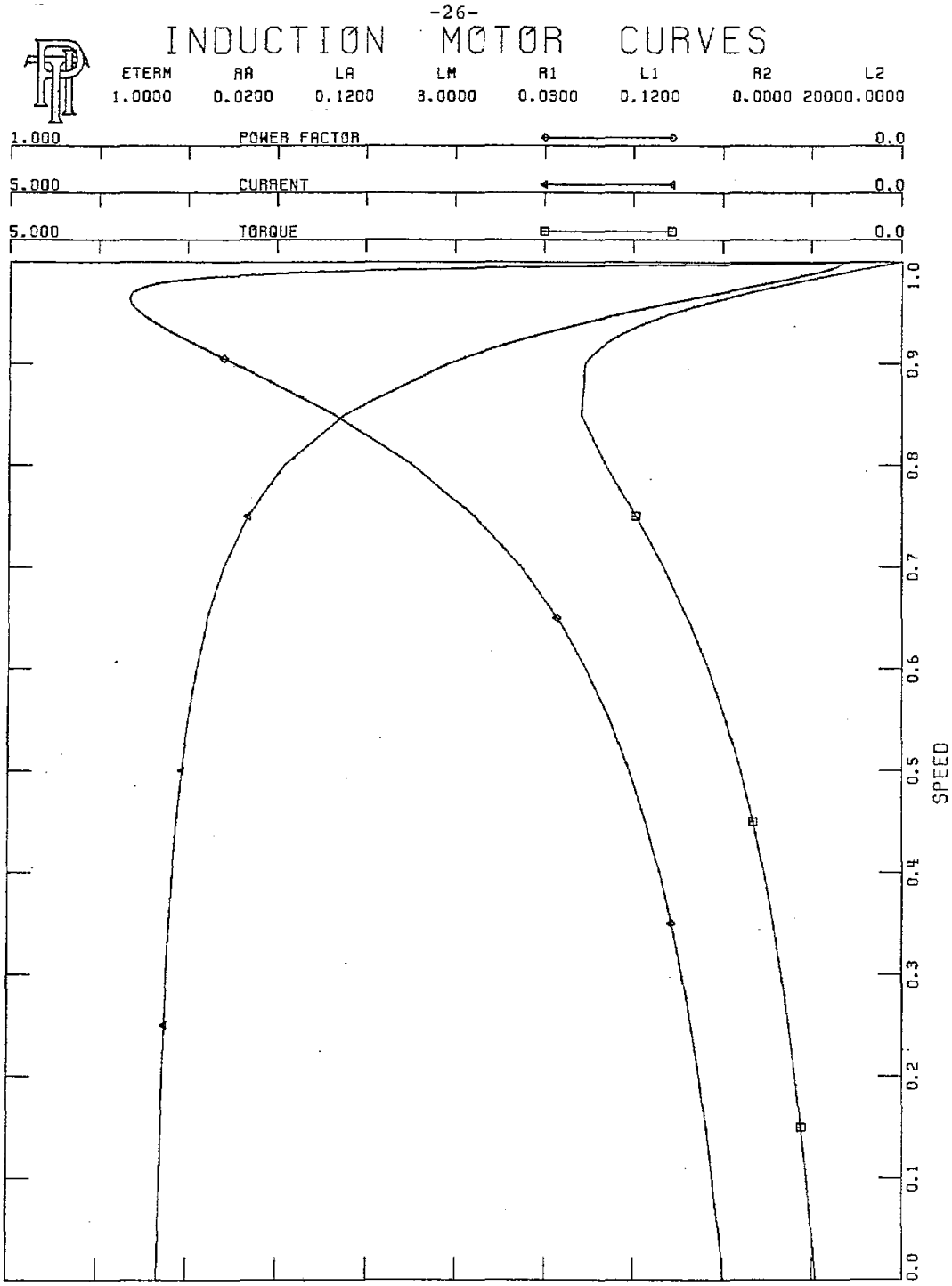
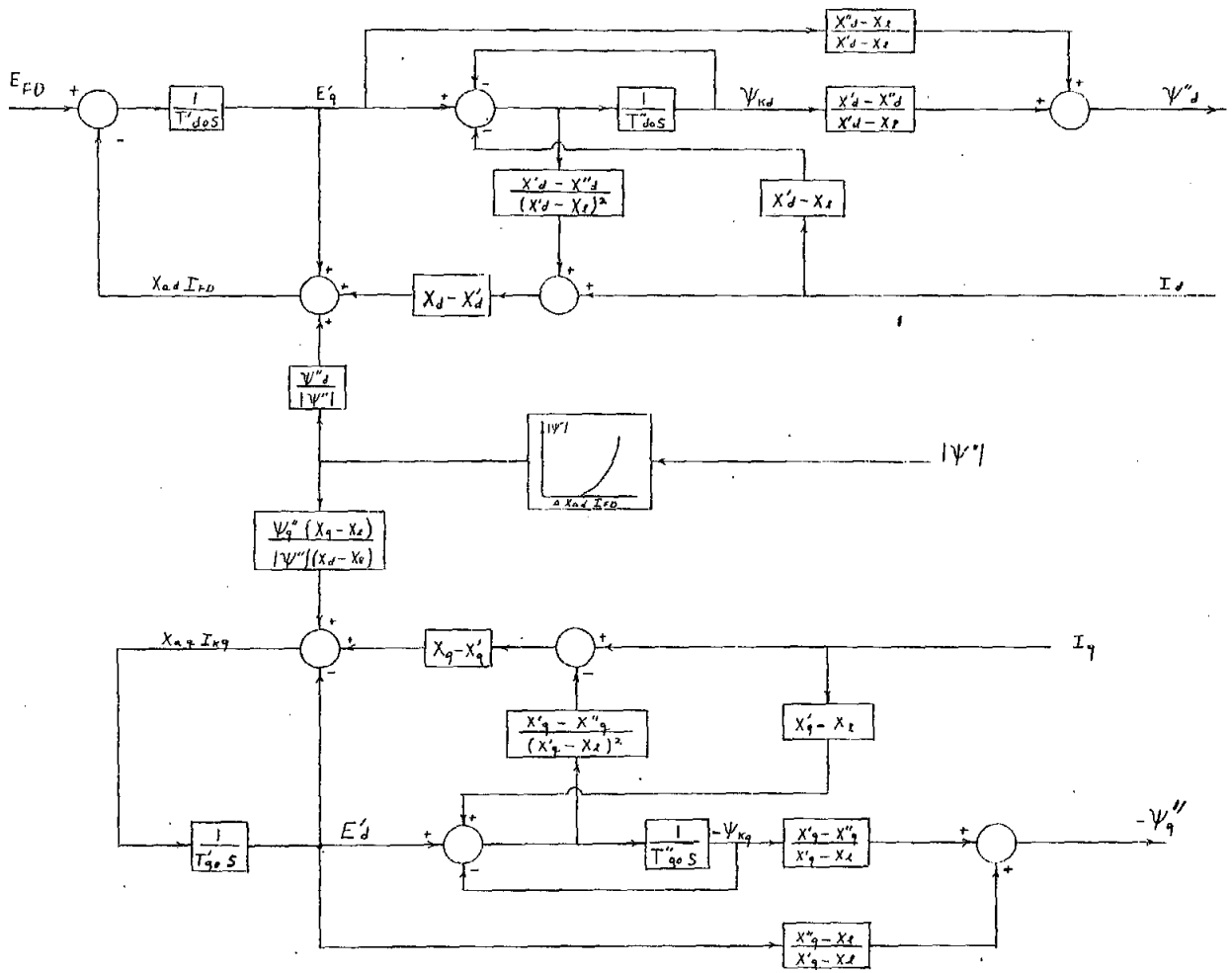

INDUCTION MOTOR CURVES
ETERM RA LA LM R1 L1 R2 L2
1.0000 0.0200 0.1200 3.0000 0.0300 0.1200 0.0000 20000.0000
1.000 POWER FACTOR 0.0
5.000 CURRENT 0.0
5.000 TORQUE 0.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
SPEED

FIGURE 7

FIGURE 8

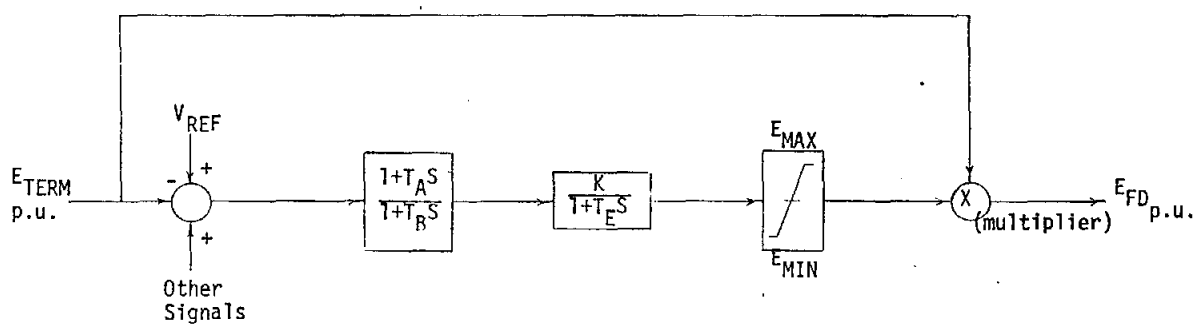


GENERATOR MODEL

FIGURE 9

BLOCK DIAGRAM OF SCRX

EXCITATION MODEL



$T_A = 1.$

$T_B = 10$

$K = 200$

$T_E = 0.05$

$E_{MIN} = -3.2$

$E_{MAX} = 4$

FIGURE 10

SYNCHRONOUS MACHINE AND EXCITER DATA

Synchronous Generator Constants

X_d	1.47 pu	Direct axis reactance
X'_d	0.234 pu	Direct axis transient reactance
X''_d	0.141 pu	Direct axis subtransient reactance
X_q	0.96 pu	Quadrature axis reactance
X''_q	0.141 pu	Quadrature axis subtransient reactance
X_L	0.12 pu	Stator leakage reactance
T'_{do}	4.0 sec	Direct axis transient time constant
T''_{do}	0.06 sec	Direct axis subtransient time constant
T''_{qo}	0.06 sec	Quadrature axis subtransient time constant
H	*	Inertia
S(1.0)	0.11	Saturation at 100% flux**
S(1.2)	0.48	Saturation at 120% flux

Exciter Constants

T_a	1.0 sec	Lead
T_b	10.0 sec	Lag
K	200	Gain
T_E	0.05 sec	Exciter time constant
E_{min}	-3.2	Minimum field voltage
E_{max}	4.0	Maximum field voltage

* Refer to Figure 5

** S is the per unit difference in field current between saturation curve and air gap line.

SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
OPEN CIRCUIT RESPONSE TEST - REGULATOR GAIN K=200

FIGURE 11

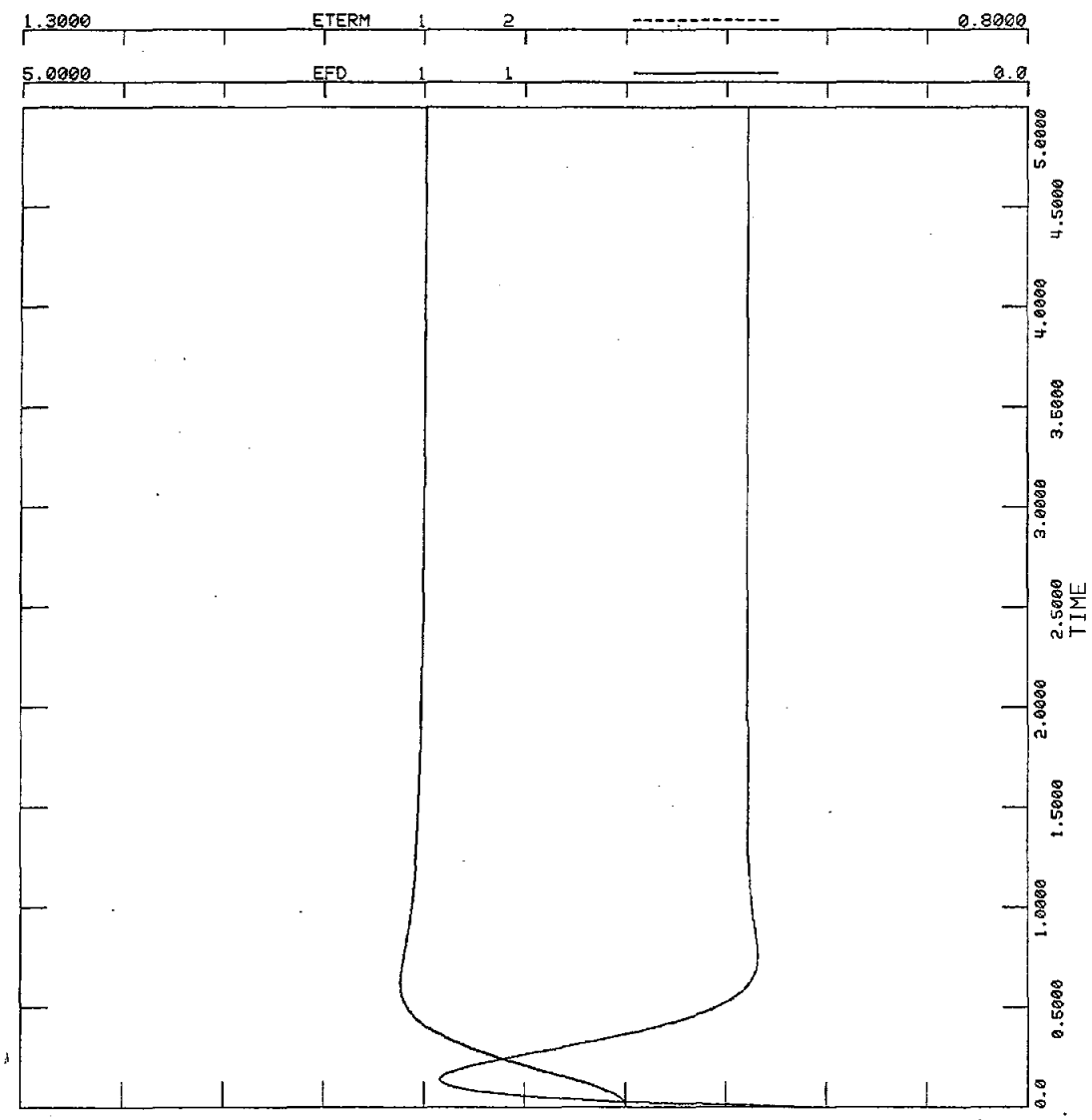
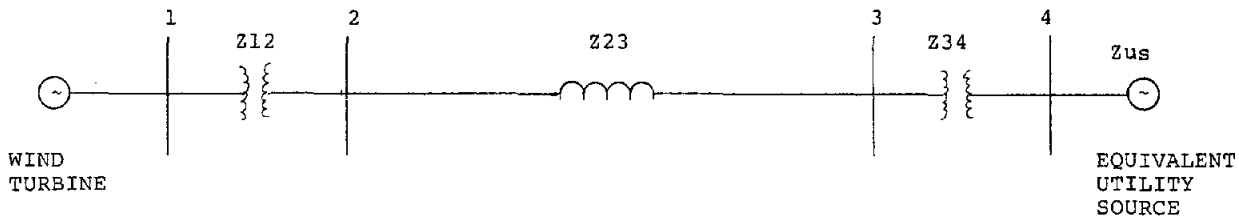


FIGURE 12

SINGLE WIND TURBINE

ELECTRICAL SYSTEM

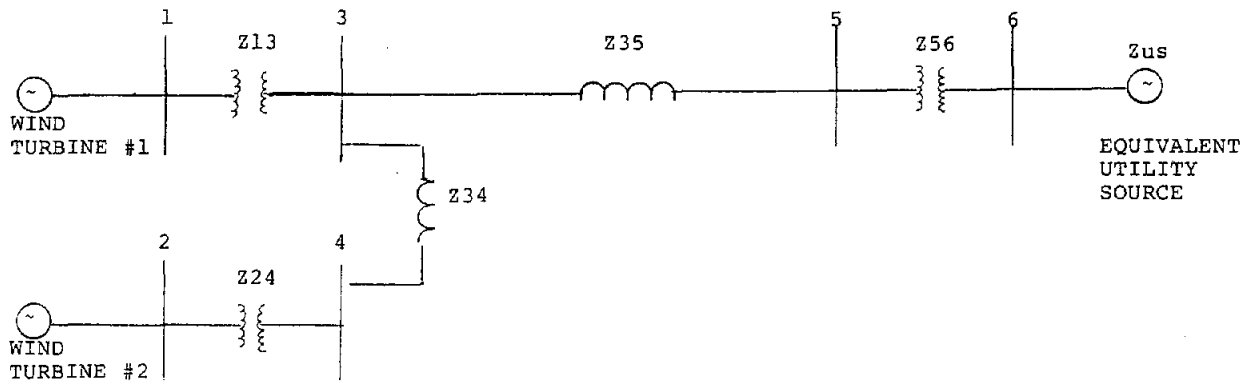


	60 kW	200 kW	500 kW	1600 kW
Z12	0.01+j0.05	0.01+j0.05	0.01+j0.05	0.01+j0.05
Z23	0.0005+j0.0006	0.0017+j0.00185	0.0043+j0.0047	0.0136+j0.0149
Z34	0.001+j0.005	0.001+j0.005	0.001+j0.005	0.001+j0.005
Zus	0.0005+j0.001	0.0005+j0.001	0.0005+j0.001	0.0005+j0.001

FIGURE 13

WIND TURBINE CLUSTER

ELECTRICAL SYSTEM



	200 kW - Infinite System	200 kW - Weak System
Z13	0.01+j0.05	0.01+j0.05
Z24	0.01+j0.05	0.01+j0.05
Z34	0.0003+j0.0004	0.0003+j0.0004
Z35	0.0017+j0.00185	0.0017+j0.00185
Z56	0.001+j0.005	0.001+j0.005
Zus	0.0005+j0.001	0.008+j0.0017

FIGURE 14

Reactance in Per Unit/Mile for Three-Phase

Transmission Line with Current Rating of 200 Amperes

Line Voltage [kV]	System Base [kVA]			
	75	250	625	2000
4.16	0.0033	0.0108	0.027	0.0867
13.2	0.00033	0.0011	0.00278	0.00891
34.5	0.000053	0.000176	0.000441	0.00141

FIGURE 15

Resistance in Per Unit/Mile for Three-Phase

Transmission Line with Current Rating of 200 Amperes

Line Voltage [kV]	System Base [kVA]			
	75	250	625	2000
4.16	0.00307	0.0102	0.0256	0.0818
13.2	0.0003	0.001	0.0025	0.0081
34.5	0.000045	0.000149	0.000372	0.00189

FIGURE 16

FORCING AND NATURAL FREQUENCIES

Turbine Size	(kW)	60	200	500	1600
Torque Ripple Frequency	(Hz)	1.75	1.34	1.04	0.68
Natural Frequency of Electromechanical System - Based on Simulation	(Hz)	0.63	0.80	0.82	0.47
Estimate of First Natural Frequency of Drive Train	(Hz)	0.68	1.16	1.18	0.62
Estimate of Natural Frequency of Electromechanical System (Synchronous Generator Only)	(Hz)	2.07	1.79	1.89	1.54

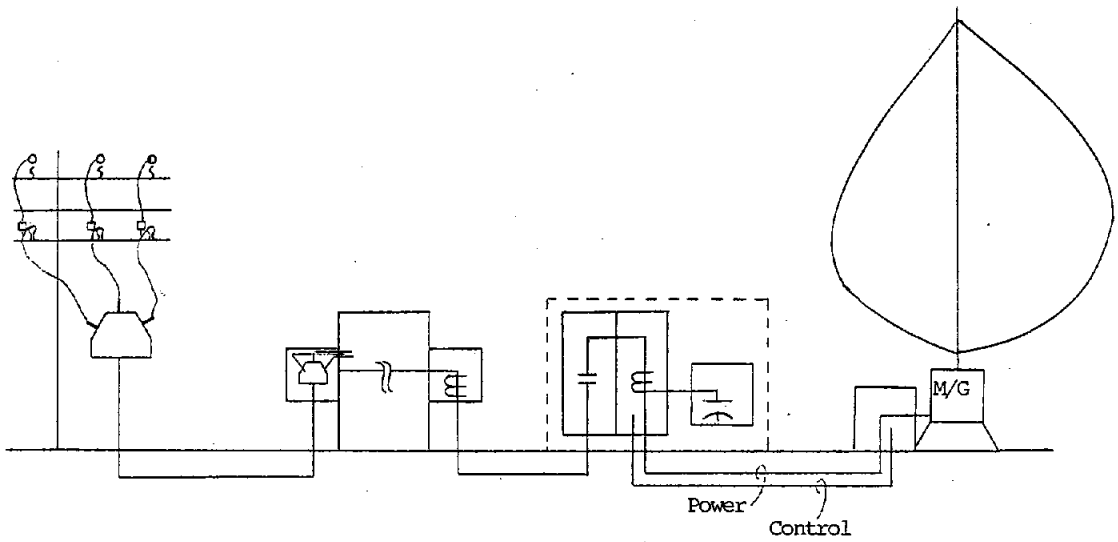


Figure 17. Conceptual Layout of Wind Turbine Station for 60 kW, 200 kW, 500 kW

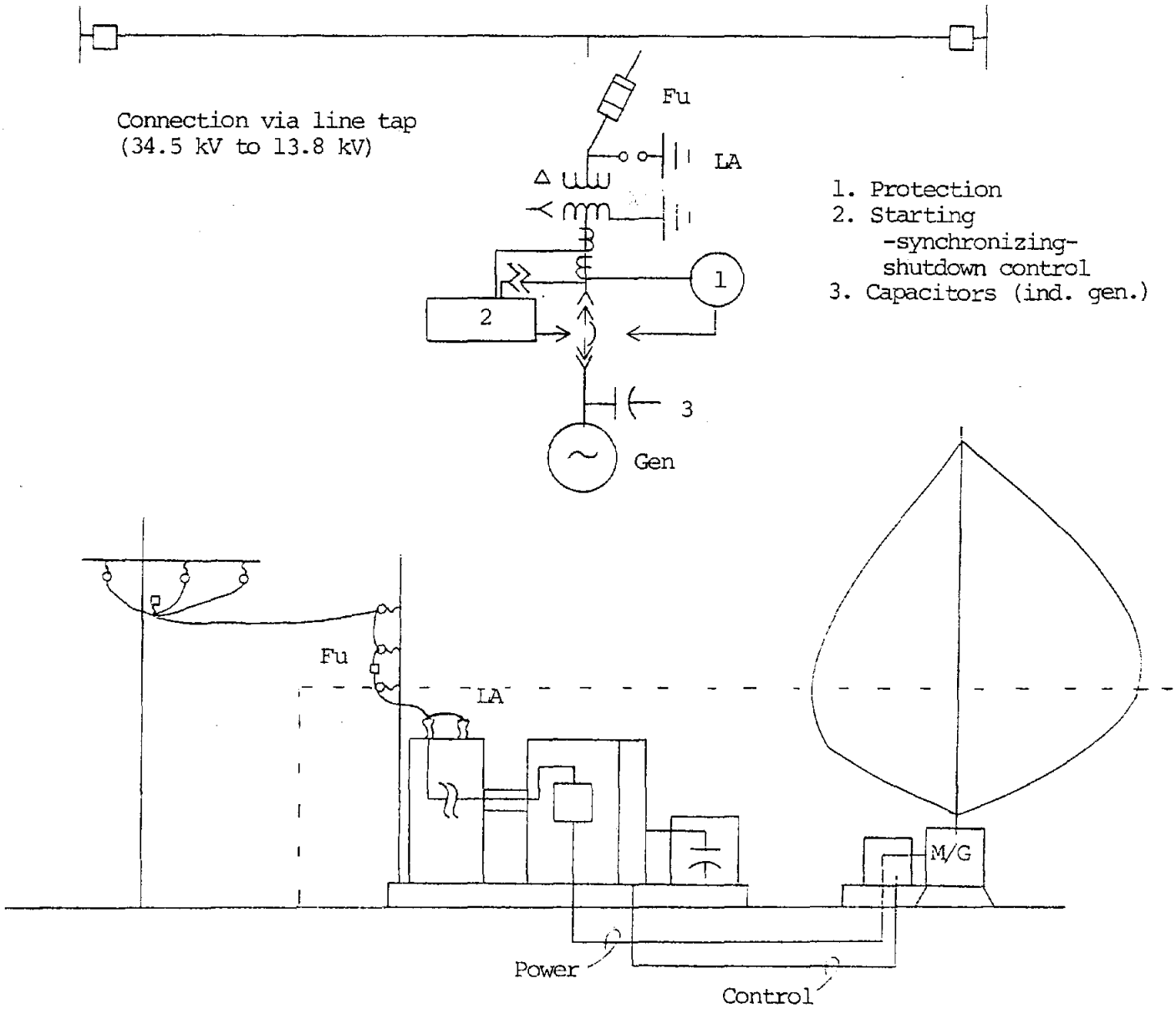


Figure 18. Connection Diagram and Conceptual Layout of Wind Turbine Station for 1600 kW

9.0 SIMULATION CASES

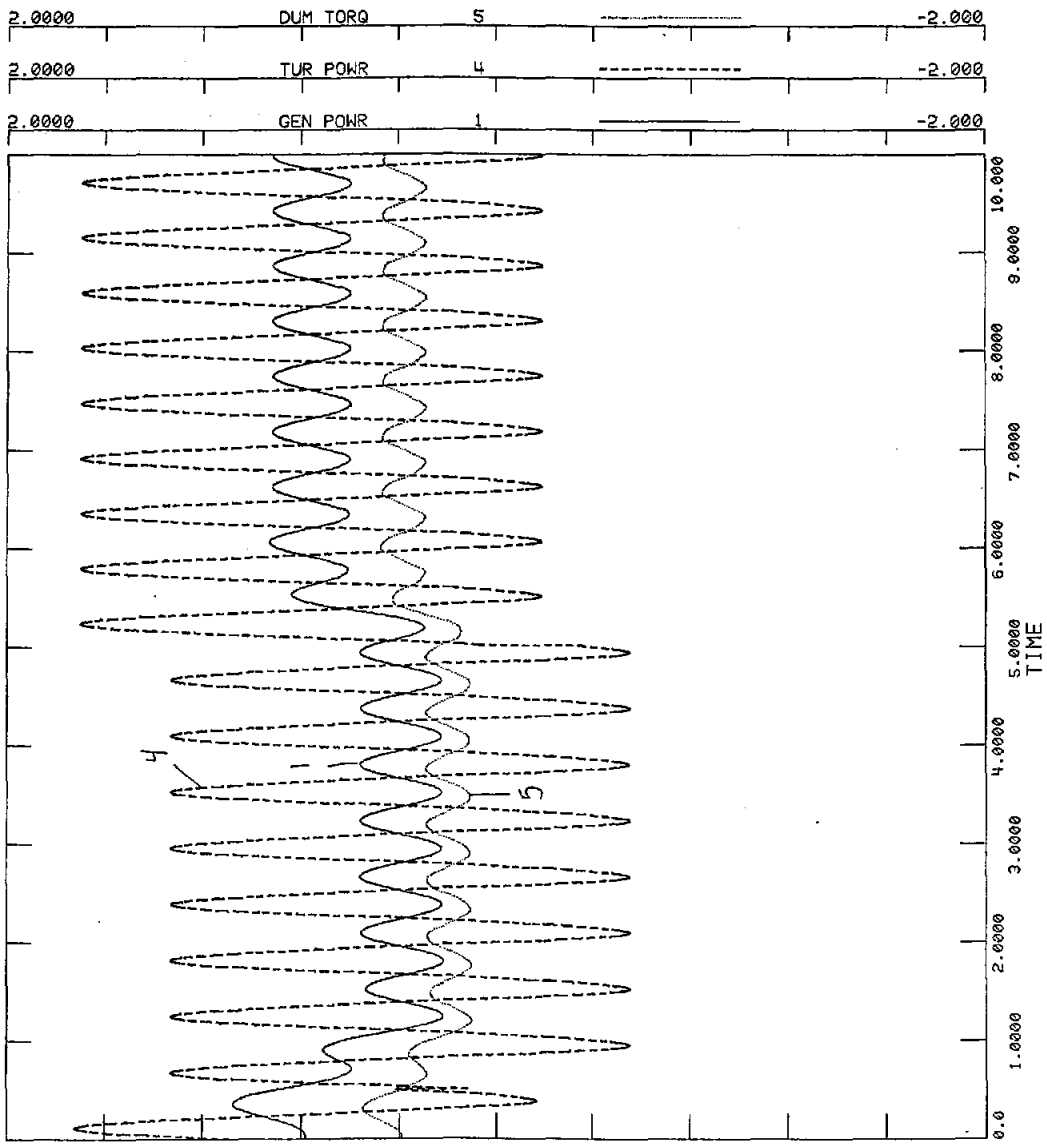
Number	Description	Page Number
I11	Induction - Single - 60 kW	39-40
I12	Induction - Single - 60 kW - Low K2	41-43
I13	Induction - Single - 200 kW	44-46
I14	Induction - Single - 200 kW - Weak System	47-49
I15	Induction - Single - 500 kW	51-52
I16	Induction - Single - 1600 kW	53-55
I17	Induction - Single - 200 kW - w/o Voltage Support	56-58
S11	Synchronous - Single - 60 kW	60-61
S12	Synchronous - Single - 60 kW - Low K2	62-64
S13	Synchronous - Single - 200 kW	66-67
S14	Synchronous - Single - 200 kW - Weak System	68-69
S15	Synchronous - Single - 500 kW	71-72
S16	Synchronous - Single - 1600 kW	74-75
S17	Synchronous - Single - 200 kW w/o Torque Ripple	76-77
S18	Synchronous - Single - 200 kW w/o Torque Ripple	78-79
S19	Synrhconous - Single - 200 kW w/o Torque Ripple	80-81
S110	Synchronous - Single - 200 kW w/o Torque Ripple	82-83
I21	Induction - Cluster - 200 kW	85-86
I22	Induction - Cluster - 200 kW - Weak System	88-91
S21	Synchronous - Cluster - 200 kW	93-94
S22	Synchronous - Cluster - 200 kW - Weak System	96-99
IS1	Induction - Starting - 60 kW	100
IS2	Induction - Starting - 200 kW	101
IS3	Induction - Starting - 500 kW	102
IS4	Induction - Starting - 1600 kW	103
SS1	Synchronous - Starting - 60 kW	104
SS2	Synchronous - Starting - 200 kW	105-106
SS3	Synchronous - Starting - 500 kW	107-108
SS4	Synchronous - Starting - 1600 kW	109

P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS

BUS	1 GENR	AREA	CKT	MW	MVAR	MVA	%	1.0039PU	2.53	1
GENERATION		1		58.7	-37.2R	69.5	93	KV		
TO LOAD-PQ				0.0	-31.7	31.7				
TO	2 LINE-GEN	1	1	58.7	-5.5	59.0	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	MW	MVAR	MVA	%	1.0006PU	0.26	2
		1						KV		
TO	1 GENR	1	1	-58.2	7.8	58.8	0	1.0000LK		
TO	3 LINE-SYS	1	1	58.2	-7.8	58.7	0			
BUS	3 LINE-SYS	AREA	CKT	MW	MVAR	MVA	%	1.0002PU	0.23	3
		1						KV		
TO	2 LINE-GEN	1	1	-58.2	7.8	58.7	0			
TO	4 SYSTEM	1	1	58.3	-7.8	58.8	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	0.00	4
GENERATION		1		-58.2	8.1R	58.8	78	KV		
TO	3 LINE-SYS	1	1	-58.2	8.1	58.8	0	1.0000LK		

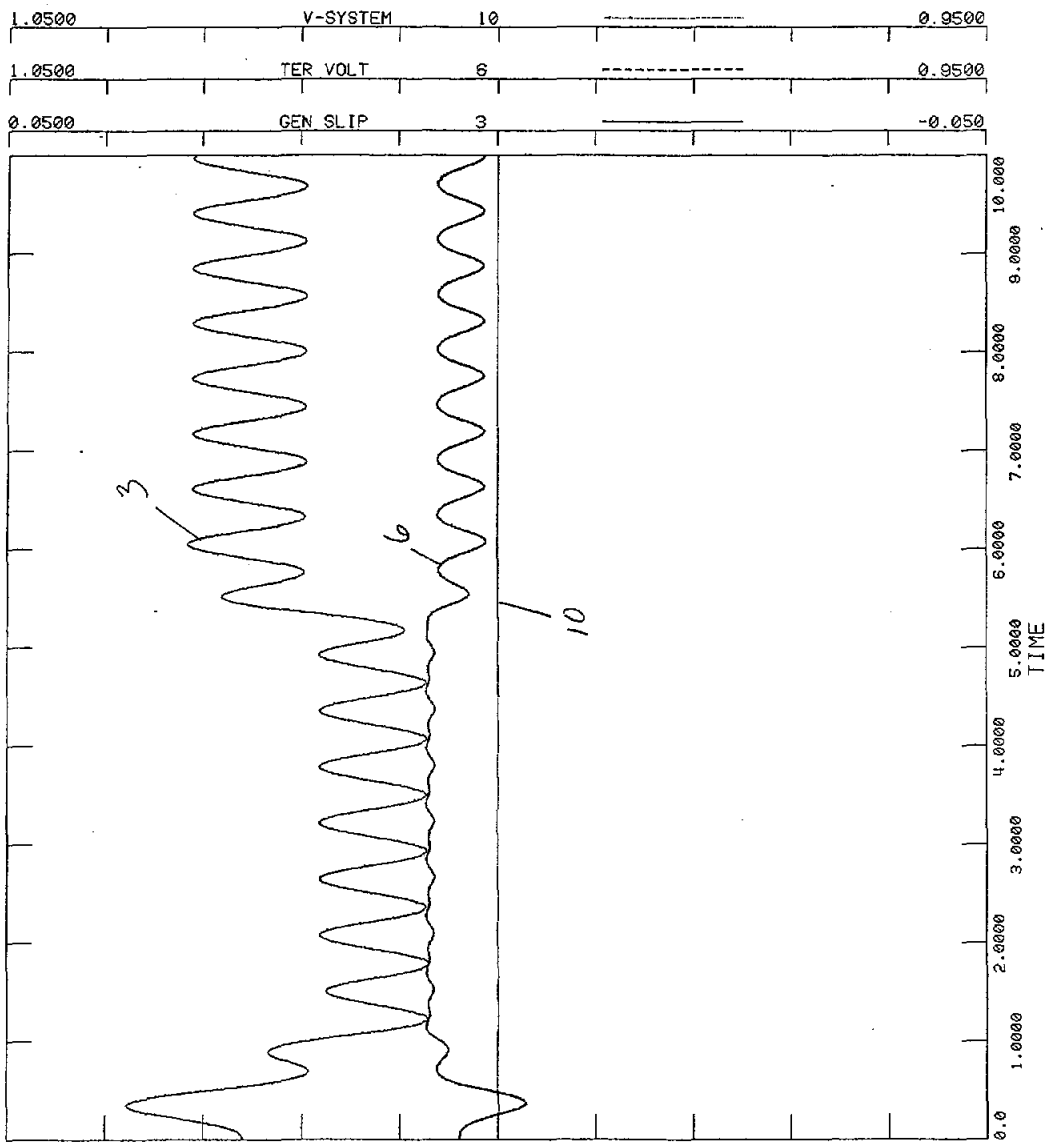
CASE I11, I12

SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
TEST - *WIND SPEED TRANSIENT*
CASE I11



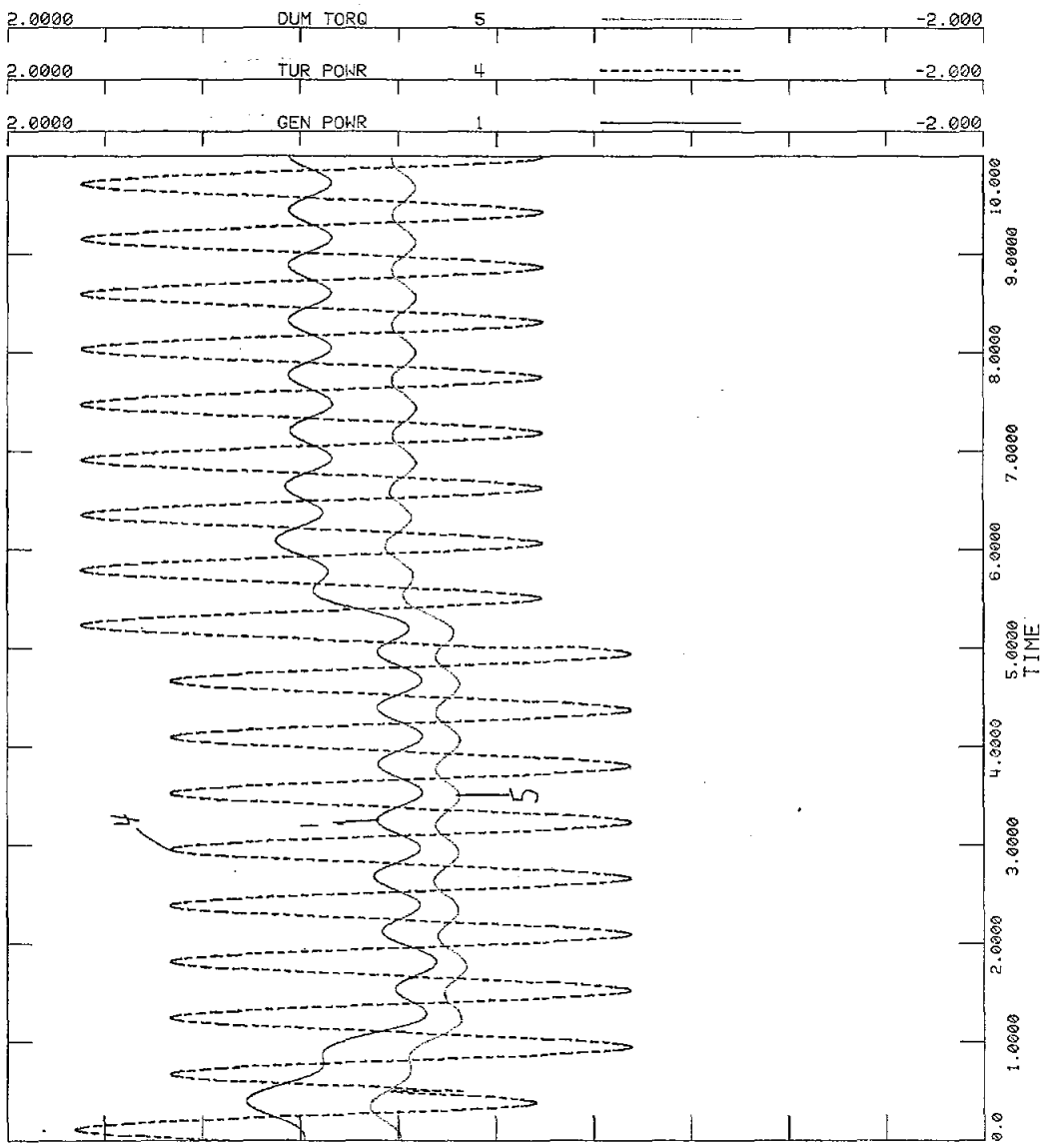
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
TEST - *WIND SPEED TRANSIENT*

CASE I 11

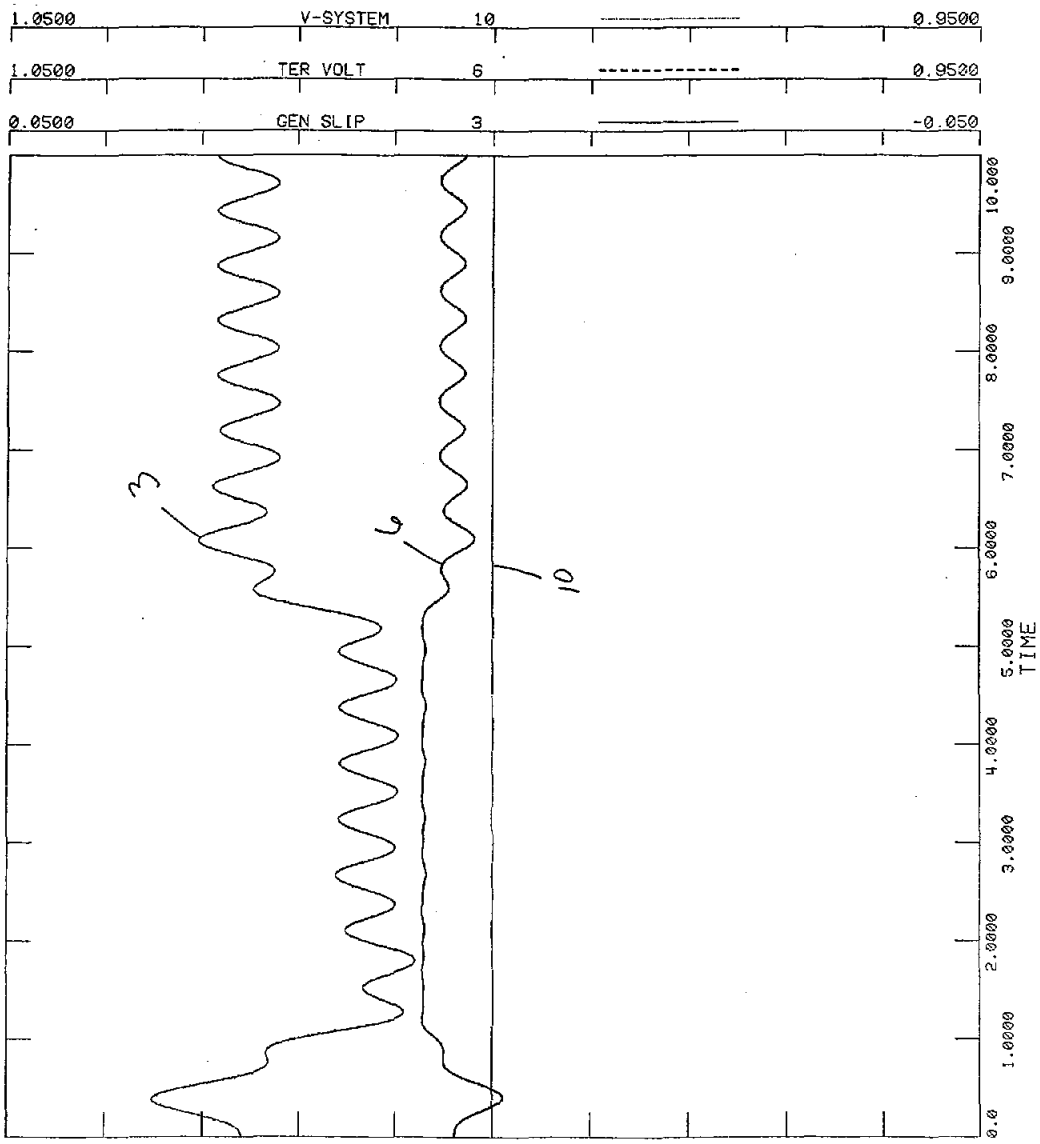


SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE

CASE I/2

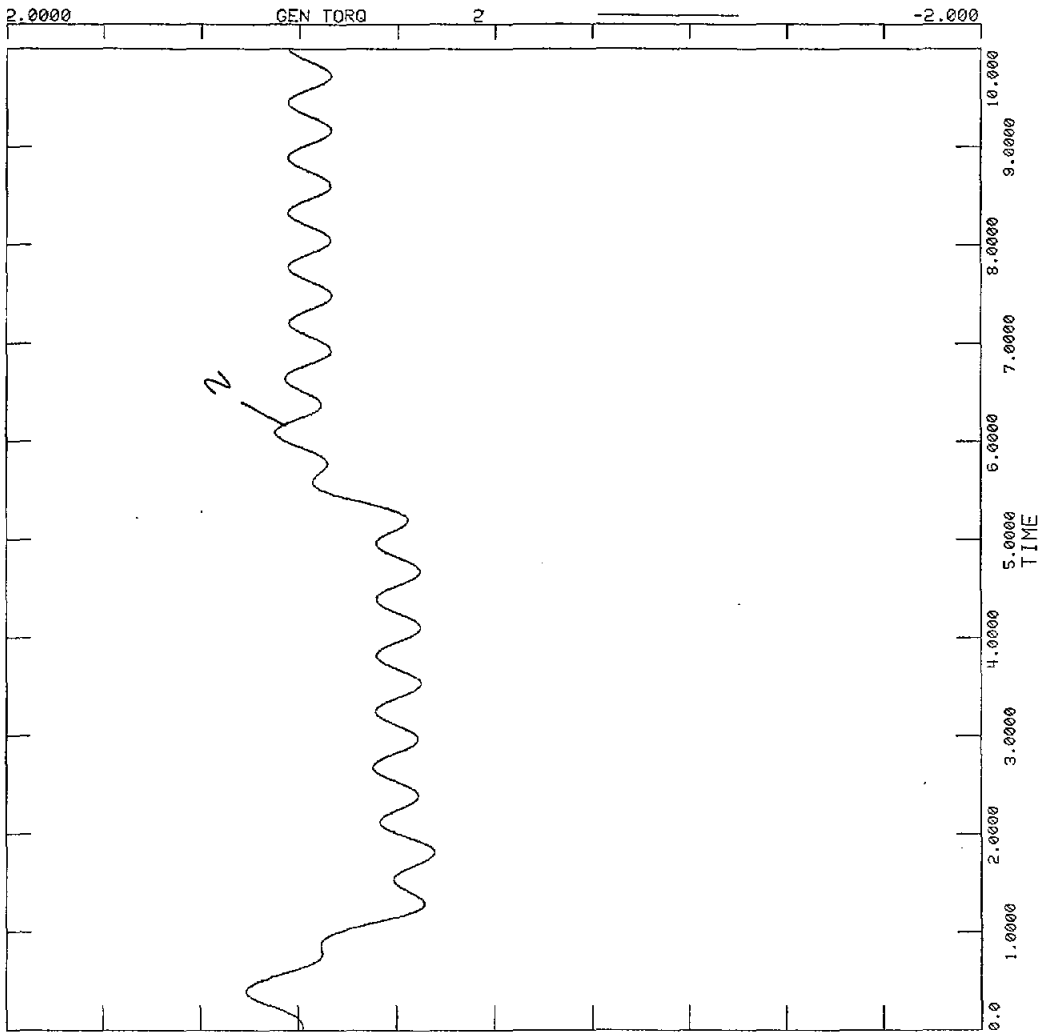


SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE
CASE I12



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE

CASE I/2



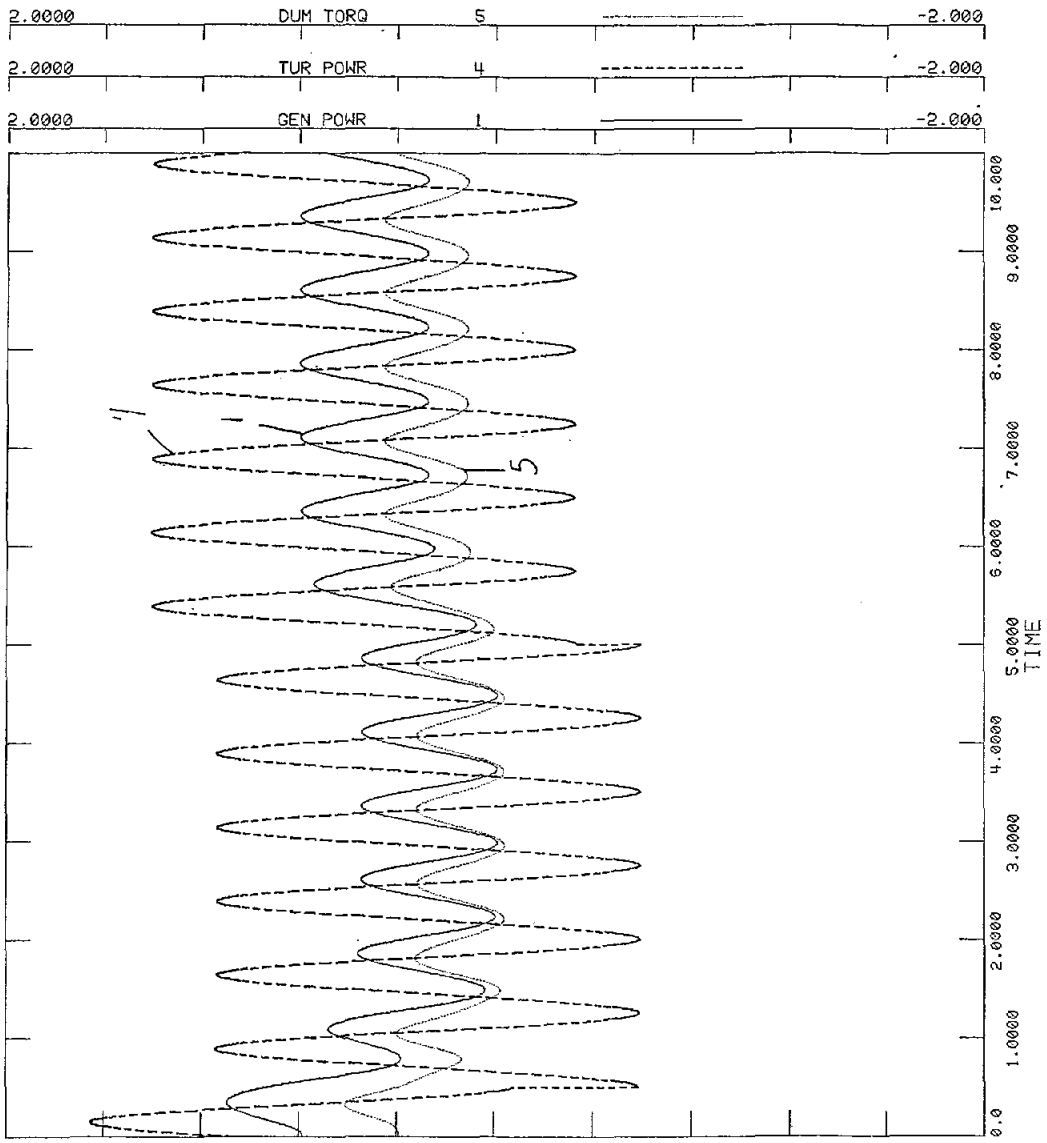
P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS

BUS	1 GENR	AREA	CKT	KW	KVAR	KVA	%	1.0047PU	2.60	1
GENERATION		1		196.0	-124.3R	232.0	93	KV		
TO LOAD-PQ				0.0	-105.7	105.7				
TO	2 LINE-GEN	1	1	196.0	-18.6	196.8	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0014PU	0.32	2
		1						KV		
TO	1 GENR	1	1	-194.4	26.2	196.2	0	1.0000LK		
TO	3 LINE-SYS	1	1	194.4	-26.2	196.2	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	1.0002PU	0.23	3
		1						KV		
TO	2 LINE-GEN	1	1	-194.2	26.5	196.0	0			
TO	4 SYSTEM	1	1	194.2	-26.5	196.0	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-194.1	27.3R	196.0	78	KV		
TO	3 LINE-SYS	1	1	-194.1	27.3	196.0	0	1.0000LK		

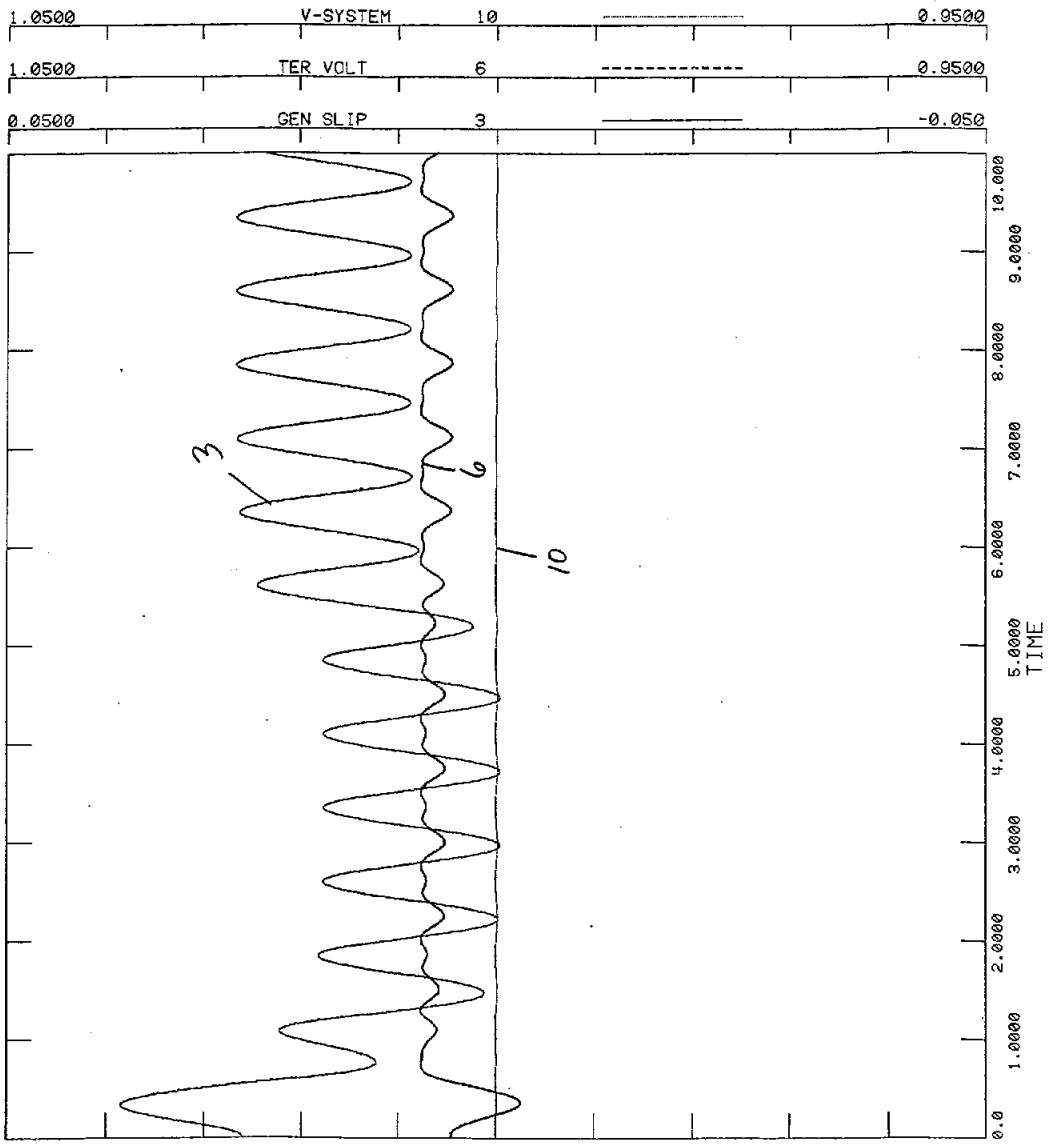
CASE I13

SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
TEST - WIND SPEED TRANSIENT

CASE I13



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
TEST- *WIND SPEED TRANSIENT*
CASE I13

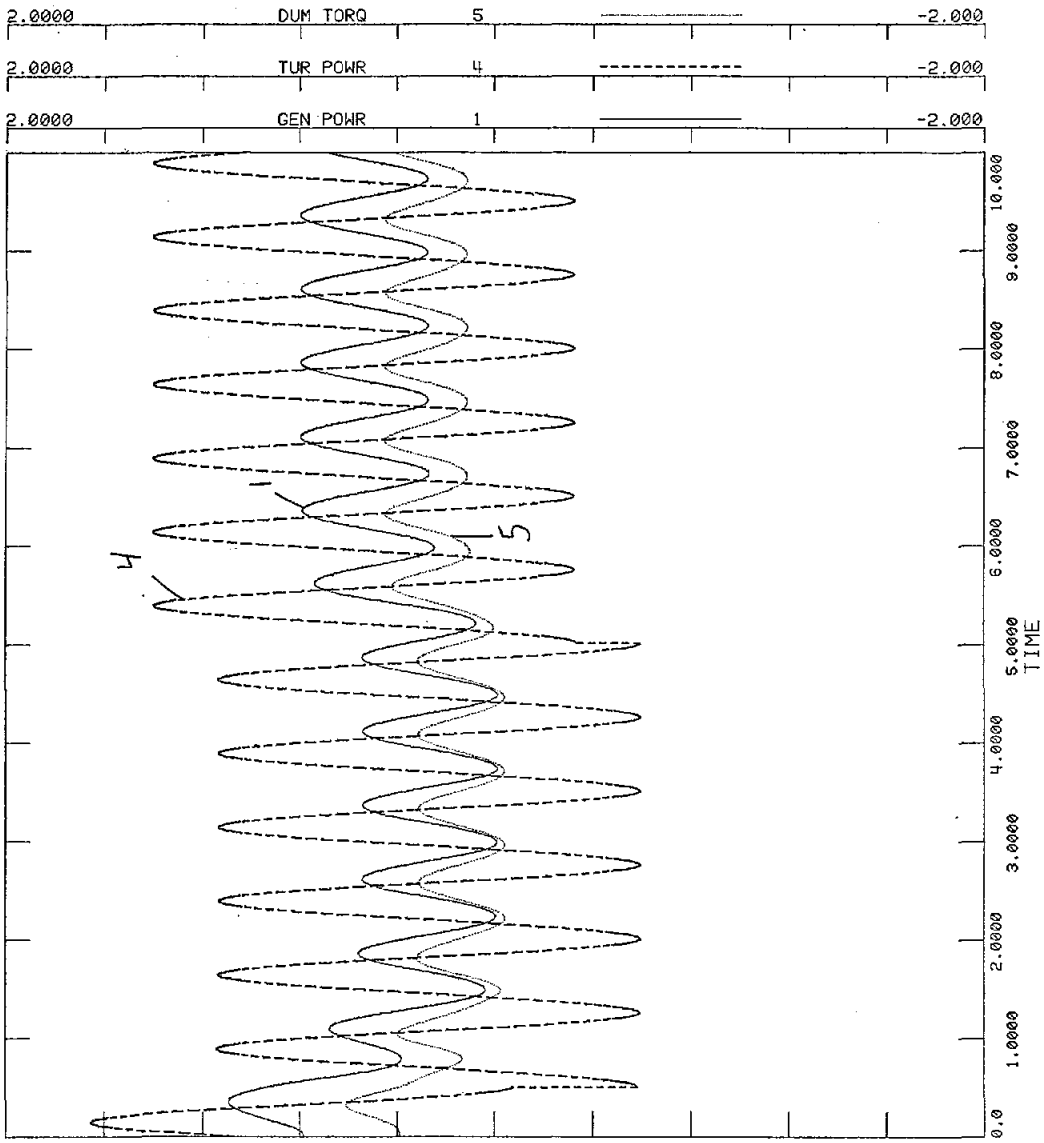


P. T. I. INTERACTIVE LOAD FLOW PROGRAM—PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO WEAK BUS

		AREA	CKT	KW	KVAR	KVA	%			
BUS	1 GENR							1.0047PU	2.60	1
GENERATION		1		196.0	-124.3R	232.0	93	KV		
TO LOAD-PQ				0.0	-105.7	105.7				
TO	2 LINE-GEN	1	1	196.0	-18.6	196.8	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0014PU	0.32	2
		1						KV		
TO	1 GENR	1	1	-194.4	26.2	196.2	0	1.0000LK		
TO	3 LINE-SYS	1	1	194.4	-26.2	196.2	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	1.0002PU	0.23	3
		1						KV		
TO	2 LINE-GEN	1	1	-194.2	26.5	196.0	0			
TO	4 SYSTEM	1	1	194.2	-26.5	196.0	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-194.1	27.3R	196.0	78	KV		
TO	3 LINE-SYS	1	1	-194.1	27.3	196.0	0	1.0000LK		

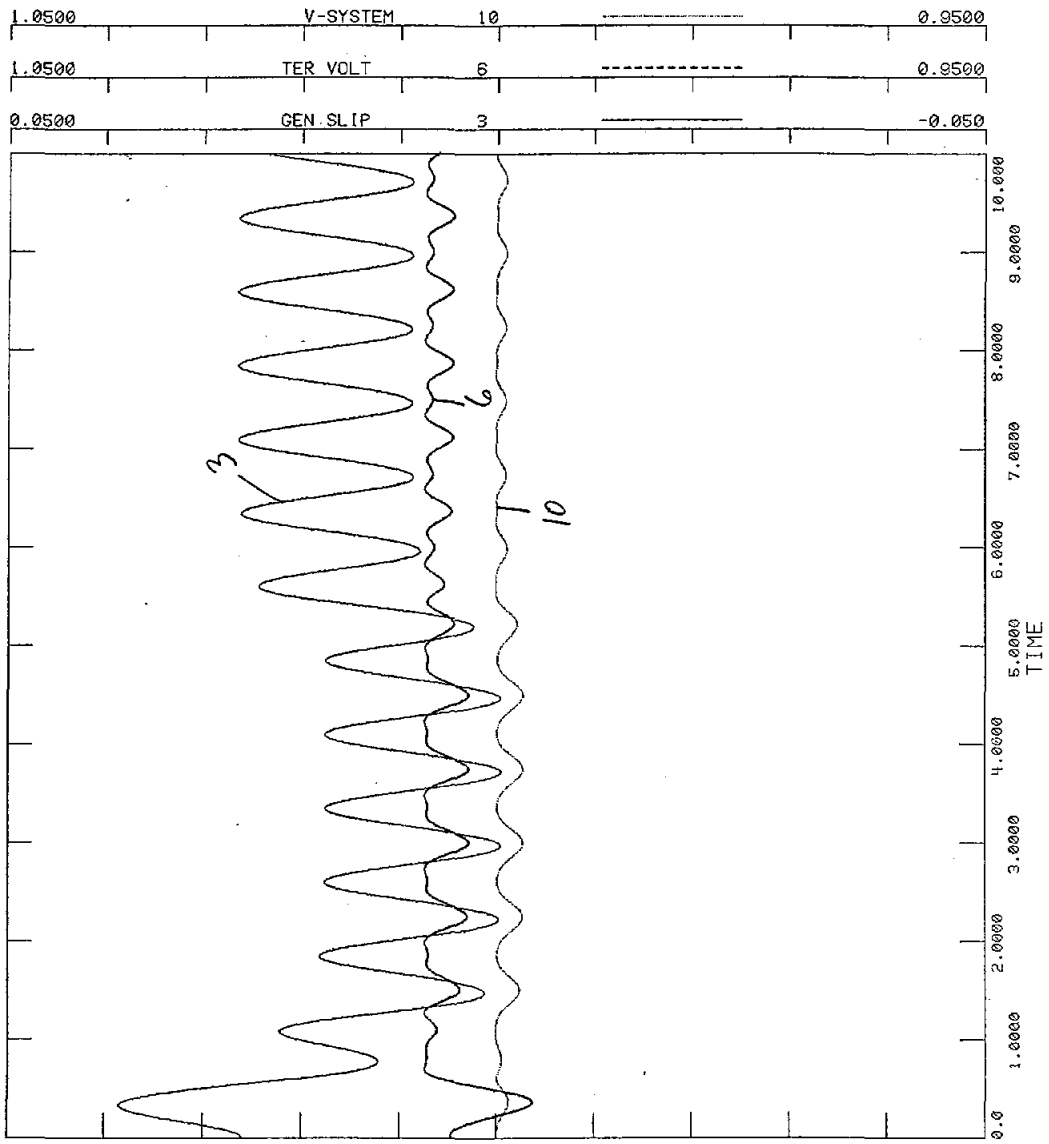
CASE I14

SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT
CASE I/4



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO *WEAK BUS*
WIND SPEED TRANSIENT

CASE I14

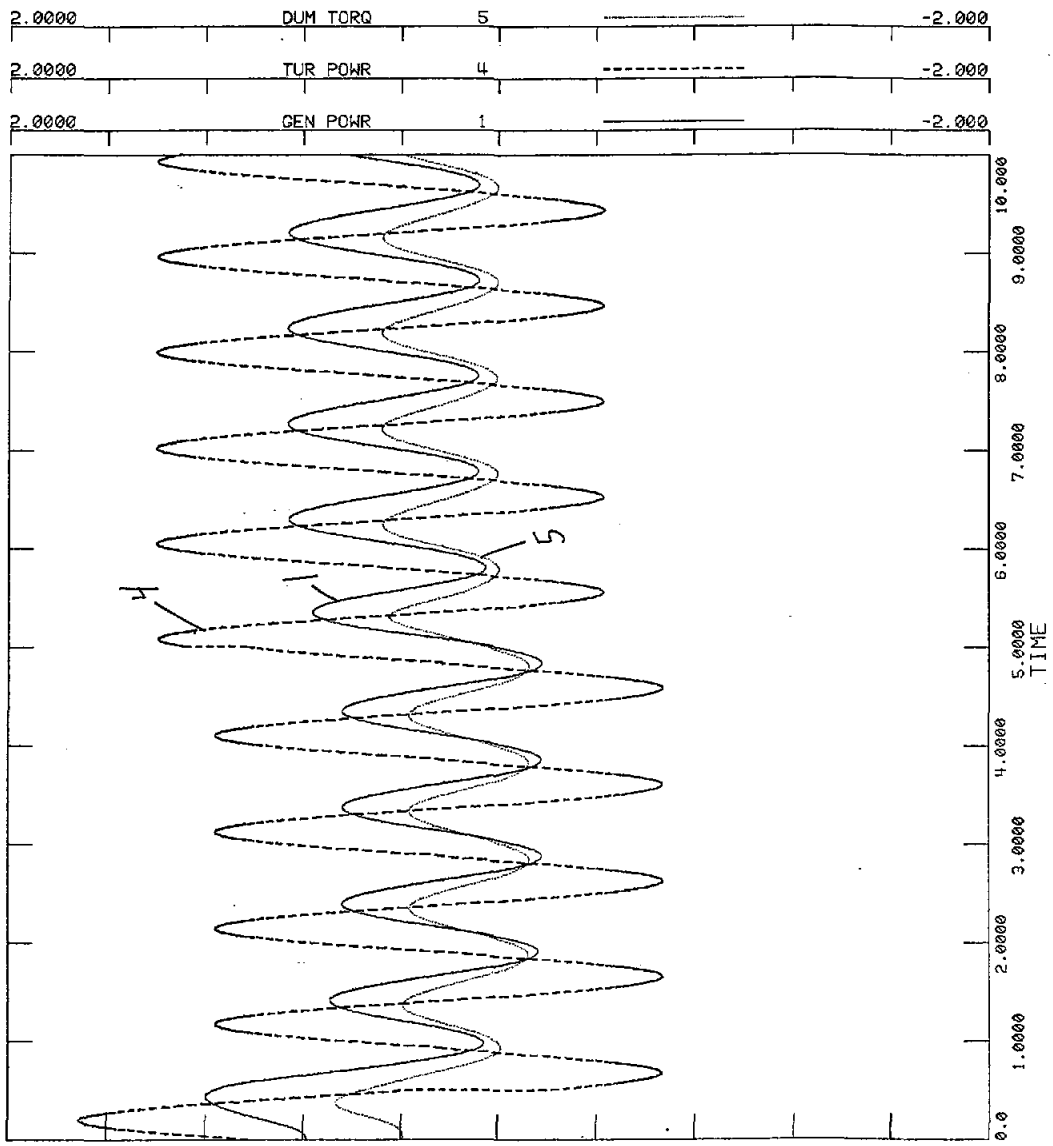


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 500 KW
CONNECTED TO INFINITE BUS

BUS 1 GENR	AREA	CKT	KW	KVAR	KVA	%	1.0061PU	2.74	1
GENERATION	1		491.2	-311.5R	581.6	93	KV		
TO LOAD-PQ			0.0	-261.5	261.5				
TO 2 LINE-GEN	1	1	491.2	-50.0	493.7	0	1.0000UN		
BUS 2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0030PU	0.47	2
	1						KV		
TO 1 GENR	1	1	-487.4	69.3	492.3	0	1.0000LK		
TO 3 LINE-SYS	1	1	487.4	-69.2	492.3	0			
BUS 3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	1.0002PU	0.23	3
	1						KV		
TO 2 LINE-GEN	1	1	-485.7	71.1	490.9	0			
TO 4 SYSTEM	1	1	485.8	-71.0	491.0	0	1.0000UN		
BUS 4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION	1		-485.4	73.0R	490.9	79	KV		
TO 3 LINE-SYS	1	1	-485.4	73.1	490.9	0	1.0000LK		

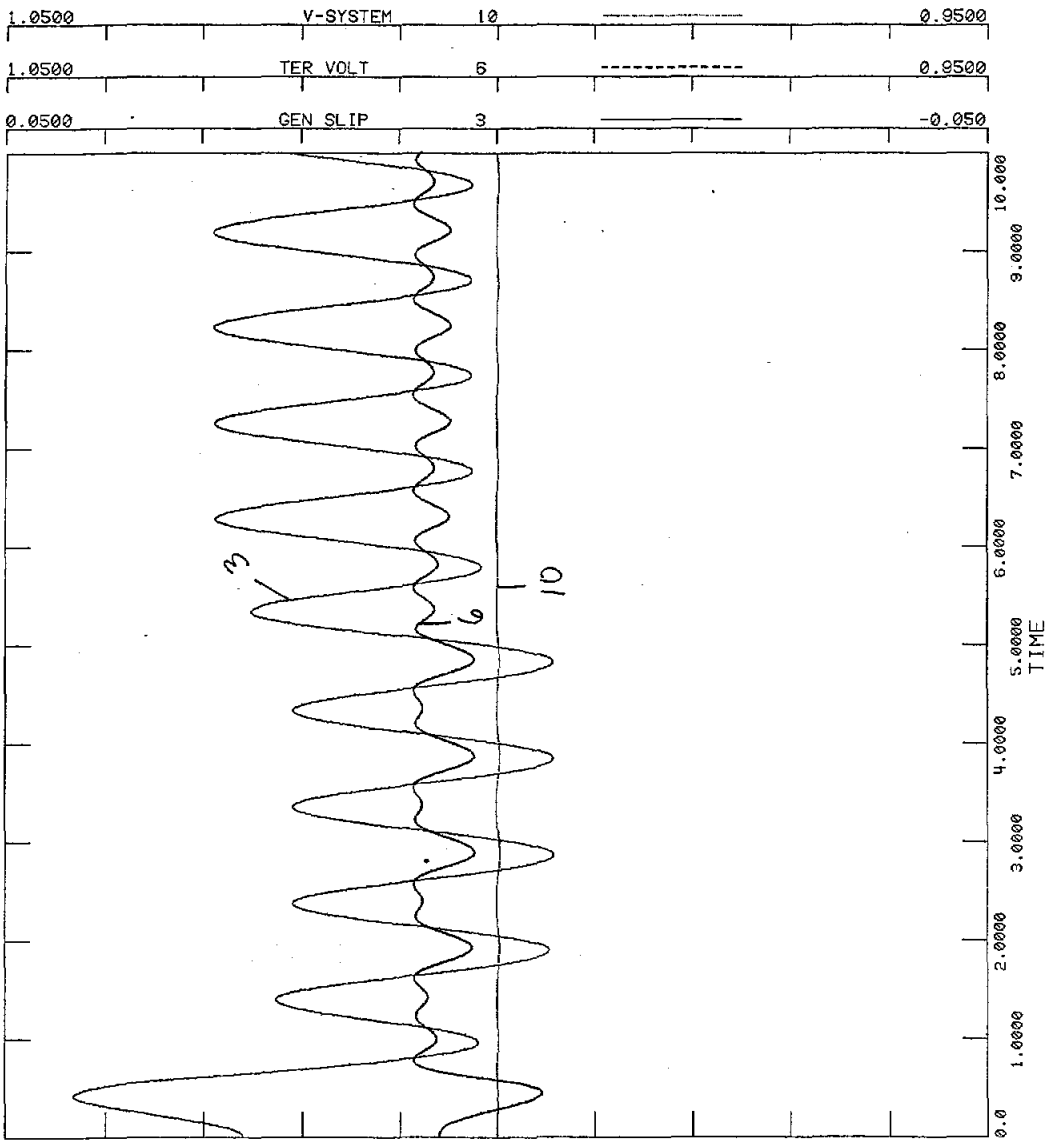
CASE I15

SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
TEST - WIND SPEED TRANSIENT
CASE I15



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
TEST - *WIND SPEED TRANSIENT*

CASE I15

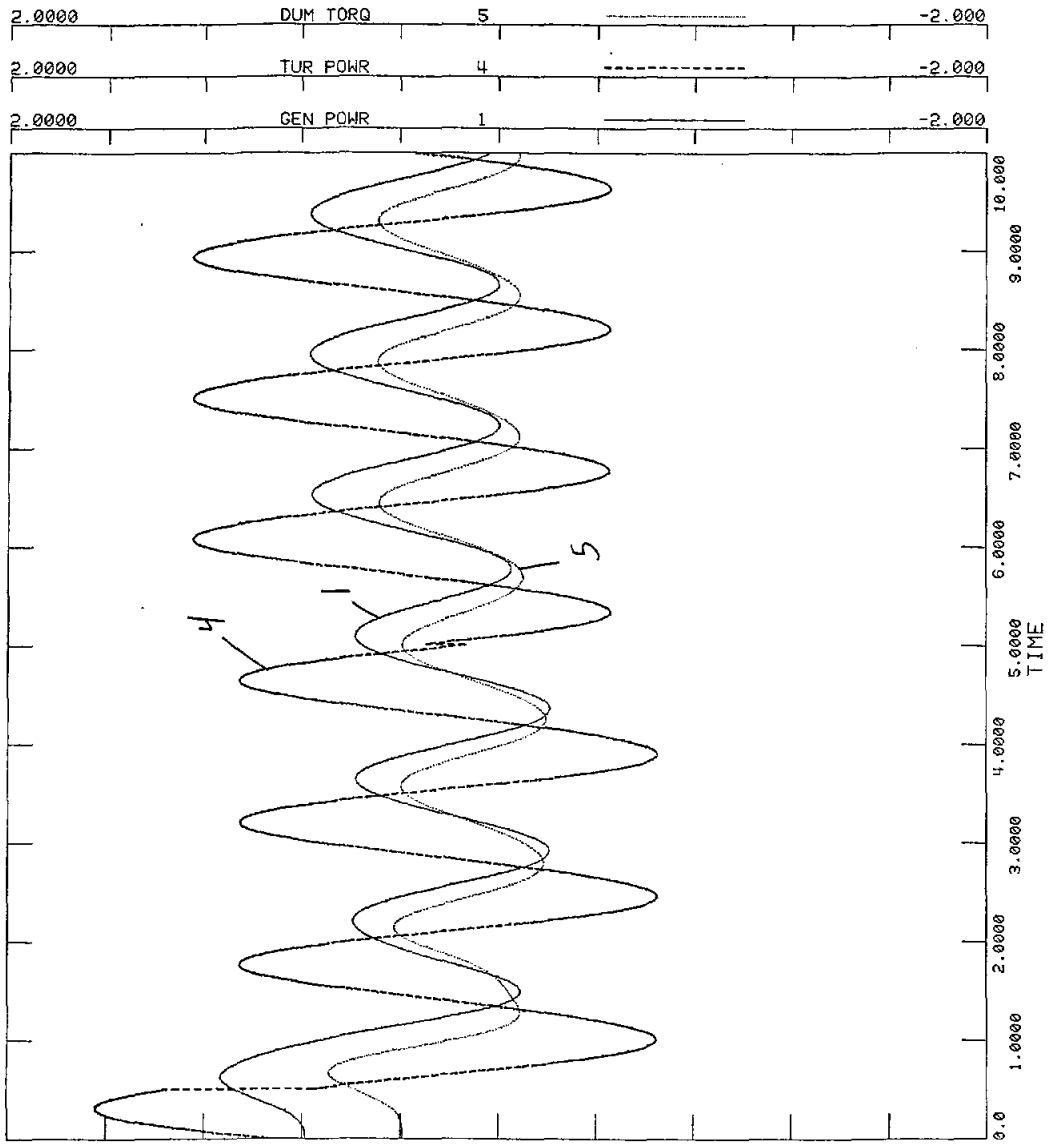


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS

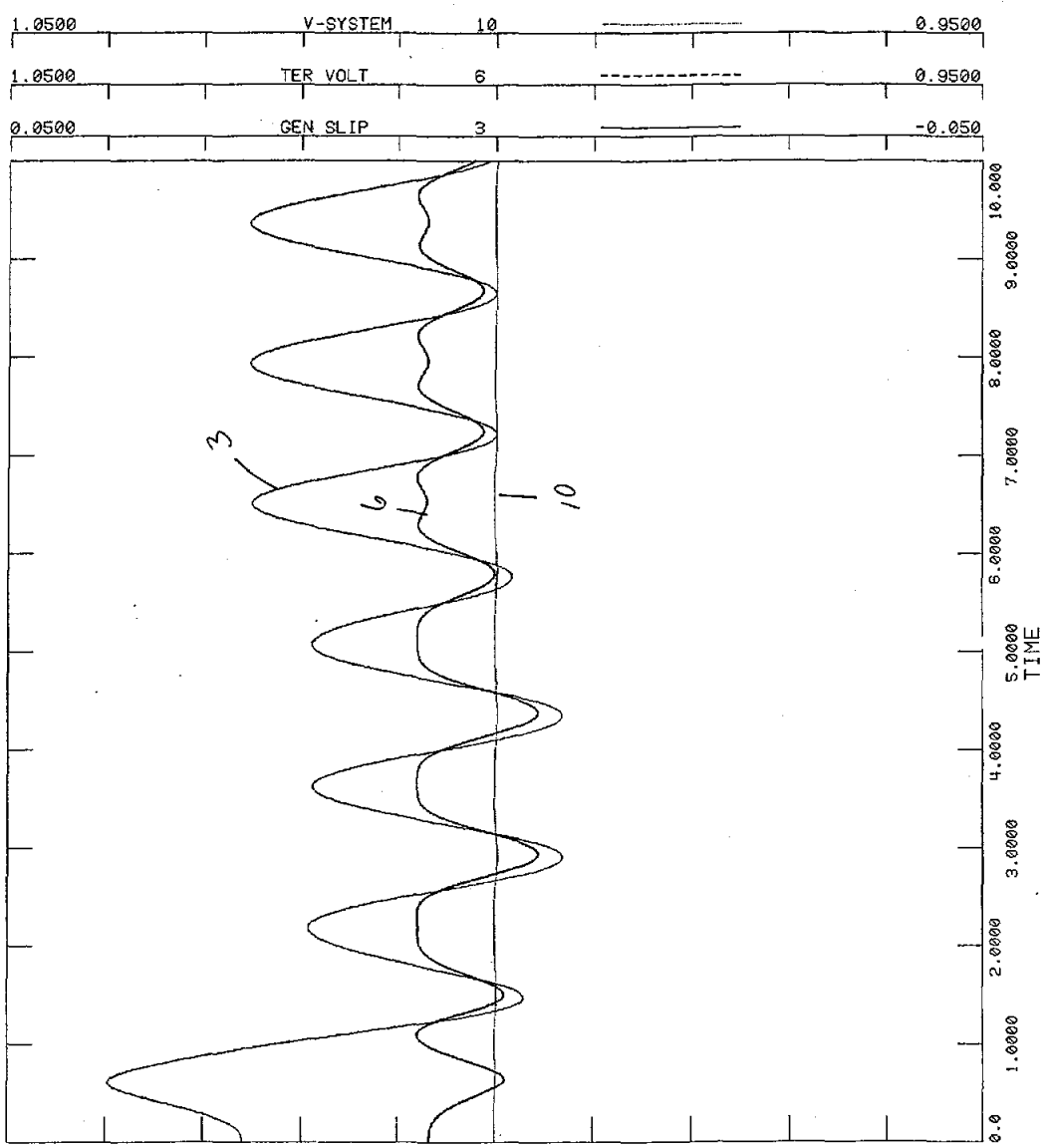
BUS	1 GENR	AREA	CKT	KW	KVAR	KVA	%	1.0067PU	3.35	1
GENERATION		1		1573.8	-998.0R	1863.6	93	KV		
TO LOAD-PQ				0.0	-686.0	686.0				
TO	2 LINE-GEN	1	1	1573.8	-312.0	1604.5	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0074PU	1.04	2
		1						KV		
TO	1 GENR	1	1	-1561.1	375.6	1605.7	0	1.0000LK		
TO	3 LINE-SYS	1	1	1561.1	-375.5	1605.7	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	0.9998PU	0.23	3
		1						KV		
TO	2 LINE-GEN	1	1	-1543.9	394.5	1593.5	0			
TO	4 SYSTEM	1	1	1544.0	-394.3	1593.5	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-1542.8	400.9R	1594.0	80	KV		
TO	3 LINE-SYS	1	1	-1542.8	401.0	1594.0	0	1.0000LK		

CASE I16

SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
TEST - *WIND SPEED TRANSIENT*
CASE I16



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
TEST - *WIND SPEED TRANSIENT*
CASE I16



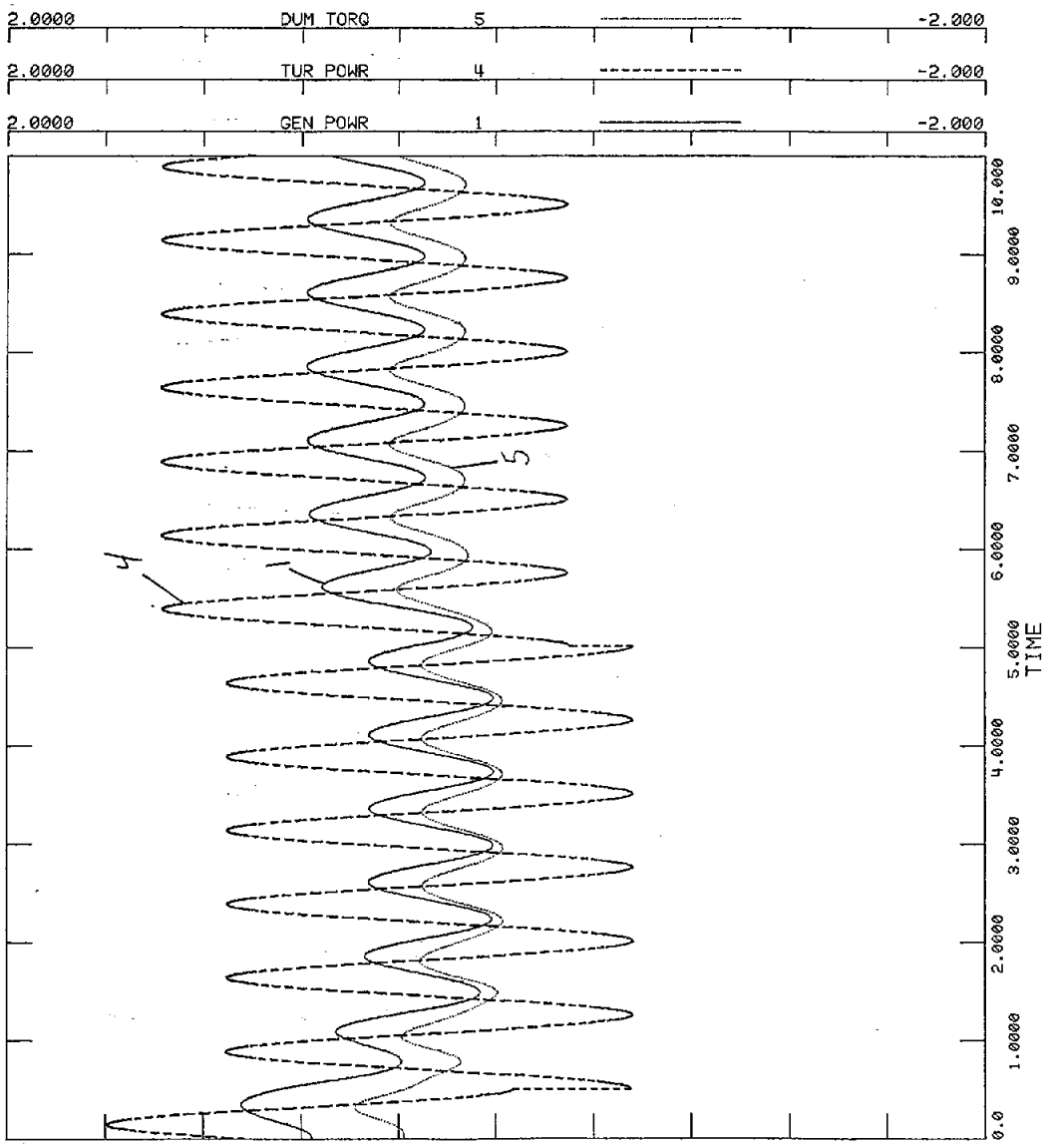
P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS — NO VOLTAGE SUPPORT

		AREA	CKT	KW	KVAR	KVA	%			
BUS	1 GENR							0.9810PU	2.83	1
GENERATION		1		186.8	-118.5R	221.2	88	KV		
TO	2 LINE-GEN	1	1	186.8	-118.5	221.2	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	0.9984PU	0.37	2
		1						KV		
TO	1 GENR	1	1	-184.8	128.6	225.2	0	1.0000LK		
TO	3 LINE-SYS	1	1	184.8	-128.6	225.1	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	0.9981PU	0.24	3
		1						KV		
TO	2 LINE-GEN	1	1	-184.4	129.0	225.1	0			
TO	4 SYSTEM	1	1	184.5	-129.0	225.1	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-184.3	130.0R	225.6	90	KV		
TO	3 LINE-SYS	1	1	-184.3	130.1	225.6	0	1.0000LK		

CASE I17

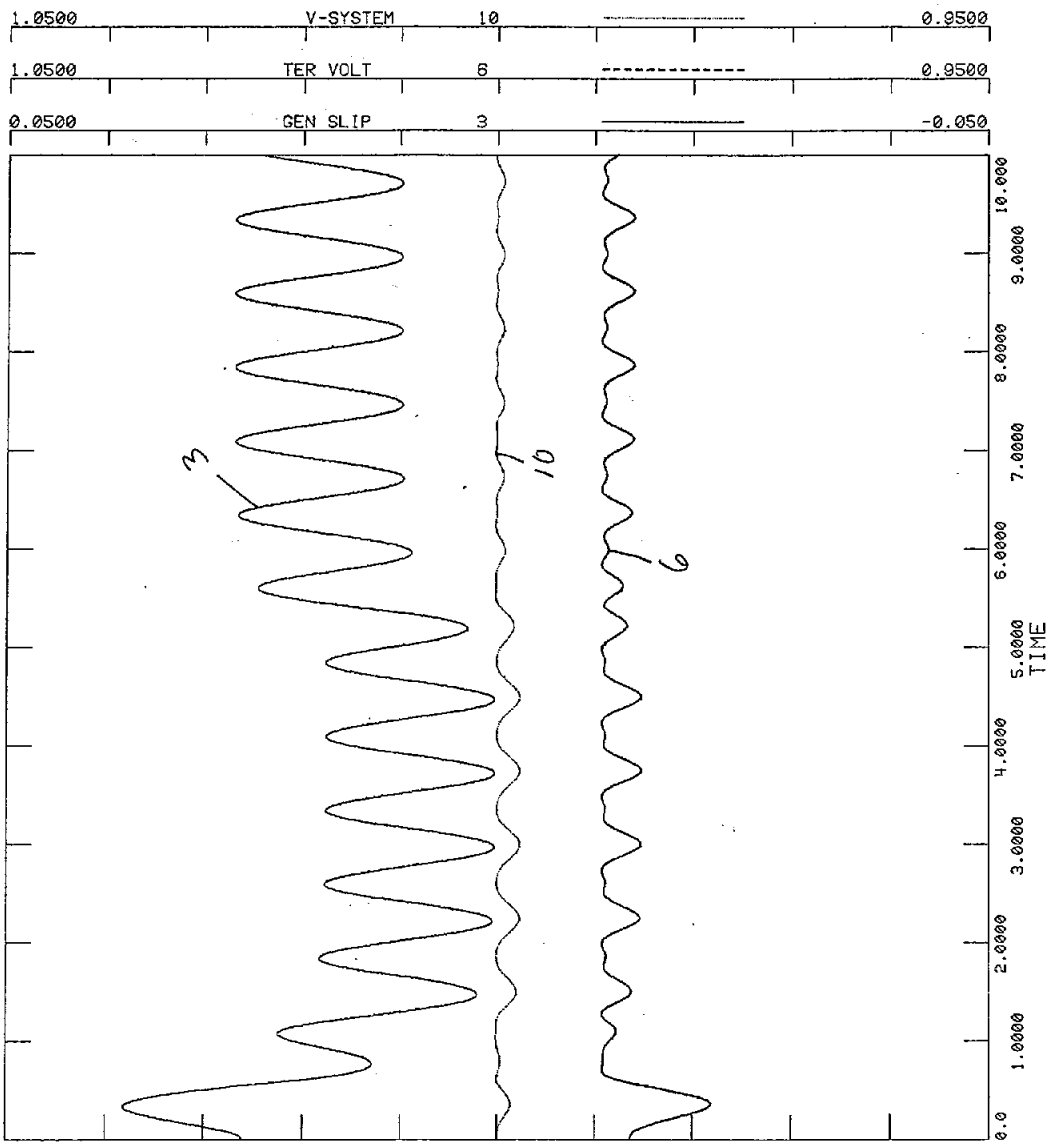
SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *NO VOLTAGE SUPPORT*

CASE I/7



SANDIA LABS - WIND TURBINE - INDUCTION GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - *NO VOLTAGE SUPPORT*

CASE I/7



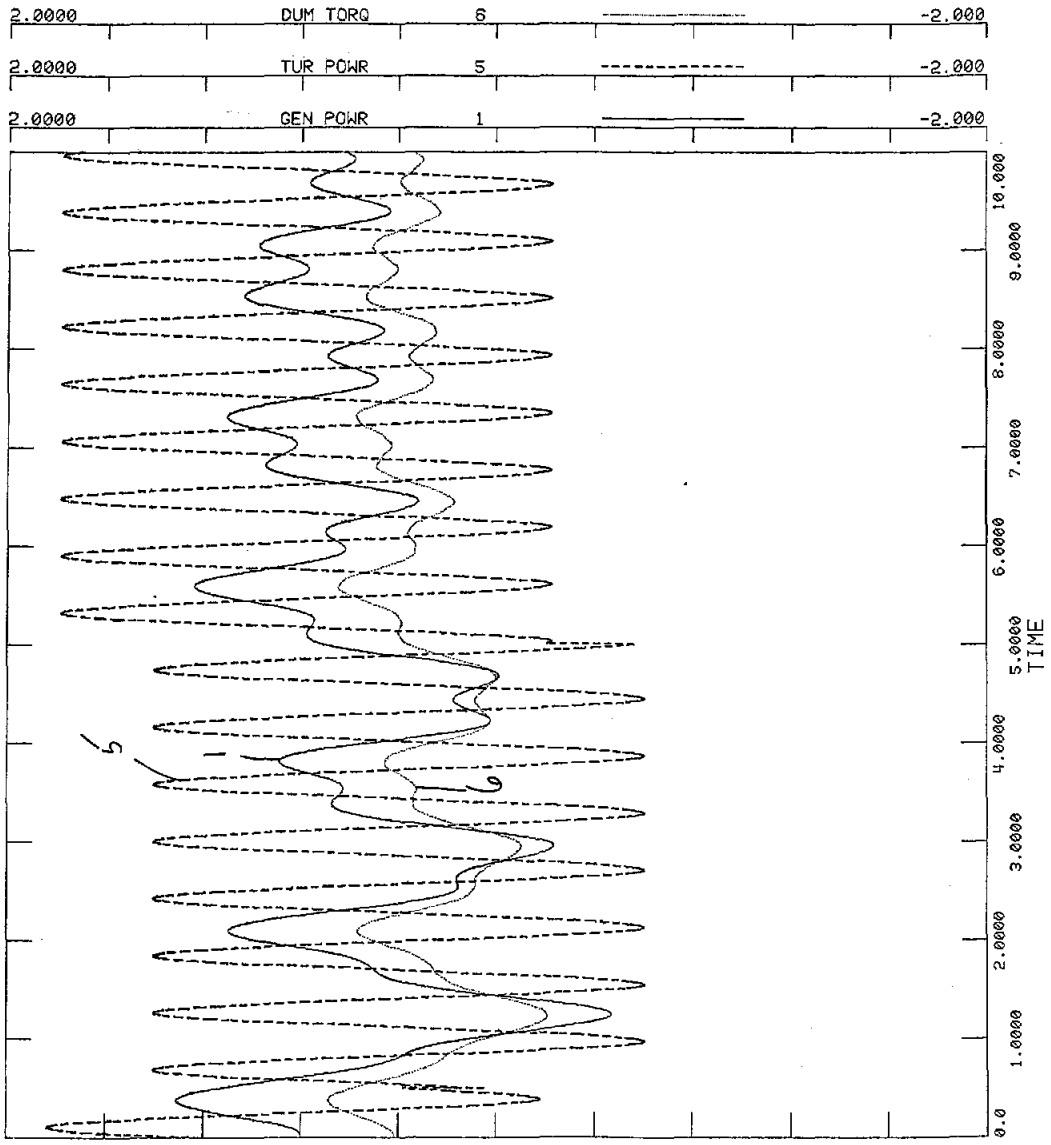
P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS

BUS	1 GENR	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	2.65	1
GENERATION		1		60.0	-11.0R	61.0	81	KV		
TO	2 LINE-GEN	1	1	60.0	-11.0	61.0	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	MW	MVAR	MVA	%	1.0002PU	0.27	2
		1						KV		
TO	1 GENR	1	1	-59.5	13.5	61.0	0	1.0000LK		
TO	3 LINE-SYS	1	1	59.5	-13.4	61.0	0			
BUS	3 LINE-SYS	AREA	CKT	MW	MVAR	MVA	%	0.9999PU	0.24	3
		1						KV		
TO	2 LINE-GEN	1	1	-59.5	13.5	61.0	0			
TO	4 SYSTEM	1	1	59.5	-13.5	61.0	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	0.00	4
GENERATION		1		-59.5	13.7R	61.0	81	KV		
TO	3 LINE-SYS	1	1	-59.5	13.7	61.0	0	1.0000LK		

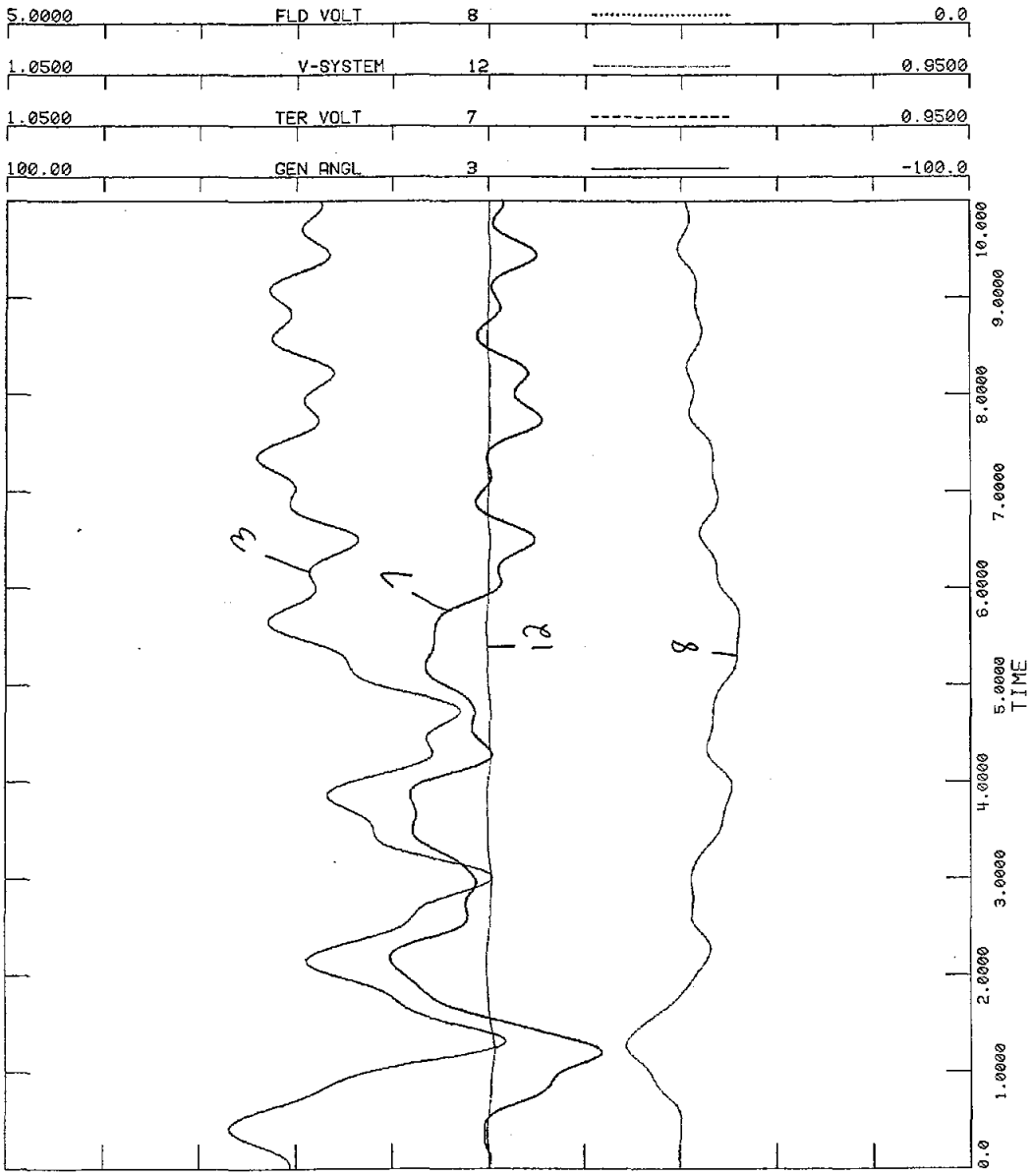
CASE S11, S12

SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT

CASE S11

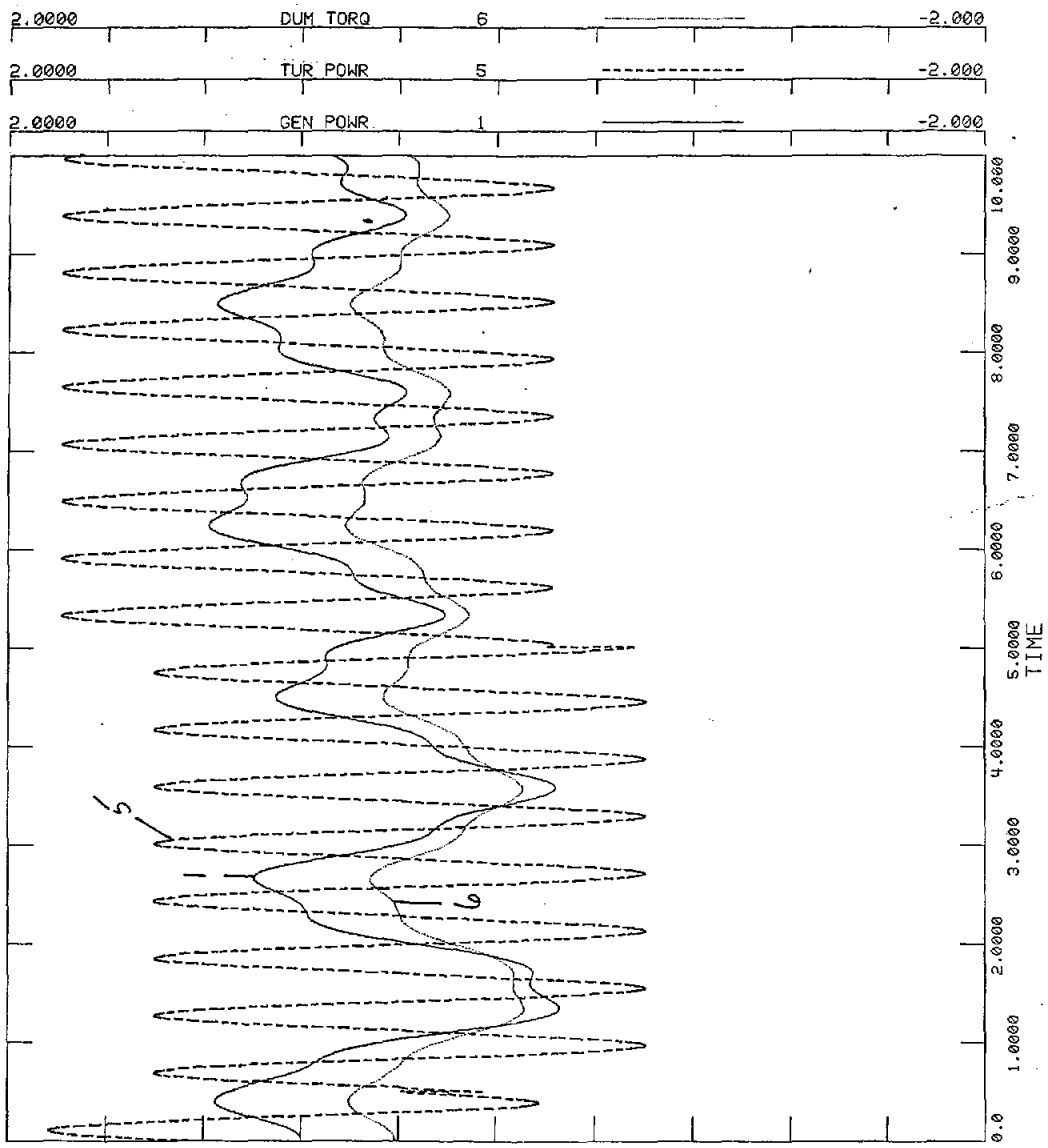


SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE S11

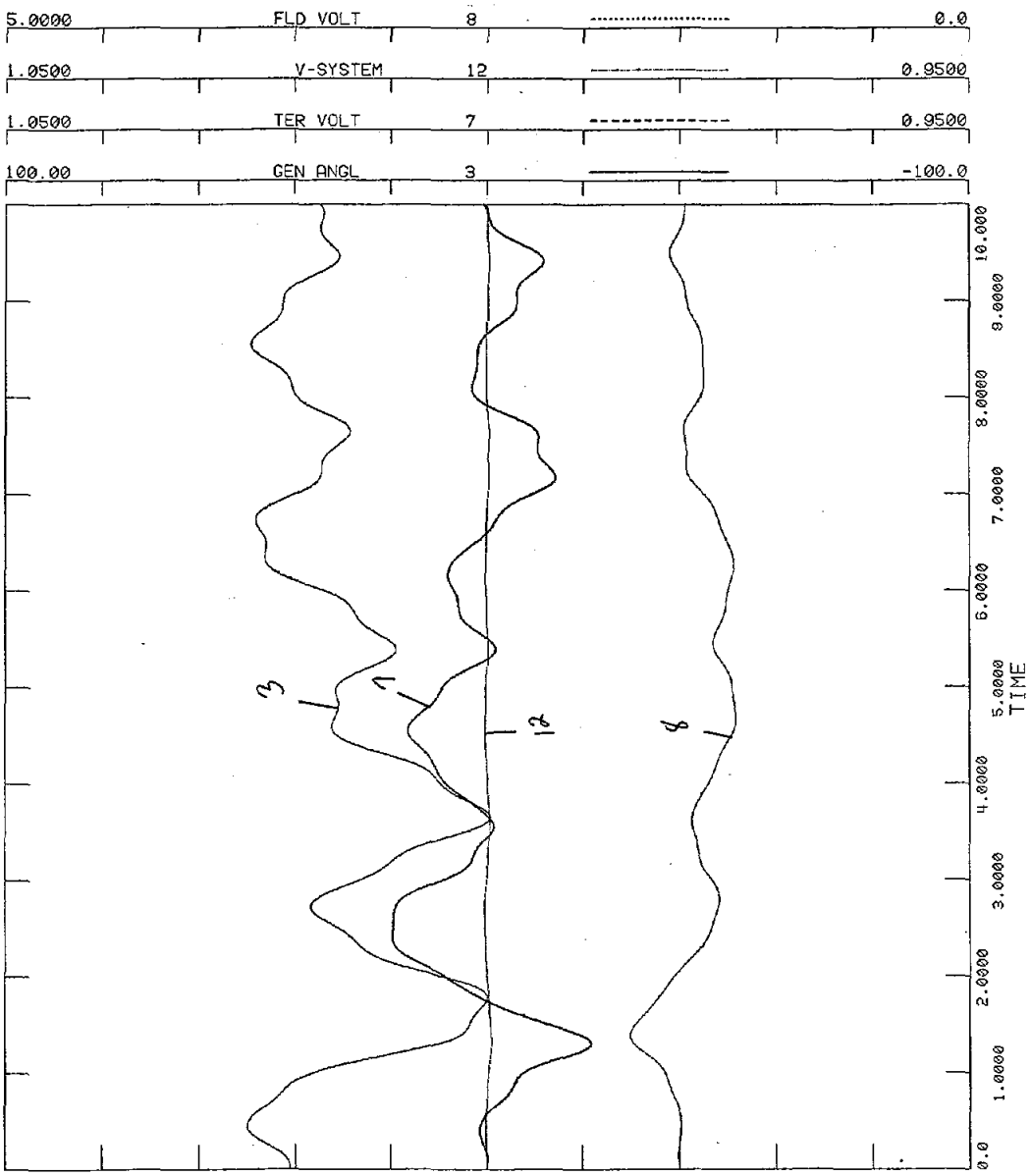


SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE

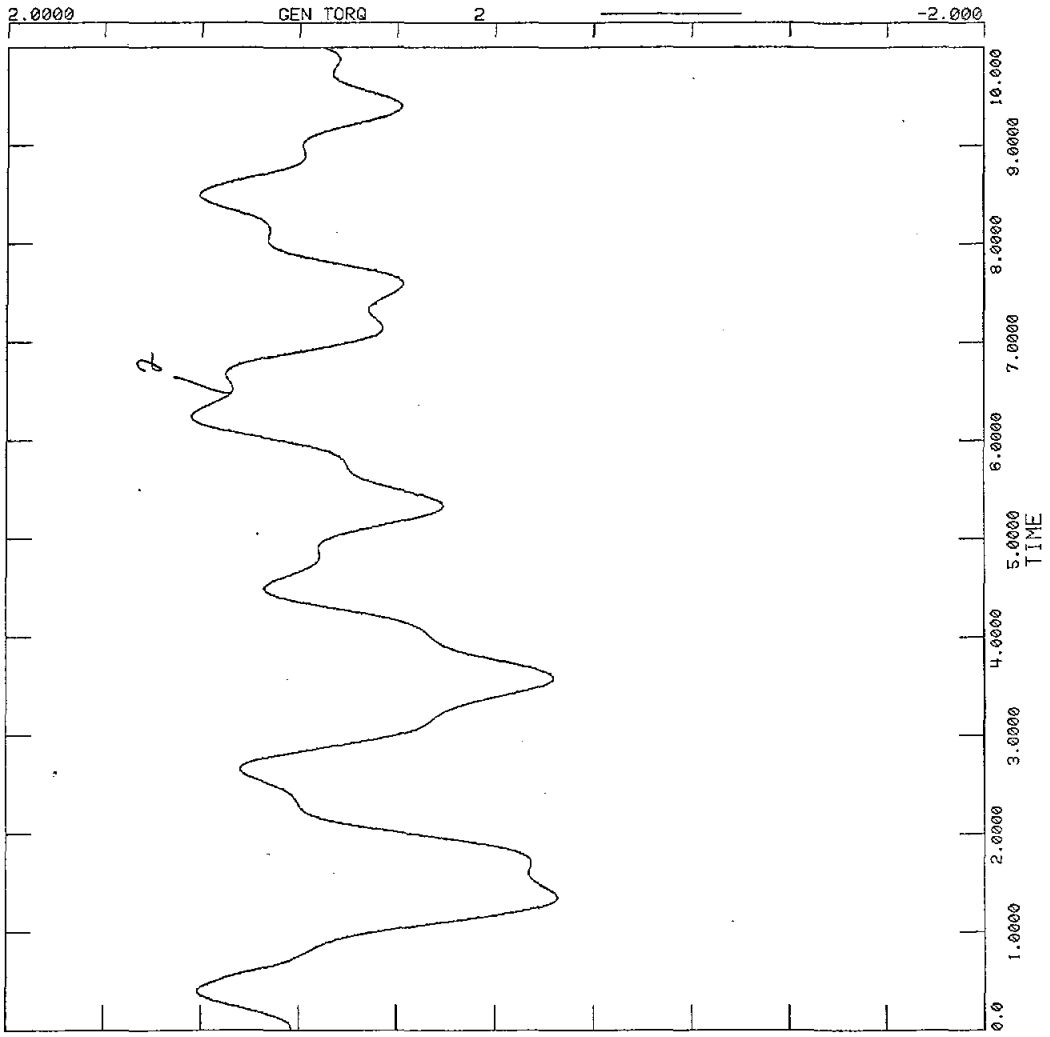
CASE S12



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE
CASE 512



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - K2 57 % OF NORMAL VALUE
CASE S12

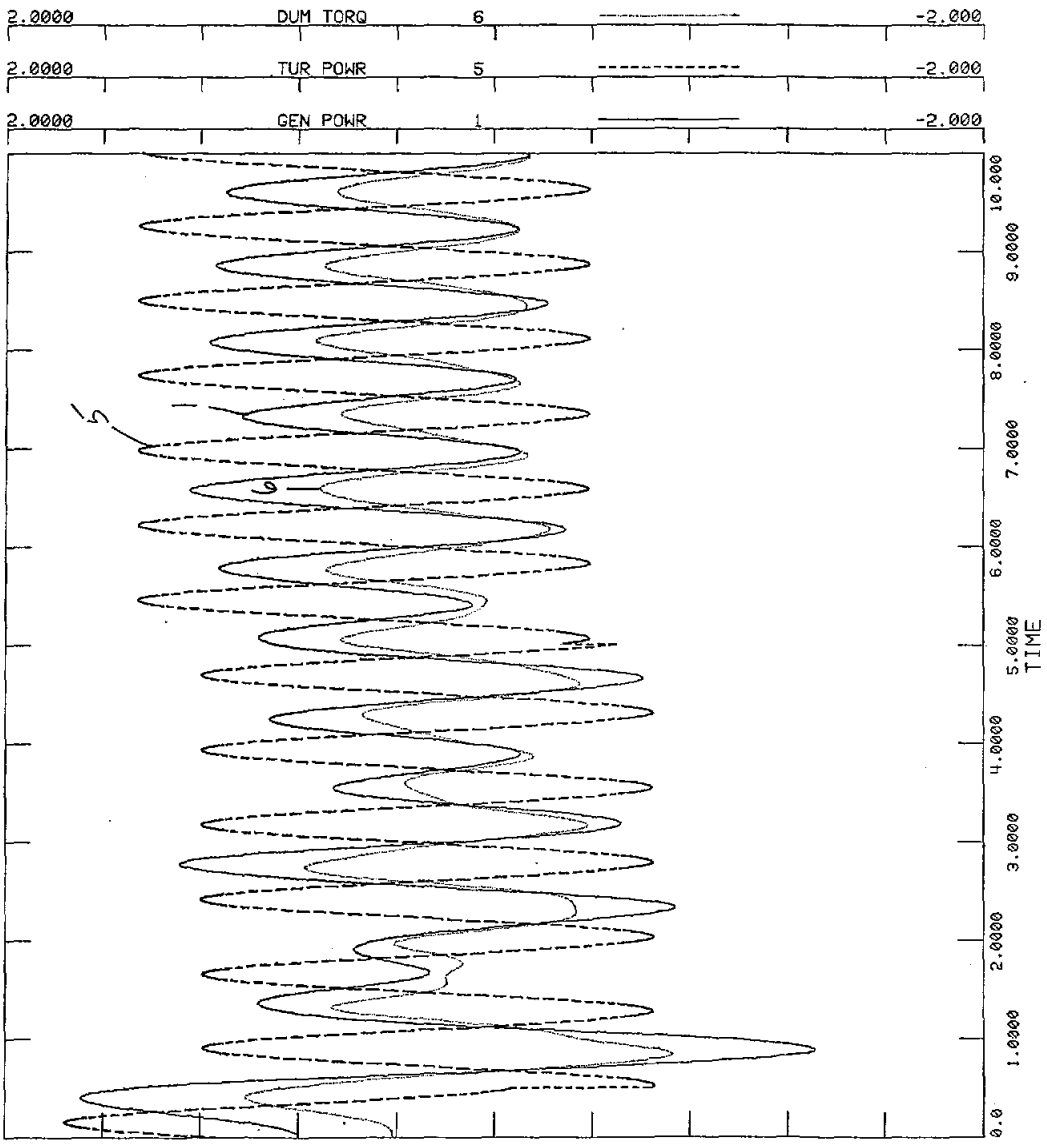


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO INFINITE BUS

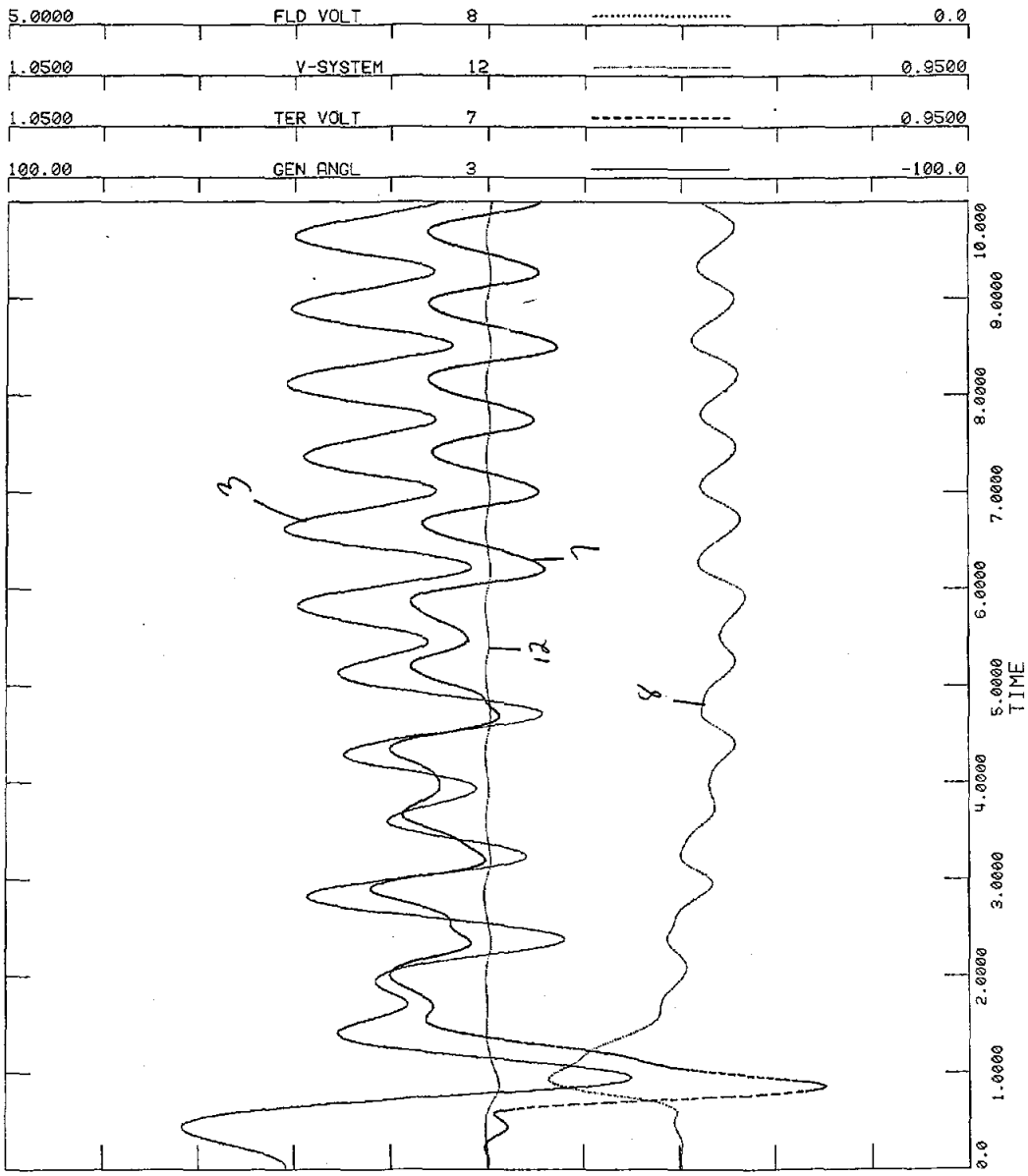
BUS	1 GENR	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	2.72	1
GENERATION		1		200.0	-39.7R	203.9	82	KV		
TO	2 LINE-GEN	1	1	200.0	-39.7	203.9	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0008PU	0.34	2
		1						KV		
TO	1 GENR	1	1	-198.3	48.0	204.1	0	1.0000LK		
TO	3 LINE-SYS	1	1	198.4	-48.0	204.1	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	0.9998PU	0.24	3
		1						KV		
TO	2 LINE-GEN	1	1	-198.1	48.3	203.9	0			
TO	4 SYSTEM	1	1	198.1	-48.3	203.9	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-198.0	49.2R	204.0	82	KV		
TO	3 LINE-SYS	1	1	-198.0	49.2	204.0	0	1.0000LK		

CASE S13

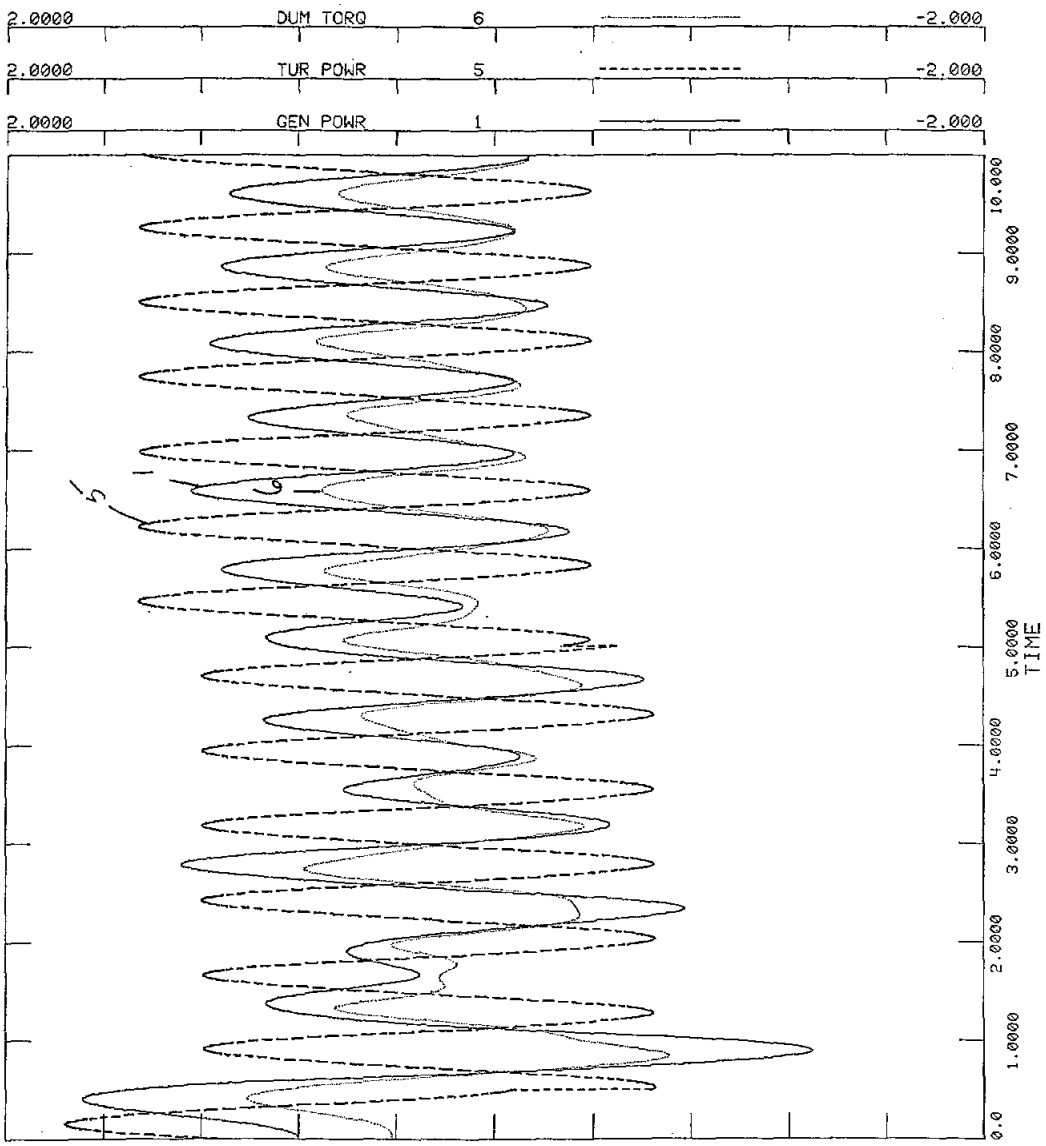
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE 5/3



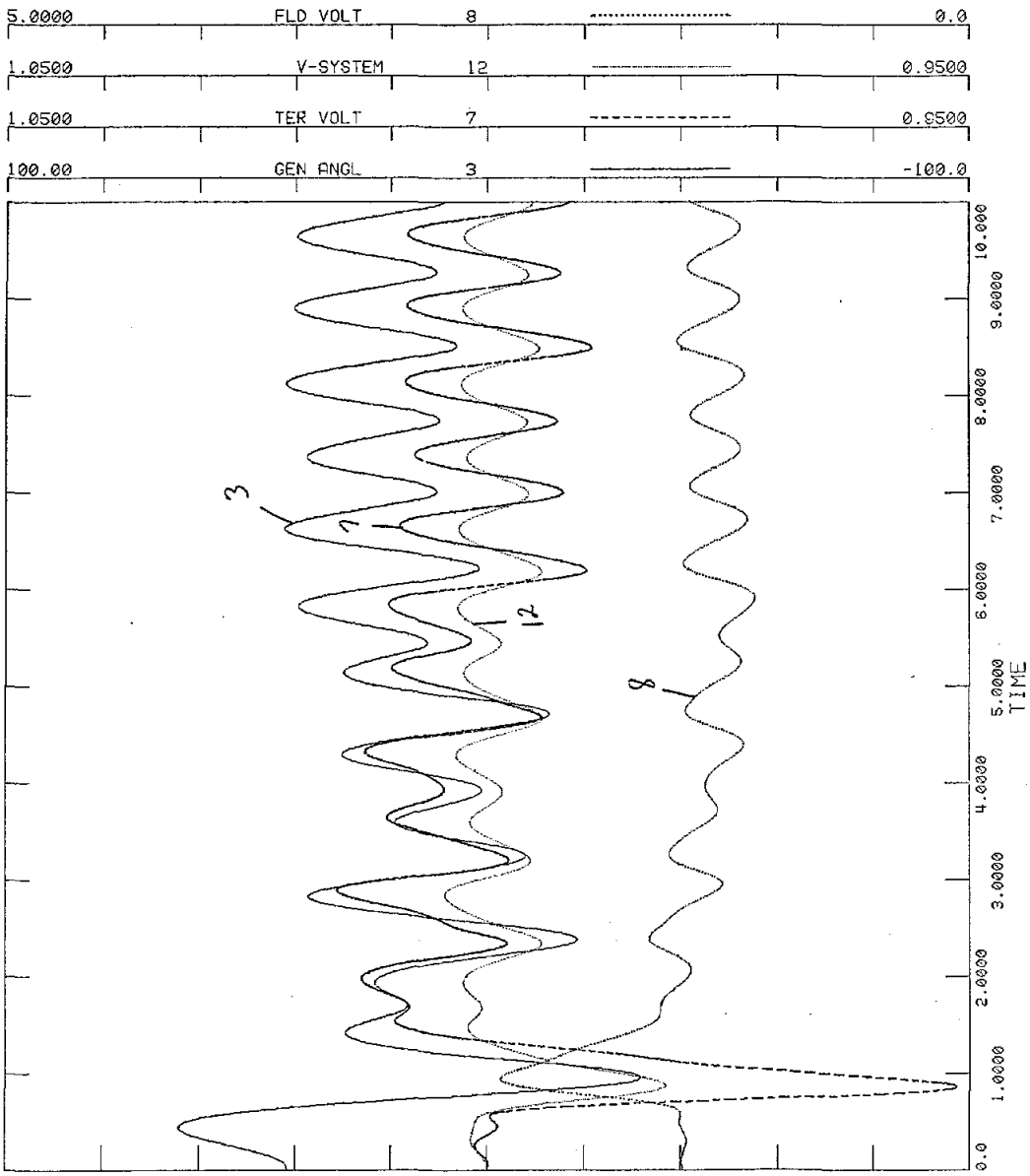
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE 513



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT
CASE 514



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT
CASE S14

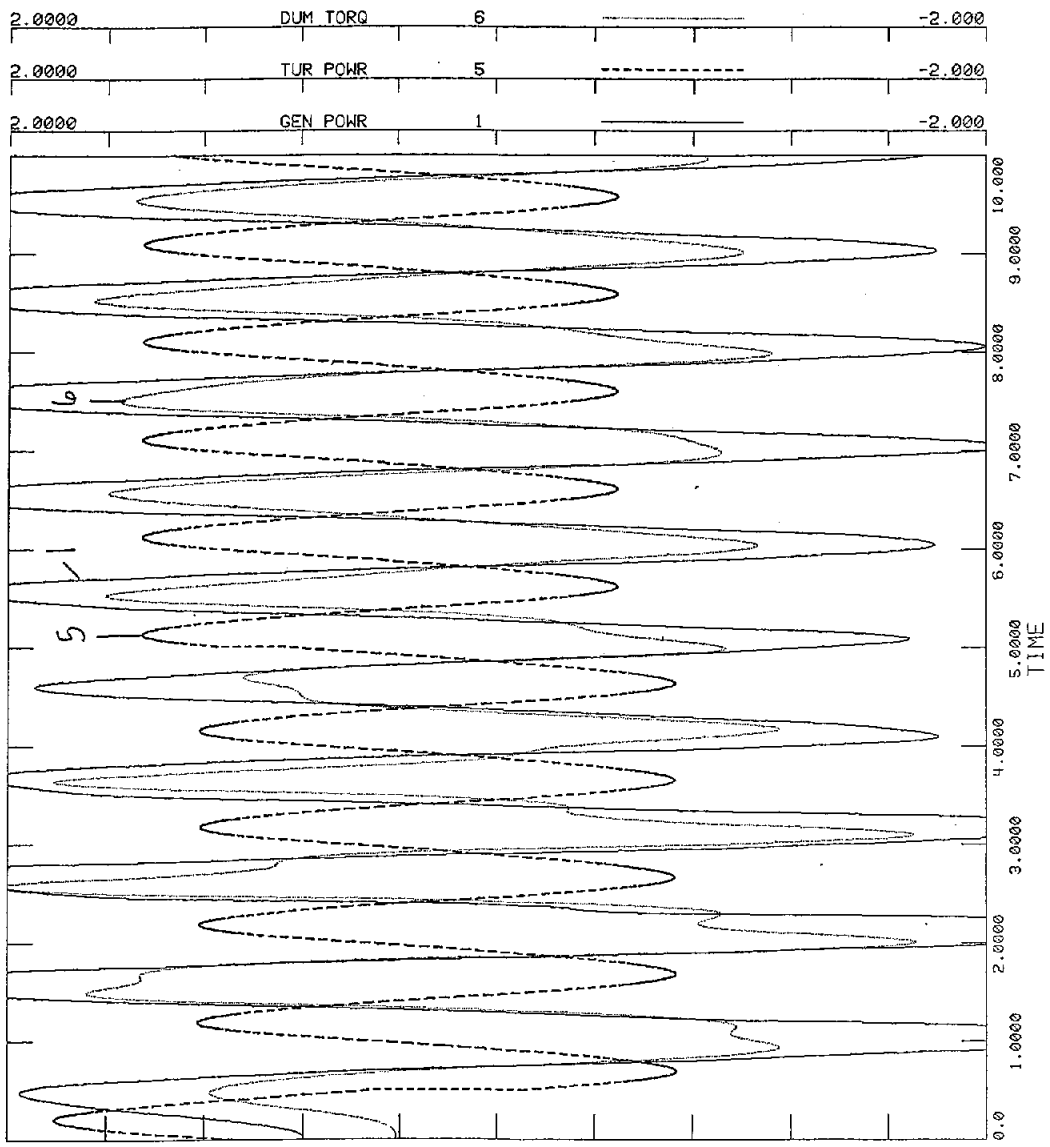


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 500 KW
CONNECTED TO INFINITE BUS

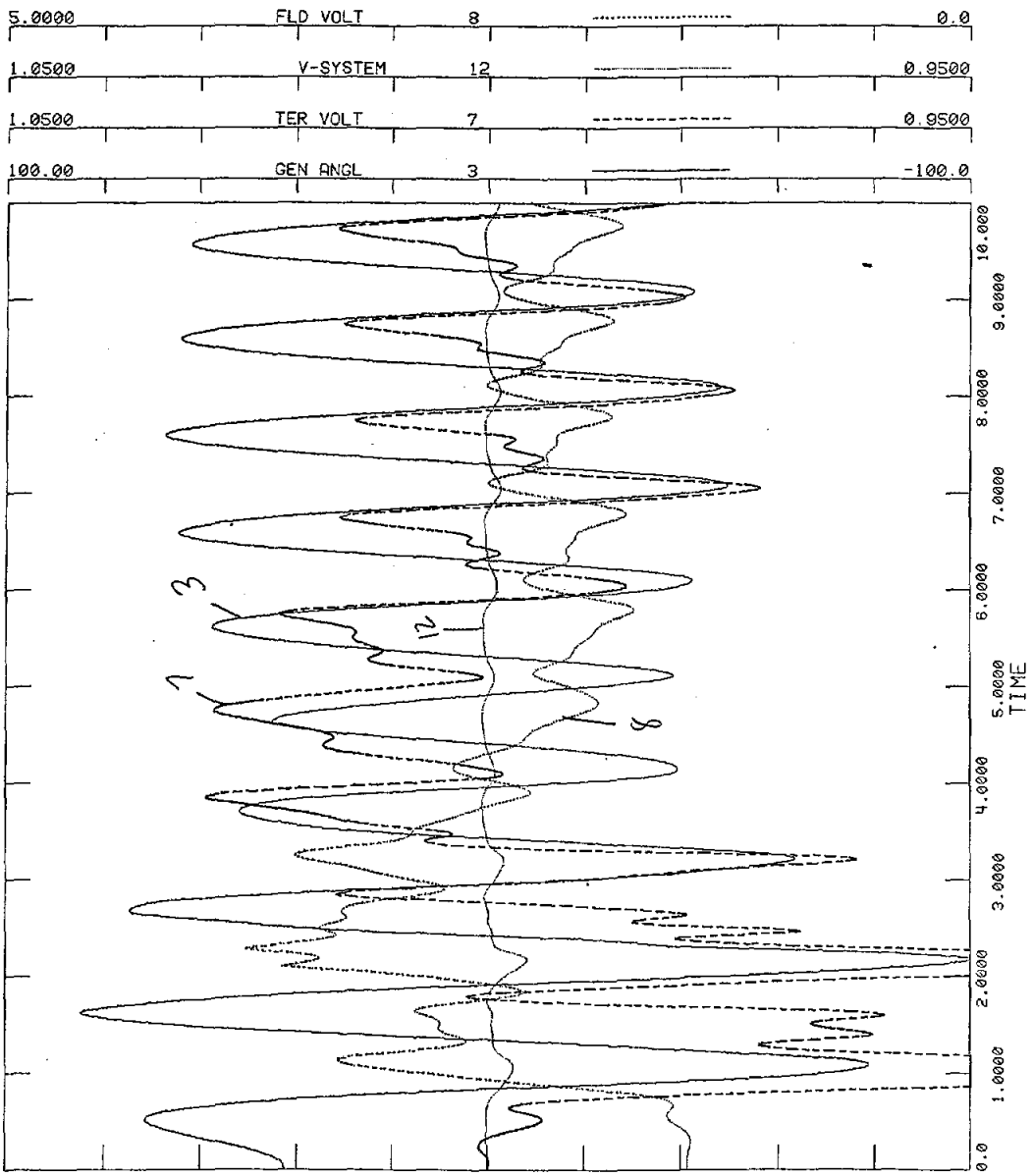
BUS	1 GENR	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	2.90	1
GENERATION		1		500.0	-114.8R	513.0	82	KV		
TO	2 LINE-GEN	1	1	500.0	-114.8	513.0	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0021PU	0.51	2
		1						KV		
TO	1 GENR	1	1	-495.8	135.8	514.1	0	1.0000LK		
TO	3 LINE-SYS	1	1	495.8	-135.8	514.1	0			
BUS	3 LINE-SYS	AREA	CKT	KW	KVAR	KVA	%	0.9997PU	0.24	3
		1						KV		
TO	2 LINE-GEN	1	1	-494.0	137.8	512.9	0			
TO	4 SYSTEM	1	1	494.0	-137.7	512.9	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-493.6	139.9R	513.1	82	KV		
TO	3 LINE-SYS	1	1	-493.6	139.9	513.1	0	1.0000LK		

CASE 515

SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE S15



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE S15

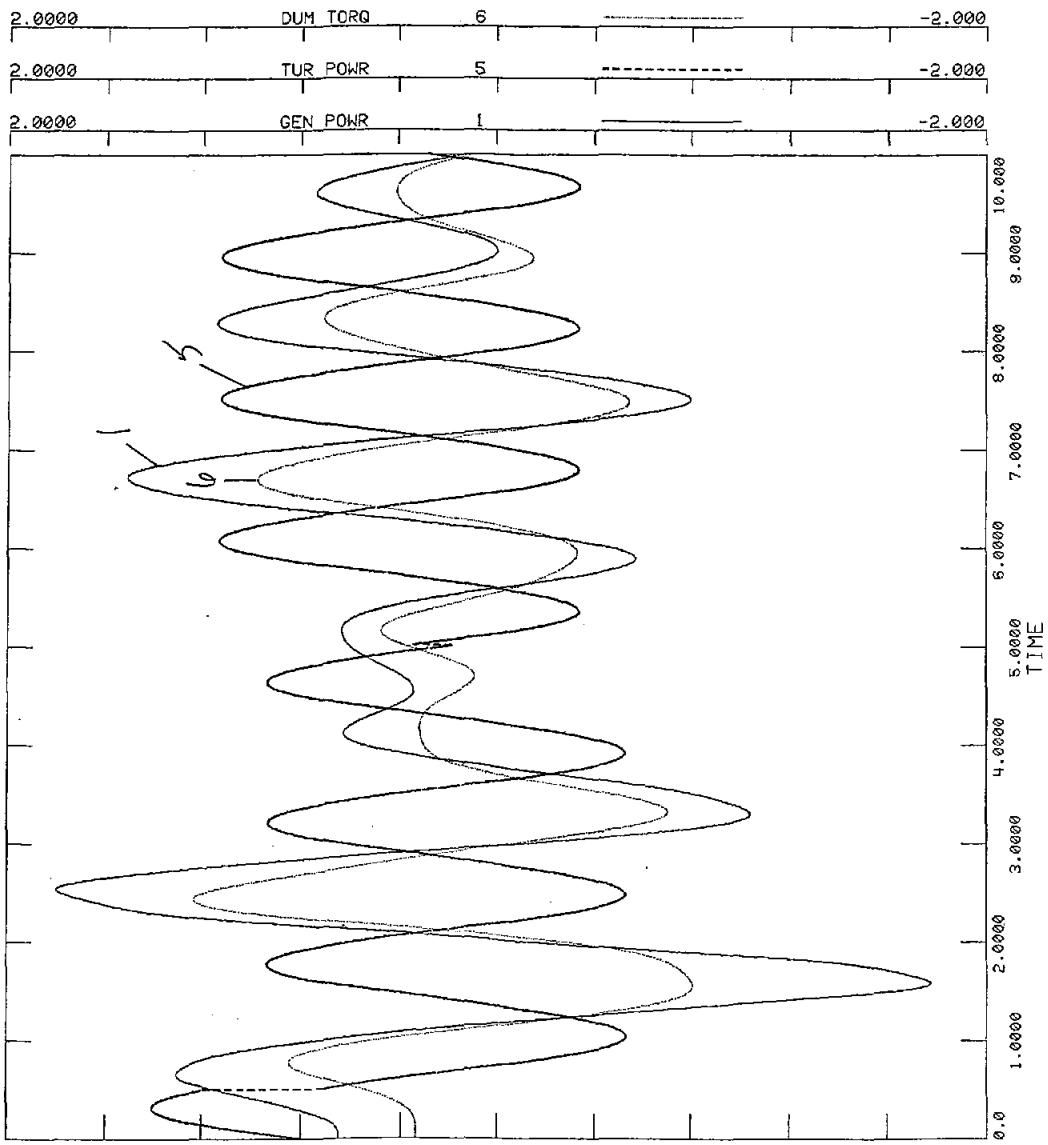


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS

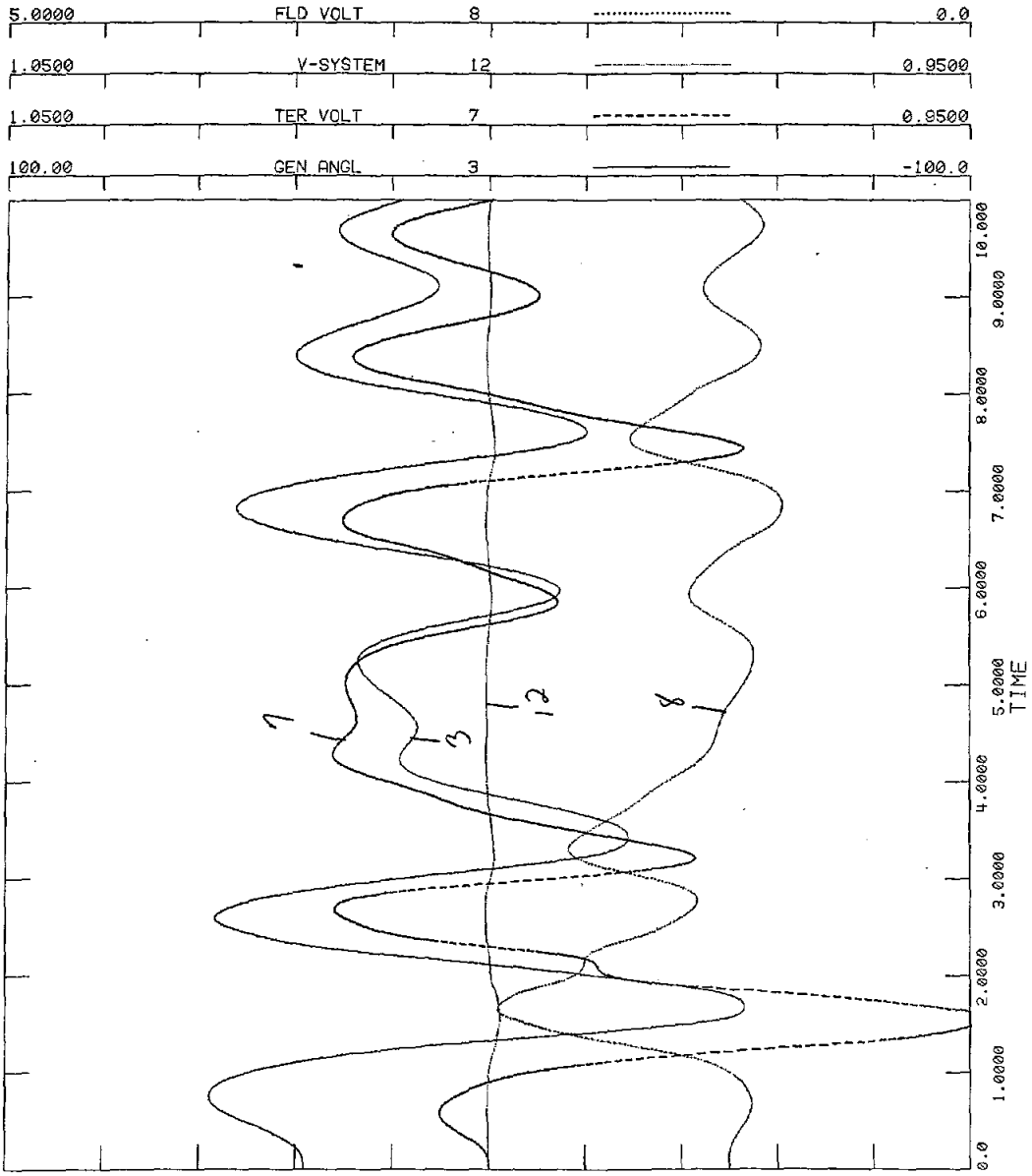
		AREA	CKT	KW	KVAR	KVA	%	1.0000PU	2.90	1
BUS	1 GENR									
GENERATION		1		1300.0	-420.9R	1366.4	68	KV		
TO	2 LINE-GEN	1	1	1300.0	-420.9	1366.4	0	1.0000UN		
BUS	2 LINE-GEN	AREA	CKT	KW	KVAR	KVA	%	1.0046PU	0.93	2
		1						KV		
TO	1 GENR	1	1	-1290.7	467.6	1372.8	0	1.0000LK		
TO	3 LINE-SYS	1	1	1290.7	-467.5	1372.8	0			
BUS	3 LINE-SYS	AREA	CKT	MW	KVAR	KVA	%	0.9994PU	0.20	3
		1						KV		
TO	2 LINE-GEN	1	1	-1278.0	481.5	1365.7	0			
TO	4 SYSTEM	1	1	1278.0	-481.4	1365.7	0	1.0000UN		
BUS	4 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	4
GENERATION		1		-1277.1	486.3R	1366.6	68	KV		
TO	3 LINE-SYS	1	1	-1277.1	486.4	1366.6	0	1.0000LK		

CASE S16

SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE S16

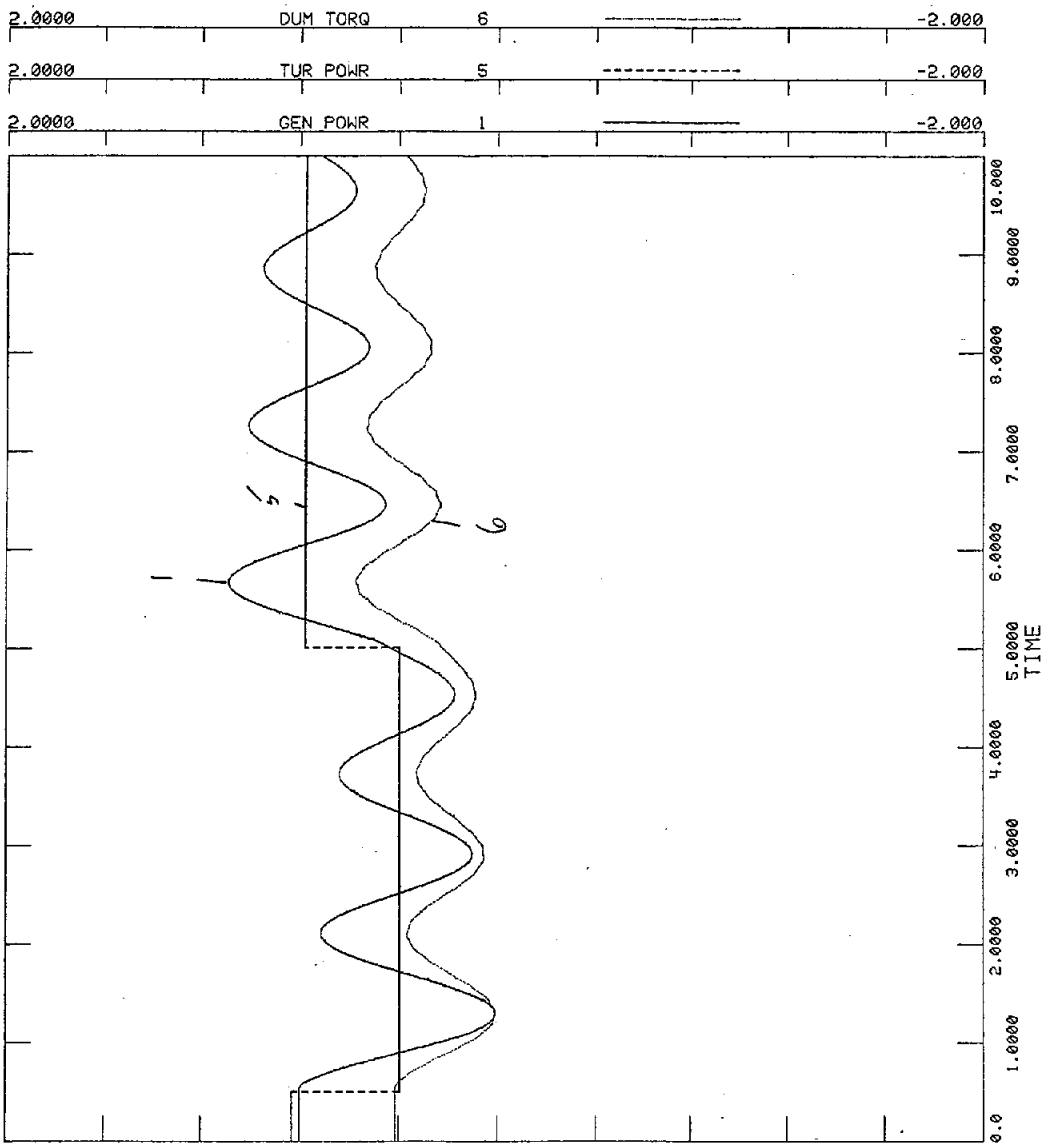


SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT
CASE S16

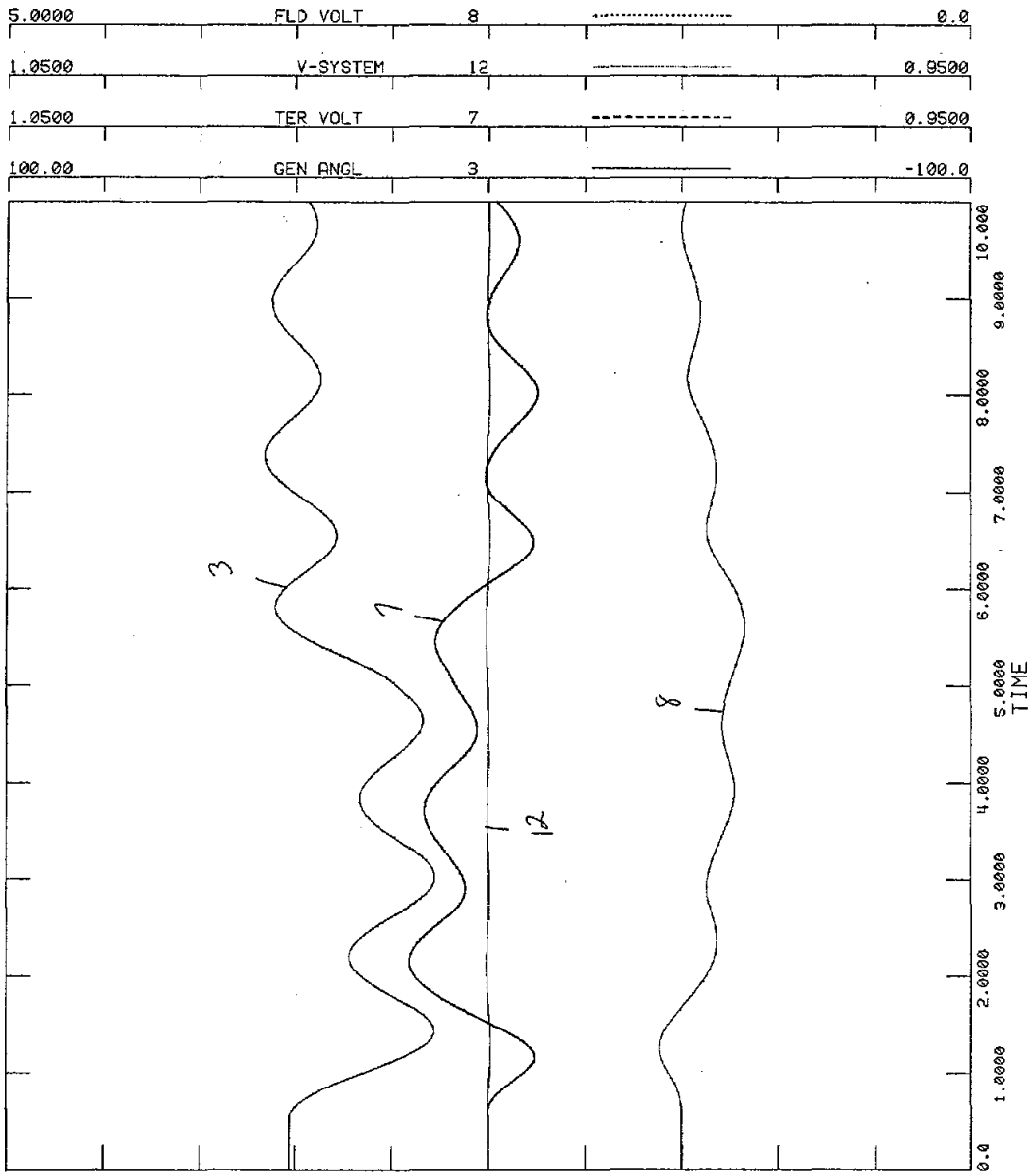


SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*

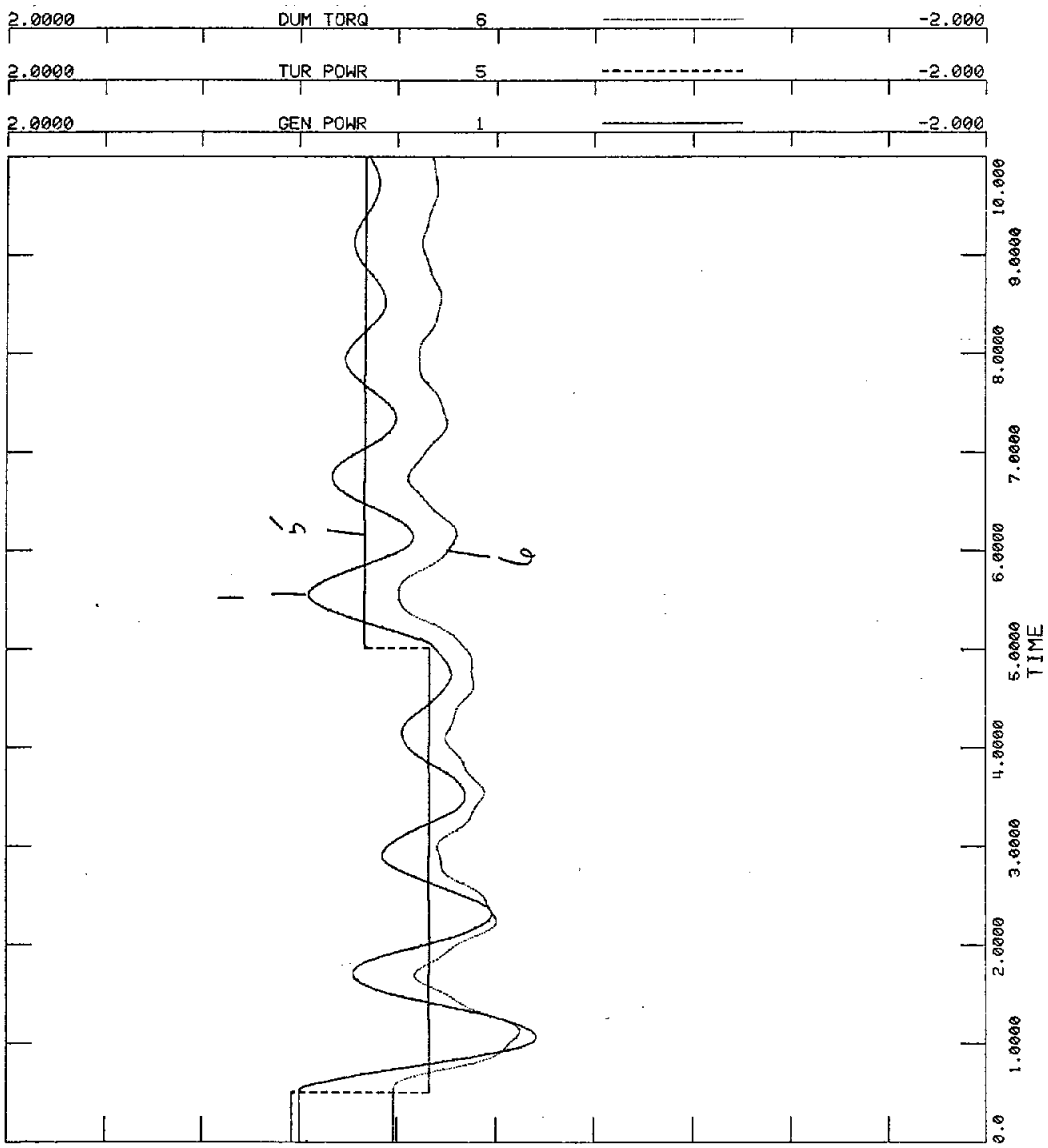
CASE S17



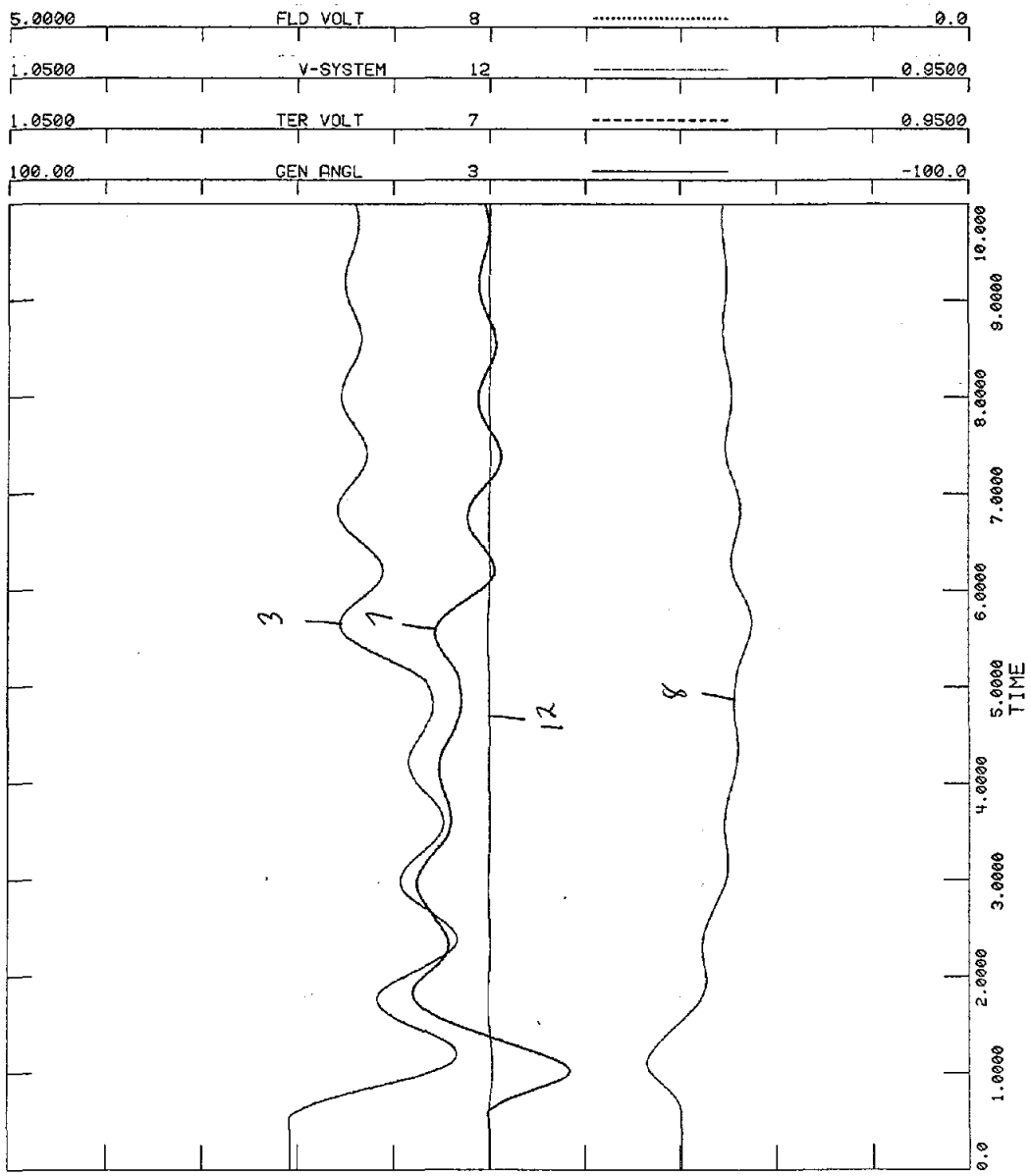
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 60 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*
CASE S 17



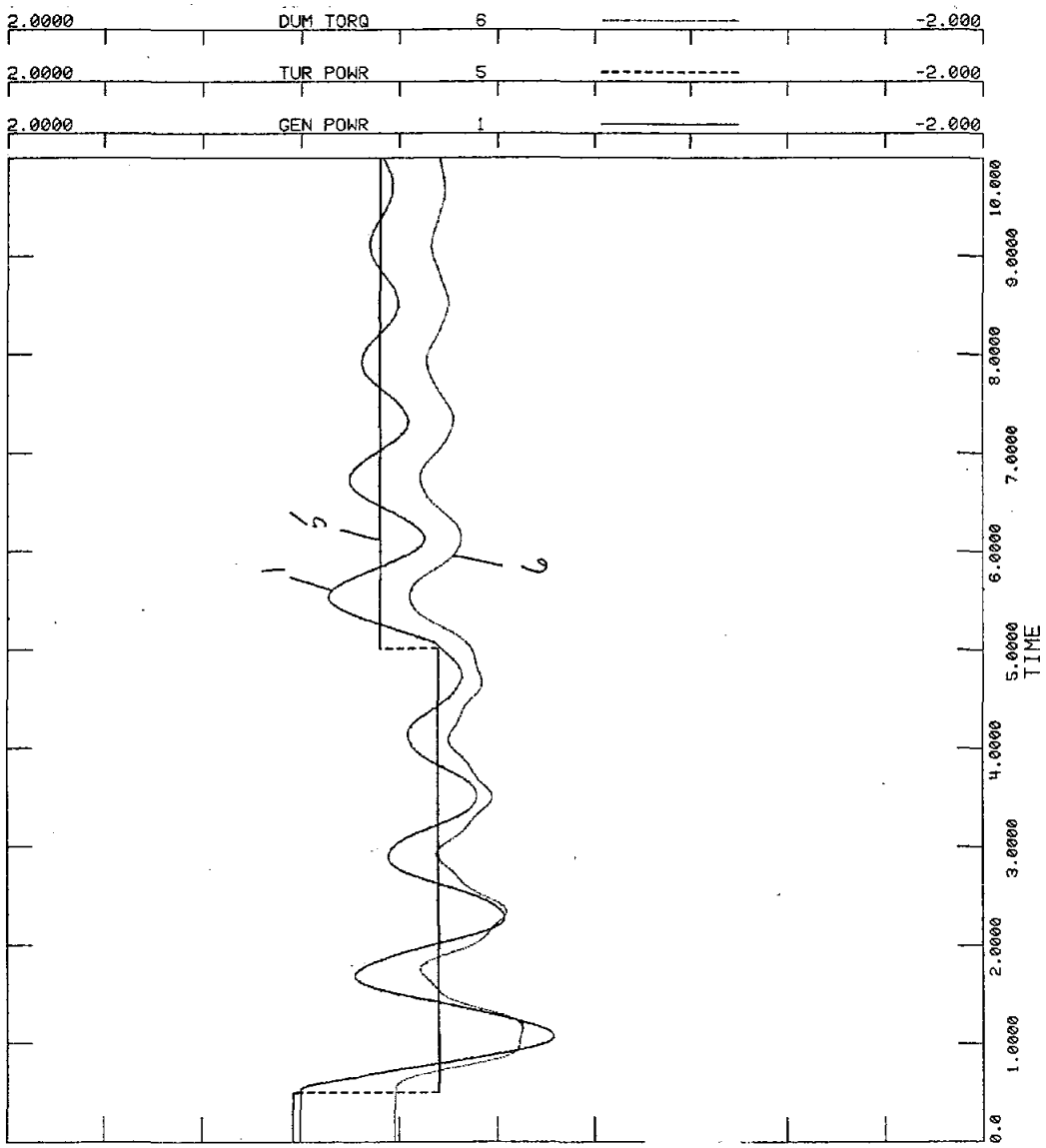
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*
CASE S18



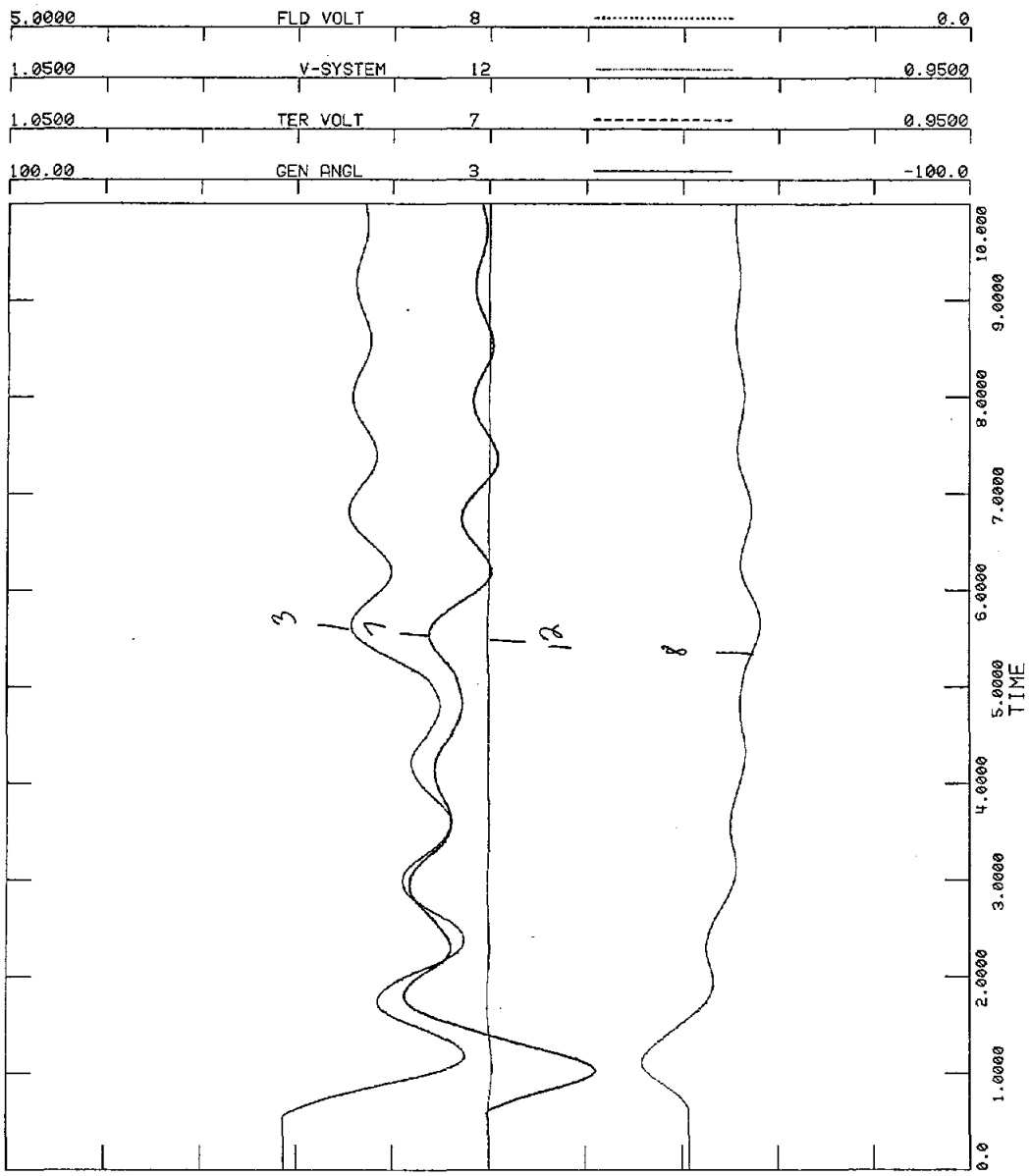
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 200 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*
CASE S18



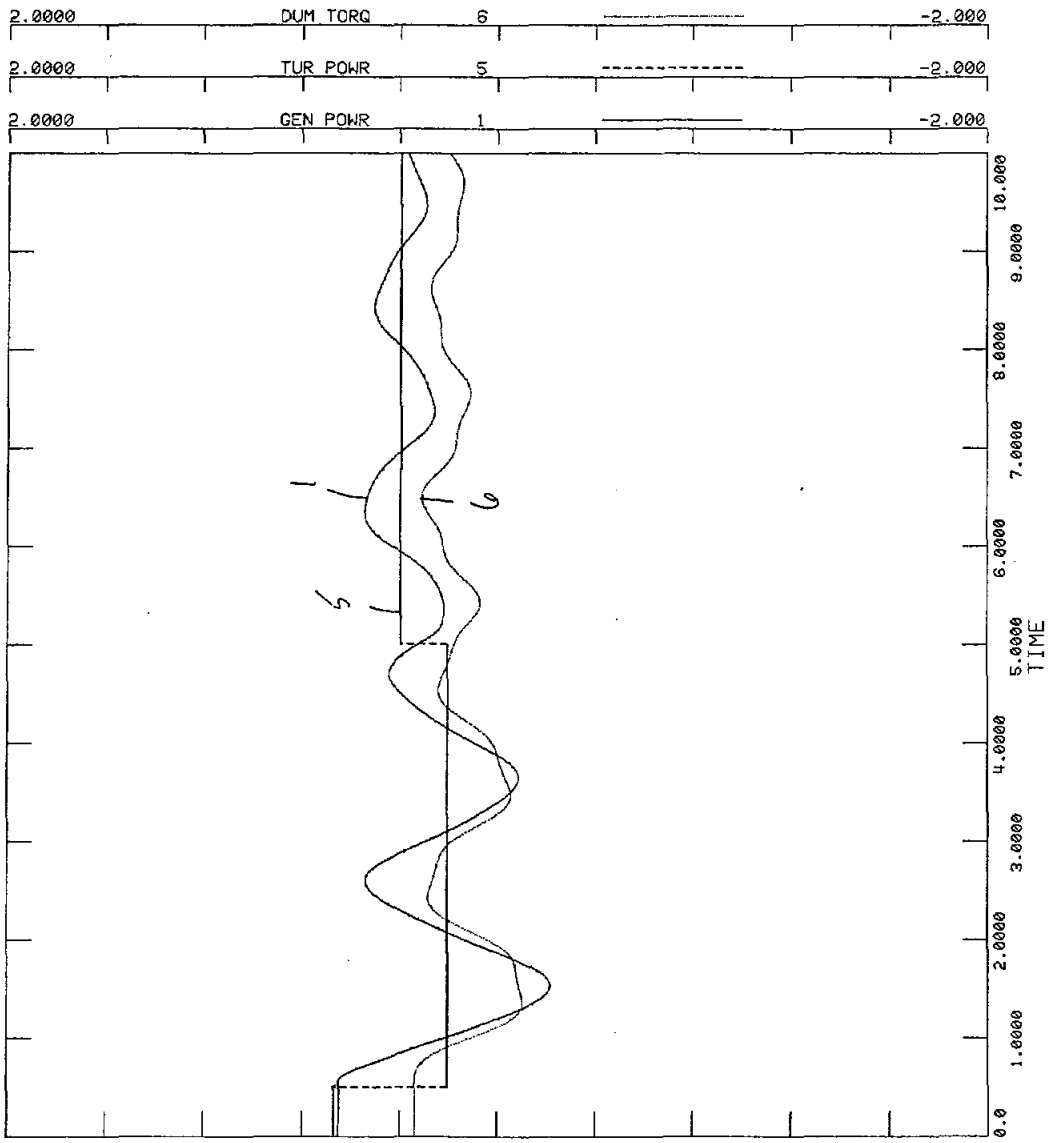
SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*
CASE S 19



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 500 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT - *WITHOUT TORQUE RIPPLE*
CASE 519

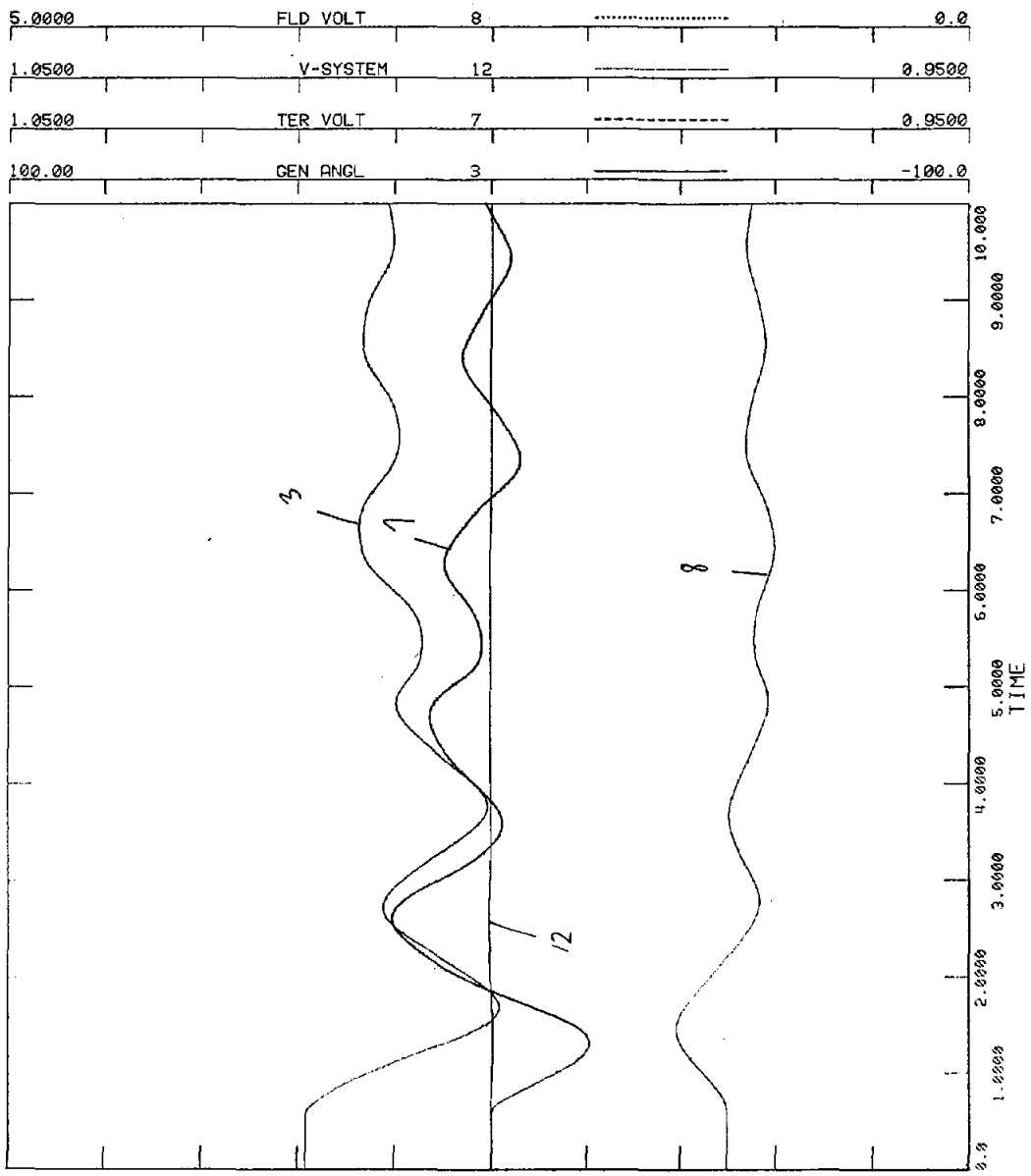


SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*
CASE S110



SANDIA LABS - WIND TURBINE - SYNCH GENERATOR - 1600 KW
CONNECTED TO INFINITE BUS
WIND SPEED TRANSIENT — *WITHOUT TORQUE RIPPLE*

CASE S110

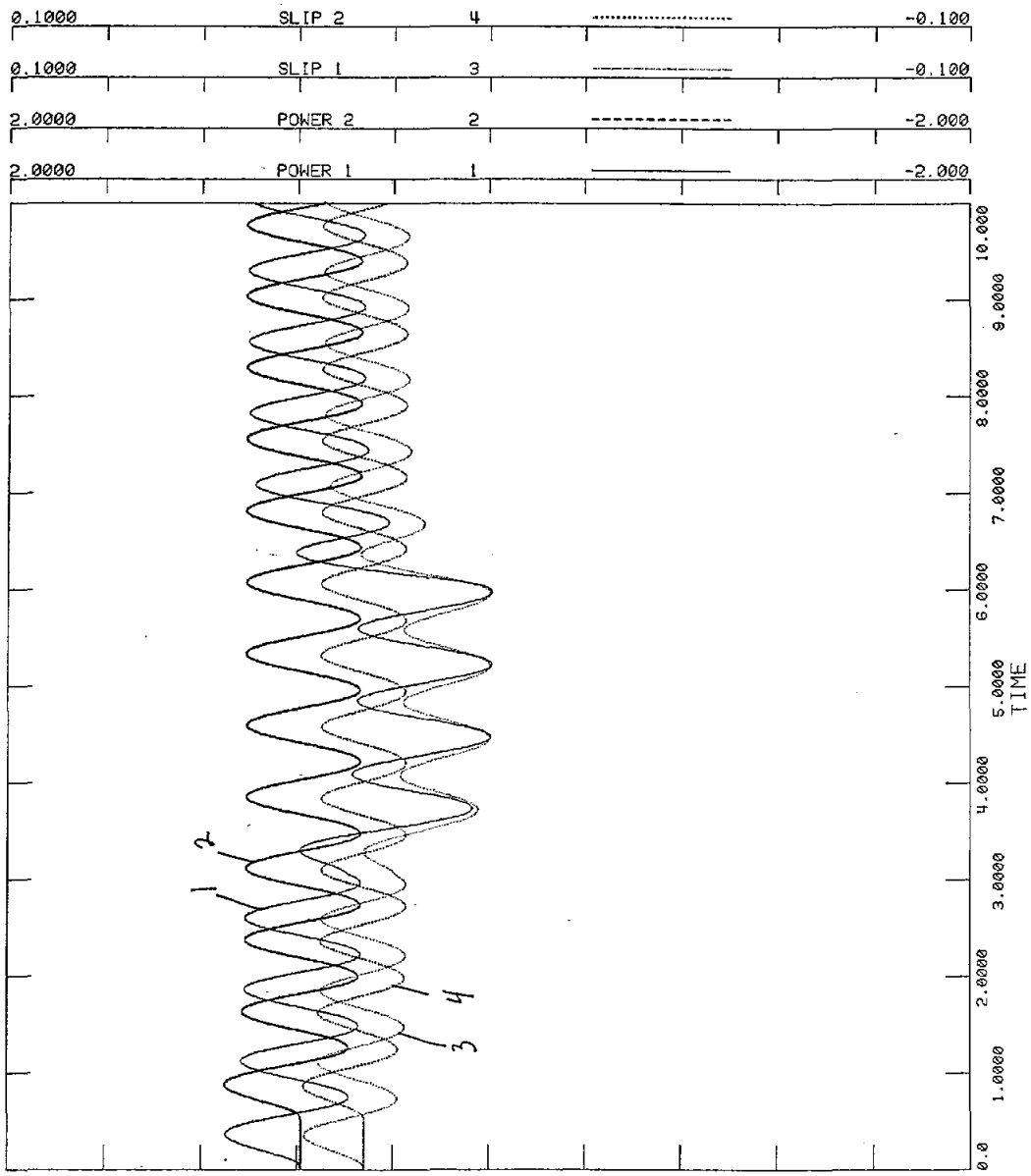


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO INFINITE SYSTEM

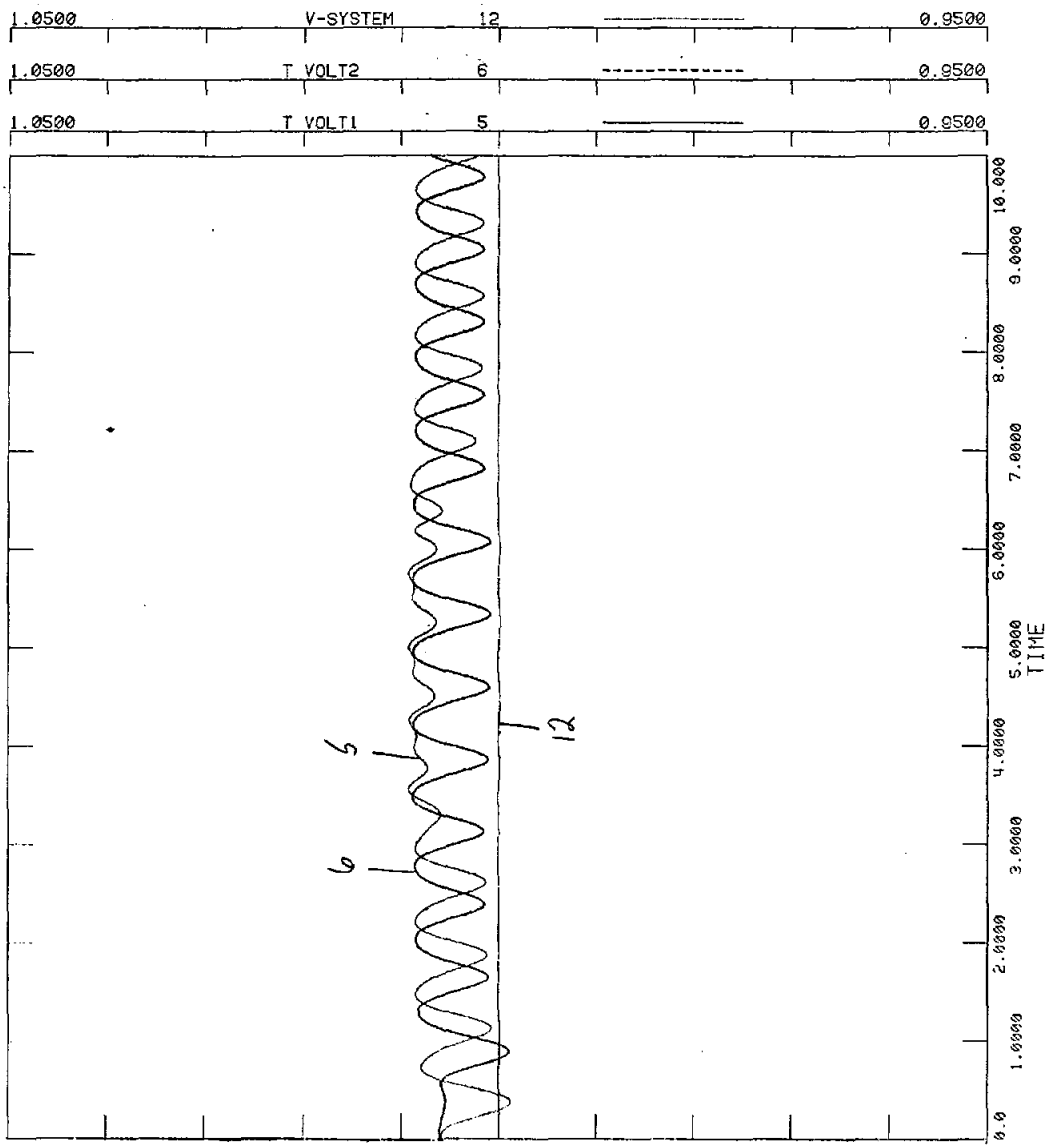
BUS 1 GEN1	AREA	CKT	MW	MVAR	MVA	%	1.0060PU	2.92	1
GENERATION	1		196.4	-124.6R	232.6	93	KV		
TO LOAD-PQ			0.0	-105.7	105.7				
TO 3 LOAD1	1	1	196.4	-18.9	197.4	0	1.0000LK		
BUS 2 GEN2	AREA	CKT	MW	MVAR	MVA	%	1.0061PU	2.94	2
GENERATION	1		196.5	-124.6R	232.7	93	KV		
TO LOAD-PQ			0.0	-105.7	105.7				
TO 4 LOAD2	1	1	196.5	-18.9	197.4	0	1.0000LK		
BUS 3 LOAD1	AREA	CKT	MW	MVAR	MVA	%	1.0027PU	0.64	3
	1						KV		
TO 1 GEN1	1	1	-194.9	26.6	196.7	0	1.0000UN		
TO 4 LOAD2	1	1	-195.3	26.9	197.1	0			
TO 5 LOAD3	1	1	390.1	-53.1	393.7	0			
BUS 4 LOAD2	AREA	CKT	MW	MVAR	MVA	%	1.0029PU	0.66	4
	1						KV		
TO 2 GEN2	1	1	-195.0	26.6	196.8	0	1.0000UN		
TO 3 LOAD1	1	1	195.2	-26.6	197.0	0			
BUS 5 LOAD3	AREA	CKT	MW	MVAR	MVA	%	1.0004PU	0.46	5
	1						KV		
TO 3 LOAD1	1	1	-389.1	54.3	392.9	0			
TO 6 SYSTEM	1	1	389.2	-54.3	392.9	0	1.0000LK		
BUS 6 SYSTEM	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	0.00	6
GENERATION	1		-388.6	57.4R	392.8	157	KV		
TO 5 LOAD3	1	1	-388.6	57.4	392.8	0	1.0000UN		

CASE I21

SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO INFINITE SYSTEM
WIND SPEED TRANSIENT - TURBINE 1
CASE I21



SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO INFINITE SYSTEM
WIND SPEED TRANSIENT - TURBINE 1
CASE I21

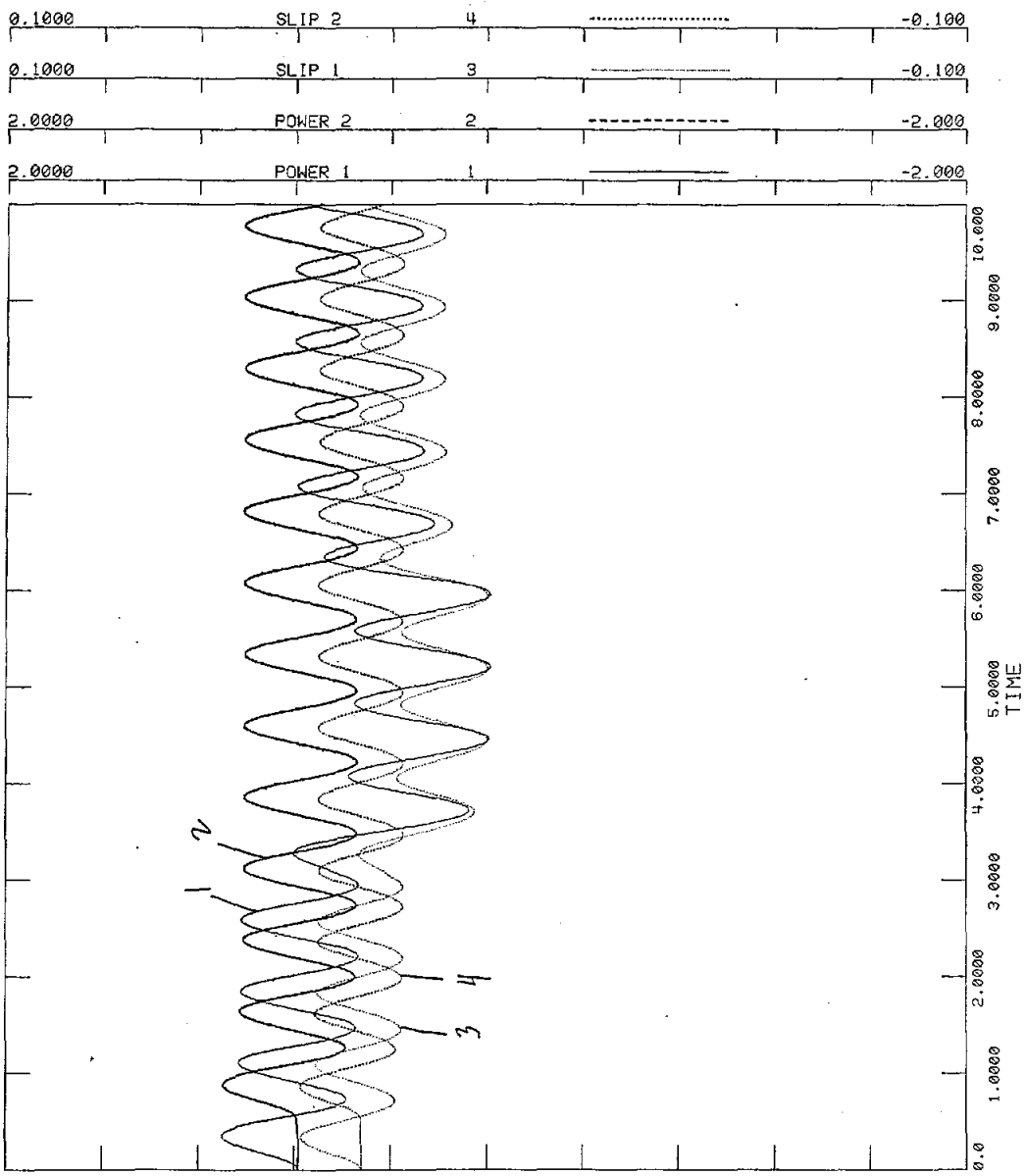


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO WEAK BUS

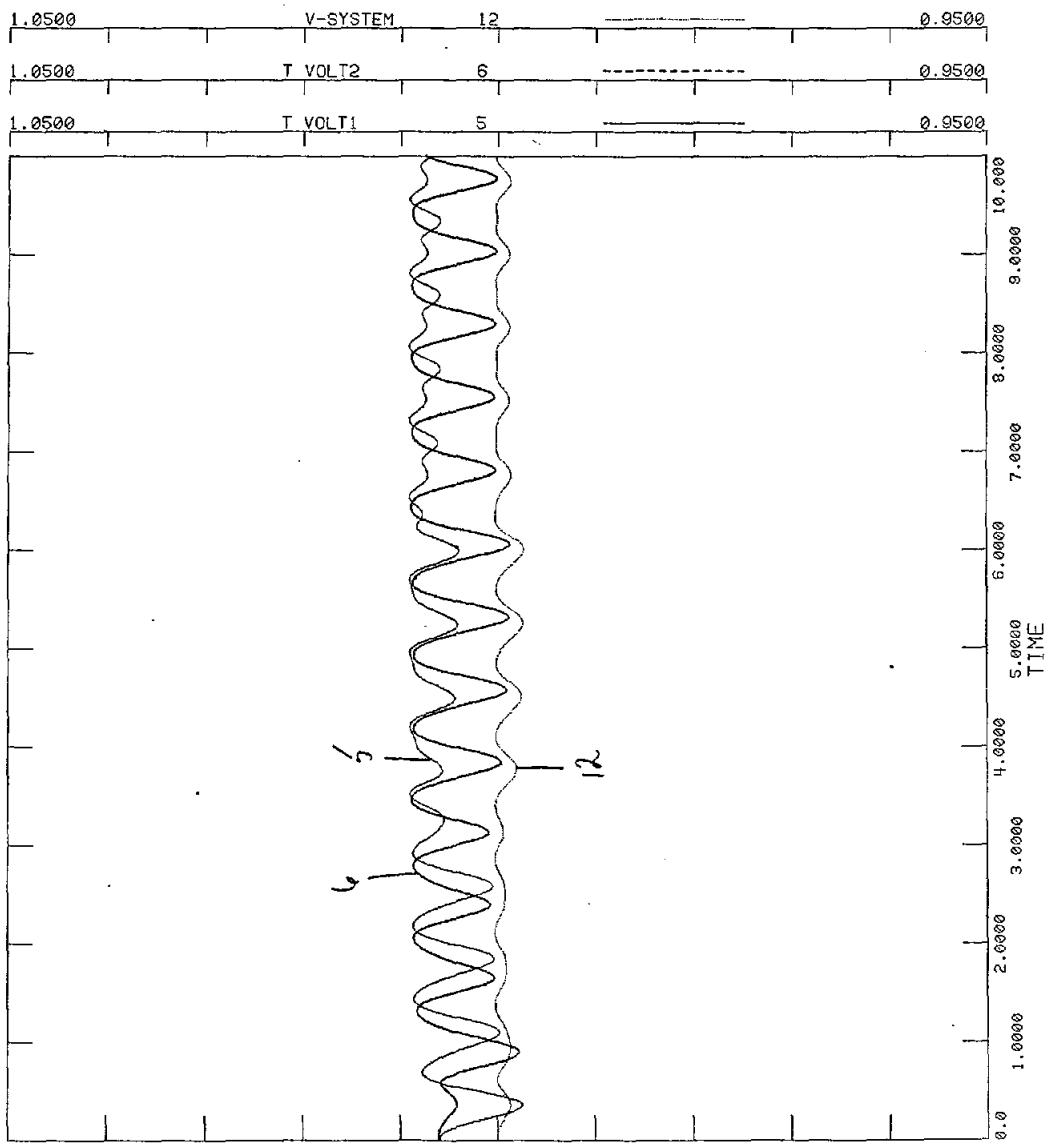
BUS 1 CEN1	AREA	CKT	KW	KVAR	KVA	%	1.0060PU	2.92	1
GENERATION	1		196.4	-124.6R	232.6	93	KV		
TO LOAD-PQ			0.0	-105.7	105.7				
TO 3 LOAD1	1	1	196.4	-18.9	197.4	0	1.0000LK		
BUS 2 CEN2	AREA	CKT	KW	KVAR	KVA	%	1.0061PU	2.94	2
GENERATION	1		196.5	-124.6R	232.7	93	KV		
TO LOAD-PQ			0.0	-105.7	105.7				
TO 4 LOAD2	1	1	196.5	-18.9	197.4	0	1.0000LK		
BUS 3 LOAD1	AREA	CKT	KW	KVAR	KVA	%	1.0027PU	0.64	3
	1						KV		
TO 1 CEN1	1	1	-194.9	26.6	196.7	0	1.0000UN		
TO 4 LOAD2	1	1	-195.3	26.9	197.1	0			
TO 5 LOAD3	1	1	390.1	-53.1	393.7	0			
BUS 4 LOAD2	AREA	CKT	KW	KVAR	KVA	%	1.0029PU	0.66	4
	1						KV		
TO 2 CEN2	1	1	-195.0	26.6	196.8	0	1.0000UN		
TO 3 LOAD1	1	1	195.2	-26.6	197.0	0			
BUS 5 LOAD3	AREA	CKT	KW	KVAR	KVA	%	1.0004PU	0.46	5
	1						KV		
TO 3 LOAD1	1	1	-389.1	54.3	392.9	0			
TO 6 SYSTEM	1	1	389.2	-54.3	392.9	0	1.0000LK		
BUS 6 SYSTEM	AREA	CKT	KW	KVAR	KVA	%	1.0000PU	0.00	6
GENERATION	1		-388.6	57.4R	392.8	157	KV		
TO 5 LOAD3	1	1	-388.6	57.4	392.8	0	1.0000UN		

CASE I22

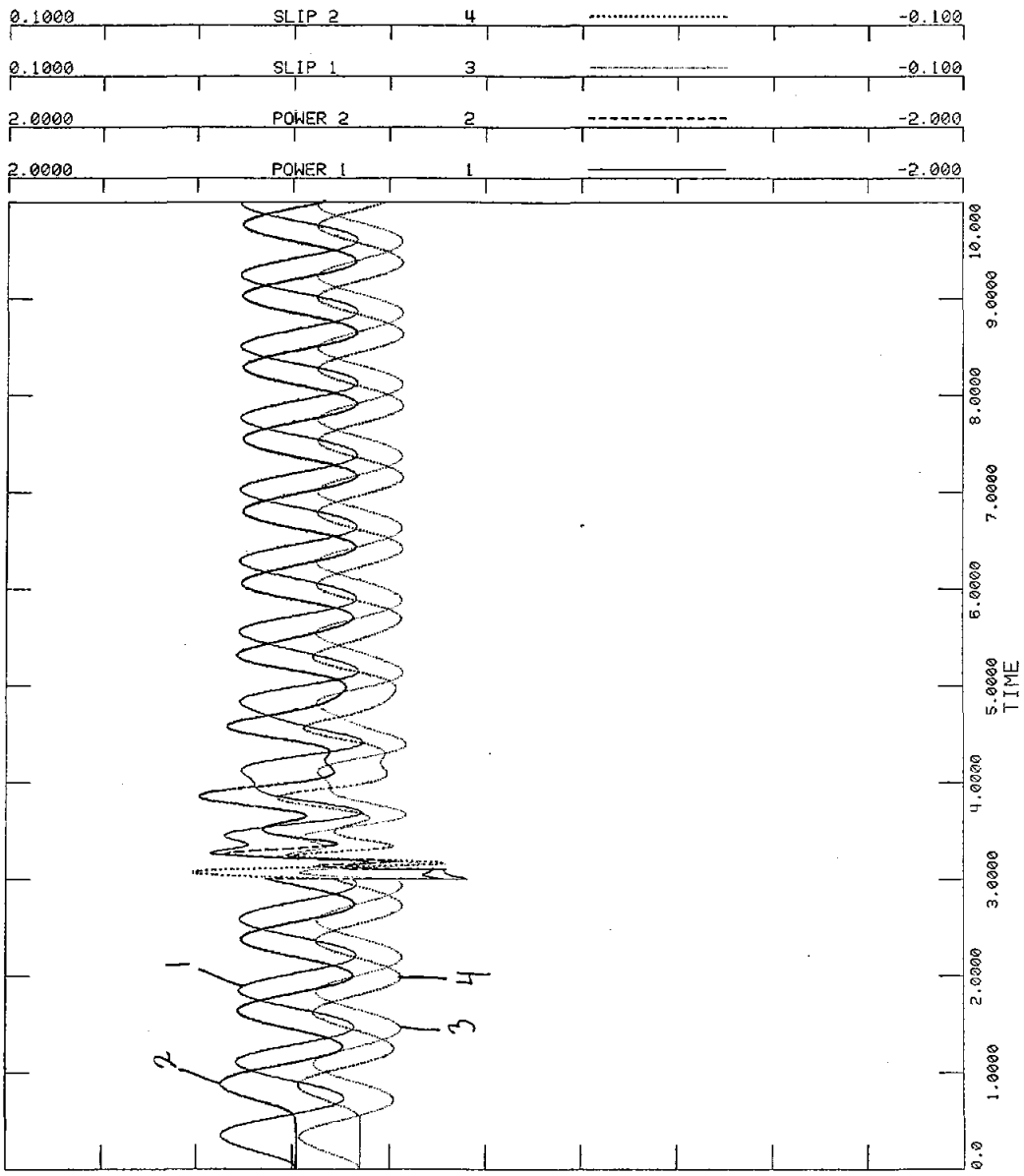
SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT - TURBINE 1
CASE I22



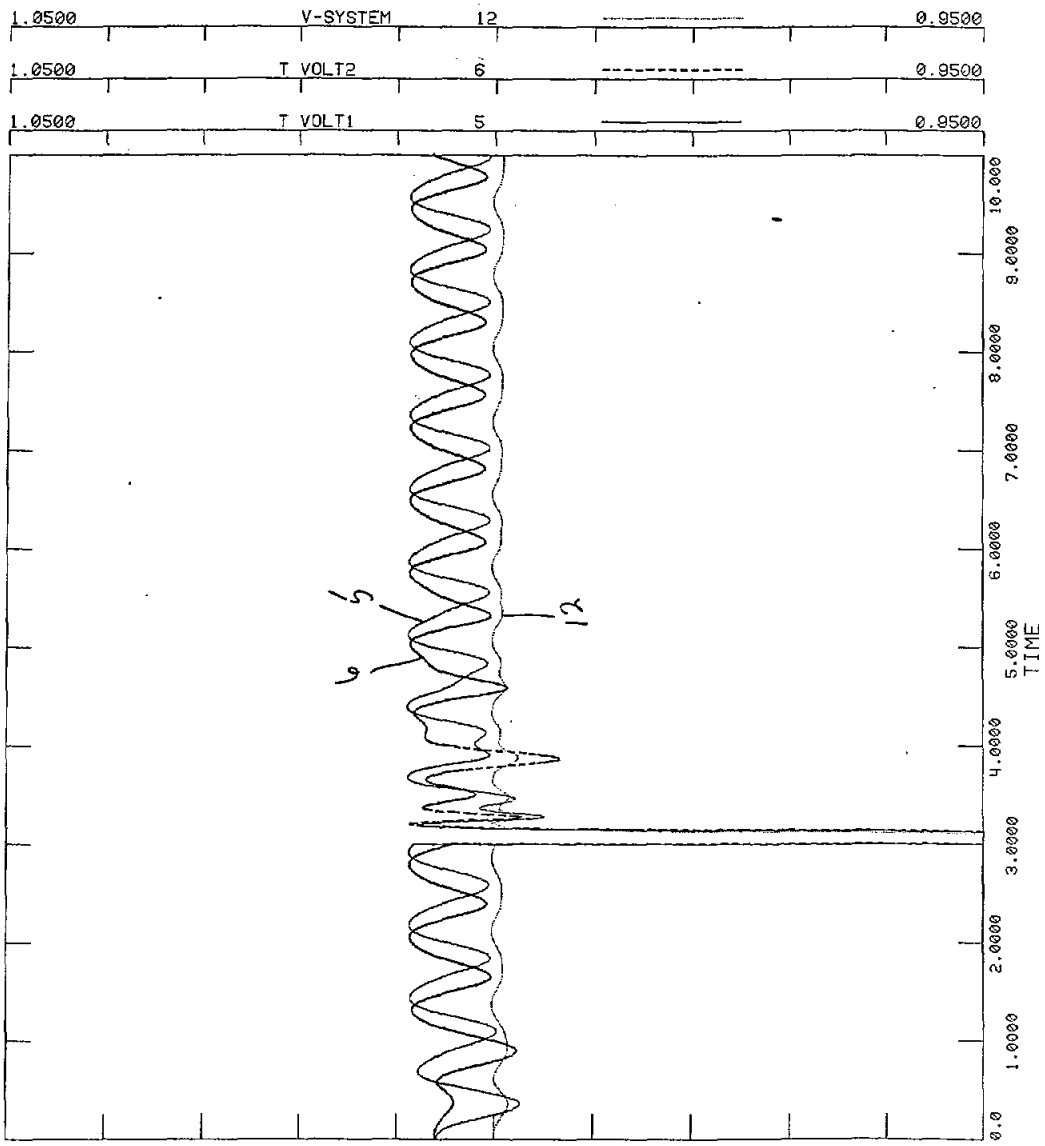
SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT - TURBINE 1
CASE I22



SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO WEAK BUS
SHORT CIRCUIT ON BUS 4 FOR 0.1 SEC
CASE I22



SANDIA LABS - WIND TURBINE CLUSTER - IND GEN - 200 KW
CONNECTED TO : WEAK BUS
SHORT CIRCUIT ON BUS 4 FOR 0.1 SEC
CASE I22

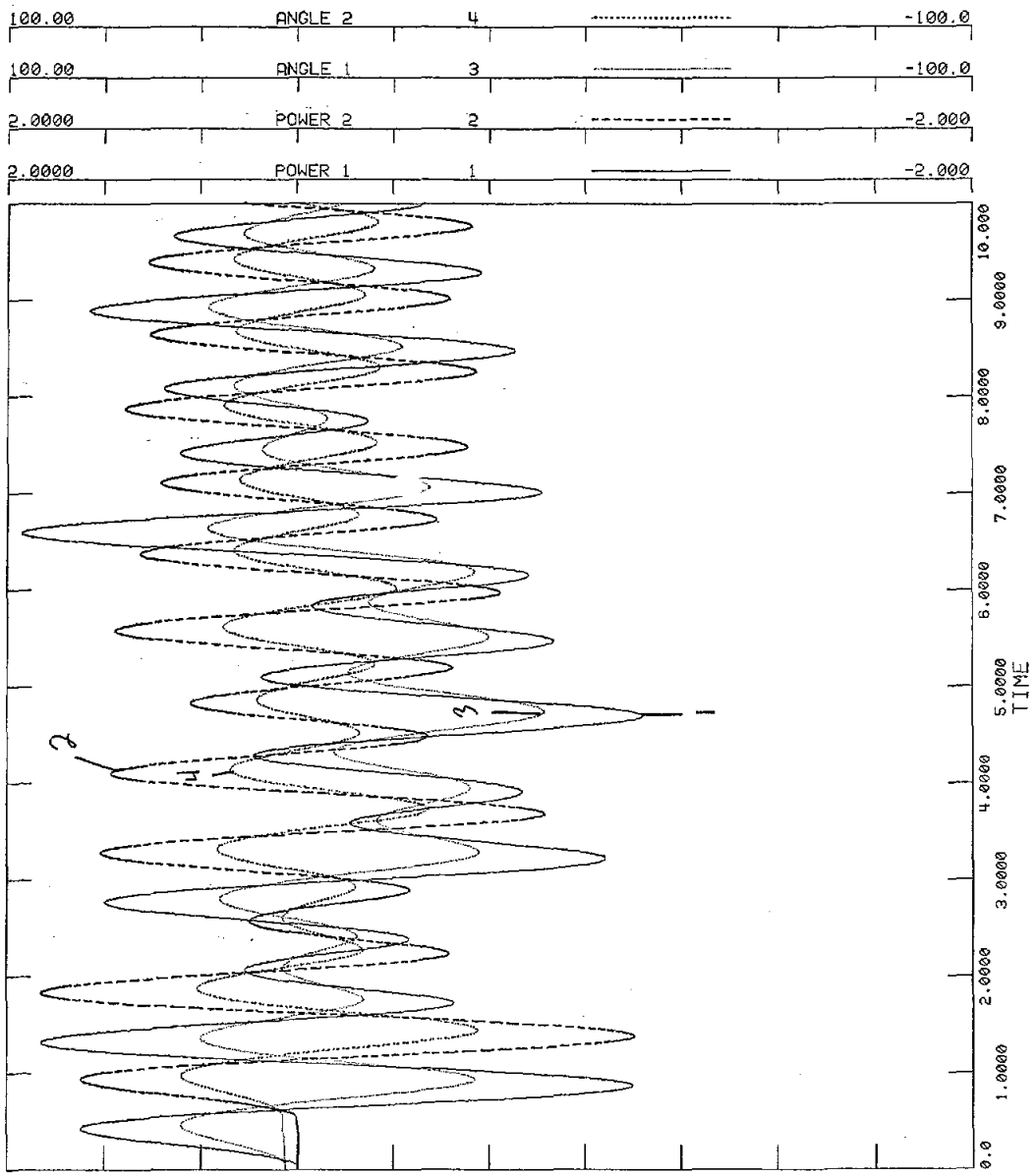


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO INFINITE SYSTEM

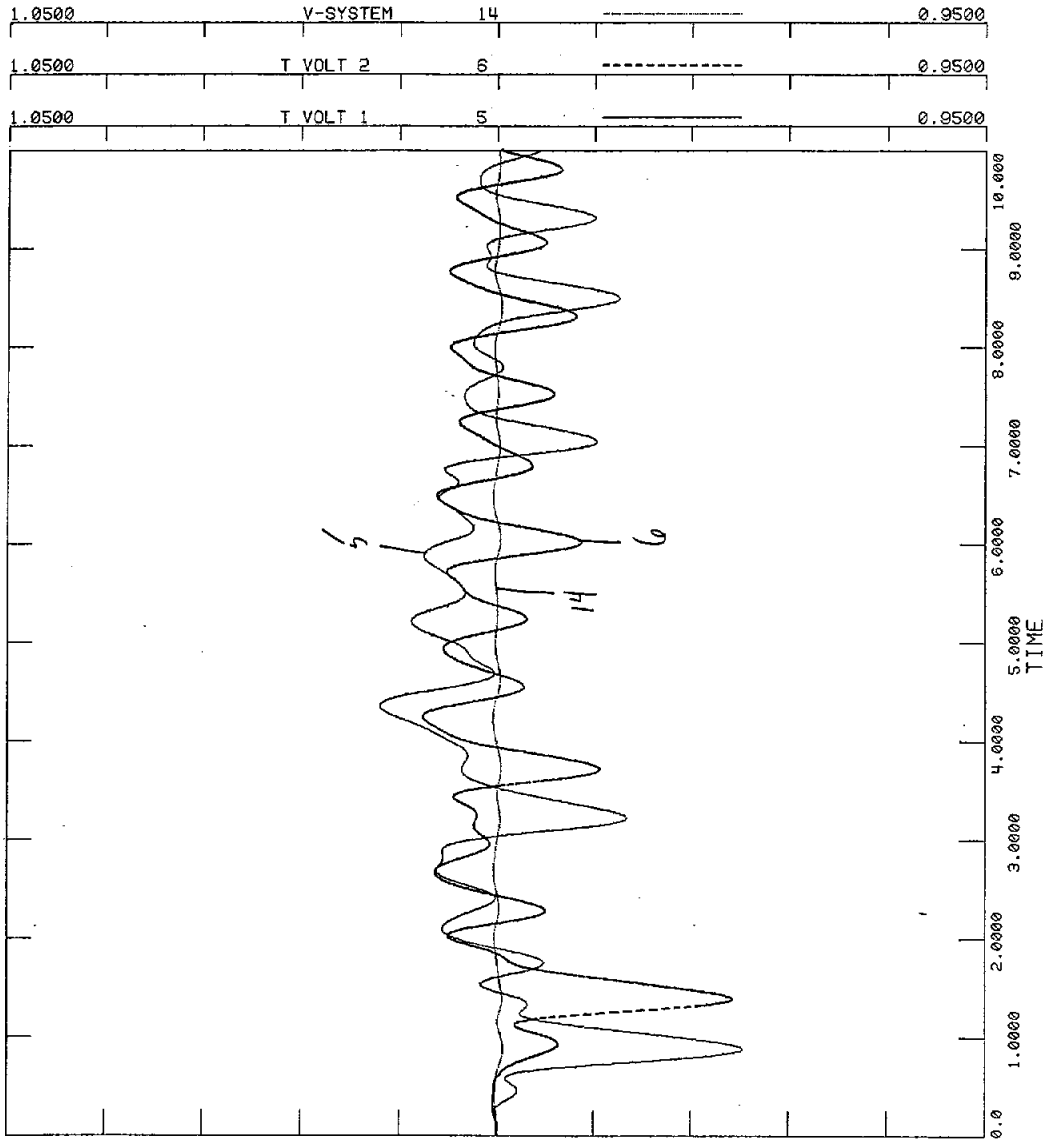
BUS	1 GEN1	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	3.07	1
GENERATION		1		200.0	-42.6R	204.5	82	KV		
TO	3 LOAD1	1	1	200.0	-42.6	204.5	0	1.0000LK		
BUS	2 GEN2	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	3.10	2
GENERATION		1		200.0	-43.4R	204.7	82	KV		
TO	4 LOAD2	1	1	200.0	-43.4	204.7	0	1.0000LK		
BUS	3 LOAD1	AREA	CKT	MW	MVAR	MVA	%	1.0014PU	0.69	3
		1						KV		
TO	1 GEN1	1	1	-198.3	51.0	204.8	0	1.0000UN		
TO	4 LOAD2	1	1	-198.5	51.9	205.2	0			
TO	5 LOAD3	1	1	396.9	-102.7	410.0	0			
BUS	4 LOAD2	AREA	CKT	MW	MVAR	MVA	%	1.0016PU	0.71	4
		1						KV		
TO	2 GEN2	1	1	-198.3	51.8	205.0	0	1.0000UN		
TO	3 LOAD1	1	1	198.5	-51.6	205.1	0			
BUS	5 LOAD3	AREA	CKT	MW	MVAR	MVA	%	0.9995PU	0.48	5
		1						KV		
TO	3 LOAD1	1	1	-395.8	104.0	409.3	0			
TO	6 SYSTEM	1	1	395.8	-104.0	409.2	0	1.0000LK		
BUS	6 SYSTEM	AREA	CKT	MW	MVAR	MVA	%	1.0000PU	0.00	6
GENERATION		1		-395.2	107.3R	409.5	164	KV		
TO	5 LOAD3	1	1	-395.2	107.3	409.5	0	1.0000UN		

CASE S21

SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO INFINITE SYSTEM
WIND SPEED TRANSIENT - TURBINE 1
CASE S21



SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO INFINITE SYSTEM
WIND SPEED TRANSIENT - TURBINE 1
CASE 521

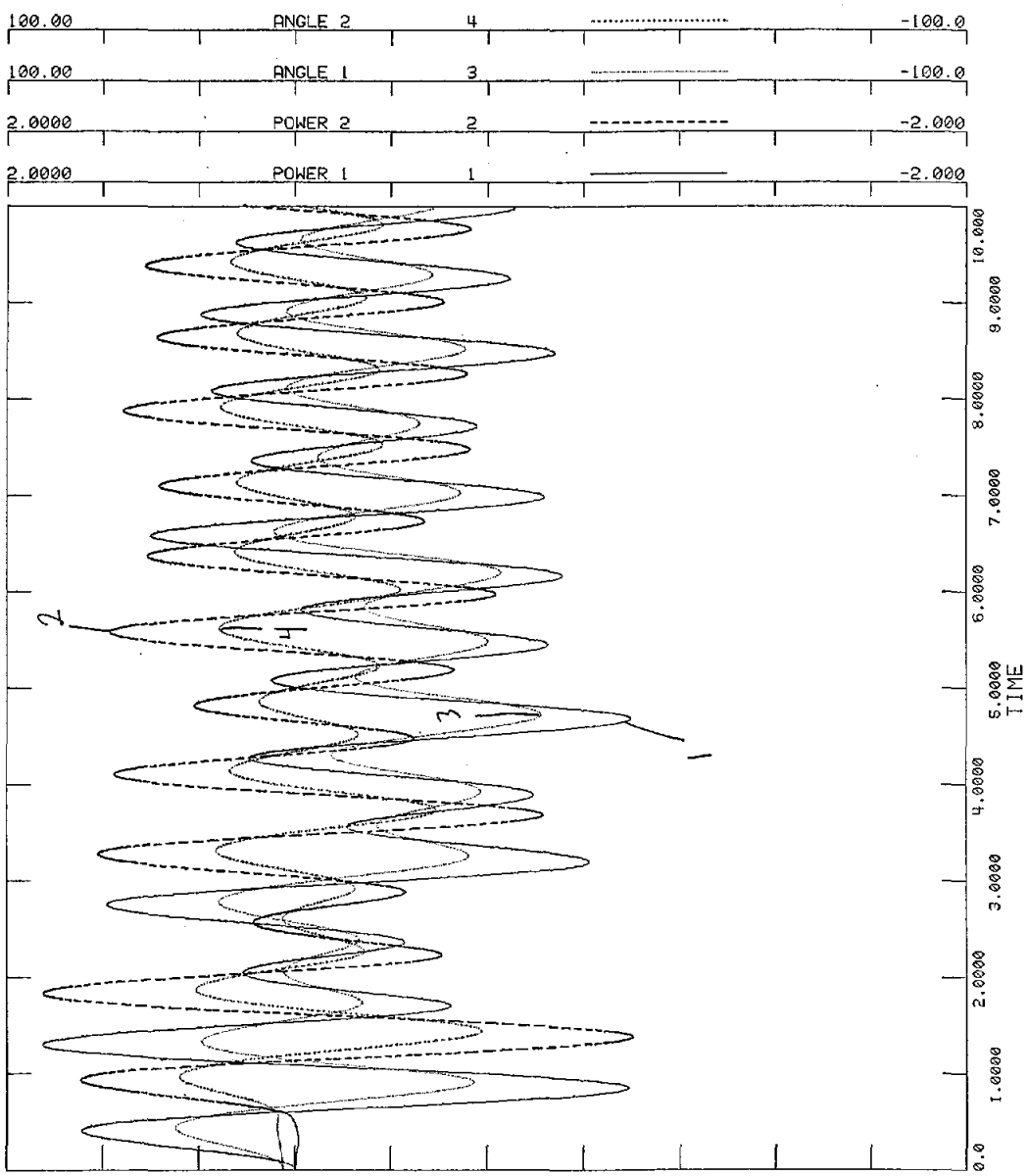


P. T. I. INTERACTIVE LOAD FLOW PROGRAM--PSS/E
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO WEAK BUS

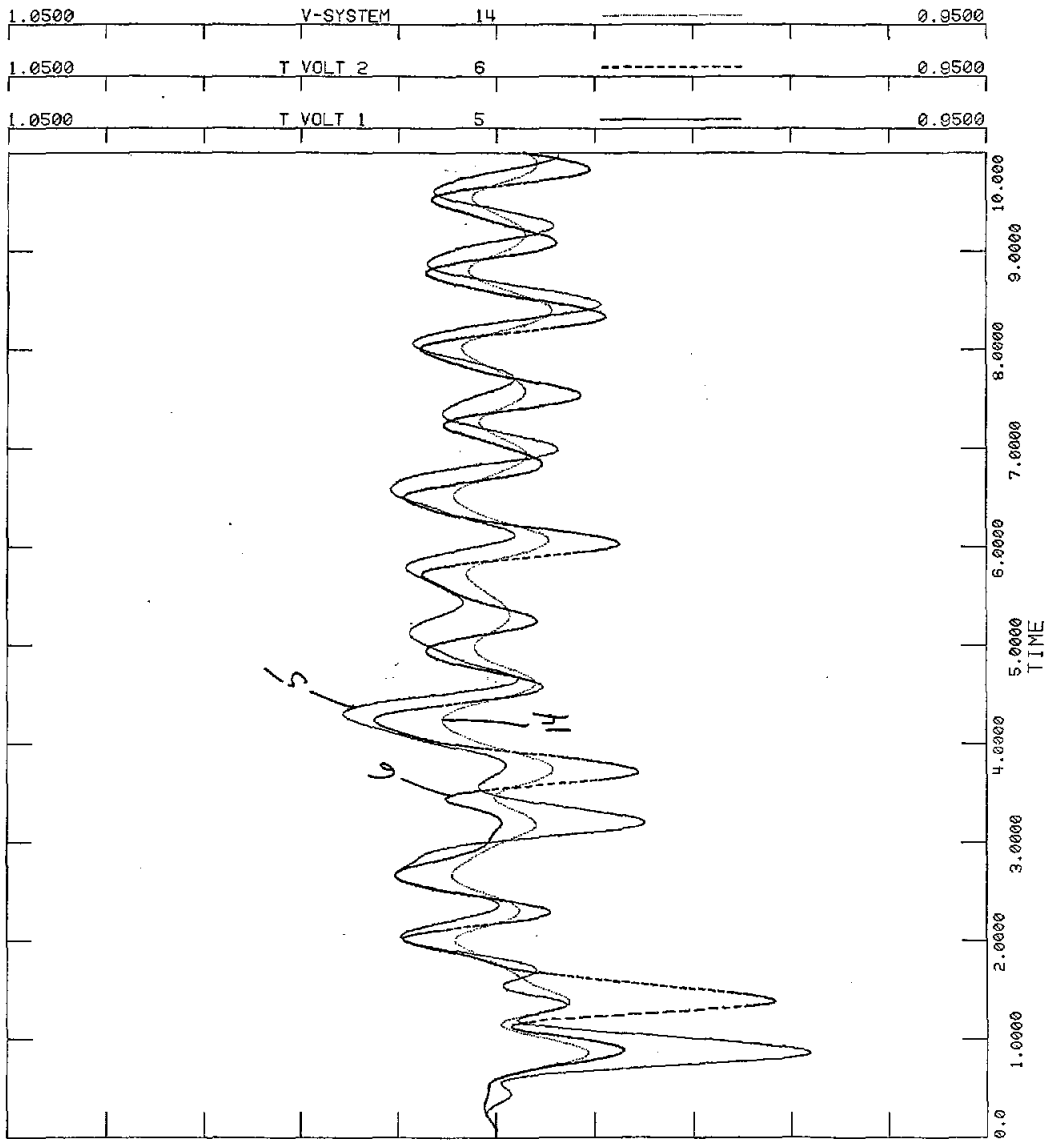
CASE S22

		AREA	CKT	MW	MVAR	MVA	%	1.0000PU	3.07	1
BUS 1 GEN1										
GENERATION		1		200.0	-42.6R	204.5	82	KV		
TO 3 LOAD1		1	1	200.0	-42.6	204.5	0	1.0000LK		
BUS 2 GEN2		AREA	CKT	MW	MVAR	MVA	%	1.0000PU	3.10	2
GENERATION		1		200.0	-43.4R	204.7	82	KV		
TO 4 LOAD2		1	1	200.0	-43.4	204.7	0	1.0000LK		
BUS 3 LOAD1		AREA	CKT	MW	MVAR	MVA	%	1.0014PU	0.69	3
		1						KV		
TO 1 GEN1		1	1	-198.3	51.0	204.8	0	1.0000UN		
TO 4 LOAD2		1	1	-198.5	51.9	205.2	0			
TO 5 LOAD3		1	1	396.9	-102.7	410.0	0			
BUS 4 LOAD2		AREA	CKT	MW	MVAR	MVA	%	1.0016PU	0.71	4
		1						KV		
TO 2 GEN2		1	1	-198.3	51.8	205.0	0	1.0000UN		
TO 3 LOAD1		1	1	198.5	-51.6	205.1	0			
BUS 5 LOAD3		AREA	CKT	MW	MVAR	MVA	%	0.9995PU	0.48	5
		1						KV		
TO 3 LOAD1		1	1	-395.8	104.0	409.3	0			
TO 6 SYSTEM		1	1	395.8	-104.0	409.2	0	1.0000LK		
BUS 6 SYSTEM		AREA	CKT	MW	MVAR	MVA	%	1.0000PU	0.00	6
GENERATION		1		-395.2	107.3R	409.5	164	KV		
TO 5 LOAD3		1	1	-395.2	107.3	409.5	0	1.0000UN		

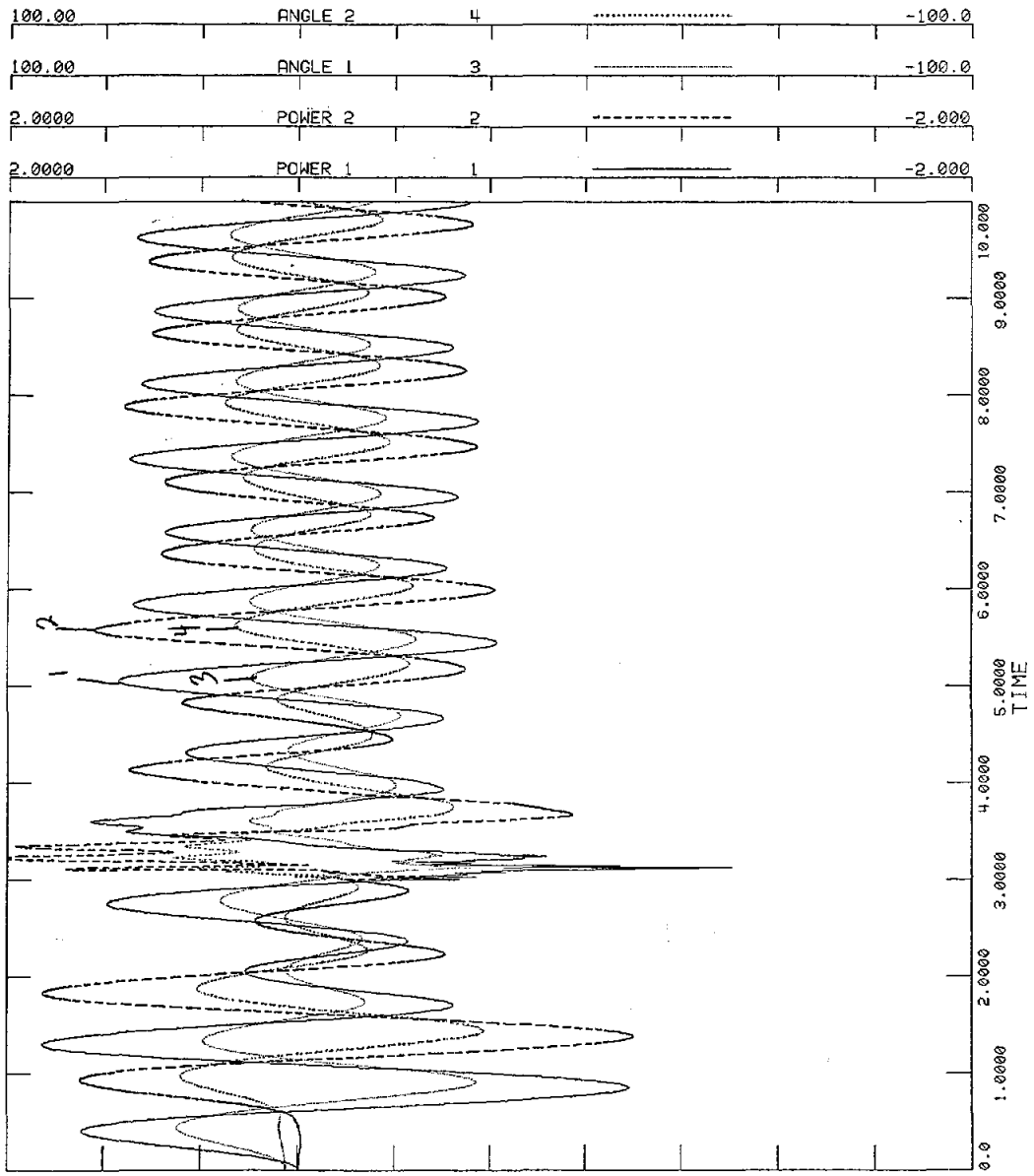
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT - TURBINE 1
CASE 522



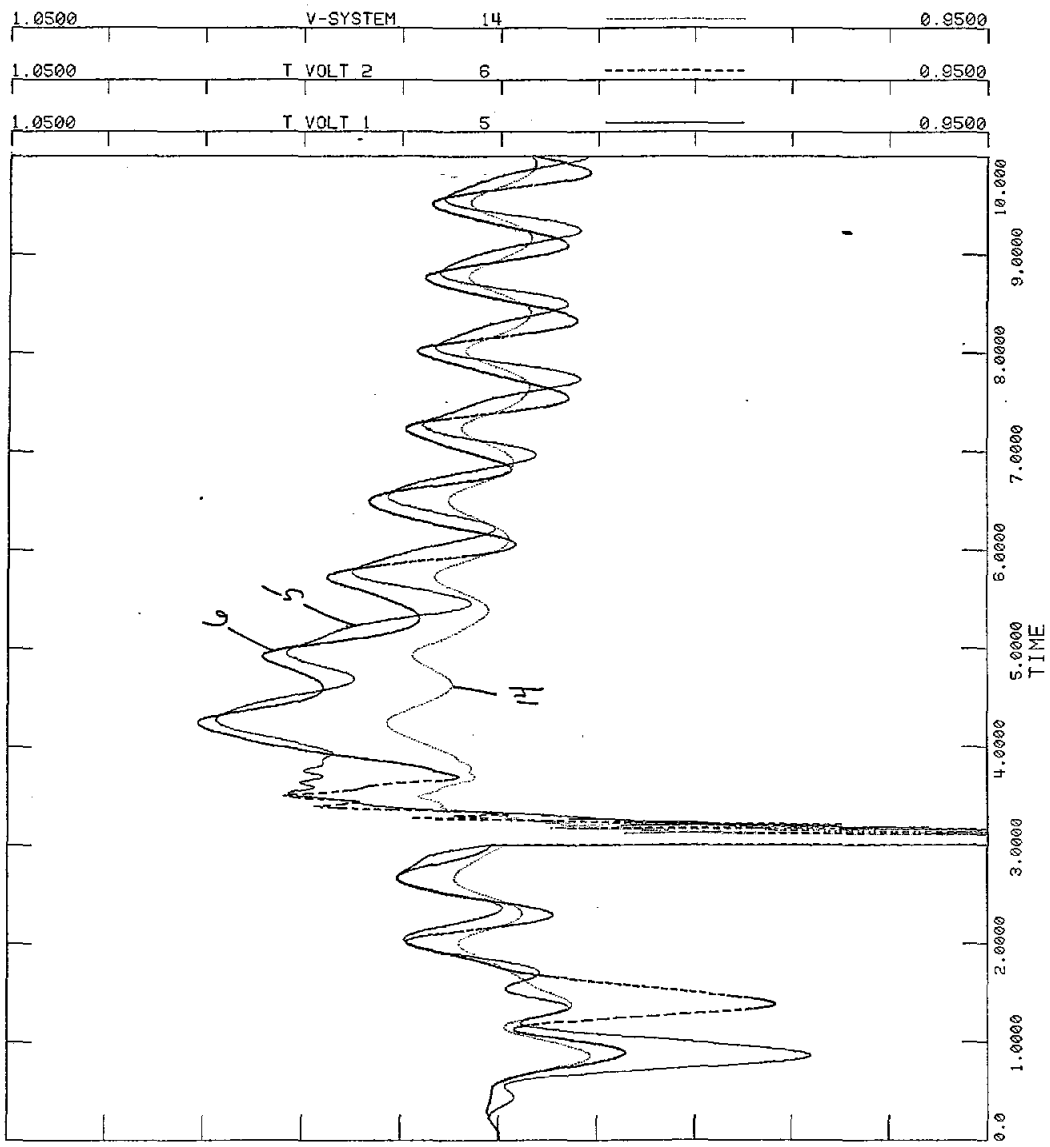
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO WEAK BUS
WIND SPEED TRANSIENT - TURBINE 1
CASE S22



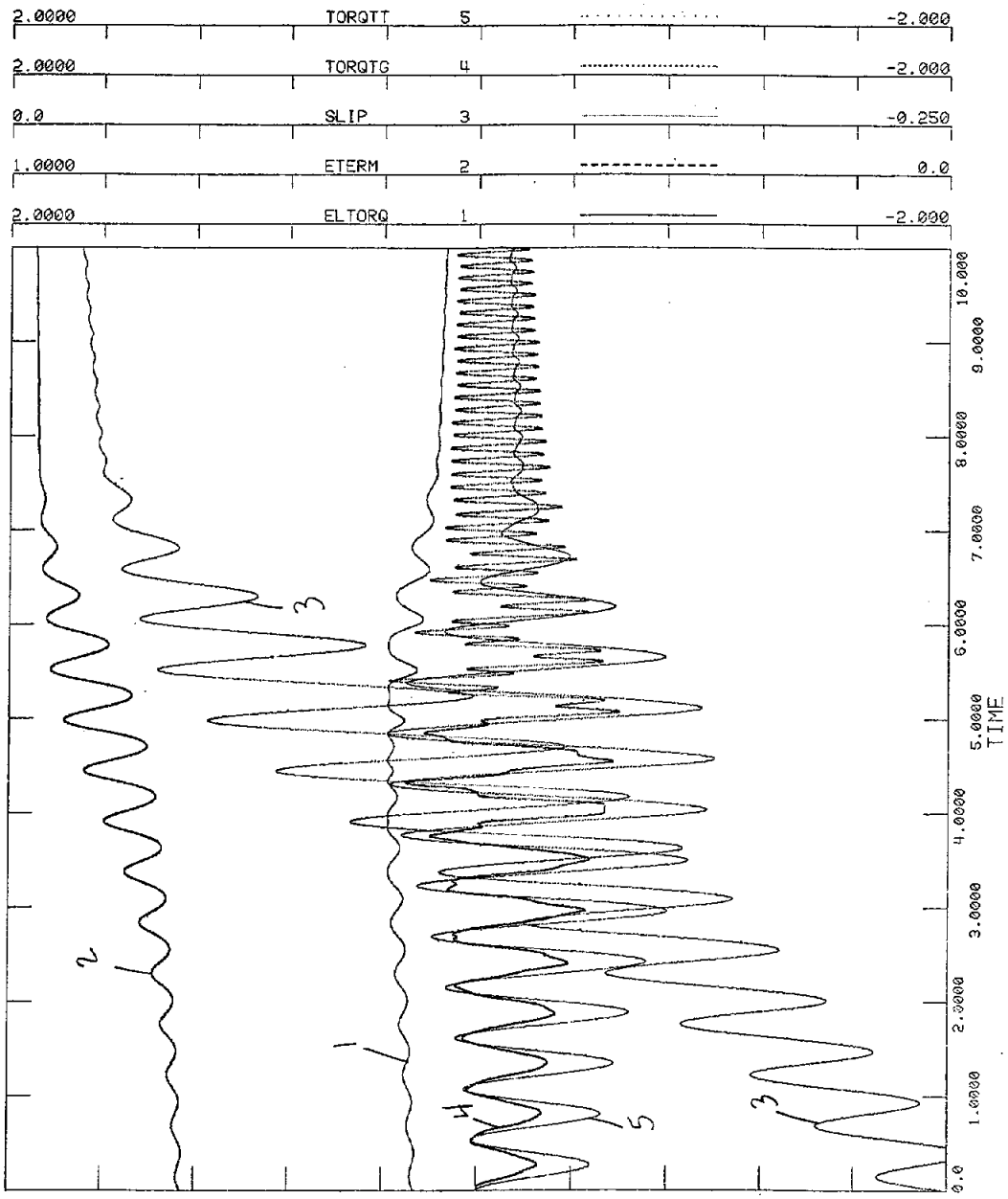
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO WEAK BUS
SHORT CIRCUIT ON BUS 4 FOR 0.1 SEC
CASE S22



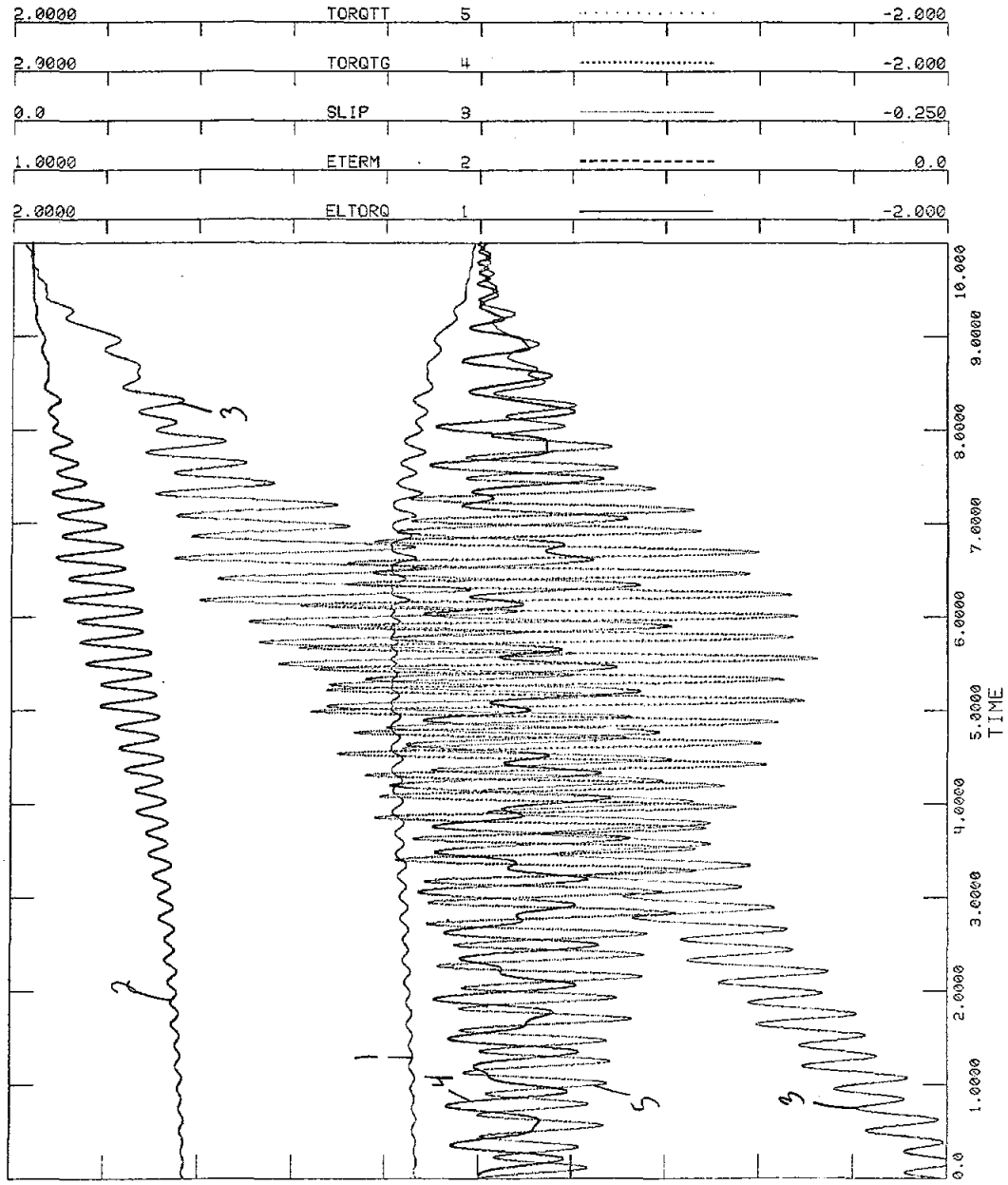
SANDIA LABS - WIND TURBINE CLUSTER - SYNCH GEN - 200 KW
CONNECTED TO WEAK BUS
SHORT CIRCUIT ON BUS 4 FOR 0.1 SEC
CASE S22



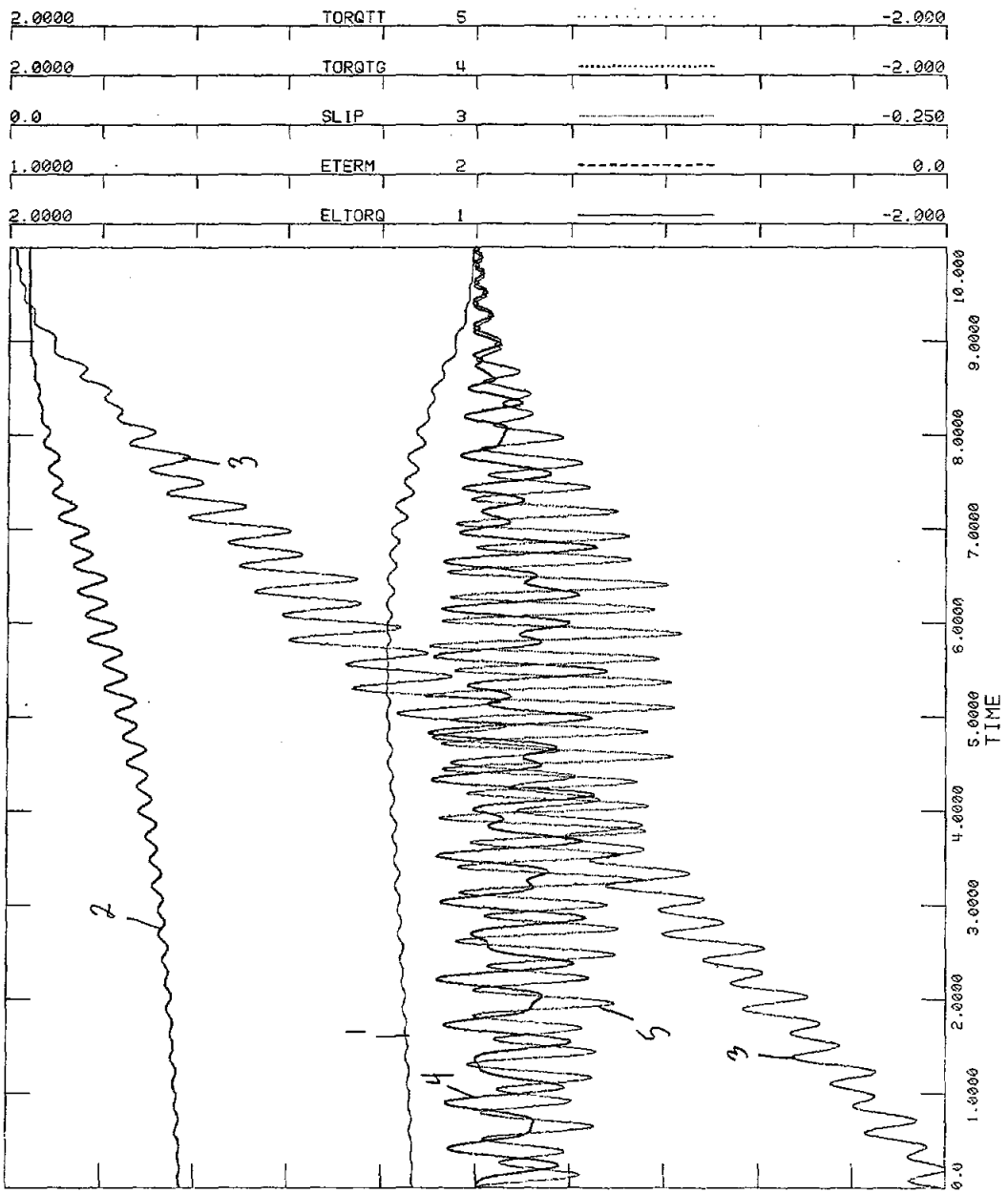
SANDIA LABS - WIND TURBINE - 60 KW
INDUCTION MACHINE STARTING
TRANSFORMER TAP 0.5
CASE IS1



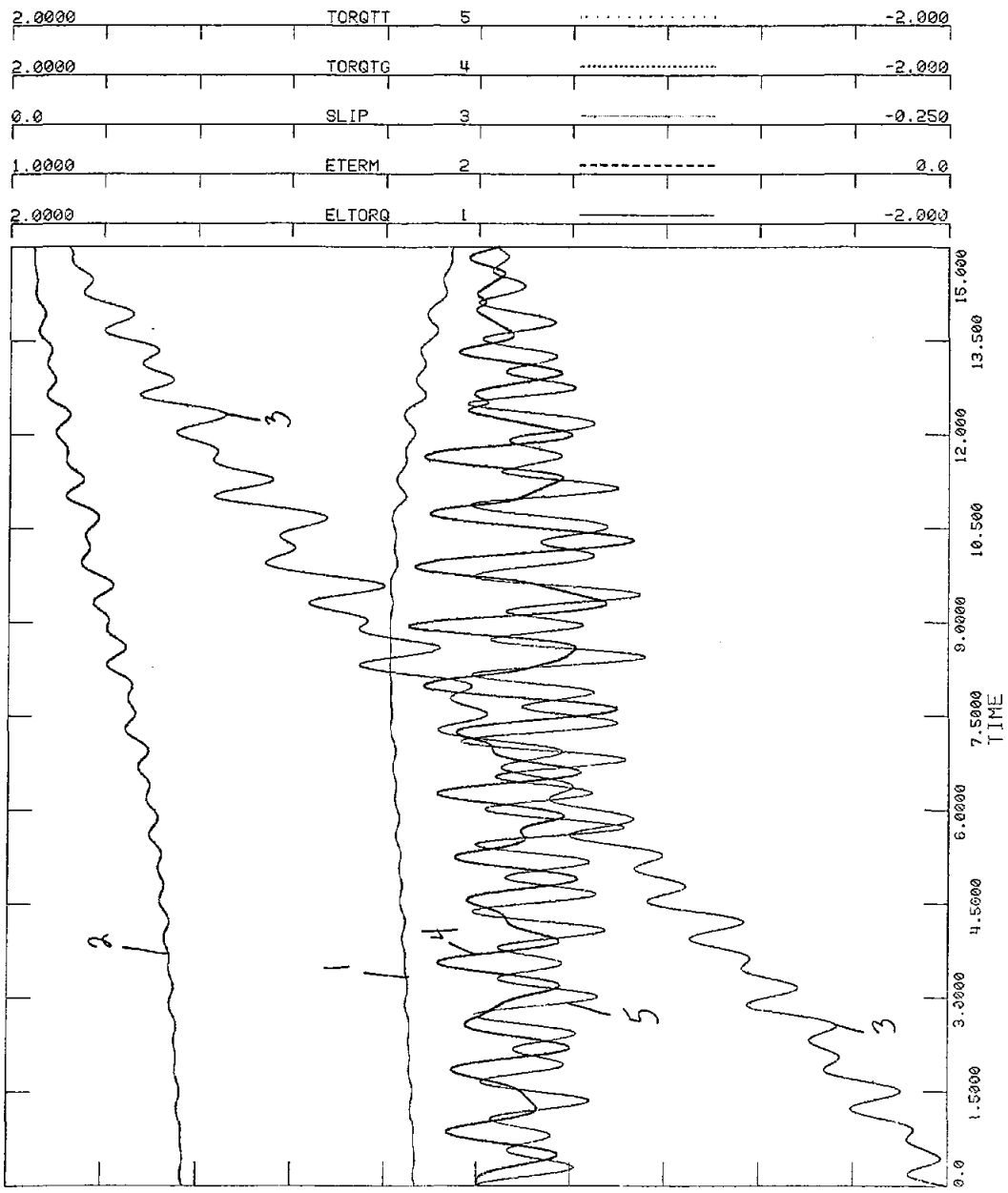
SANDIA LABS - WIND TURBINE - 200 KW
INDUCTION MACHINE STARTING
TRANSFORMER TAP 0.5
CASE IS2



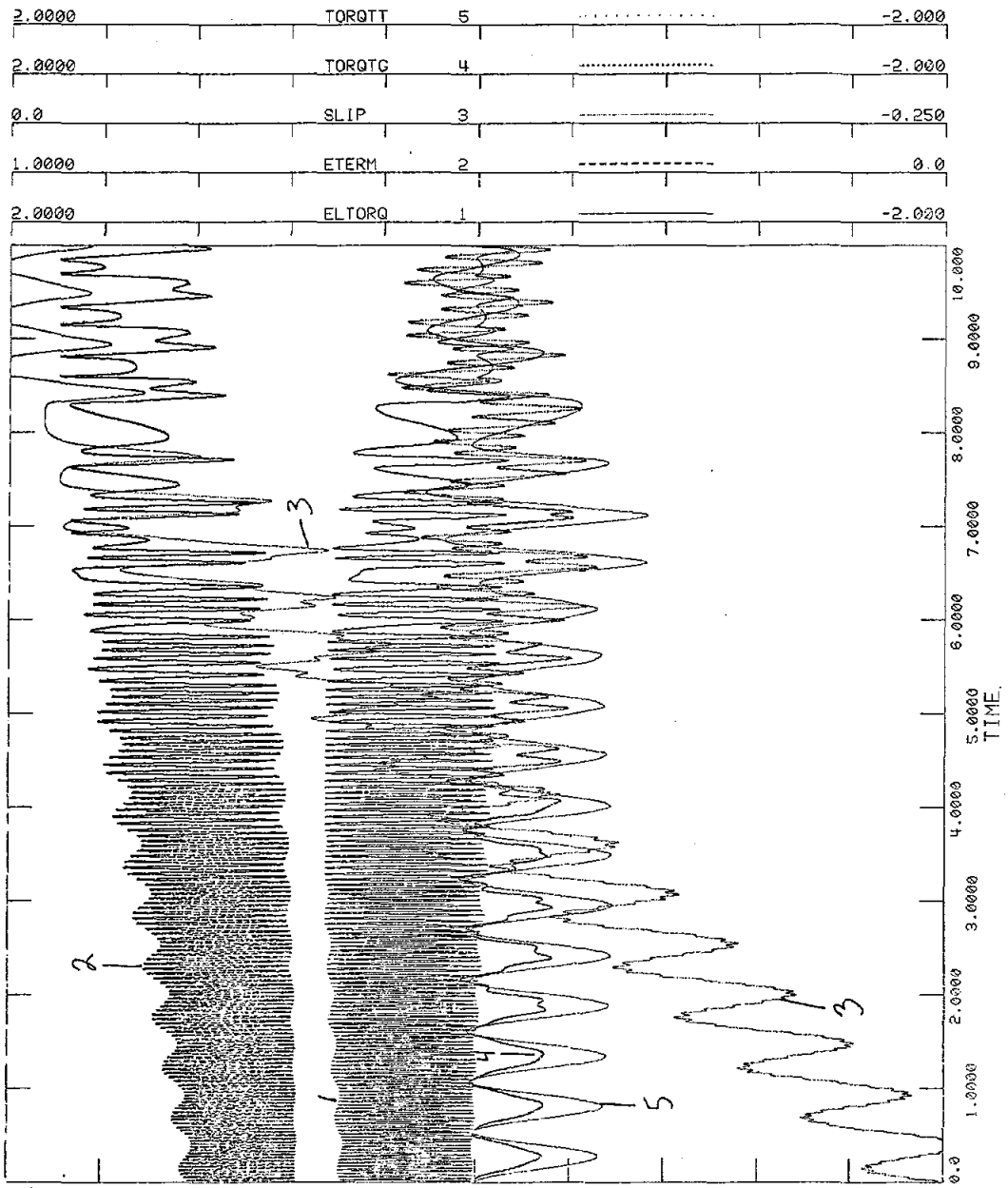
SANDIA LABS - WIND TURBINE - 500 KW
INDUCTION MACHINE STARTING
TRANSFORMER TAP 0.5
CASE IS 3



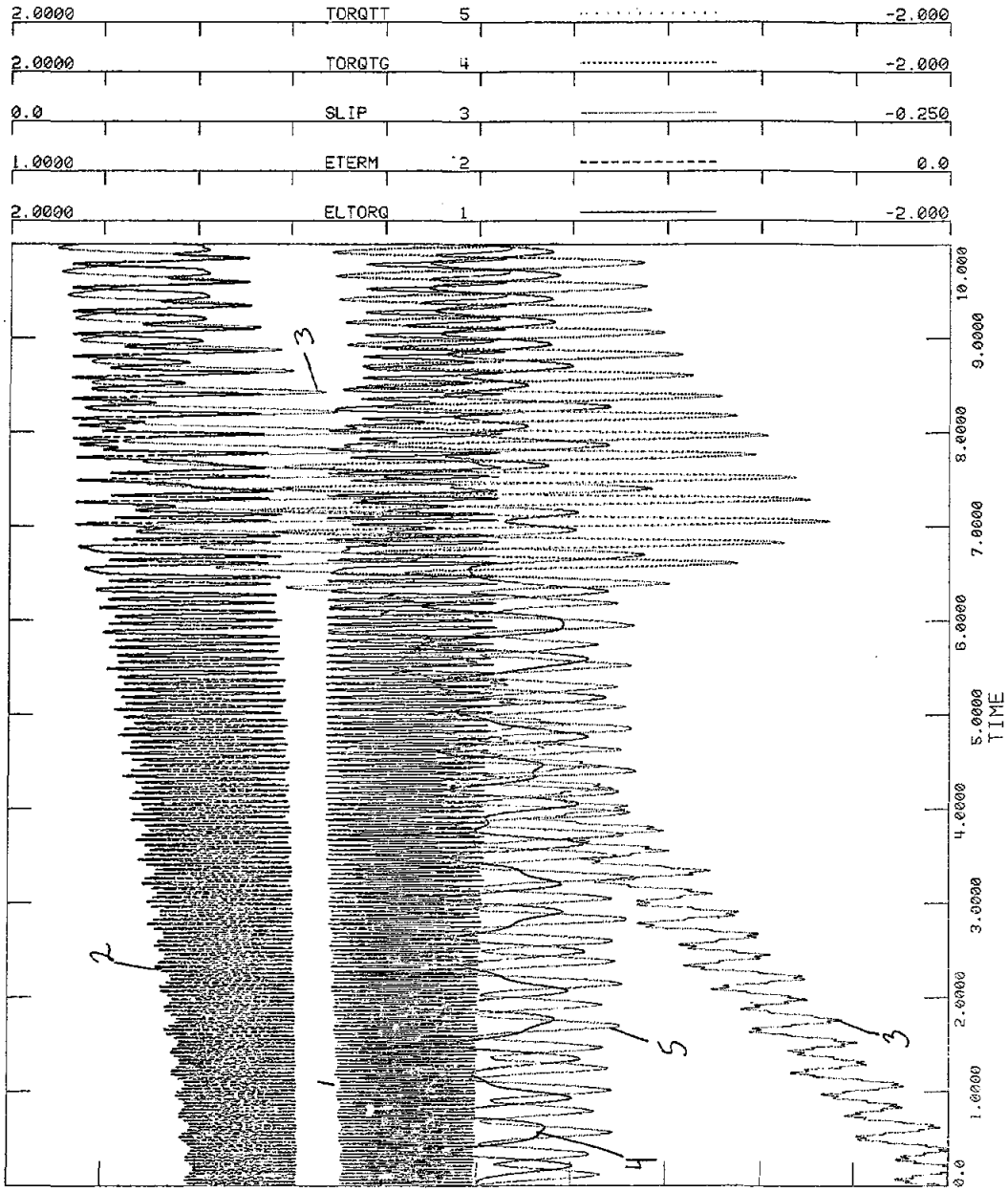
SANDIA LABS - WIND TURBINE - 1600 KW
INDUCTION MACHINE STARTING
TRANSFORMER TAP 0.5
CASE IS4



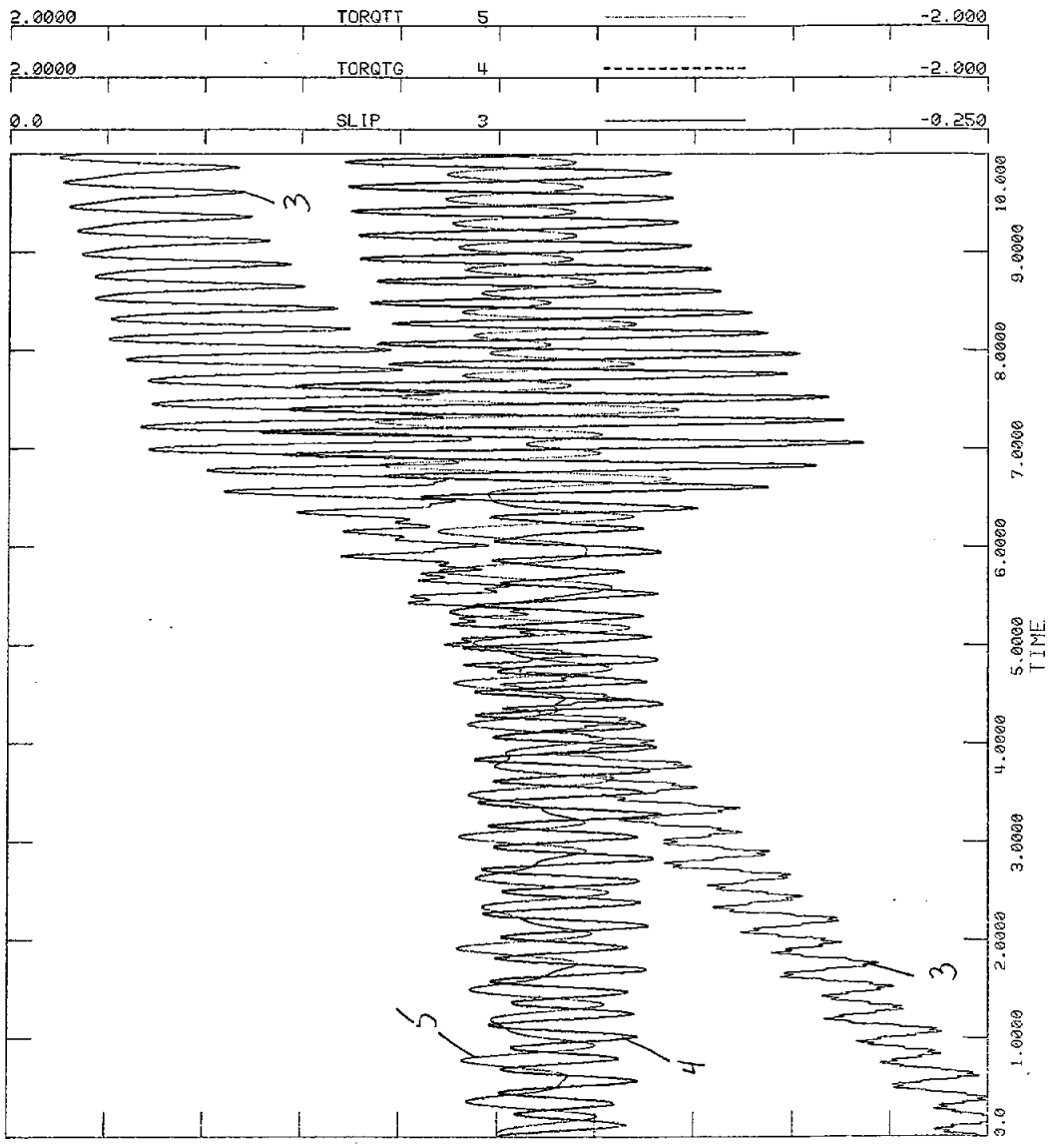
SANDIA LABS - WIND TURBINE - 60 KW
SYNCHRONOUS MACHINE STARTING
TRANSFORMER TAP 0.5
CASE SS1



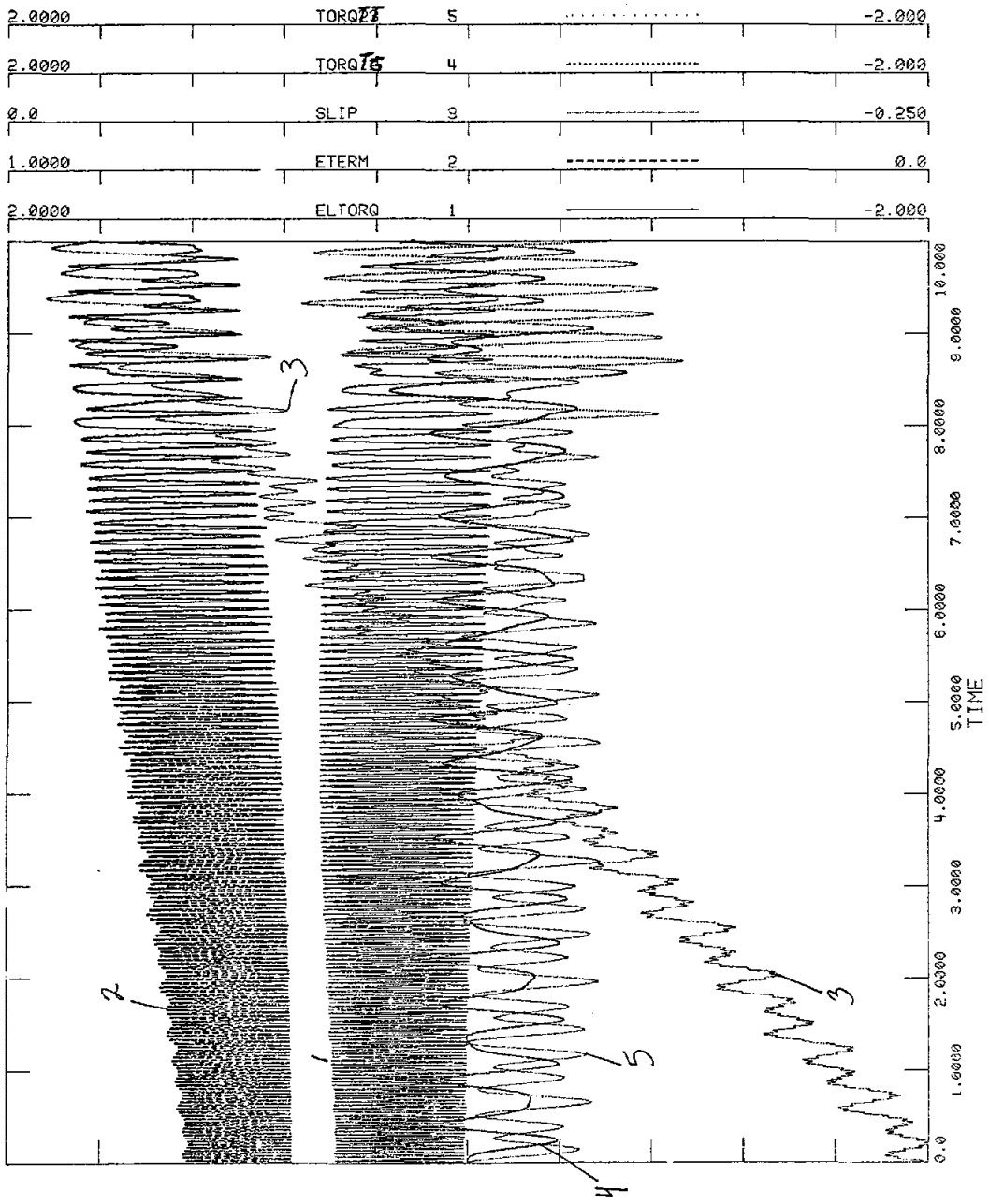
SANDIA LABS - WIND TURBINE - 200 KW
SYNCHRONOUS MACHINE STARTING
TRANSFORMER TAP 0.5
CASE SS2



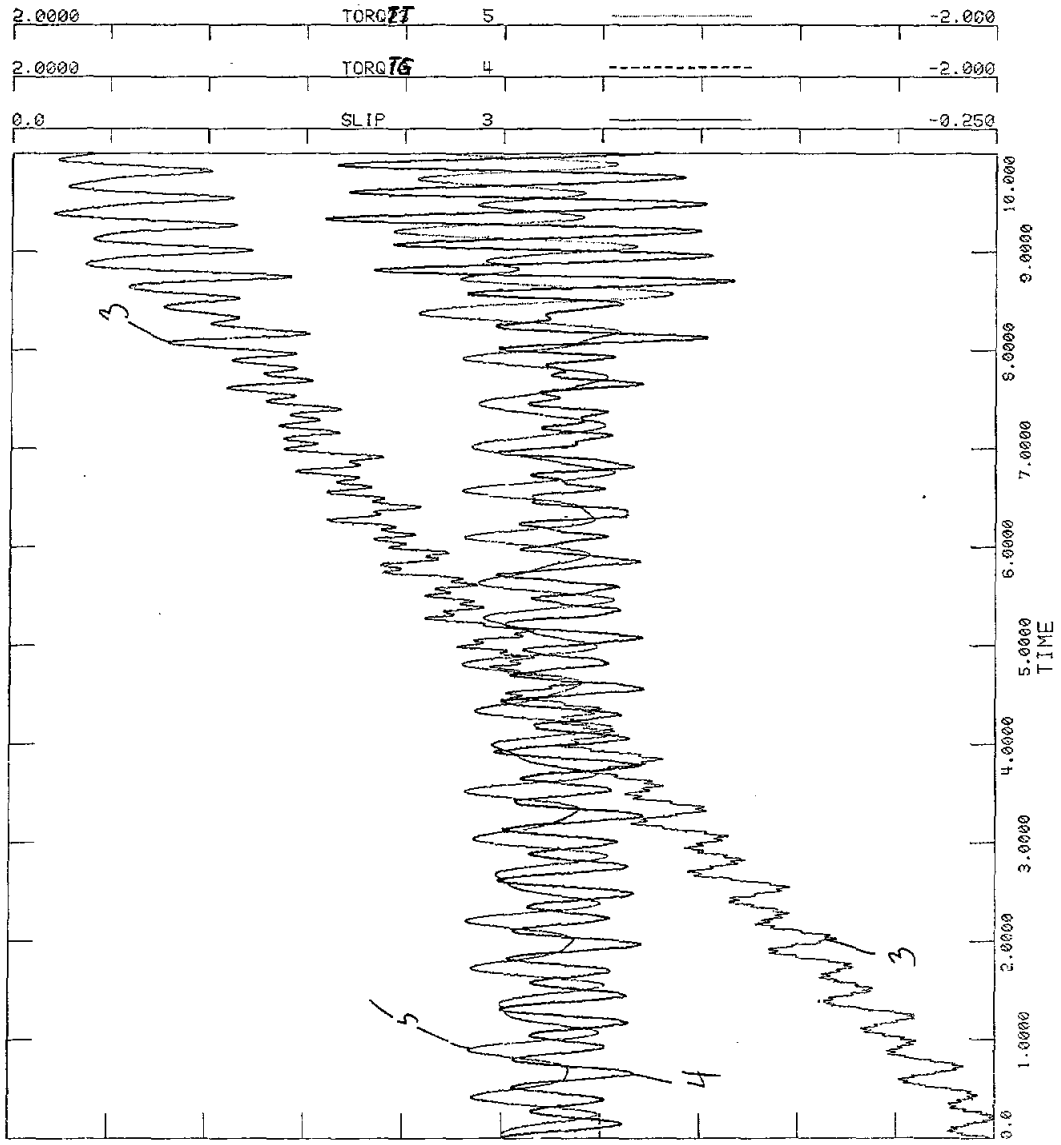
SANDIA LABS - WIND TURBINE - 200 KW
SYNCHRONOUS MACHINE STARTING
TRANSFORMER TAP 0.5
CASE SS2



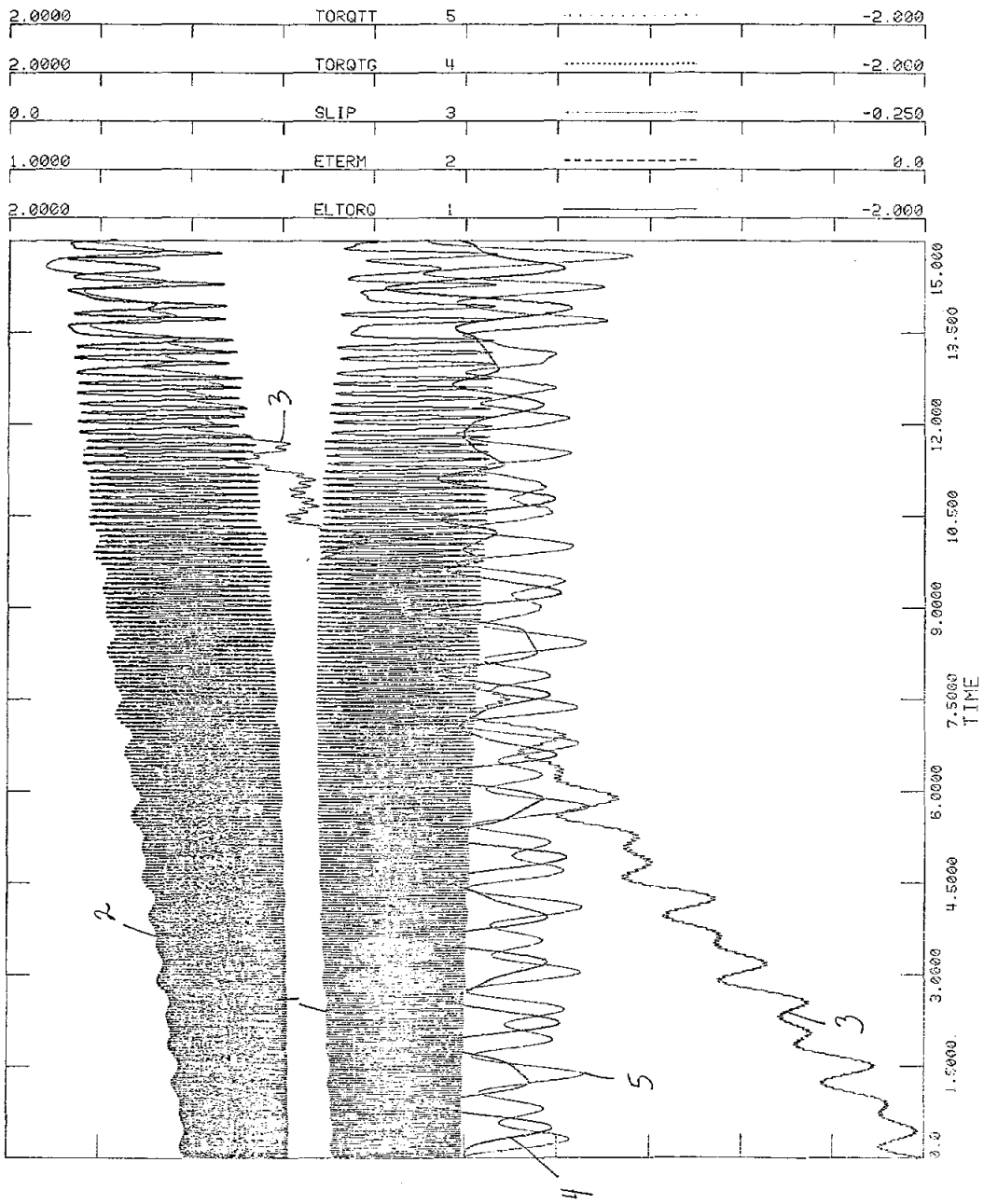
SANDIA LABS - WIND TURBINE - 500 KW
SYNCHRONOUS MACHINE STARTING
TEST - TRANSFORMER TAP 0.5
CASE 553



SANDIA LABS - WIND TURBINE - 500 KW
SYNCHRONOUS MACHINE STARTING
PLOT STARTS AT 1350 RPM - SLIP FRQUENCY 15 HERTZ
CASE SS3



SANDIA LABS - WIND TURBINE - 1600 KW
SYNCHRONOUS MACHINE STARTING
TEST — TRANSFORMER TAP 0.5
CASE SS4



10.0 SAMPLE CALCULATIONS

10.1 Drive Train Inertias and Stiffnesses for 200 kW Turbine

Gear Ratio: $N = 44.89$

Inertia of upper/lower turbine halves: $J1 = J2 = 8.518 * 10^4$ N-SEC^2-M

Inertia of gear box, relative to low speed: $J3 = 608$ N-SEC^2-M

Inertia of generator: $J4 = 6.98$ N-SEC^2-M

Inertia Constant $H = \frac{\text{Kinetic Energy}}{\text{Generator Base Power}}$

Base Generator Power: $P_B = 250 \text{ kW} = 250 * 10^3 \frac{\text{N-M}}{\text{Sec}}$

$$H = \frac{0.5 * J * w^2}{250 * 10^3}$$

$$H_4 = \frac{0.5 * 6.98 * (1800 * 2\pi/60)^2}{250 * 10^3} = 0.496 \text{ sec.}$$

$$H_3 = \frac{608}{6.98} * 0.496 * \left(\frac{1}{44.89}\right)^2 = 0.021 \text{ sec.}$$

$$H_2 = \frac{8.518 * 10^4}{607.58} * 0.021 = 2.94 \text{ sec.}$$

$$H_1 = H_2 = 2.94 \text{ sec.}$$

Shaft stiffness between turbine halves: $K_1 = 1.27 * 10^7 \frac{\text{N-M}}{\text{rad}}$

Shaft stiffness between turbine and gear box: $K_2 = 1.13 * 10^7 \frac{\text{N-M}}{\text{rad}}$

Shaft stiffness between gear box and generator: $K_1 = 2.02 * 10^4 \frac{\text{N-M}}{\text{rad}}$

Base generator torque: $T_B = \frac{P_B}{W_B}$

Per unit torque: $\overline{K} = \frac{K}{T_B}$

$$\overline{K_I} = \frac{2.02 * 10^4 * 2\pi * 1800}{250 * 10^3 * 2 * 60} = 7.62 \frac{\text{pu torque}}{\text{rad el}}$$

$$\overline{K_2} = 7.62 * \frac{1.13 * 10^7}{2.02 * 10^4} * \left(\frac{1}{44.89}\right)^2 = 2.11 \frac{\text{pu torque}}{\text{rad el}}$$

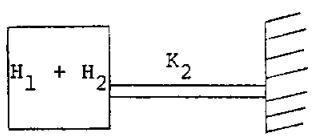
$$\overline{K_1} = 2.11 * \frac{1.27 * 10^7}{1.13 * 10^7} = 2.38 \frac{\text{pu torque}}{\text{rad el}}$$

The transmission inertia is neglected and the shaft stiffness on both sides of the gear box are combined.

$$\frac{1}{K_{1,2}} = \frac{1}{K_1} + \frac{1}{K_2}$$

$$K_{1,2} = 1.65$$

10.2 Estimate of First Natural Frequency of Drive Train for 200 kW Turbine



$$f = \frac{1}{2\pi} \sqrt{\frac{K_2 * 2\pi * 60}{2 * (H_1 + H_2)}} = \frac{1}{2\pi} \sqrt{\frac{1.65 * 377}{2 * 5.88}}$$

$$f = 1.16 \text{ Hz}$$

10.3 Estimate of Natural Frequency of Electromechanical System for 200 kW Turbine with Synchronous Generator

$$f = \frac{1}{2\pi} \sqrt{\frac{T}{2H}}$$

T Synchronizing power coefficient

$$T = \frac{V_1 V_2}{X_{12}} * \cos \delta_{12} * w$$

Assume: $\delta_{12} = 45^{\circ}$

$V_1 = V_2 = 1.0$

$X_{12} = 0.18$

$$f = \frac{1}{2\pi} \sqrt{\frac{0.71 * 377}{0.18 * 2 * 5.88}} = 1.79 \text{ Hz}$$

10.4 Per Unit Line Reactance and Resistance for 200A 4.16 kV Transmission Line in 250 kW System

Reactance $X = 0.142\Omega/1000$ Ft

Resistance $R = 0.134\Omega/1000$ Ft

Impedance Base $X_B = \frac{V_B^2 * 10^3}{P_B} = \frac{4.16^2 * 10^3}{250} = 69.2\Omega$

PU Reactance/Mile $\overline{X} = 0.142 * 5.28/69.2 = 0.0108$

PU Resistance/Mile $\overline{R} = 0.134 * 5.28/69.2 = 0.0102$

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