

Strategic Energy Research

DYNAMIC CIRCUIT THERMAL LINE RATING

Gray Davis, Governor

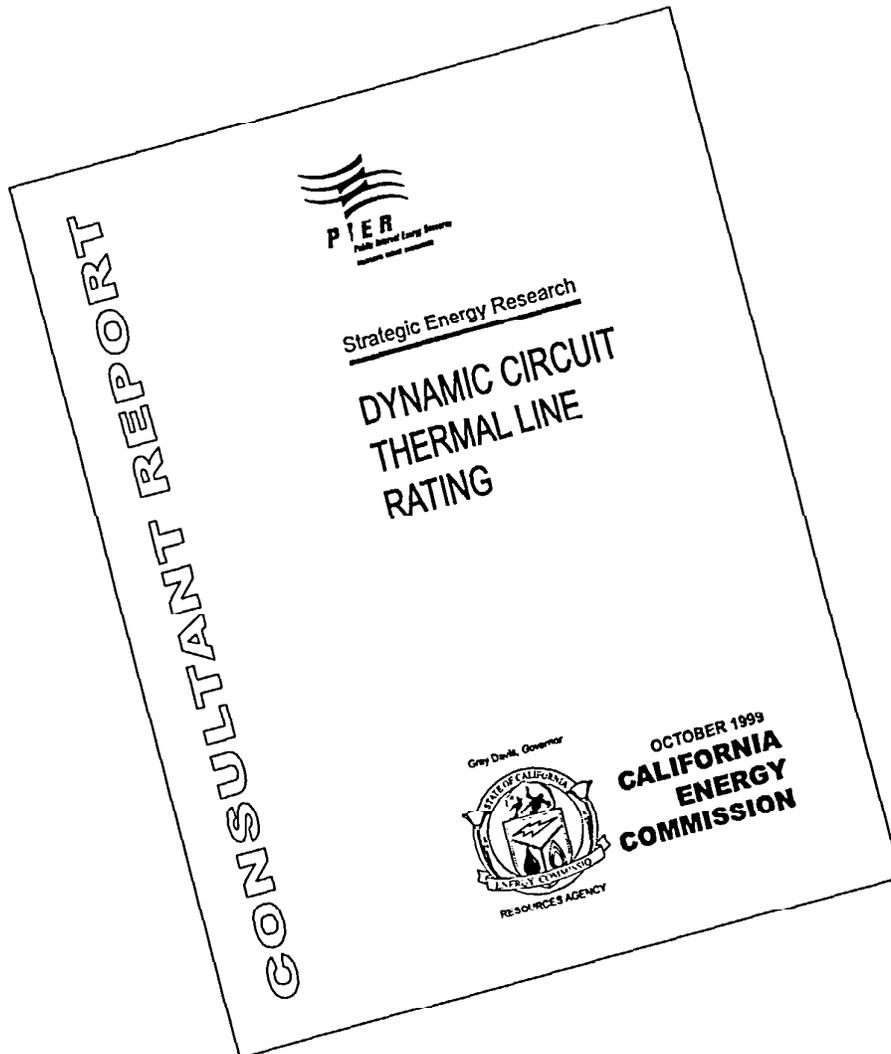


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Table of Contents

Section	Page
PREFACE	VI
EXECUTIVE SUMMARY	1
ABSTRACT	5
1.0 INTRODUCTION	7
1.1 Background.....	7
1.2 Project Objectives	7
1.3 Report Organization.....	7
2.0 PROJECT APPROACH	9
2.1 Plan Development.....	9
2.2 Equipment Configuration.....	9
2.2.1 Load Cell Testing and Calibration	10
2.3 SDG&E’s Energy Management System (EMS) Interface	11
2.4 Software Development.....	11
2.5 Equipment Installation	11
2.6 Operator Displays	15
2.7 System Operation and Data Collection	16
2.8 Evaluation of Data	16
2.8.1 System Modifications.....	18
2.9 Project Outcomes	19
3.0 CONCLUSIONS AND RECOMMENDATIONS	21
3.1 Conclusions.....	21
3.1.1 Economic Benefits	21
3.1.2 Benefits to California	22
3.1.3 Commercialization Potential	22
3.2 Recommendations.....	22
Appendices	
Appendix A	Collected Data
Appendix B	Theory of Cable Tension Monitors and Related Technical Papers

List of Figures

Figure	Page
Figure 1. Real-Time Line Rating System Schematic Diagram.....	10
Figure 2. Load Cells Used for Measuring Conductor Tension	12
Figure 3. CAT Main Unit and Radio Transmitter.....	13
Figure 4. CATmaster Station at San Mateo Substation	13
Figure 5. CAT Installation on 230 kV Tower	14
Figure 6. CATmaster Unit Installed at San Mateo Substation	14
Figure 7. Operator Display of Real-Time Line Rating.....	15
Figure 8. Display of Real-Time Transmission Line Rating Trend	16
Figure 9. Calculated Line Rating Prior to Thermal Averaging.....	17
Figure 10. Calculated Transmission Line Real-Time Rating after Thermal Averaging	18

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately \$17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Dynamic Circuit Thermal Line Ratings project, one of six projects conducted by San Diego Gas and Electric. This project contributes to the Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: <http://www.energy.ca.gov/research/index.html> or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Historically, transmission lines have had static or fixed ratings that limit the amount of power that can be transferred on the electric grid. This method provides a constant (static) rating that can be used by the system operator to ensure that transmission line conductors do not sag below specified limits and come in contact with trees or other objects thus affecting reliability and safety.

However, transmission line ratings change constantly. At times, there is significantly more transmission line capacity than the standard static transmission line rating. As system load grows and the siting of new transmission lines becomes more difficult, increasing the capacity of existing transmission lines through new technology is critical.

In this project San Diego Gas & Electric (SDG&E) investigated the feasibility of providing real-time transmission line ratings to system operators by monitoring actual conductor tension and environmental factors. Unlike previous systems that stored data for collection and later analysis, the monitoring system provided real-time rating directly to the system operator.

Objectives

The primary objective of this project was to evaluate and document the feasibility and reliability of implementing real-time transmission line ratings.

To achieve this the following specific objectives were developed:

- Develop a plan for testing real-time line ratings.
- Procure or modify equipment to test real-time line ratings.
- Develop an interface with SDG&E's Energy Management System (EMS).
- Modify and develop interface software.
- Install equipment, including communication equipment, on a transmission line
- Create operator displays of real-time line ratings.
- Operate the CAT monitoring system and collect data to evaluate system efficiency.

Outcomes

Project successfully demonstrated the feasibility and reliability of providing real-time transmission line ratings to the system operator. Real-time line ratings for the transmission lines monitored in this study had 40 to 80 percent more power transfer capacity than the static transmission line ratings presently applied.

- SDG&E developed a plan for testing real-time line.
- SDG&E modified the existing CAT monitor for use on a real-time basis and procured a CATmaster station to act as a receiver and remote terminal unit (RTU) for interface with the EMS.
- SDG&E developed and tested an interface with the EMS.
- SDG&E developed software to interface calculated results for display on the EMS.
- SDG&E installed the real-time line rating system.

- SDG&E developed two operator displays: real-time line rating and transmission line rating trends.
- The real-time line rating system was operated over a four month period. Data was collected during two of those months.

Benefits to California

Because real-time line rating systems potentially allow using existing transmission lines to their full capability, the need for new transmission lines is reduced. Fewer new lines mean less land use and decreased environmental impacts. Additionally, real-time transmission line ratings could provide more transmission capacity during periods of high system load decreasing the need to use local generating resources.

This could reduce capital expenditures for new transmission facilities and generating resources, while at the same time allowing more efficient operation of the power grid, resulting in lower utility rates. The ability to monitor transmission lines in real-time would also improve system reliability and safety.

Commercialization Potential

Fifteen utilities in the United States have used CAT monitors to implement on-line real-time line rating systems. More than 150 CAT monitors have been installed and used off-line for data collection and analysis of overhead transmission line ratings.

Conclusions

Real-time transmission line ratings can be implemented on transmission lines critical to providing power to constrained areas. This could result in significant capital cost savings in deferred transmission line projects and improved usage of existing generating resources.

- By monitoring the transmission lines that limit transfer capability, it may be possible to increase transfer capacity and allow increased transmission line usage.
- Increased capacity on congested transmission lines would permit increased power transfers and reduced the use of generators.
- The real-time transmission line rating system eliminates the possibility of overheated transmission lines and sagging conductors coming in contact with trees or vehicles.
- Upgrading substation components that may limit transmission line rating would improve overall system efficiency. Other limiting factors such as voltage instability or transient stability can also limit transmission transfer capacity more than the thermal limitations identified in this project.

Recommendations

- More real-time line rating systems need to be installed and more data collected to more accurately determine the effectiveness of real-time line ratings.
- Further effort to interfacing with the California Independent System Operator (CAISO) to provide real-time transmission line ratings to operator displays.

- Upgrade the CAT unit to the newer net radiation temperature sensor and load cells. This would provide more accurate calculations of line ratings at low loading conditions.
- Additional transmission lines should be interfaced with transmission constraints to limit generation dispatch in California.

Abstract

Transmission of electric power has been traditionally limited by the thermal constraints of transmission lines defined in terms of fixed static rating as well as vertical clearance limitations. New technologies now allow monitoring of transmission line characteristics and environmental conditions, enabling calculation of real-time line ratings. Transmission line ratings continually change depending on the cooling effect of the wind, on-line-current, and solar-incident heat. By monitoring these conditions and calculating vertical clearance or sag to ground, it is possible to develop real-time line ratings and use the full capacity of existing transmission lines.

In this project, San Diego Gas and Electric (SDG&E) investigated the feasibility of providing real-time transmission line ratings to system operators by monitoring the conductor tension and environmental factors. SDG&E designed and installed a real-time dynamic transmission-line-rating system on one key 230 kV transmission line that limits import capability into the SDG&E system. The method monitors overhead conductor tension, ambient temperature, and net solar radiation temperature rise. Data is passed to a ground station via spread spectrum radio and sent to SDG&E's energy management system (EMS). Calculations are performed to determine line condition such as sag and dynamic thermal to constraint, as well as operating warnings (time to thermal overload under system conditions) by the EMS, with results displayed on operator screens. Signals are given to operators, who can reduce load or generation to keep the line within thermal and vertical clearance constraints.

Potential benefits of real-time transmission line ratings include: improved system reliability and safety, reduced capital expenditures, increased efficiency of generation resources, and lower rates for utility customers.

1.0 Introduction

1.1 Background

Historically, transmission lines have had static or fixed ratings that limit the amount of power that can be transferred on the electric grid. These ratings are based on assumptions regarding weather and conductor conditions. Worst-case expected conditions, such as highest expected ambient temperature, low wind speed, and low conductor emissivity, are usually used.

This method provides a constant (static) rating that can be used by the system operator to ensure that transmission line conductors do not sag below specified limits and come in contact with trees or other objects thus affecting reliability and safety.

In reality, transmission line ratings are highly dependent on the amount of cooling by wind and heating by the sun. They change constantly with the weather. At times, there is significantly more transmission line capacity than the standard static transmission line rating.

As system load grows and the siting of new transmission lines becomes more difficult, increasing existing transmission line capacity through new technology is critical. . .

San Diego Gas & Electric (SDG&E) investigated the feasibility of providing real-time transmission line ratings to system operators through monitoring conductor tension and environmental factors. Previous methods of calculating dynamic transmission line ratings used sensors to monitor conductor temperature or an off-line system that used only weather data.

In this project, monitoring of actual conductor tension provided a direct measurement of the conductor tension variable that can be used to calculate conductor sag. The project was also unique because it provided a calculated real-time rating directly to the system operator, unlike previous systems that stored data for collection and later analysis.

1.2 Project Objectives

The primary objective of this project was to evaluate and document the feasibility and reliability of implementing real-time transmission line ratings.

To achieve this, the following specific objectives were devised:

- Develop a plan for testing real-time line ratings.
- Procure equipment to test real-time line ratings.
- Develop an interface with SDG&E's Energy Management System (EMS).
- Modify and develop interface software.
- Install equipment, including communication equipment, on a transmission line
- Create operator displays of real-time line ratings.
- Operate system and collect data to evaluate feasibility of real-time line ratings.

1.3 Report Organization

The body of this report consists of two sections, Project Approach and Conclusions and Recommendations

The report contains two appendices:

Appendix A, *Collected Data*, contains additional graphs of collected data. All data collected indicated similar benefits for increasing transmission line capability.

Appendix B, *Theory of Cable Tension Monitors and Related Technical Papers*, contains a sampling of technical presentations and workshop materials on such subjects as real-time rating, thermal capabilities of transmission lines, and tension monitoring.

2.0 Project Approach

2.1 Plan Development

SDG&E examined various technologies for developing dynamic transmission line ratings. These included laser reflective measurements of conductor sag, photographic measurements of sag, power donuts, Global Positioning System (GPS) and weather monitoring.

These systems were not developed for real-time interface with an EMS. They only measure the conductor tension, weather, or sag at one point. This does not necessarily represent conditions, which could limit the line rating further down the transmission line being studied. They proved impractical for interfacing with the EMS to provide real-time line ratings for actual system operations.

SDG&E chose the CAT monitor because it was:

- Simplest to install and interface to the EMS for real-time monitoring
- Most widely used, proven technology
- Least prone to error in the development of real-time transmission line ratings
- Only device with algorithms that can accurately calculate a real-time line rating and directly translate it into a megavolt ampere (MVA) rating.

Tension monitoring measured tension over an entire ruling span, thereby giving a more accurate representation of conditions over a greater length of the transmission line. Compared to the other technology, tension monitor was more easily interfaced with a radio transmitter and remote terminal unit ground station to allow data transfer with EMS due to the widespread CATS units application in monitoring tension of support structures.

The next step was to select an appropriate location at which to install the system. A desirable location would have a dead-end configuration of the overhead conductor and be in a transmission span with sag limitations that limited the overall transmission line rating. Installation of the system on transmission lines that actually limit power transfer capability was desirable.

A review of system limitations and possible locations using sag limitations and tower accessibility led to the choice of a 230 kV transmission tower located near the spans that limit the power transfer capability of the two Talega – San Onofre 230 kV transmission lines. These lines limit the non-simultaneous import capability into the SDG&E system.

2.2 Equipment Configuration

The real-time line rating system consisted of:

- Load Cells for measuring cable tension
- Cable Tension (CAT) Monitoring Unit
- Radio transmitter
- CATmaster station.

SDG&E already possessed a CAT monitor produced by The Valley Group, Inc. This CAT monitor was not equipped for use on a real-time basis, but used a cell phone from which data

could be downloaded on demand. We added a radio transmitter to the CAT unit that would broadcast real-time data to a base station located in a nearby substation.

A CATmaster station to act as a receiver and a remote terminal unit (RTU) for interface with the EMS was purchased and the CAT unit was modified in June 1998.

Figure 1 is a diagram of the overall system layout and component interaction.

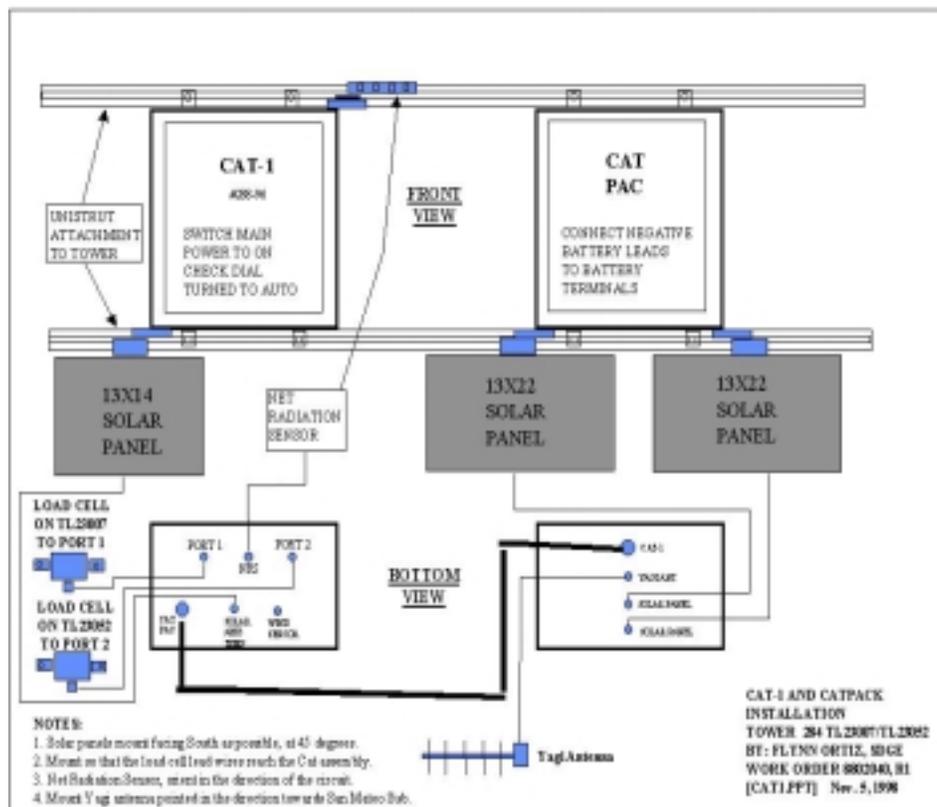


Figure 1. Real-Time Line Rating System Schematic Diagram

2.2.1 Load Cell Testing and Calibration

Prior to shipment of the load cells, The Valley Group Inc. tested and certified cell accuracy to 0.2 to 0.4 percent. They also calculated the zero set point offset of each load cell. This offset was then programmed into the CAT main unit to ensure accurate measurements of conductor tension.

SDG&E placed the load cells on a test bed and, using a tensioning device calibrated for line stringing purposes, applied various levels of known tension to the load cells. The maximum expected error over a 1000 ft. span is 0.2 to 0.3 feet. The length of the critical span for this project was 1,200 feet. Accuracy of the load cells and the CAT main unit calculations were verified.

To obtain a baseline measurement of the unloaded (no current) condition of the line, the system rating calculation was calibrated by taking various readings of tension and the net radiation temperature rise over a 90-day period. Several points on the baseline were verified by measuring conductor sag at known line loadings.

2.3 SDG&E's Energy Management System (EMS) Interface

The tower-mounted CAT station contained a computer that gathered line tension data, ambient temperature, and net radiation rise due to solar radiation on the conductor. The computer calculated the amount of sag in the conductor and the corresponding conductor temperature and directly translated it into a megavolt ampere (MVA) rating.

The data was sent via the radio to the CAT master station in the San Mateo substation. The ground station then transmitted the data to the EMS in SDG&E's Mission Valley control center.

The EMS performed calculations based on the received data and MVA data provided by the its System Control and Data Acquisition (SCADA) system. These calculations were displayed on an operator screen. Alarms notified the operator when static line rating was achieved and the real-time line rating was displayed.

The time the operator has to take action (time to clearance violation), based on line-loading trends and weather conditions, is displayed. In addition, the EMS system provided trending charts showing past line rating trends.

A leased pair telephone line was installed in the San Mateo substation located approximately three miles from, and in the direct line of sight, to the CAT transmitter. SDG&E tested the interface and coordinated the communication protocol with the EMS to ensure that communications operated smoothly and no data errors occurred.

Data was sent every ten seconds but was polled by the EMS every five minutes. The rating calculation algorithm, located in a program in the EMS computer, used the tension data, net radiation temperature, and actual line current to calculate the transmission line rating. EMS used the SCADA system to obtain the line current through other collected data points.

2.4 Software Development

The Valley Group Inc. provided the calculation algorithms to convert measured data into actual line ratings. Based on these algorithms, SDG&E developed software to interface the calculated results with their Harris software and EMS operator displays..

SDG&E developed and tested the software from February through April 1999.

2.5 Equipment Installation

Installation took place during December 1998 and January 1999.

SDG&E installed the CAT monitor on a 230 kV transmission tower (Figure 5). The system was positioned so that direct radio communications could be maintained with the ground station. The CAT computer and radio were positioned so that cables to the two load cells, installed to monitor conductor tension, could reach the dead-end insulators and still be low enough to limit interference caused by the high voltage field.

The cells monitored the conductor tension in the two bottom phases of two critical transmission circuits between the San Onofre Nuclear Generating Station and the Talega substation. These circuits limit the non-simultaneous import capability into San Diego. The critical outage that causes the overload of these lines is the loss of the Miguel – Imperial Valley 500 kV transmission line.

The real-time monitoring system was placed on a dead-end 230 kV lattice steel tower. The system had to be installed on a dead-end structure to allow it to monitor conductor tension in the entire ruling span. Actual sag could then be calculated. The limiting span for this 230 kV circuit was located on the third span from the dead-end structure.

Before and after installation, survey measurements of system sag were taken. The load cells were mounted on the end of the crossarms (Figure 2). The dead-end insulators were placed on the lower phases of each 230 kV circuit structure facing north towards the Talega substation. They were connected with shielded cables to the CAT main unit.



Figure 2. Load Cells Used for Measuring Conductor Tension

The CAT main unit (Figure 3), containing the signal conditioners, main CPU, and the data logger, was powered by a solar panel with a backup battery. It communicated data via a spread spectrum radio unit to the CATmaster station



Figure 3. CAT Main Unit and Radio Transmitter

The CATmaster unit acted both as a radio receiver and a remote terminal unit for data transmission to the EMS. The CATmaster station (Figure 4), located in a control room at the San Mateo substation, is approximately two miles from the CAT main unit located on the 230 kV tower (Figure 5).

A directional antenna on top of the control room points at the CAT main unit. A leased pair telephone line was connected to the CATmaster unit and transmits data to the EMS.



Figure 4. CATmaster Station at San Mateo Substation



Figure 5. CAT Installation on 230 kV Tower

The CATmaster unit was located within the San Mateo substation (Figure 6).



Figure 6. CATmaster Unit Installed at San Mateo Substation

2.6 Operator Displays

The underlying concept for display creation was to provide simple displays that would be familiar to the operators and would not interfere with day-to-day operations. Two operator displays were developed.

Real-Time Line Rating Display

A single line diagram was modified to display the real-time line rating above the static line rating and the amount of time the operator has to take action before a clearance violation occurs. (

Figure 7). An alarm is triggered if the actual transmission line loading (MVA) is nearing the static line rating.

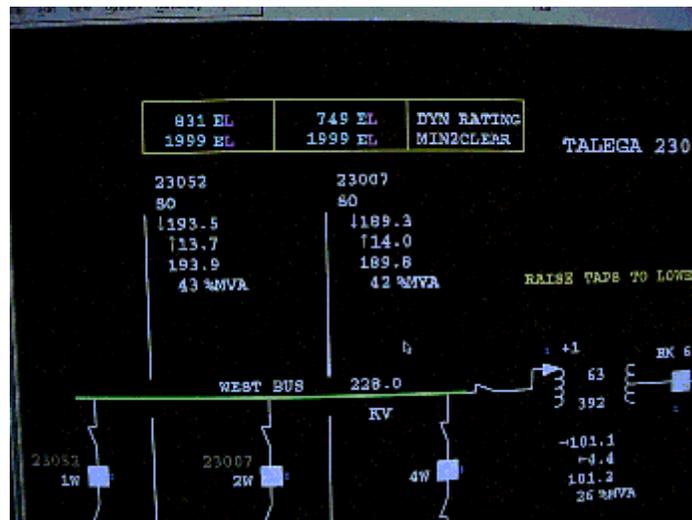


Figure 7. Operator Display of Real-Time Line Rating

Real-Time Transmission Line Rating Trend

Figure 8 graphically displays the real-time line rating trend. It was developed on the EMS and is available to the SDG&E system operator and ultimately to the CAISO control center. This screen shows the history of the calculated real-time line rating and the actual MVA. It allows the operator to determine the line rating trend and what to expect. It also verifies the transmission line rating limitation.

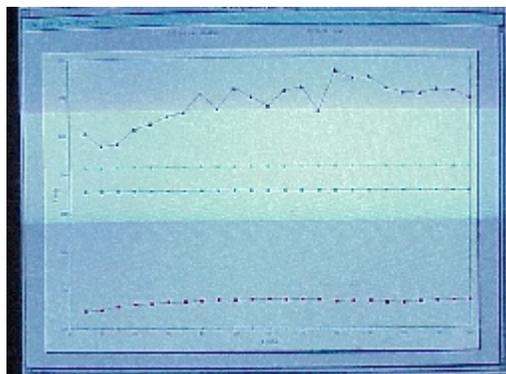


Figure 8. Display of Real-Time Transmission Line Rating Trend

2.7 System Operation and Data Collection

Real-time transmission line ratings provide more system observability to the system operators. Not only do they indicate when more transmission capacity is available, providing the system operator with more options, they also warn operators when transmission line ratings may be less than previously assumed from static ratings.

Real-time monitoring systems are located at the critical spans where conductor contact with foreign objects is most likely.

These systems could prevent system-wide outages similar to the ones in August 1997 that occurred when a 500 kV transmission line conductor came in contact with trees. The systems could provide significant improvement in overall system reliability.

The principle for developing transmission line ratings using the CAT monitor system was simple and straightforward. It was based on the ruling span concept, used in transmission line design for more than 70 years.

All transmission line design relies on this ruling span concept, which has proven to be accurate. Actual measurements of sag in every span of a ruling span are within 2.4 inches to 3.6 inches of the calculated measurement using the ruling span method. The sag in any span can be calculated by the horizontal tension component in the conductor, the weight per foot of the conductor, and span length.

2.8 Evaluation of Data

System operation and data collection occurred from April through July 1999 and a significant amount of data was collected over that period. Data for May and June was not available because of work on the radio transmitter.

Examination of tension data verified previous calculations of expected sag for similar ambient conditions. However, the calculated line rating appeared to have large swings. Figure 9 shows the calculated rating over a 24-hour period on July 14, 1999.

Further investigation revealed that these large excursions of the rating occurred due to the light (low amperage) line loading on the relatively large (1033 thousand circular mil- (kcmil)

Aluminum Conductor, Steel Reinforced (ACSR). Because the line loading was low (less than 20 percent of the static rating of 1145 amperes), heat from solar radiation determined the degree of sag.

The net solar radiation sensor used a resolution of 0.8 degrees. A newer net solar radiation sensor with better resolution at low loading conditions is available, and would result in more accurate calculation of the rating and fewer excursions of the rating.

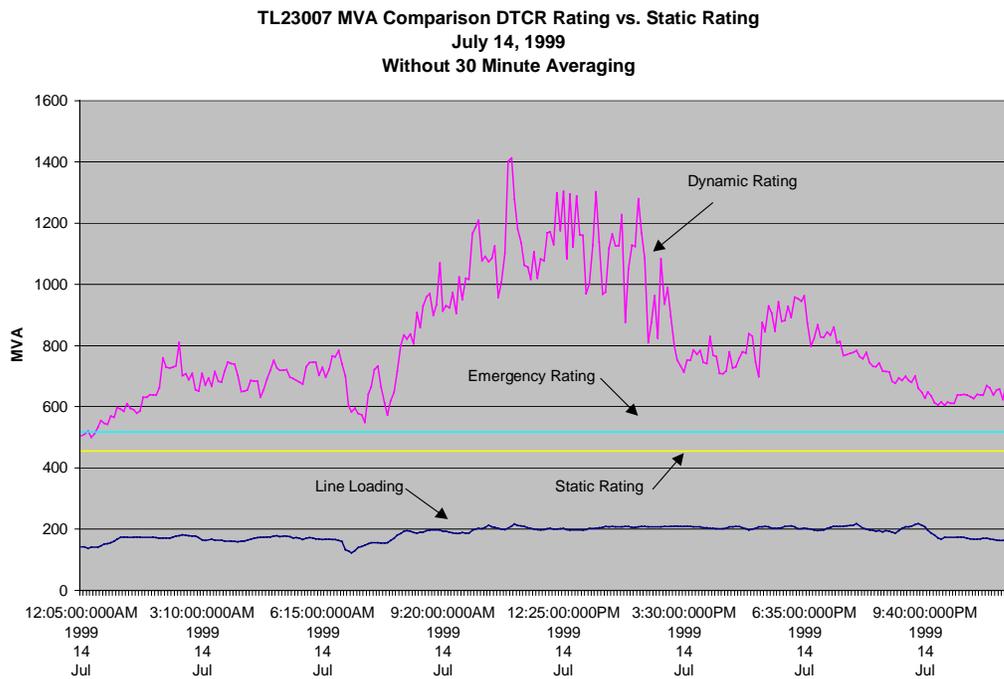


Figure 9. Calculated Line Rating Prior to Thermal Averaging

An averaging technique was developed that took into account the thermal heat storage capability of the conductor being monitored. This allowed accurate calculations of the line rating at low line loadings and provided a real-time rating that more realistically modeled the latent thermal capacity of the conductor.

Based on test data from the conductor manufacturer and an examination of thermal time constants, we determined that the heat capacity of the 1033 kcmil ACSR conductor was about 30 minutes.

The rating calculation was performed every five minutes.

It was decided to average every six data points on a rolling average basis. Thus the displayed line rating provided for the actual heat capacity of the cable and was not significantly impacted by small variations in measured heat absorption from solar radiation. Figure 10 displays a graph of the data after thermal averaging.

Normal (static) rating was 456 MVA (1145 Amps) based on a maximum conductor operating temperature of 90 degrees Centigrade. A long-term emergency rating of 517 MVA (1300 Amps) was also used.

Figure 9 and Figure 10 demonstrate that the dynamic (real-time) rating could be as much as 1200 MVA (3000 Amps) or 150 percent more than the normal rating. From nine a.m. to five p.m., the dynamic rating averaged approximately 800 MVA--a 75 percent increase over the normal rating.

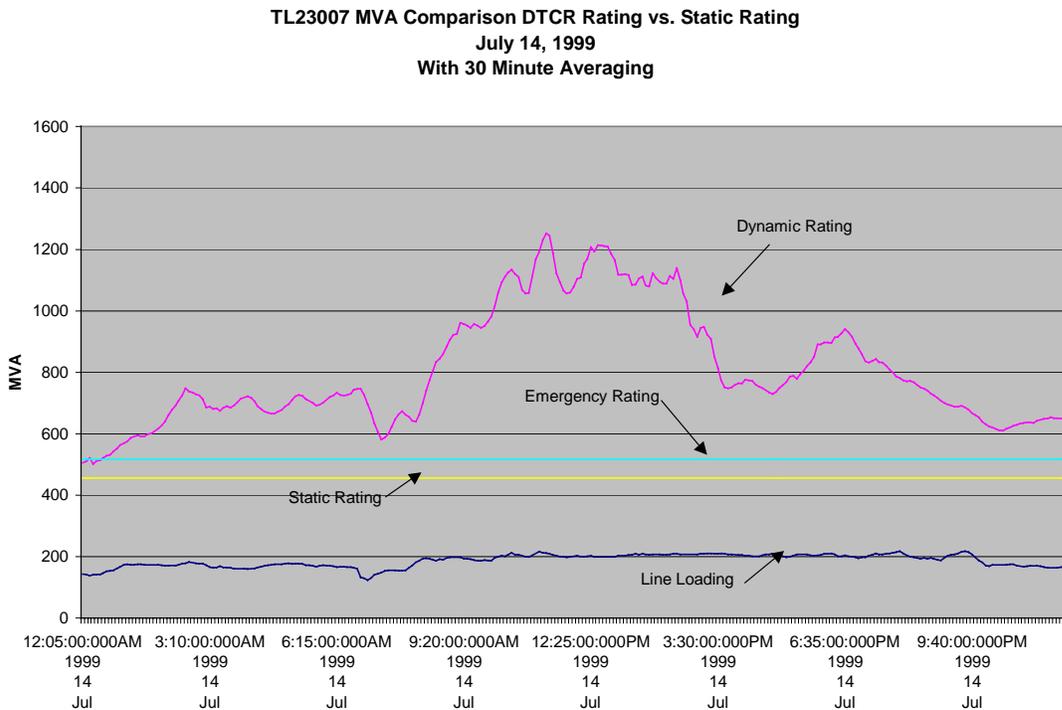


Figure 10. Calculated Transmission Line Real-Time Rating after Thermal Averaging

2.8.1 System Modifications

This installation required modifications to the calculation and display of the real-time line rating data.

The 230 kV transmission lines on which the system was placed are only heavily loaded during contingency scenarios. The CAT monitor measures very small changes in tension at low transmission line loadings—less than 30 percent of the static line rating. As a result there are large excursions of the calculated line ratings.

Since the thermal time constant is between 15 and 30 minutes for the conductor used, a 1033 kcmil ACSR, and an averaging function was added to smooth out the data and displays. Calculations and data displayed every five minutes. A rolling window average was calculated

for every six data points (every 25 minutes). This proved to be a very accurate method of displaying the data and reducing the frequency of rapid swings.

2.9 Project Outcomes

The project successfully demonstrated the feasibility and reliability of providing real-time transmission line ratings to the system operator. Results indicate that for the specific transmission lines monitored in this study, real-time line ratings have 40 to 80 percent more power transfer capacity than the static transmission line ratings presently applied

- After examining a variety of technologies applicable to line ratings, SDG&E developed a plan for testing real-time line ratings and chose a location for the tension monitoring system.
- SDG&E modified existing CAT monitor for use on a real-time basis and procured a CATmaster station to act as a receiver and remote terminal unit (RTU) for interface with the EMS.
- SDG&E developed and tested an interface with the EMS. The communication protocol with the EMS was coordinated to ensure effectiveness of communications.
- Using algorithms developed by the Valley Group, Inc., SDG&E developed software to interface calculated results with SDG&E's Harris software for display on the EMS.
- SDG&E installed the CAT monitor on a 230 kV transmission tower and the CATmaster unit in San Mateo substation.
- SDG&E developed two operator displays.
 - One displayed the real-time line rating above the static line rating and the amount of time the operator has to take action before a clearance violation occurs.
 - The other allowed operator to determine the trend, if necessary, and what to expect; and it also verifies the transmission line rating limitation.
- The real-time line rating operated successfully from April through July of 1999. since mid-June, 1999. Significant amounts of data were collected and evaluated during that period.

3.0 Conclusions and Recommendations

3.1 Conclusions

Based on the limited data collected thus far, it appears that real-time transmission line ratings can be implemented on transmission lines critical to providing power to constrained areas. The implementation of real-time transmission line ratings could result in significant capital cost savings in deferred transmission line projects and improved usage of existing generating resources.

- The transmission line rating increased during the day and generally followed the system load pattern. This was because the coastal wind generally increased from morning to afternoon. By monitoring the transmission lines that limit transfer capability, it may be possible to increase transfer capacity real-time and allow increased transmission line usage.
- This increased capacity on congested transmission lines would permit increased power transfers and reduced the use of generators required to run because of transmission constraints. Using more economic generators would result in a reduced energy system price for utility customers.
- The real-time transmission line rating system indicates the actual rating when line ratings are reduced. It eliminates the possibility of overheated transmission lines and sagging conductors coming in contact with trees or vehicles or creating a danger to the public. It provides advanced warning to the system operator of potential sag limitations.
- As transmission ampacity is increased on the dynamically rated line, other components at the substations, such as current transformers, circuit breakers, and jumpers, can often limit a transmission line rating. These components can usually be upgraded at low cost to achieve maximum rating increases. However, there may be other system limitations, such as voltage instability or transient stability that can limit transmission transfer capacity more than the thermal limitations identified by this system.

3.1.1 Economic Benefits

Real-time transmission line ratings could potential provide the following benefits:

- Reduced capital expenditures— By transferring more power when line ratings are higher, real-time transmission line ratings can increase usage of existing transmission lines and reduce the need for new transmission line facilities.
- Increased efficiency of generation resources— By reducing transmission congestion constraints, the number of must run generators could be decreased. More economic generators could be used to dispatch generation on the system grid.
- Lower rates for utility customers— More economic generation dispatch and lower capital expenditures could result in lower rates for customers.
- Increased transmission system reliability— Real-time transmission line ratings provide more information on transmission capacity availability and on possible conditions that could cause outages.

3.1.2 Benefits to California

Real-time monitoring systems offer several benefits to California.

Because real-time line rating systems potentially allow use of existing transmission lines to their full capability, the need for new transmission lines would be reduced. A typical 500 kV transmission line uses a 200-ft. wide right of way, which correlates to 24 acres per mile. Fewer new lines mean less land use and decreased environmental impacts.

Due to transmission constraints, local generating resources must serve some areas of California during periods of high system load. Real-time transmission line ratings could provide more transmission capacity during these periods, allowing more efficient generators to serve load requirements.

Real-time transmission line ratings could reduce capital expenditures for new transmission facilities and generating resources, while at the same time allowing more efficient operation of the power grid. This could result in lower utility rates.

Real-time transmission line ratings provide more information to the system operators on the amount of transmission capacity available. This would allow not only more efficient use of transmission facilities but would help prevent system-wide outages, improving system reliability and safety.

3.1.3 Commercialization Potential

On-line rating systems certainly have commercialization potential. Fifteen utilities in the United States have used CAT monitors to implement on-line real-time line rating systems. More than 150 CAT monitors have been installed and used off-line for data collection and analysis of overhead transmission line ratings.

3.2 Recommendations

This project represents the first attempt in California to interface a real-time monitoring system with an EMS and provide operator displays. Based on the results of this research, SDG&E makes the following recommendations:

- More real-time line rating systems need to be installed and more data collected to more accurately determine the effectiveness of real-time line ratings. Since their effectiveness is dependent on the system load shape (time of system peak) and wind and weather patterns, further data must be obtained to validate the accuracy of this approach in implementing real-time transmission line ratings.
- Further effort in interfacing to the California Independent System Operator (CAISO) to providing real-time transmission line ratings to operator displays.
- Upgrade the CAT unit to the newer net radiation temperature sensor and load cells. This would provide more accurate calculations of line ratings at low loading conditions.
- Additional transmission lines should be interfaced with transmission constraints to limit generation dispatch in California.

APPENDIX A

COLLECTED DATA

TL 23007 REAL-TIME LINE RATING DATA
TL 23052 REAL-TIME LINE RATING DATA

APPENDIX B

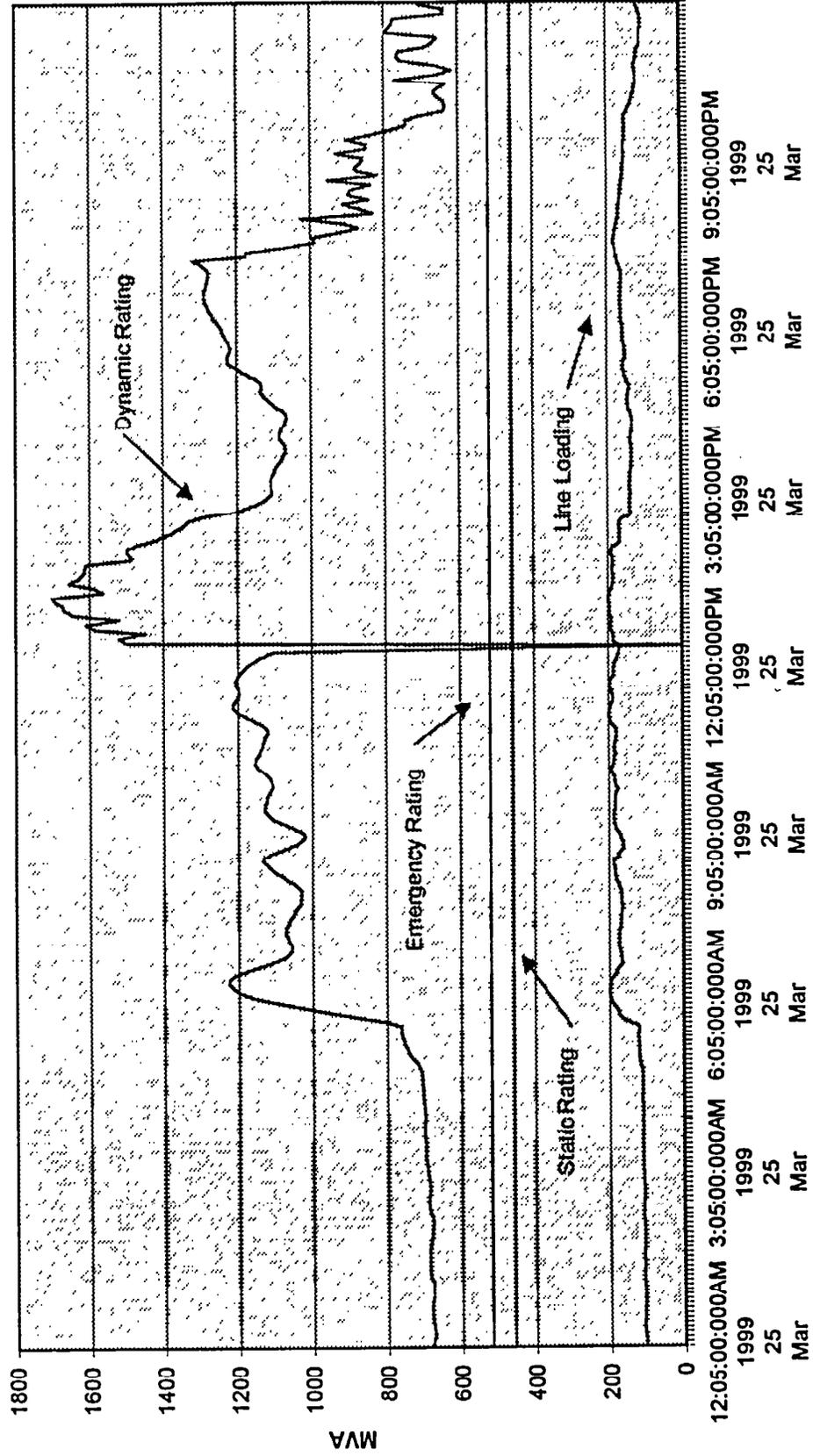
THEORY OF CABLE TENSION MONITORS AND RELATED TECHNICAL PAPERS

Appendix A
Collected Data

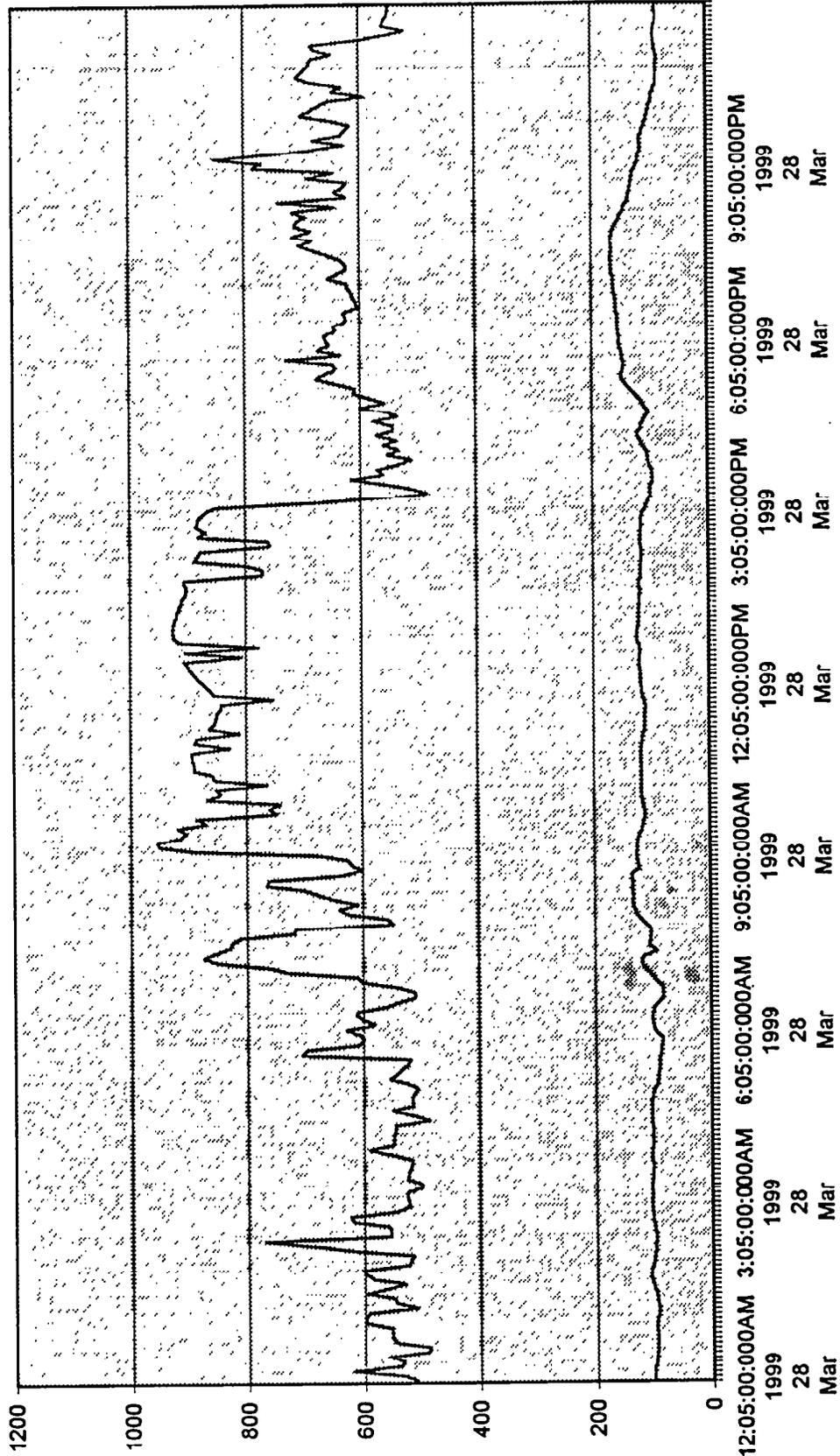
TL 23007

Real Time Line Rating Data

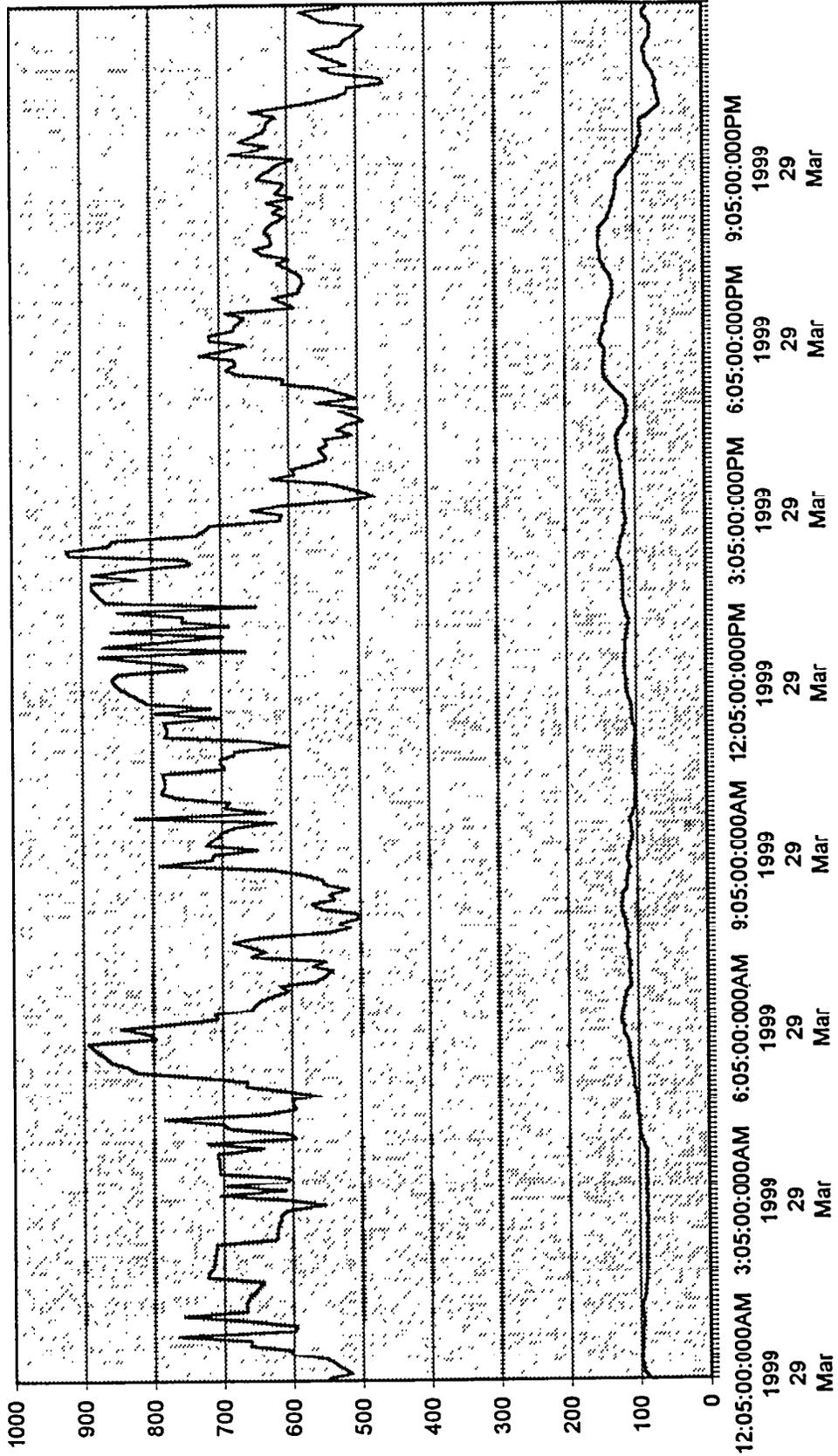
TL23007 MVA Comparison DTCR Rating vs. Static Rating
March 25, 1999
Without 30 Minute Averaging



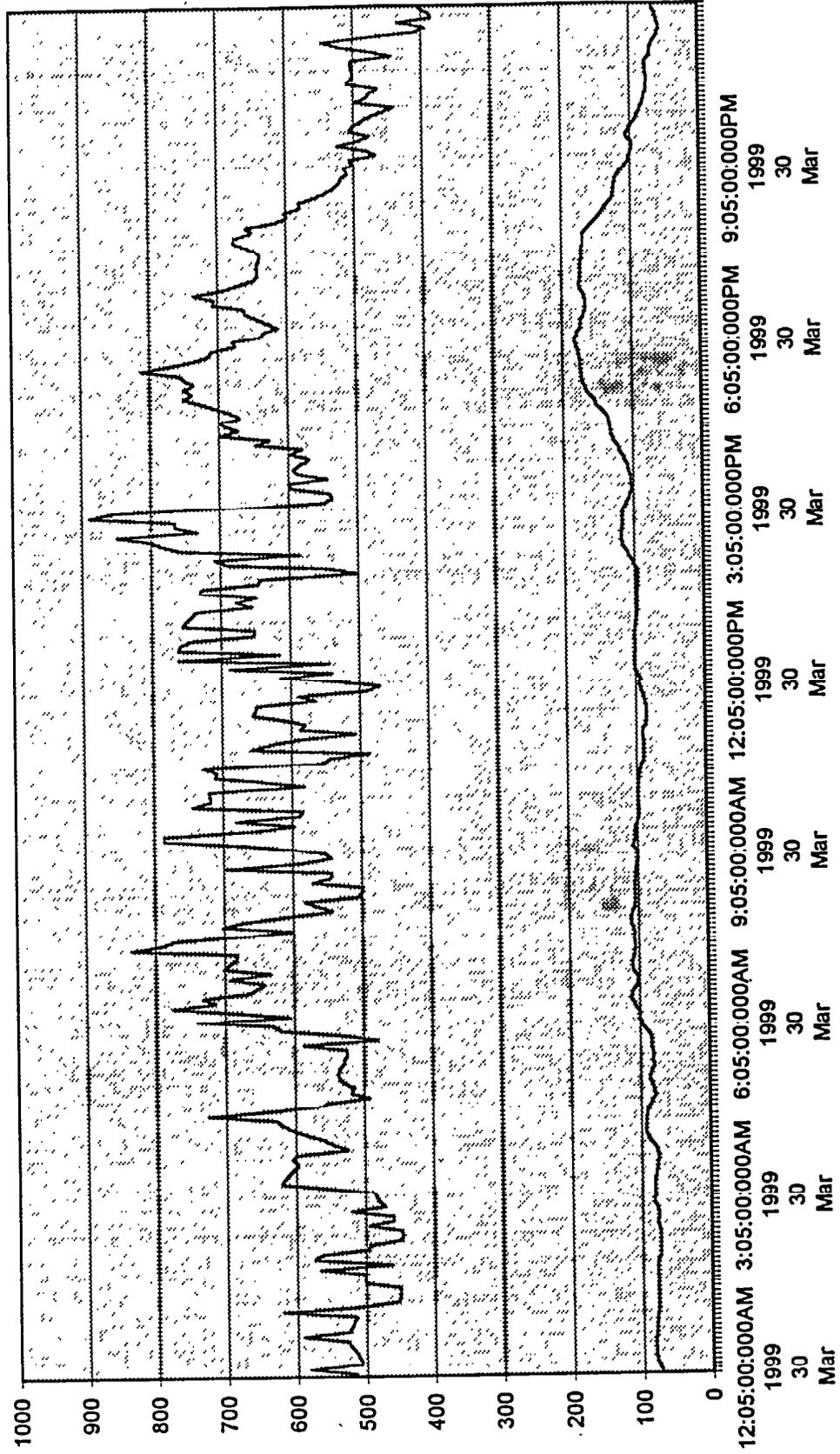
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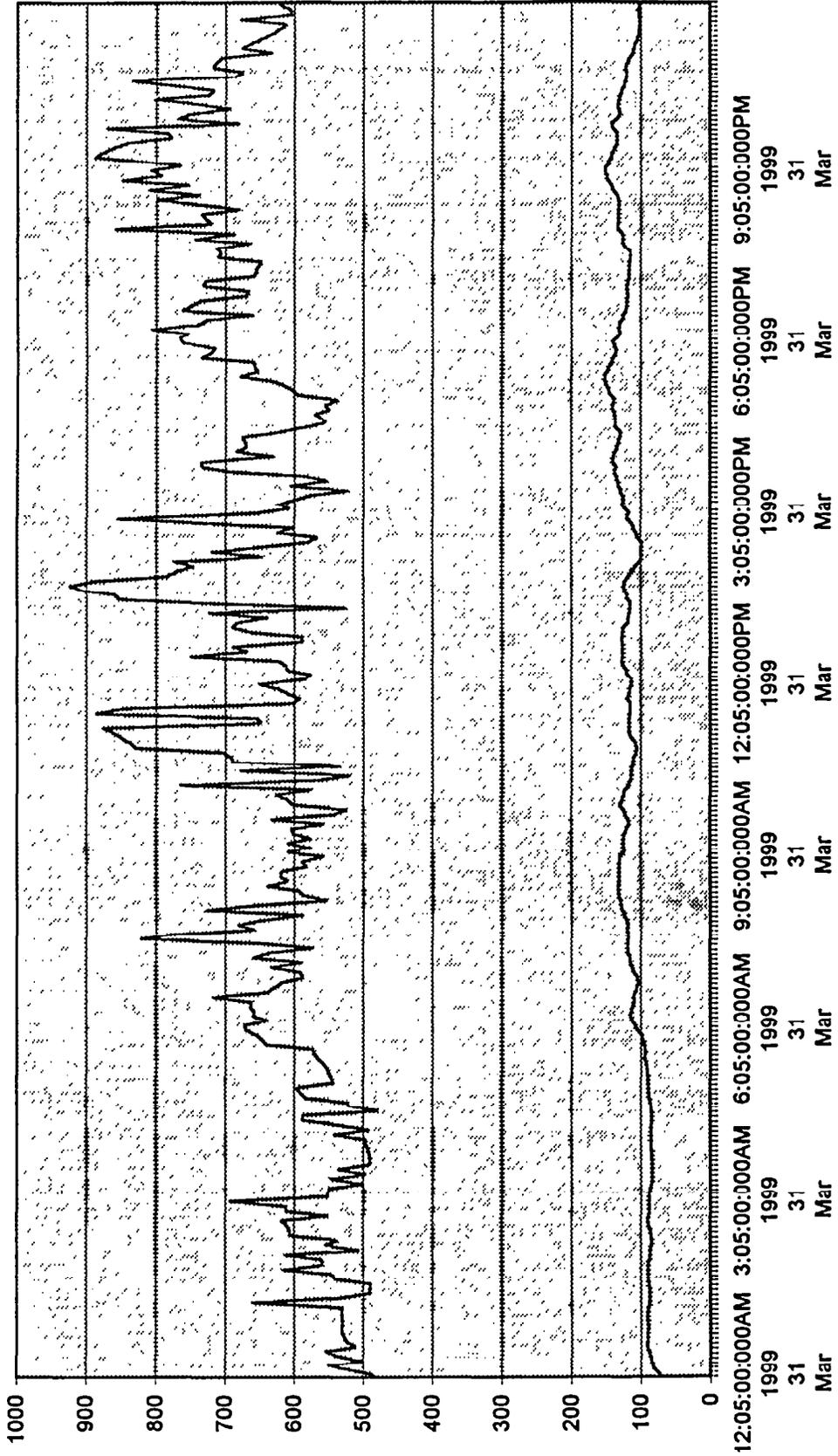
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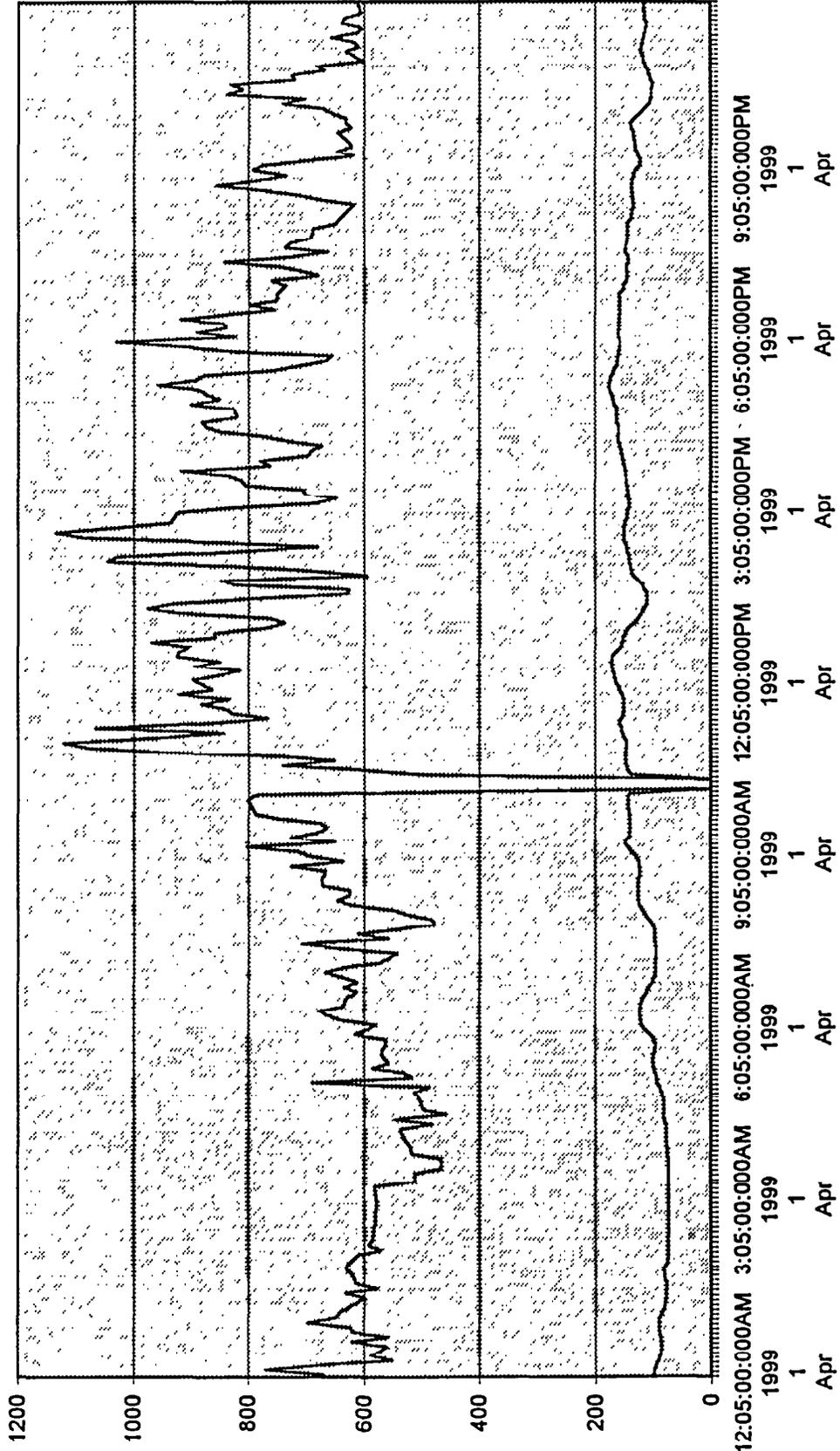
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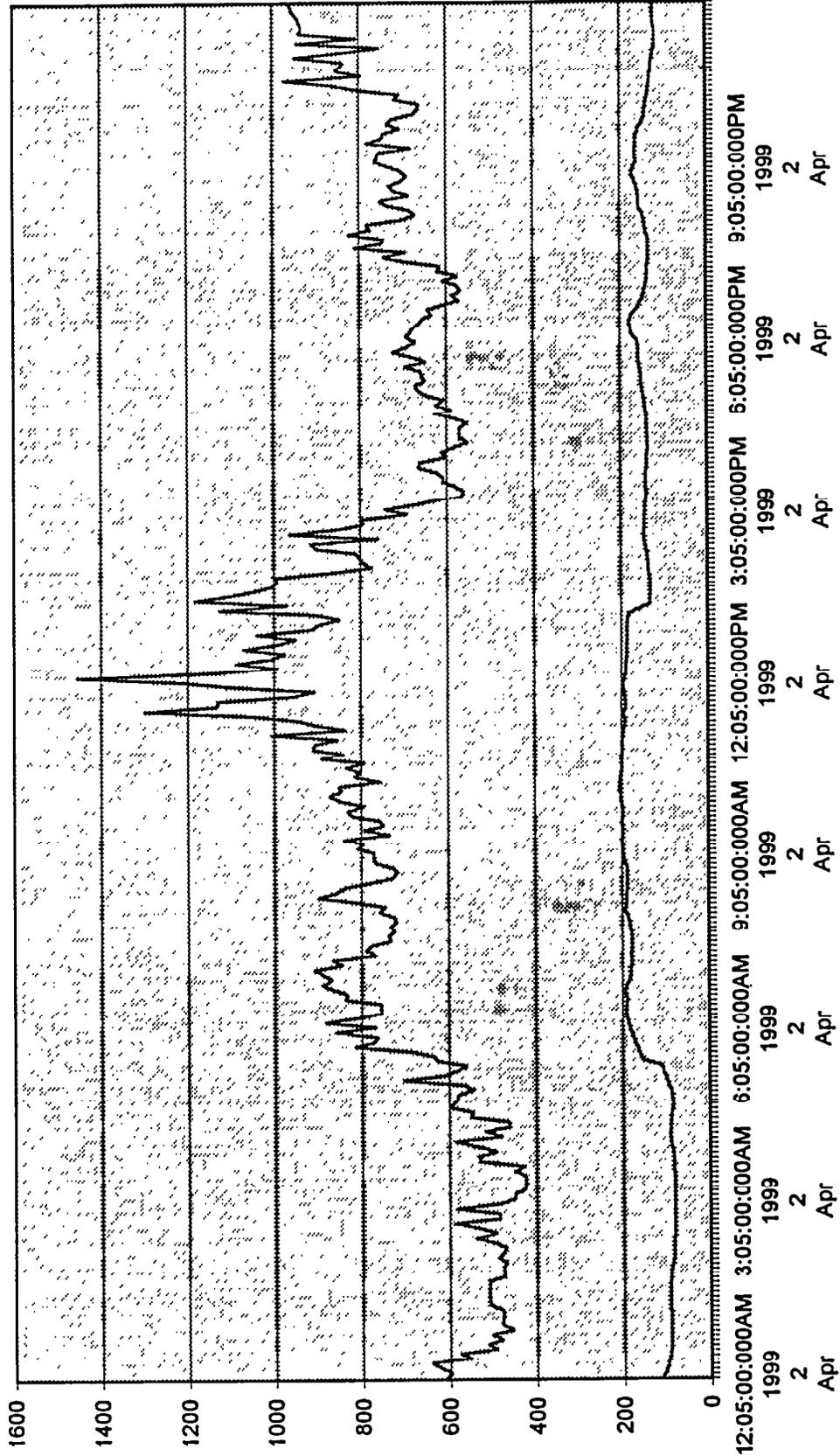
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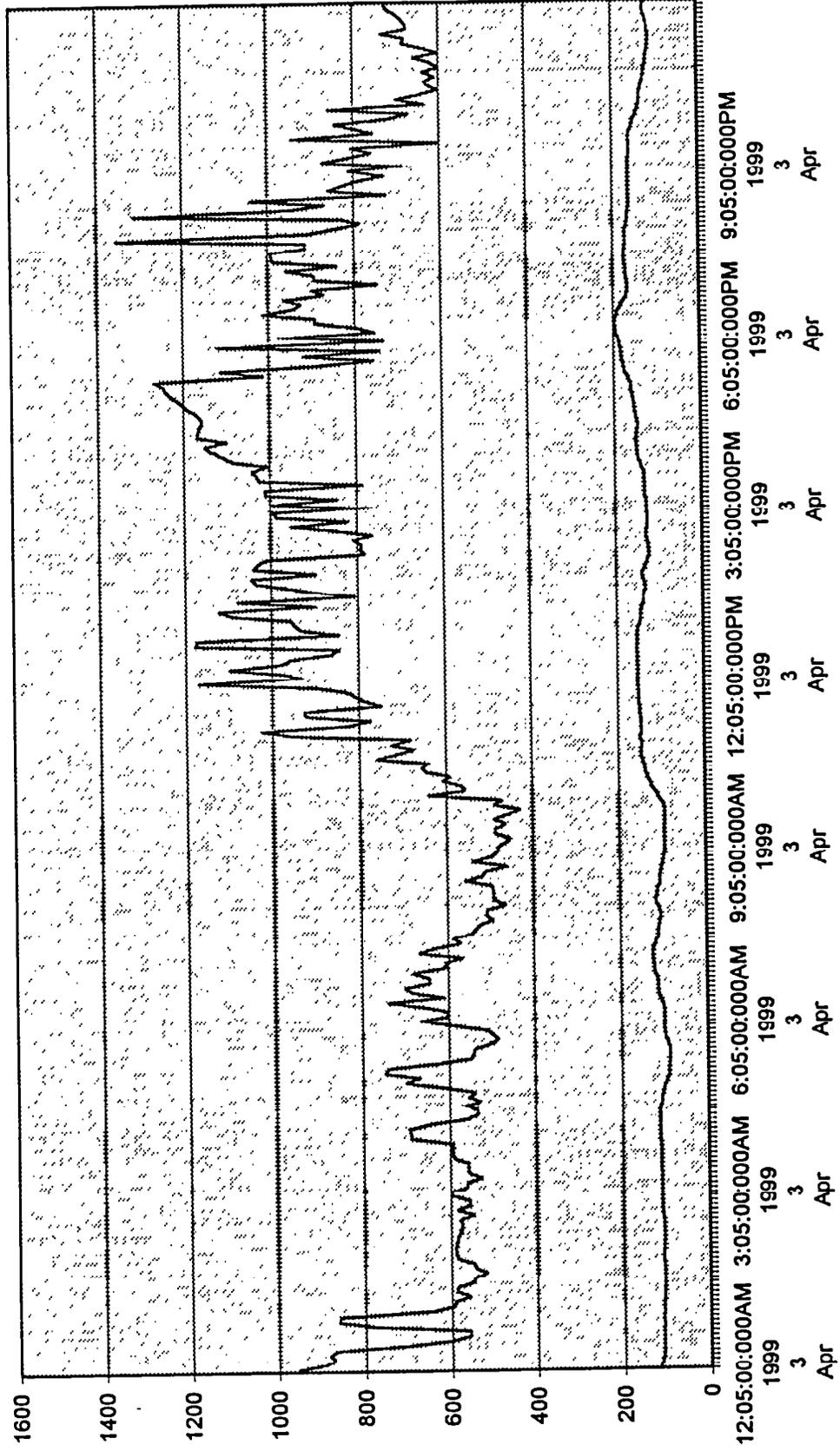
TI 23007 MVA Comparison
April 1, 1999



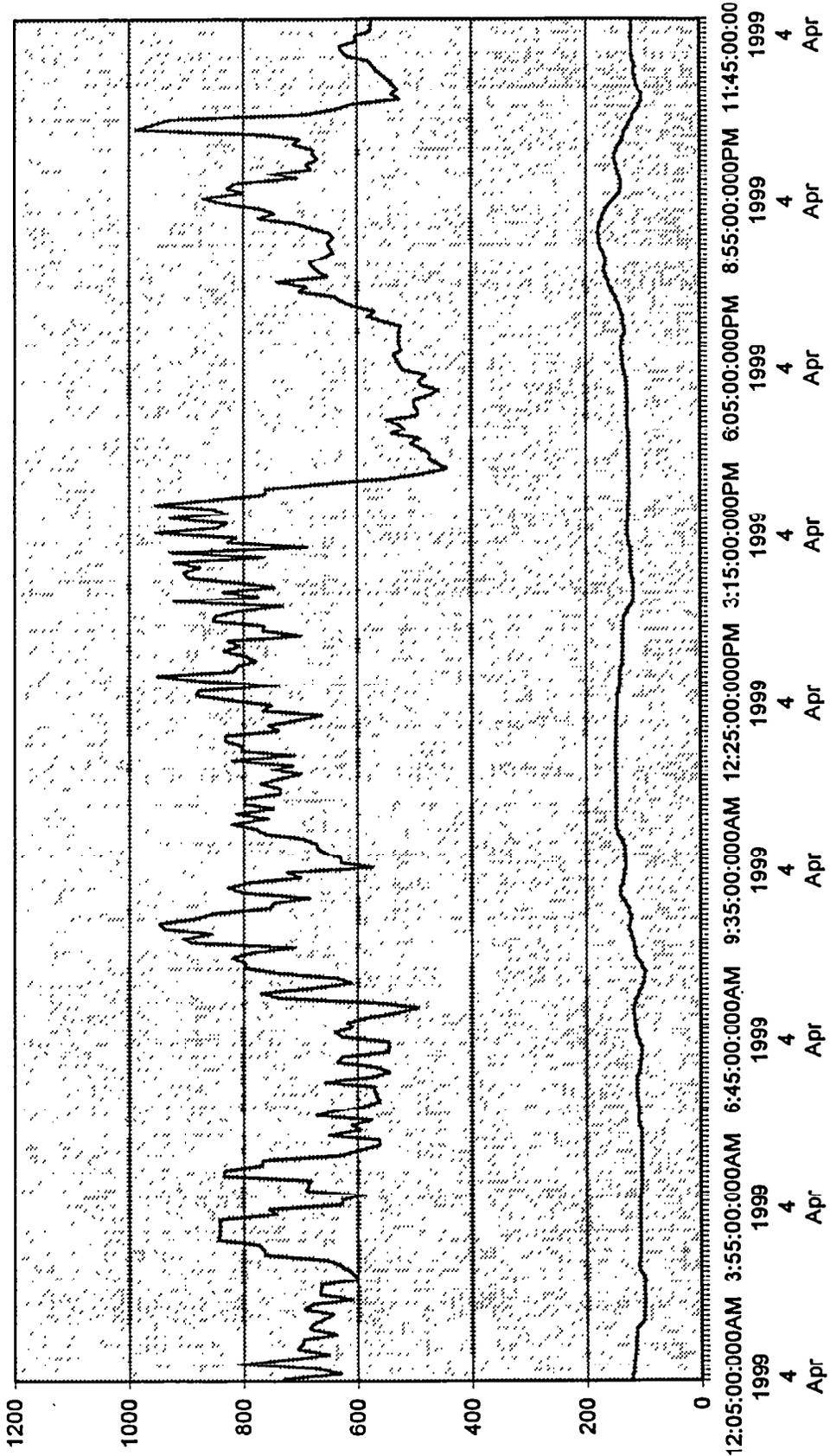
TL23007 MVA Comparison
April 2, 1999



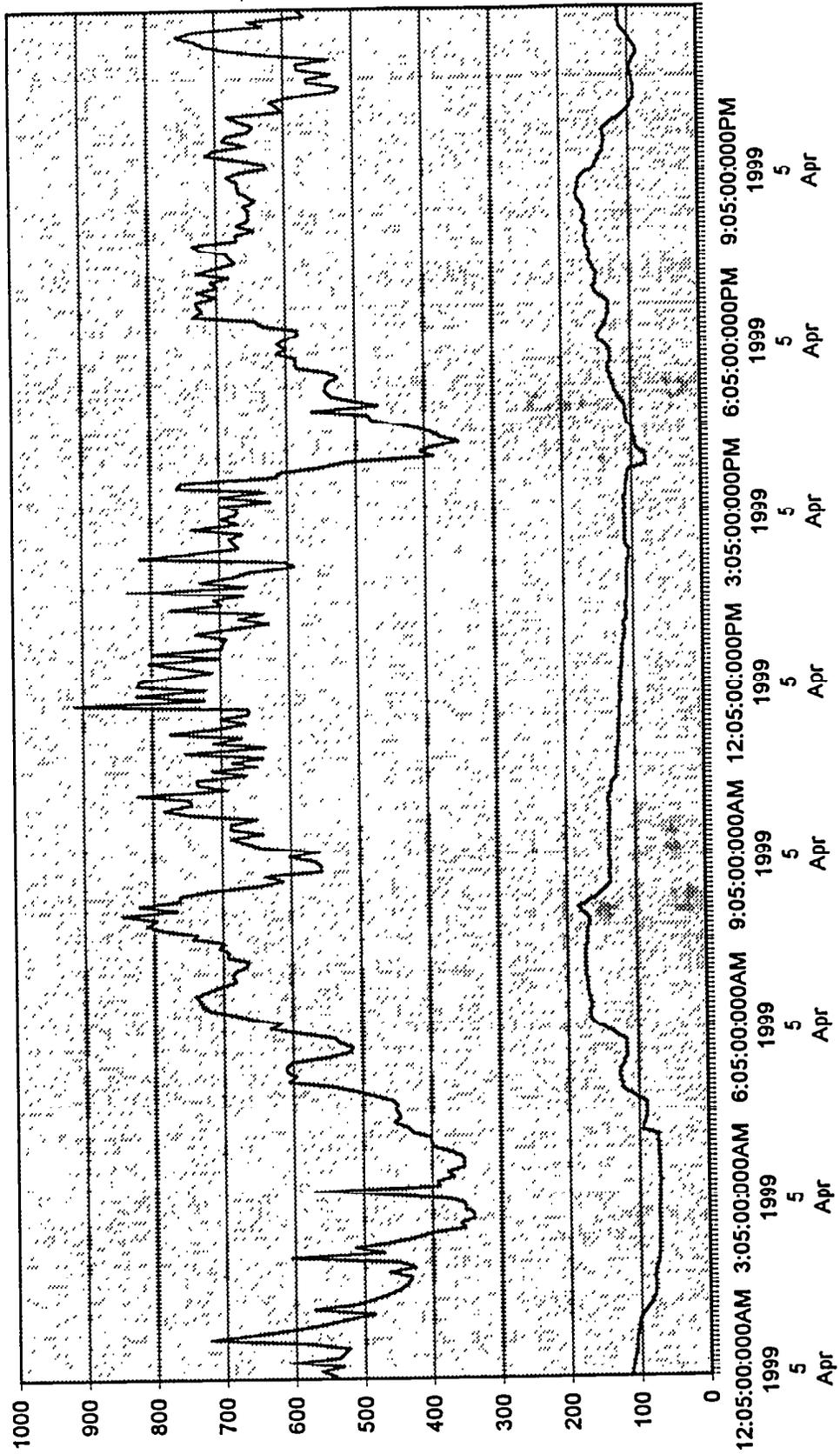
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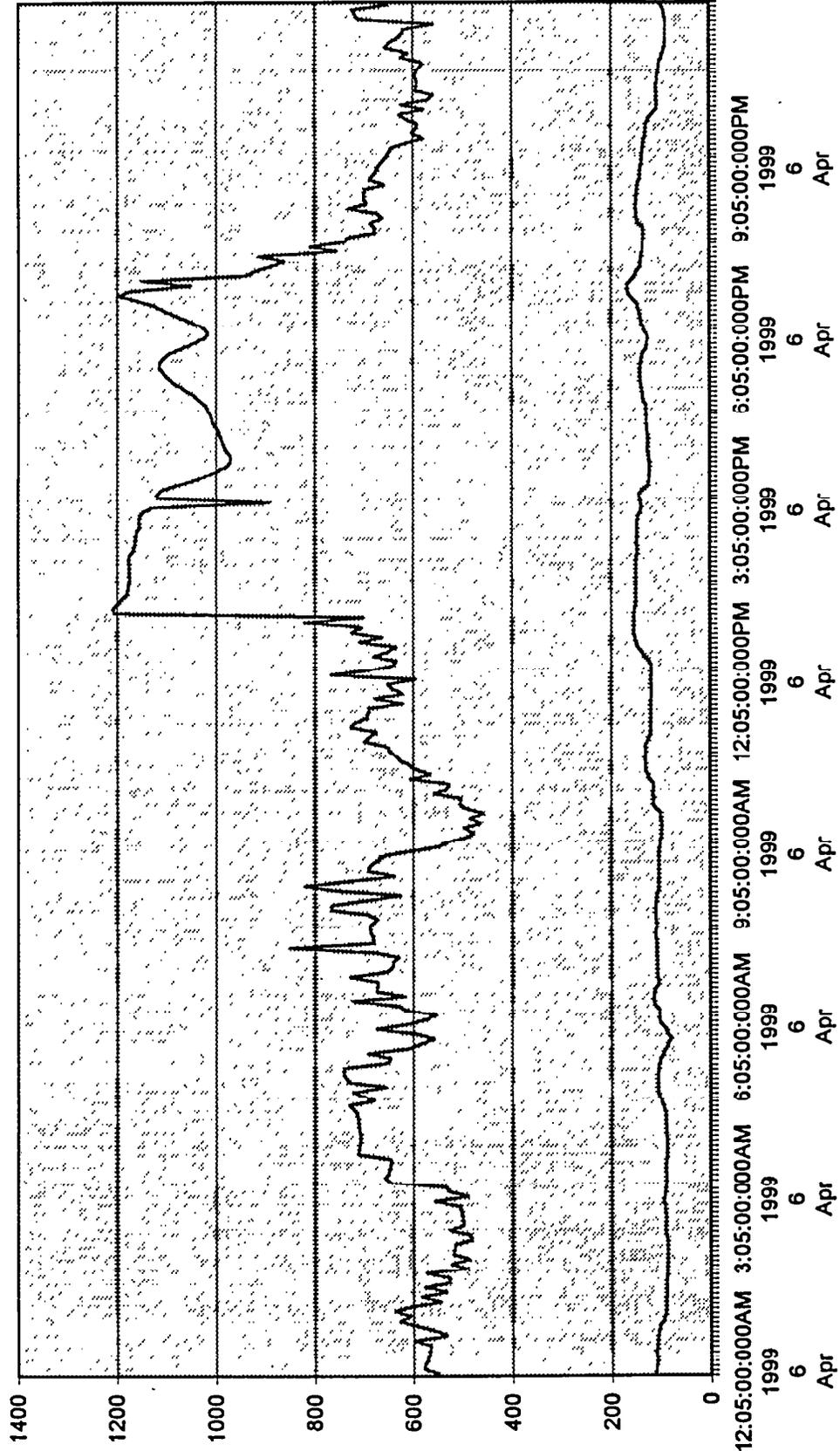
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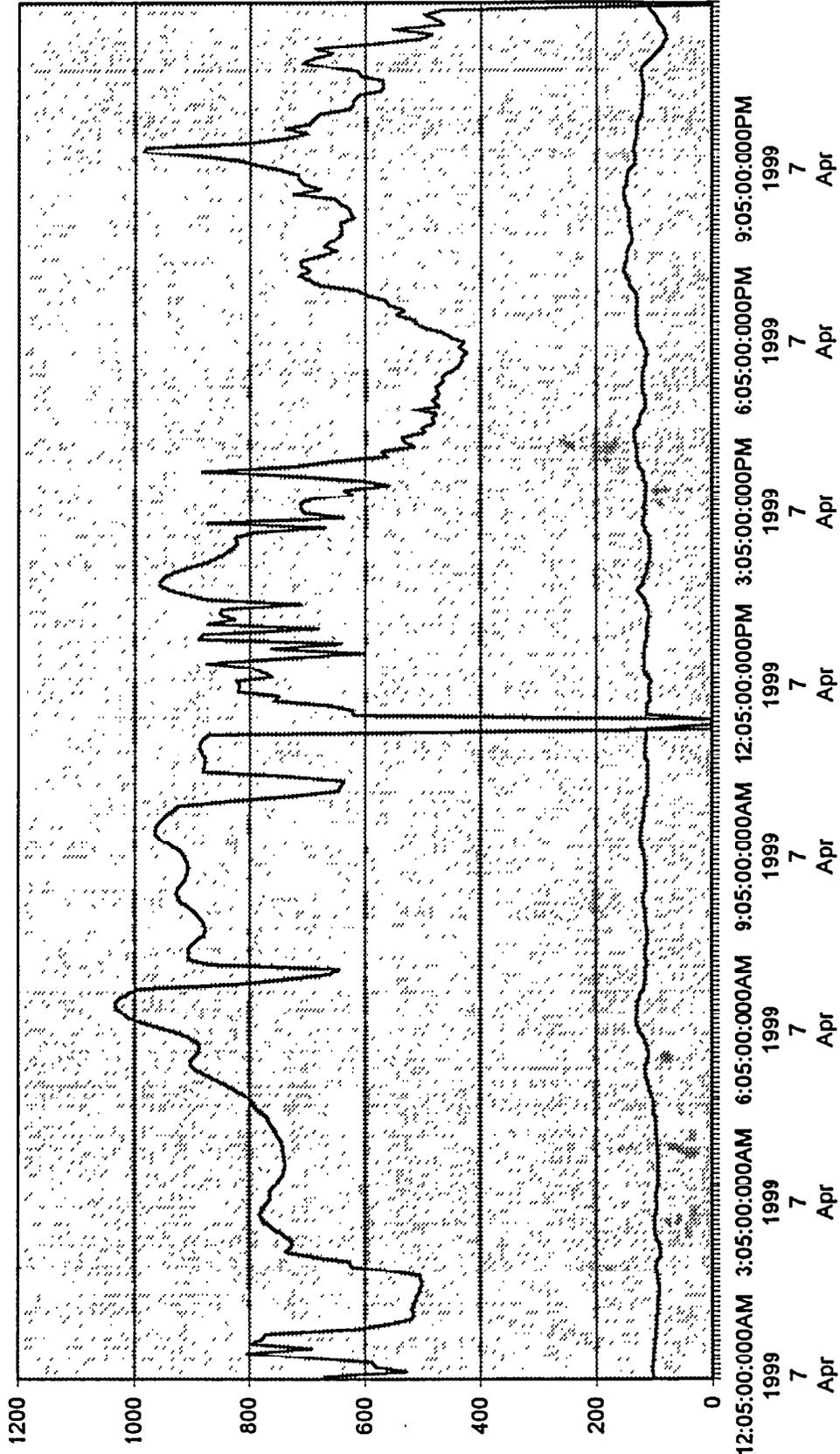
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April 5, 1999



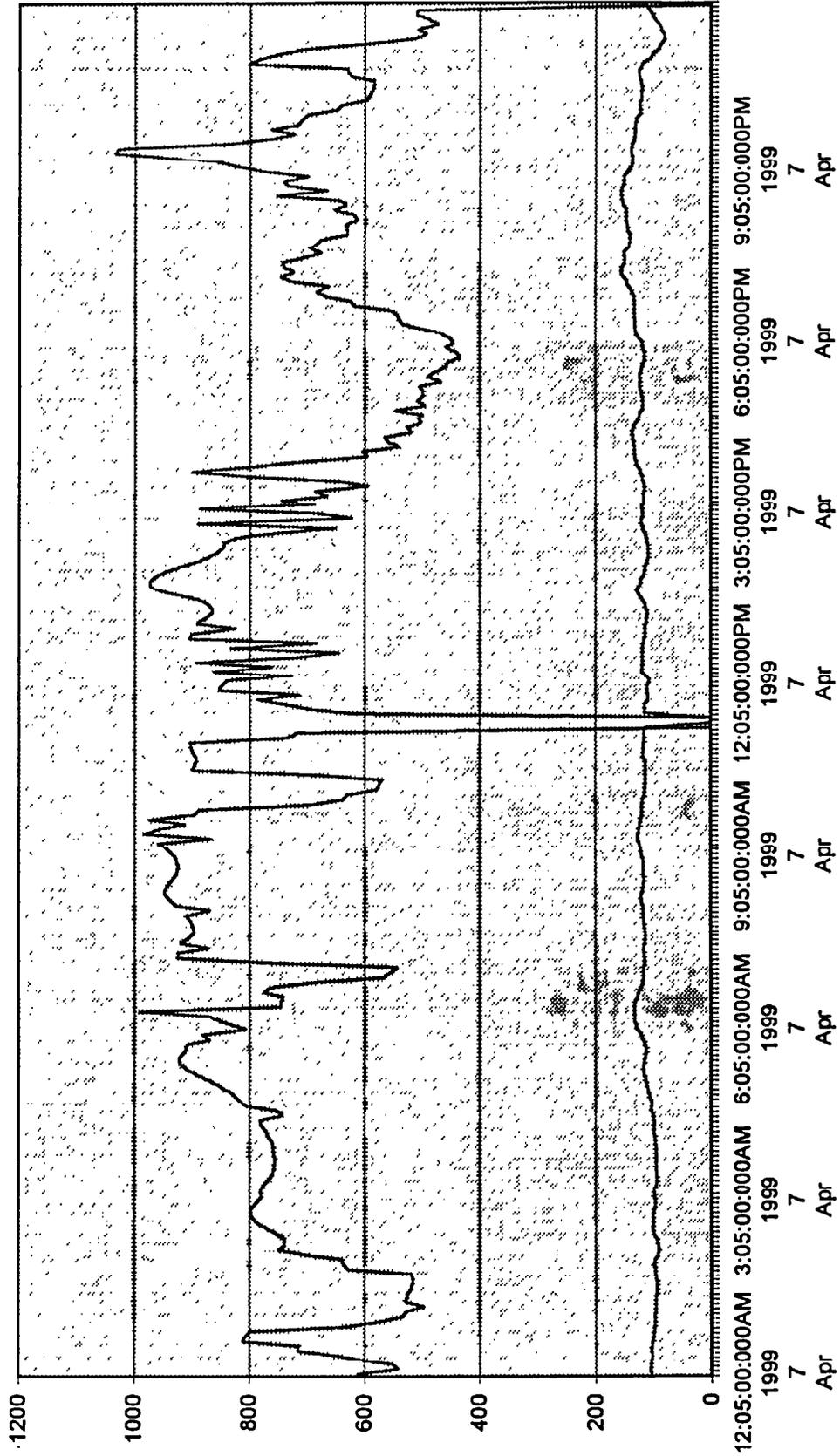
TL23007 MVA Comparison
April 6, 1999



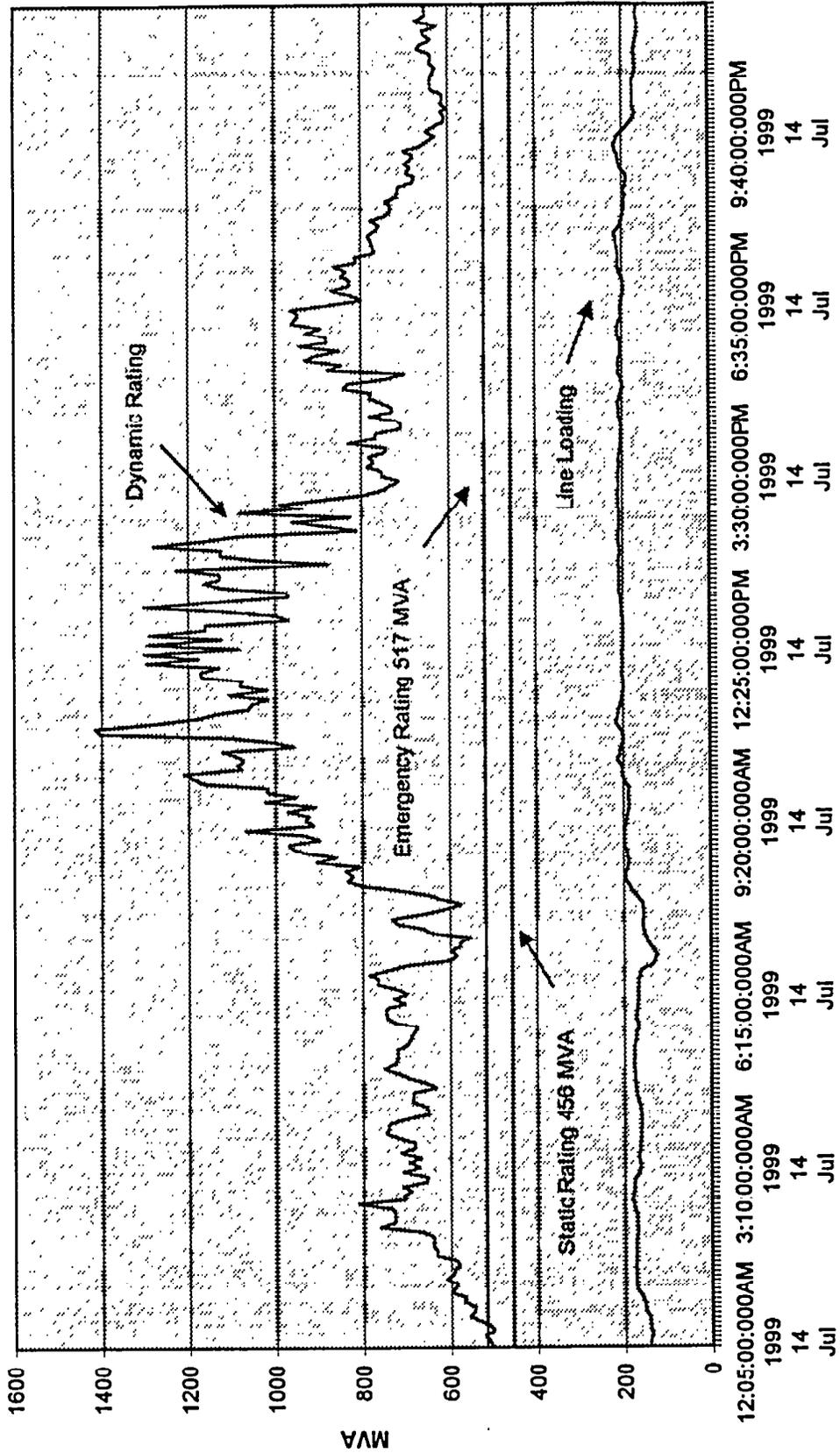
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April 7, 1999



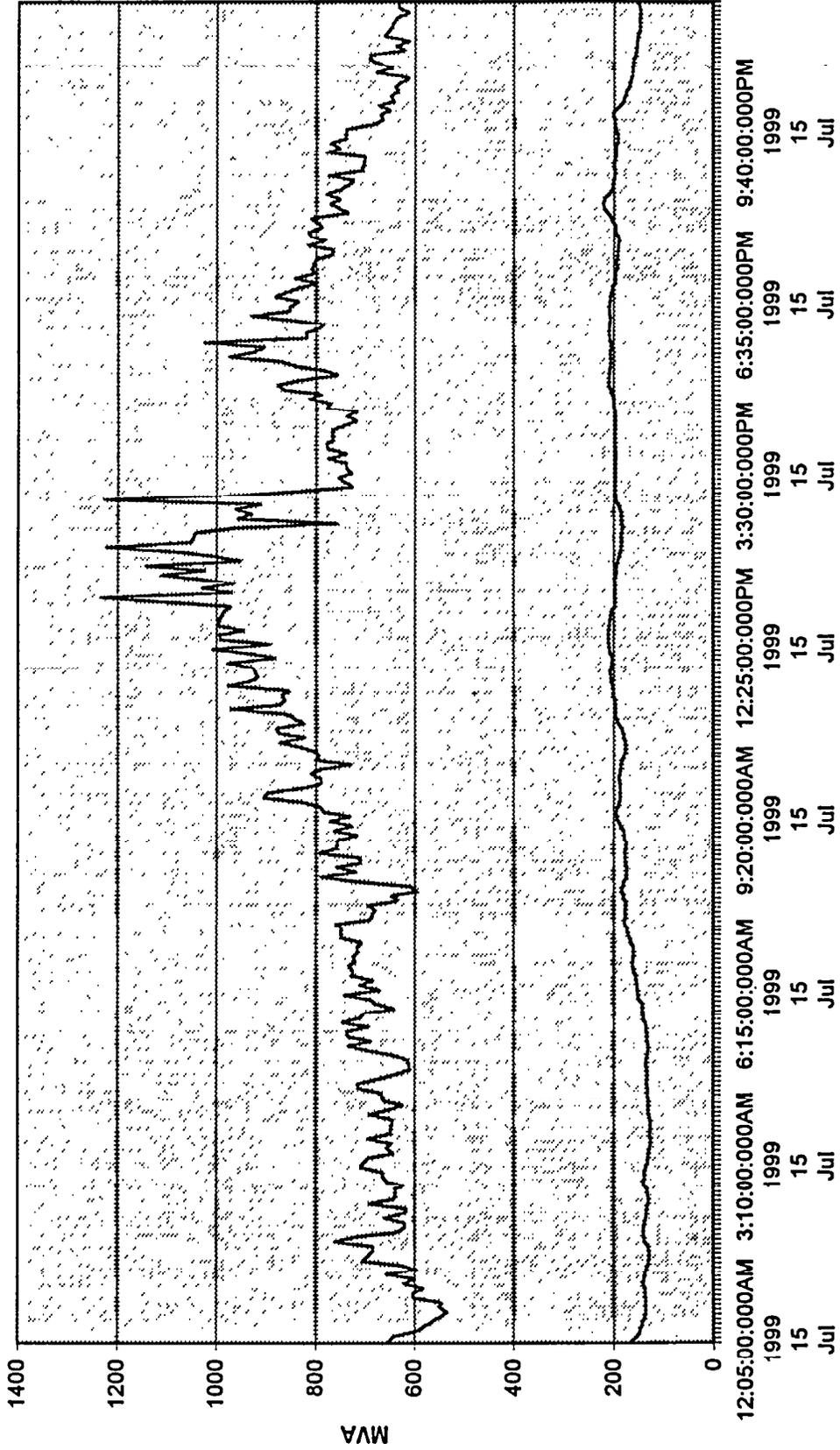
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April 7, 1999



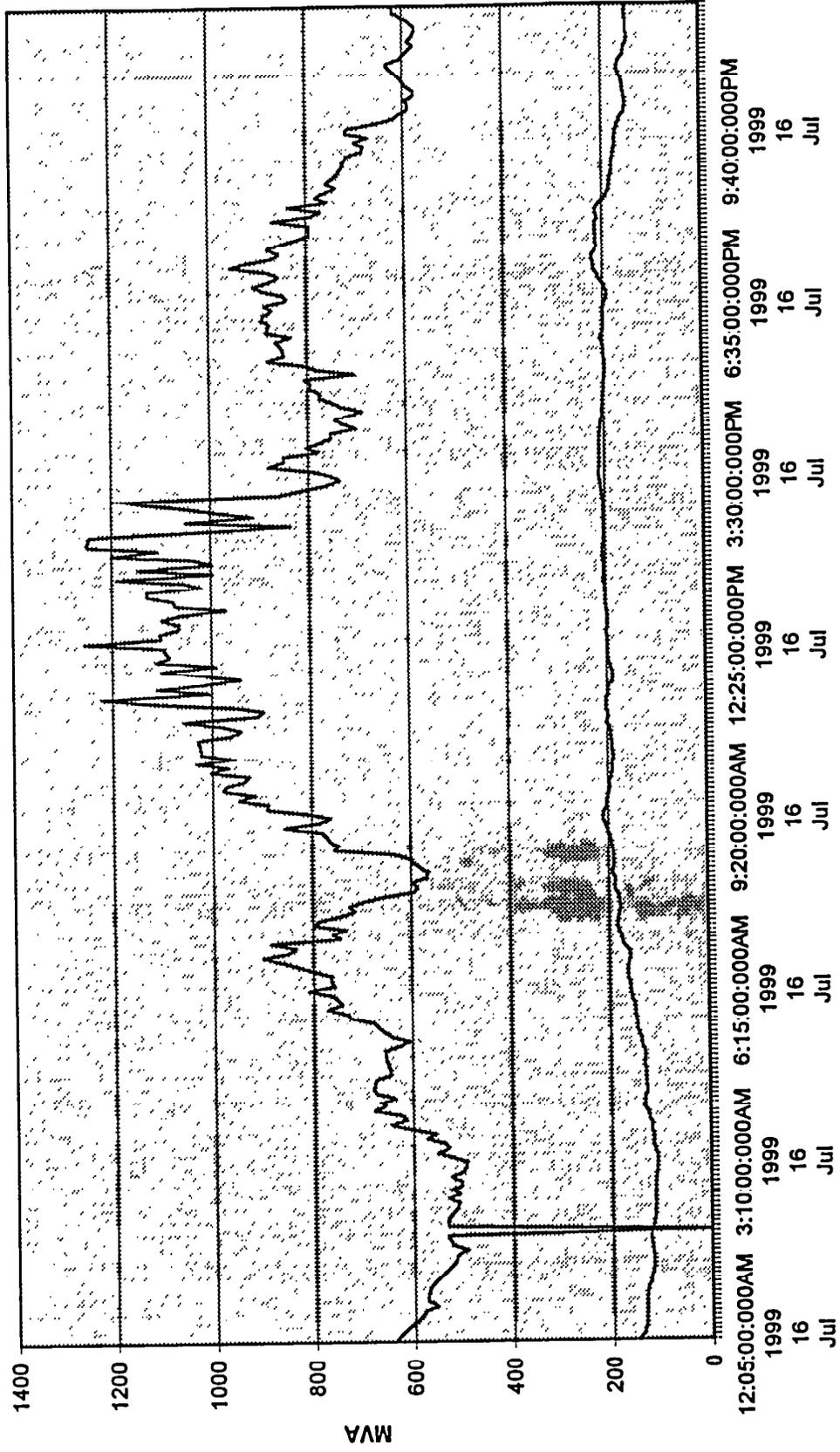
TL23007 MVA Comparison
DTCR vs. Static Rating July 14, 1999



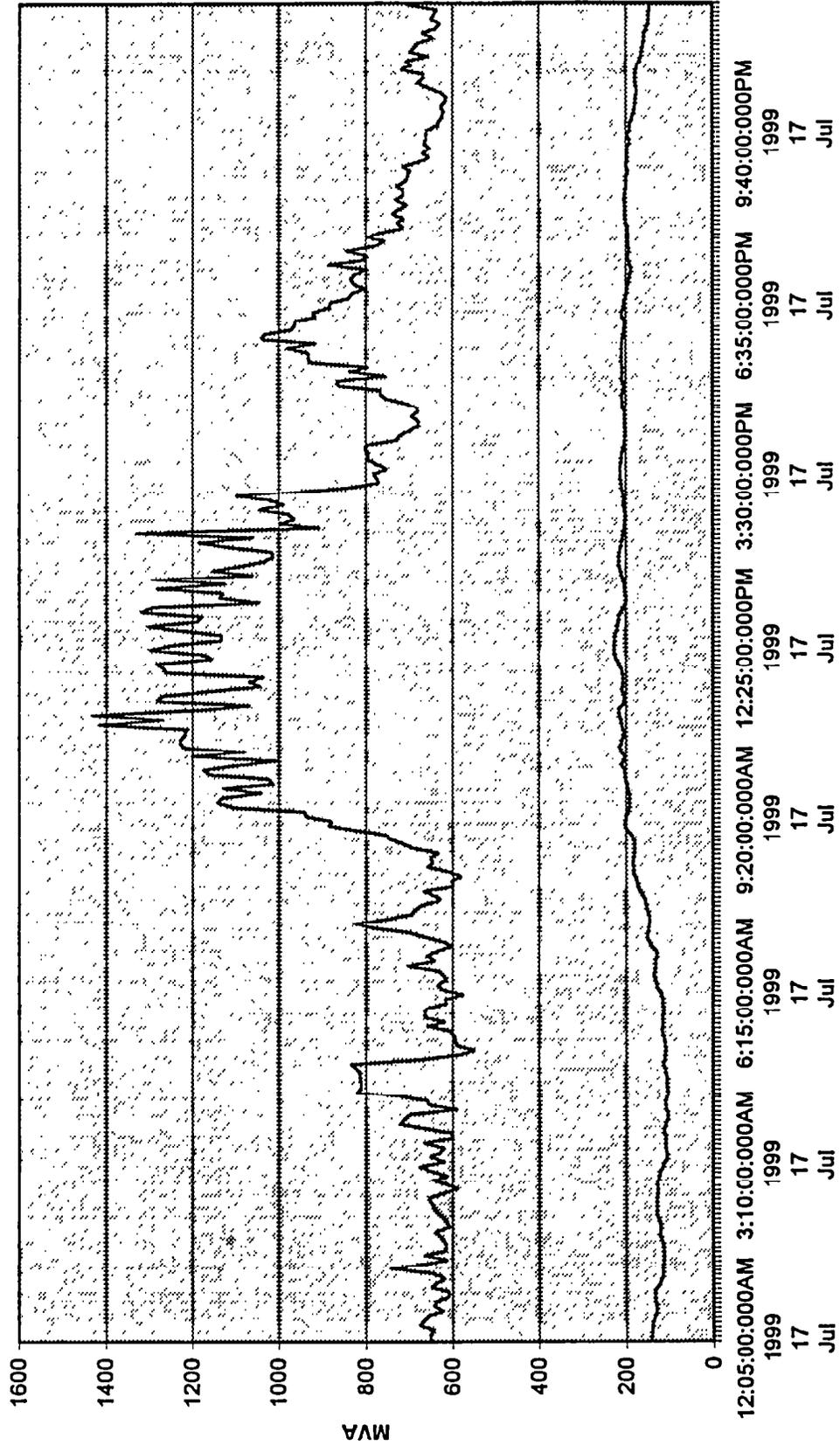
TL 23007 DTCR Rating & Line Loading
July 15, 1999



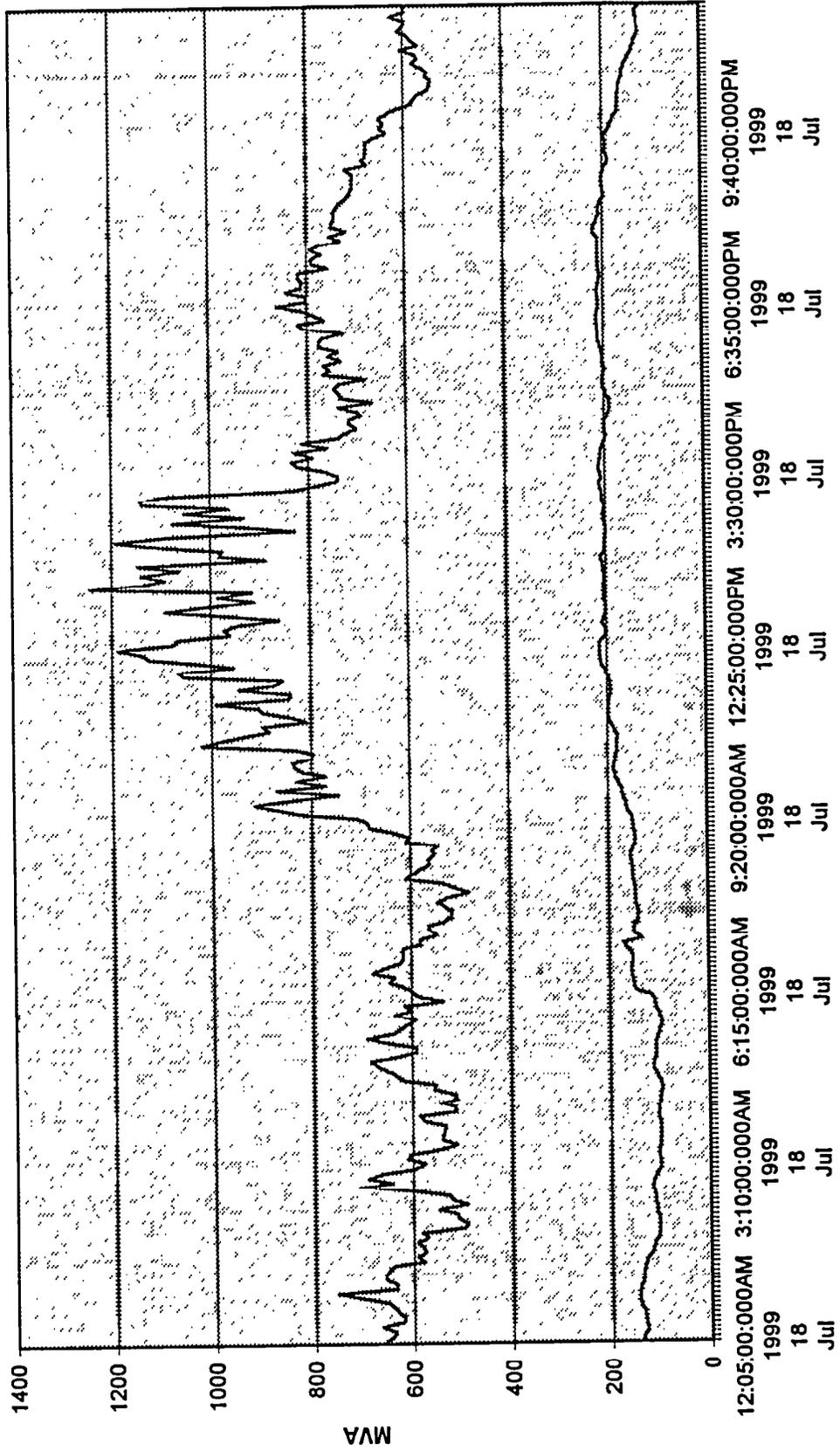
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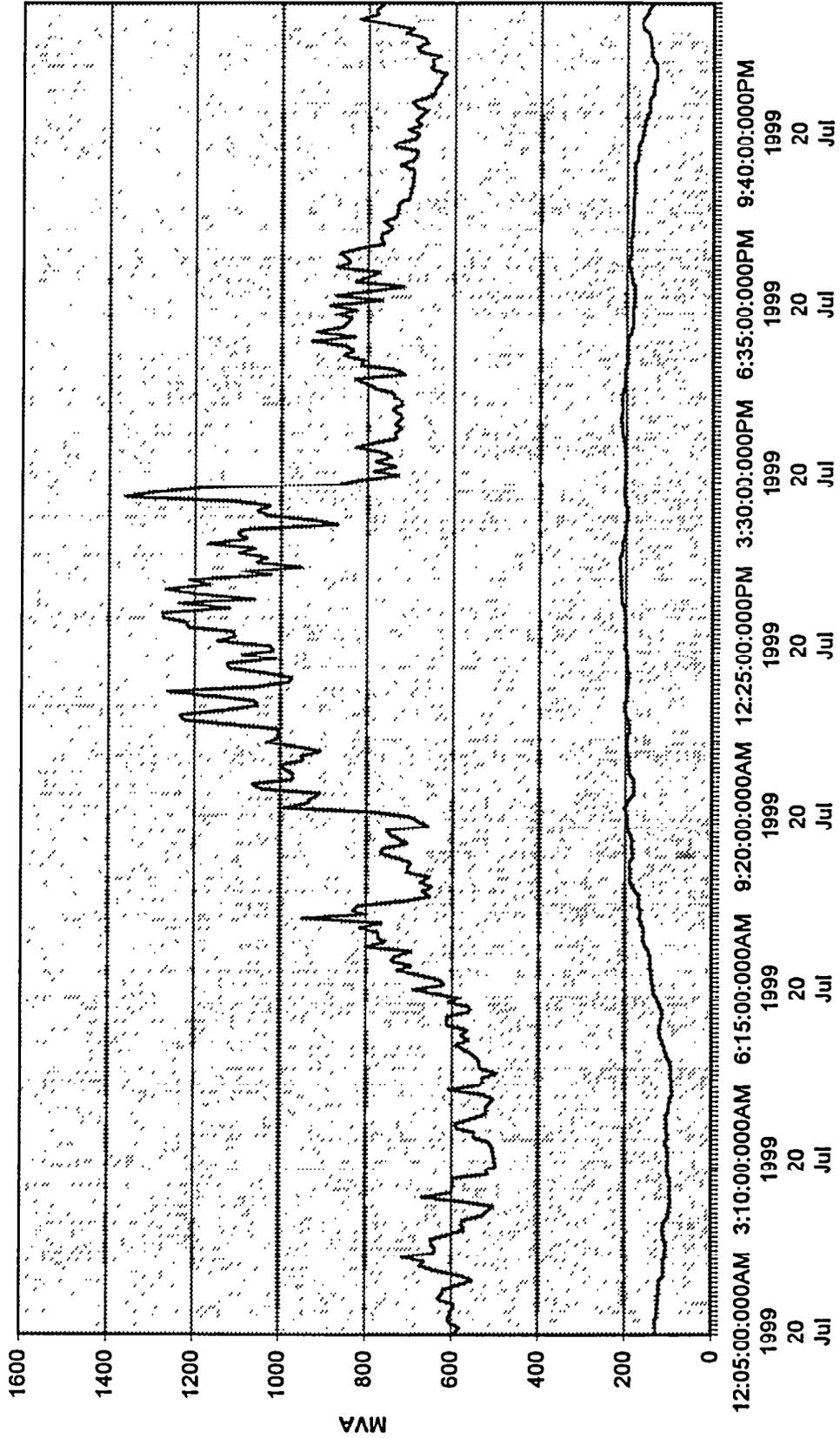
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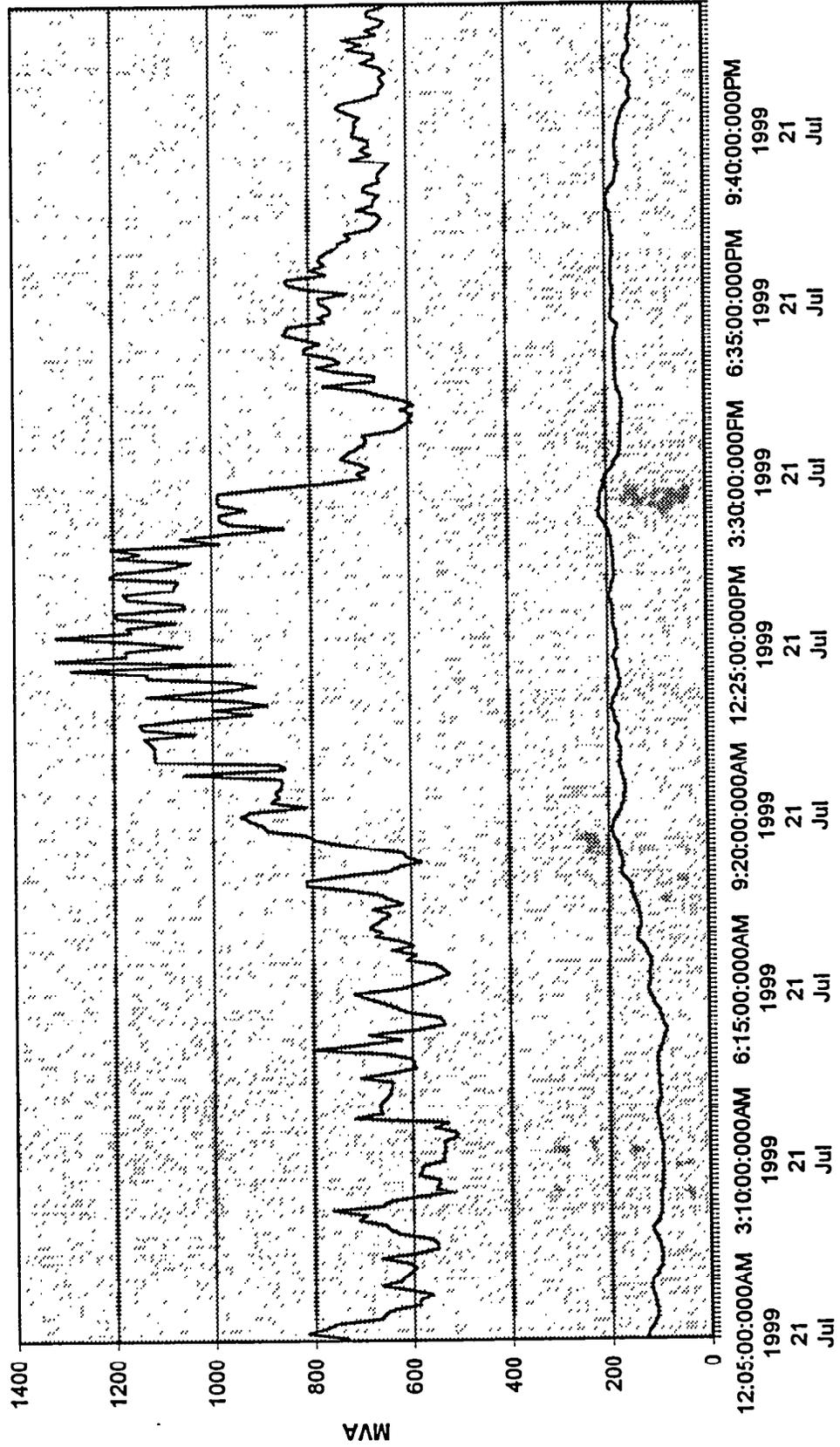
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July 18, 1999



TL23007 DTCR Rating & Line Loading
July 20, 1999



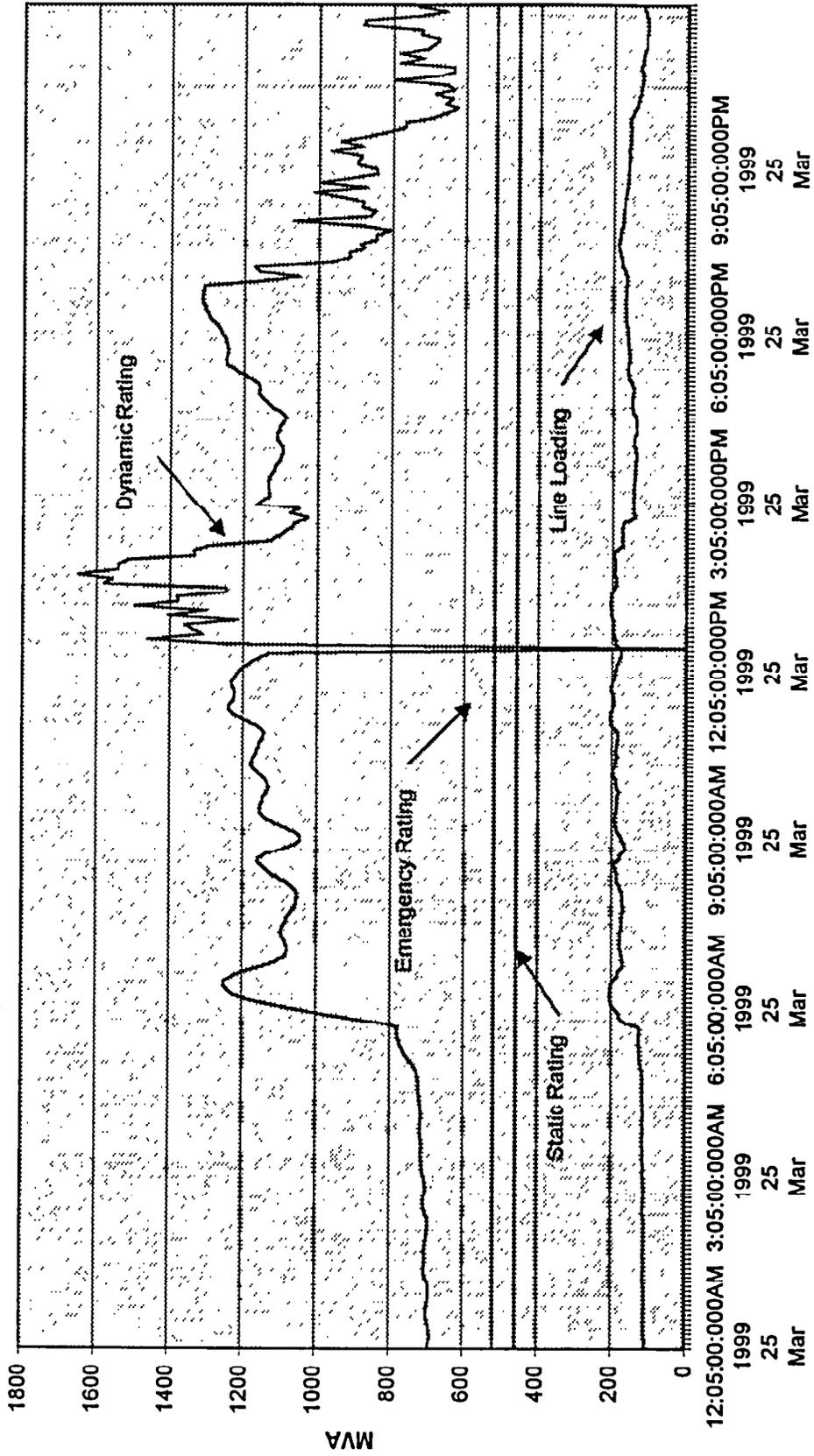
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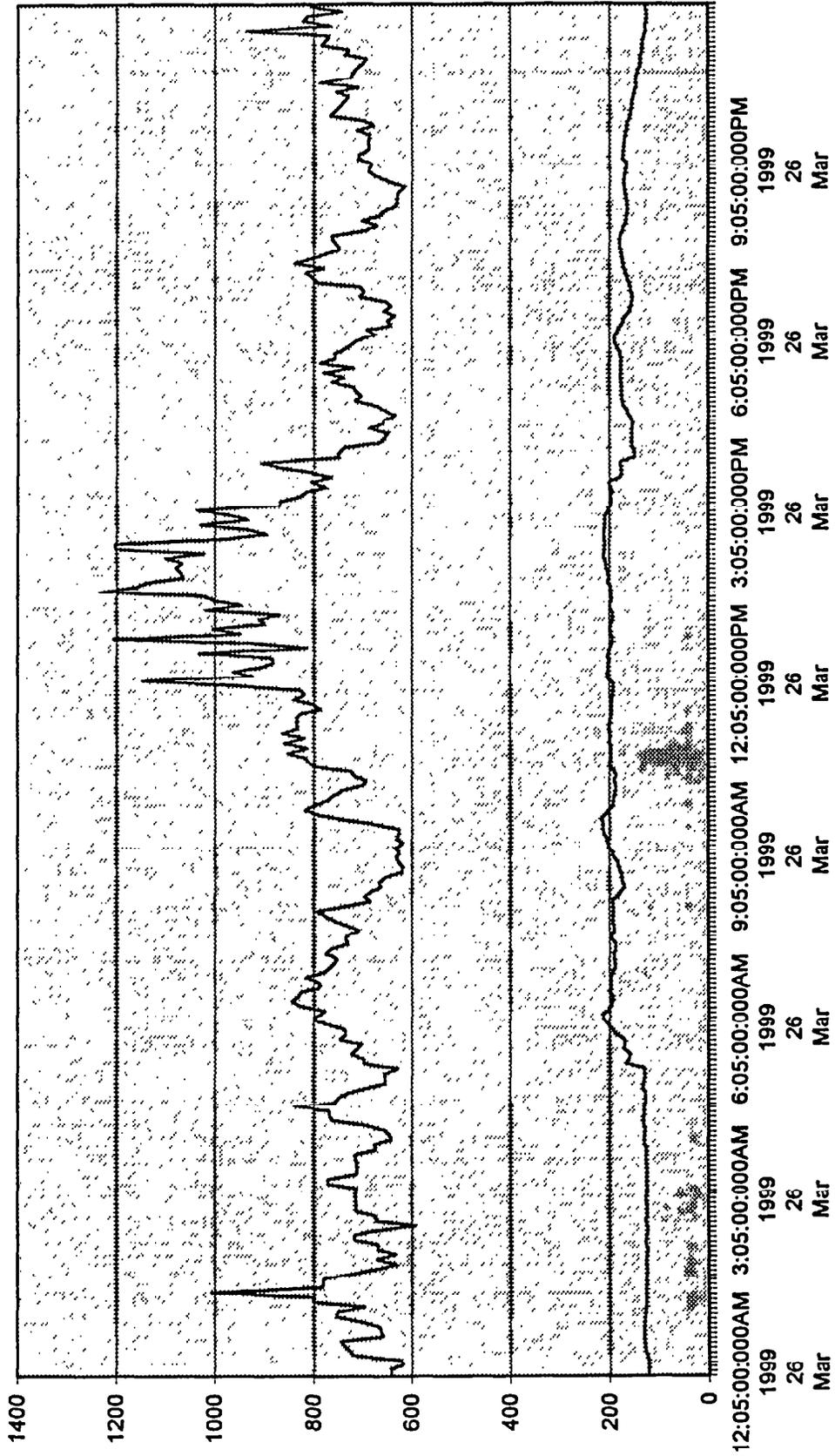
TL 23052

Real Time Line Rating Data

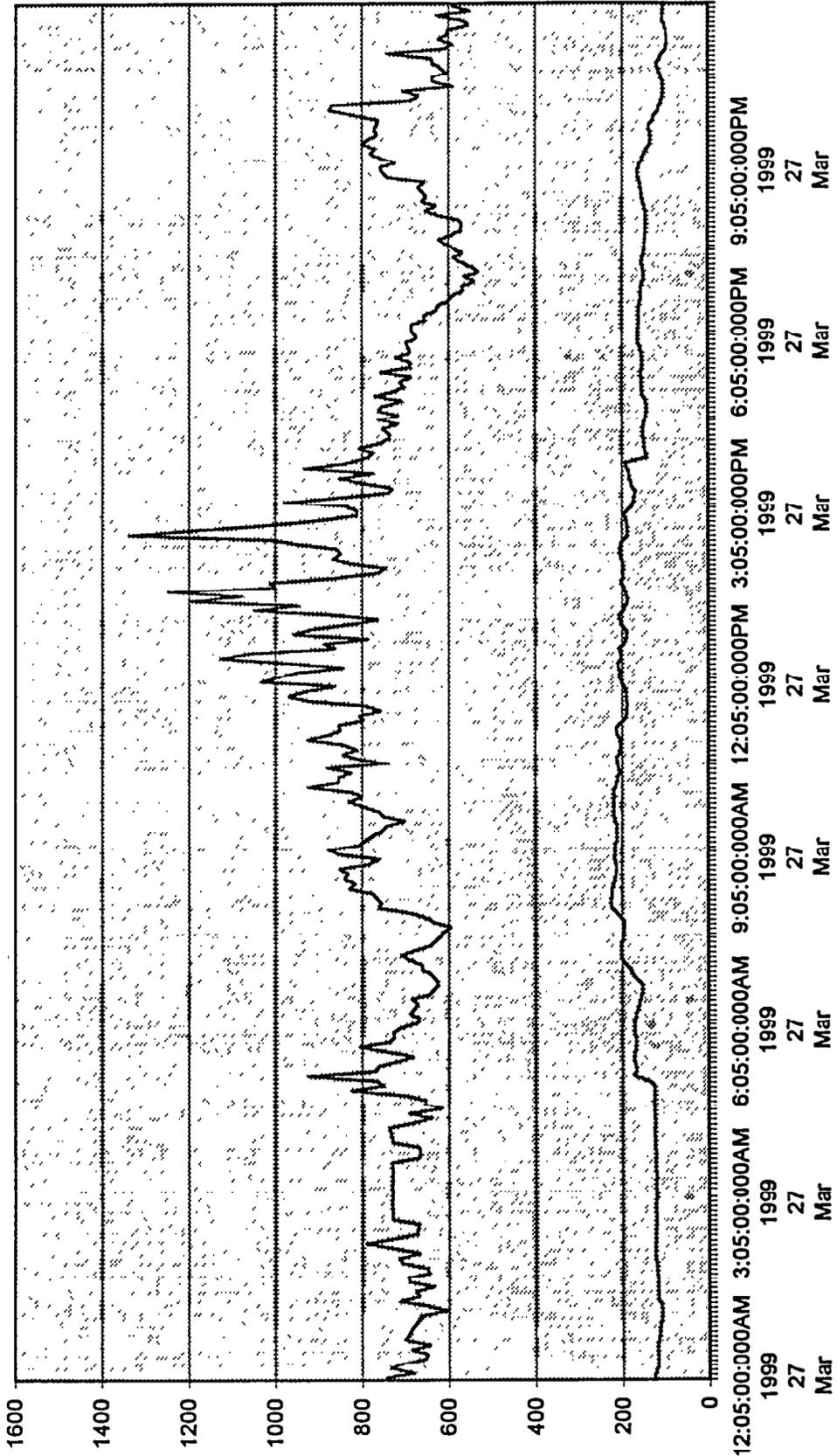
TL23052 MVA Comparison DTCR Rating vs. Static Rating
March 25, 1999
Without 30 Minute Averaging



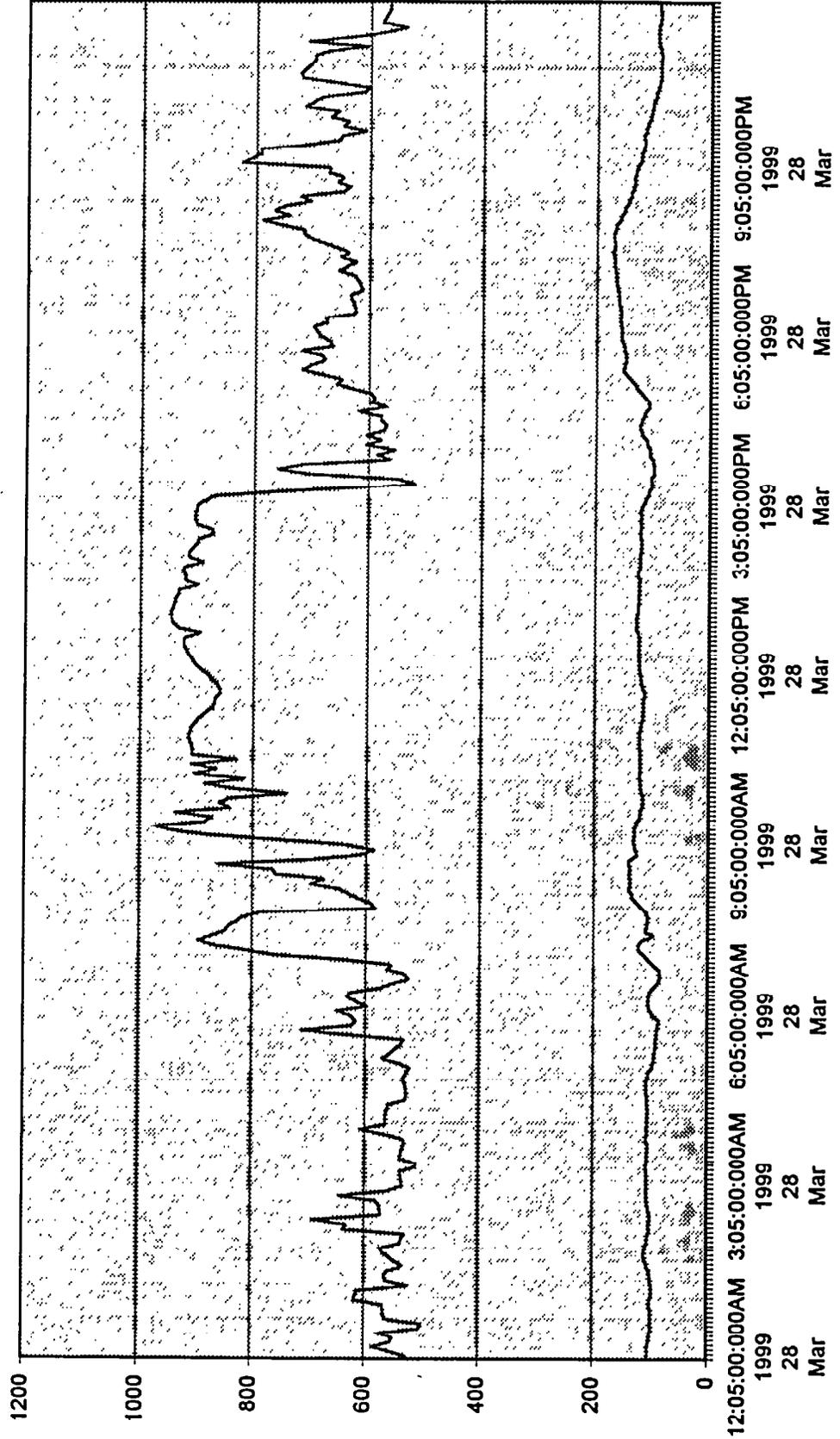
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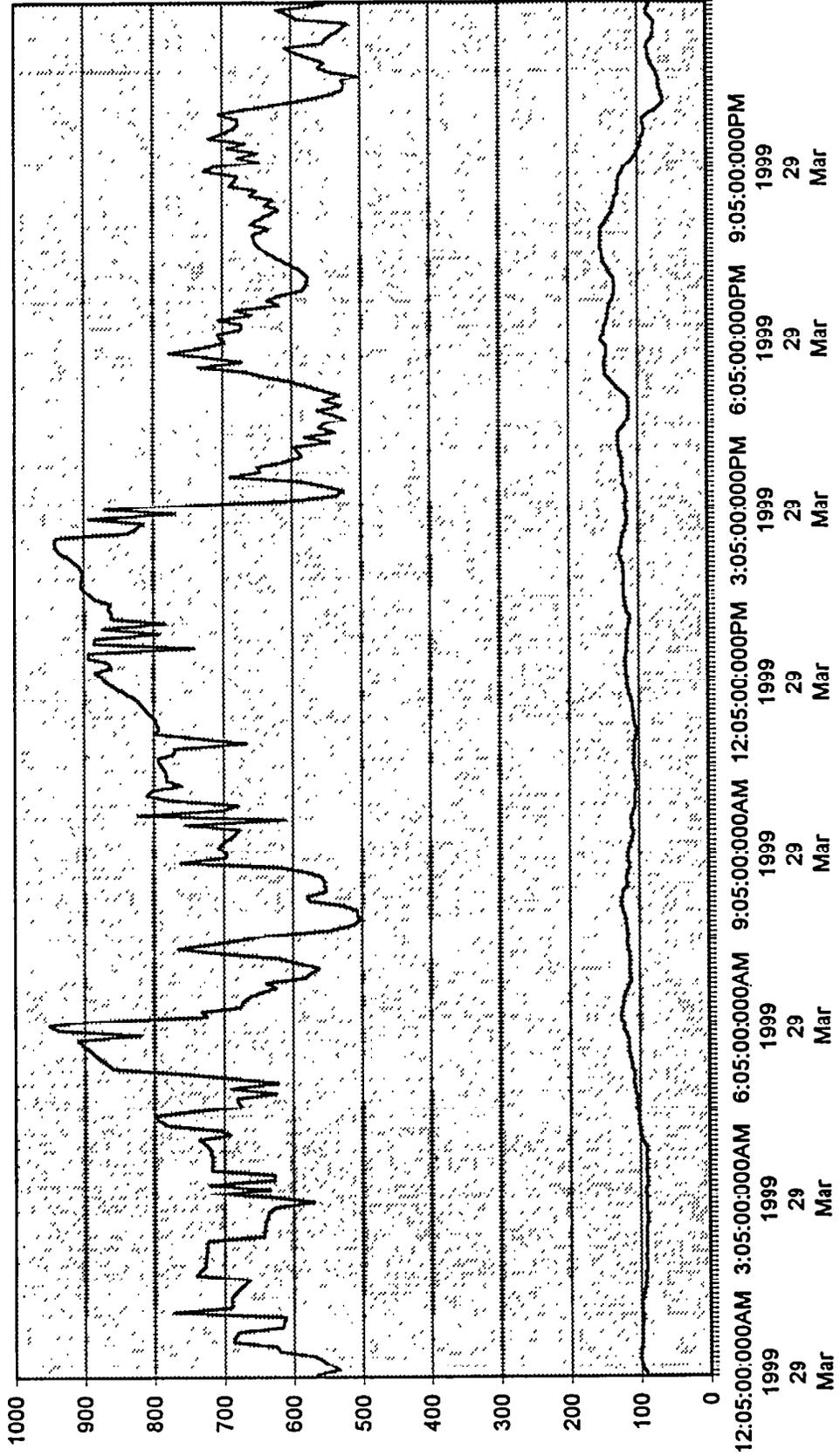
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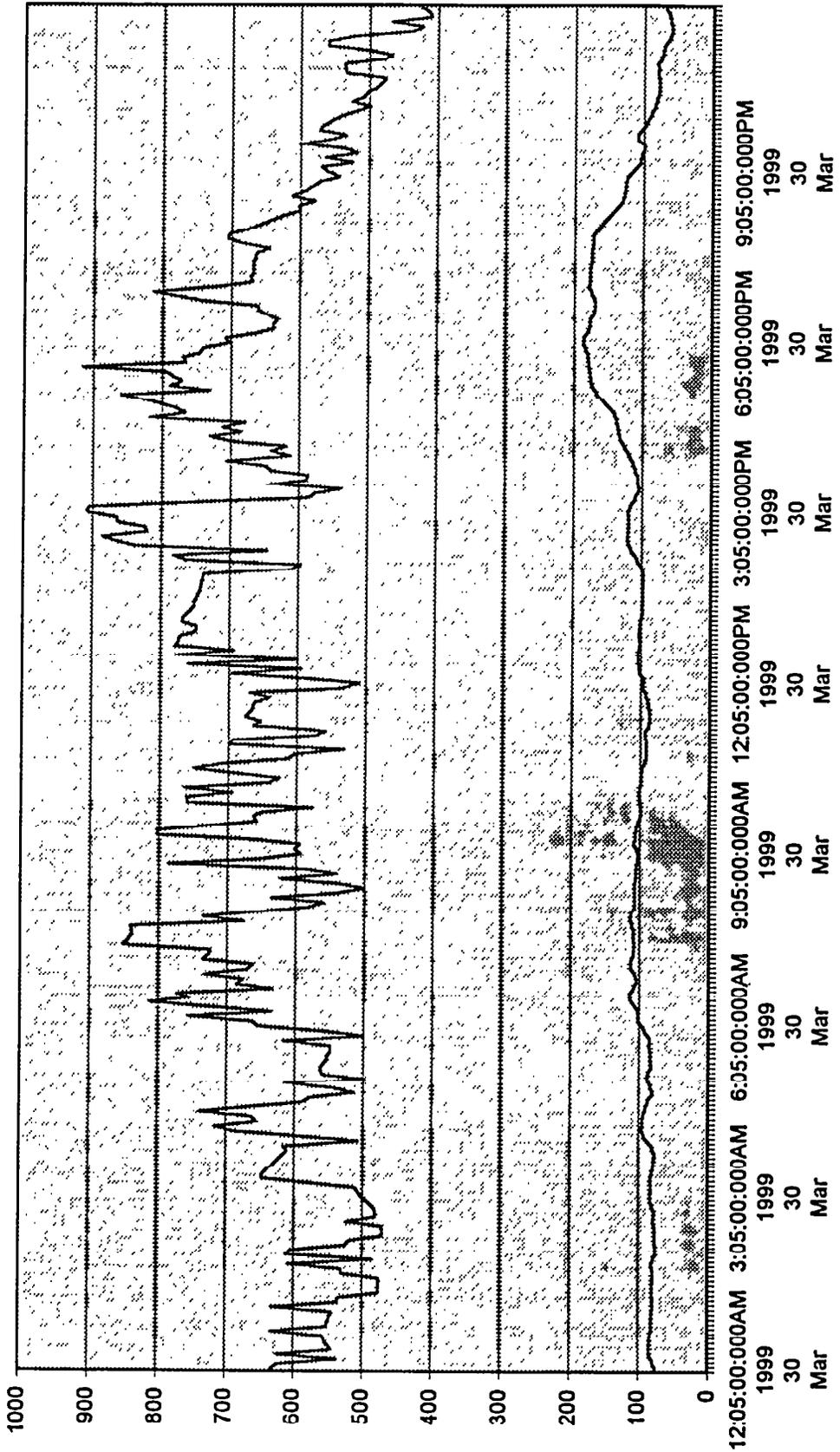
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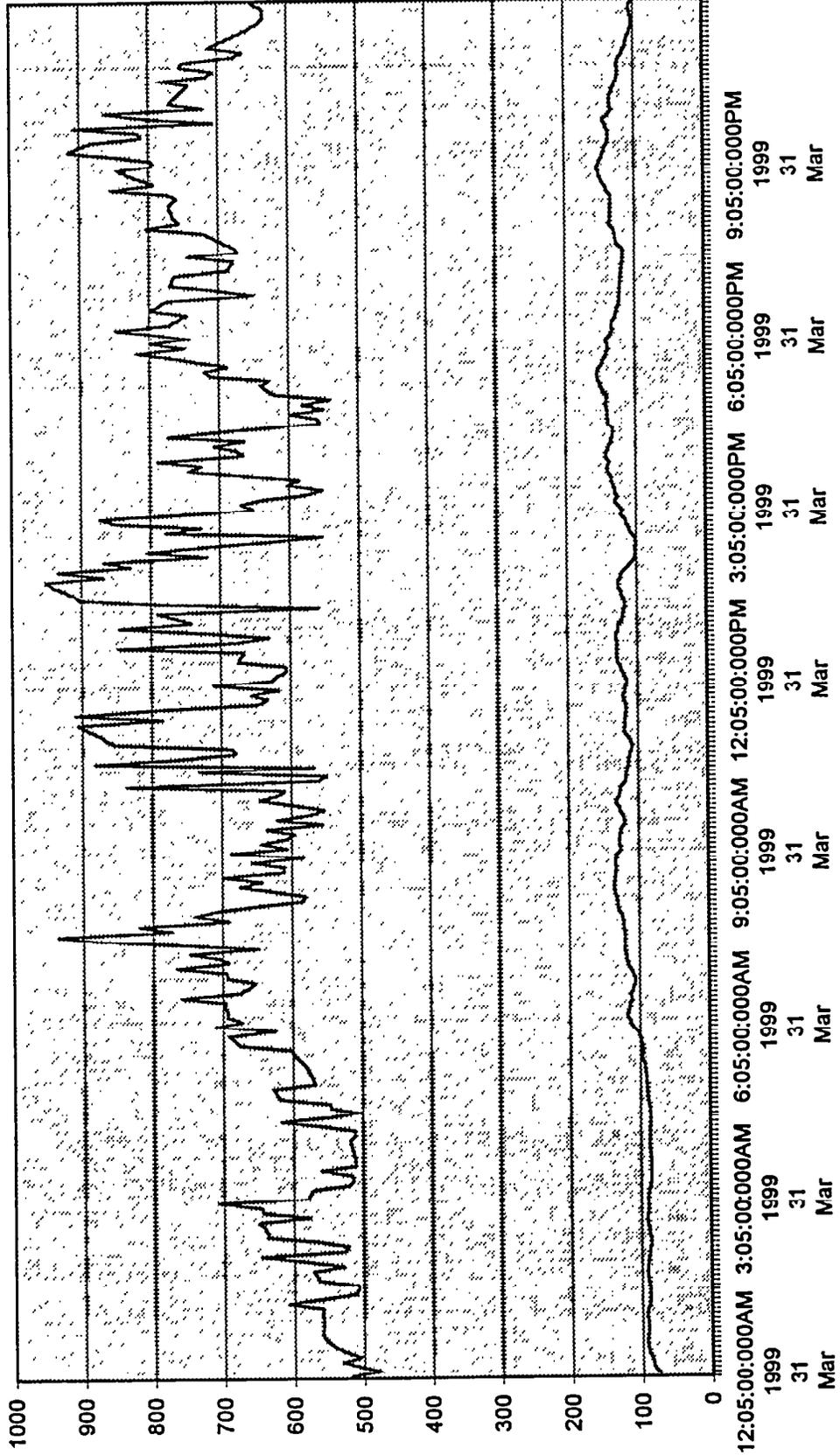
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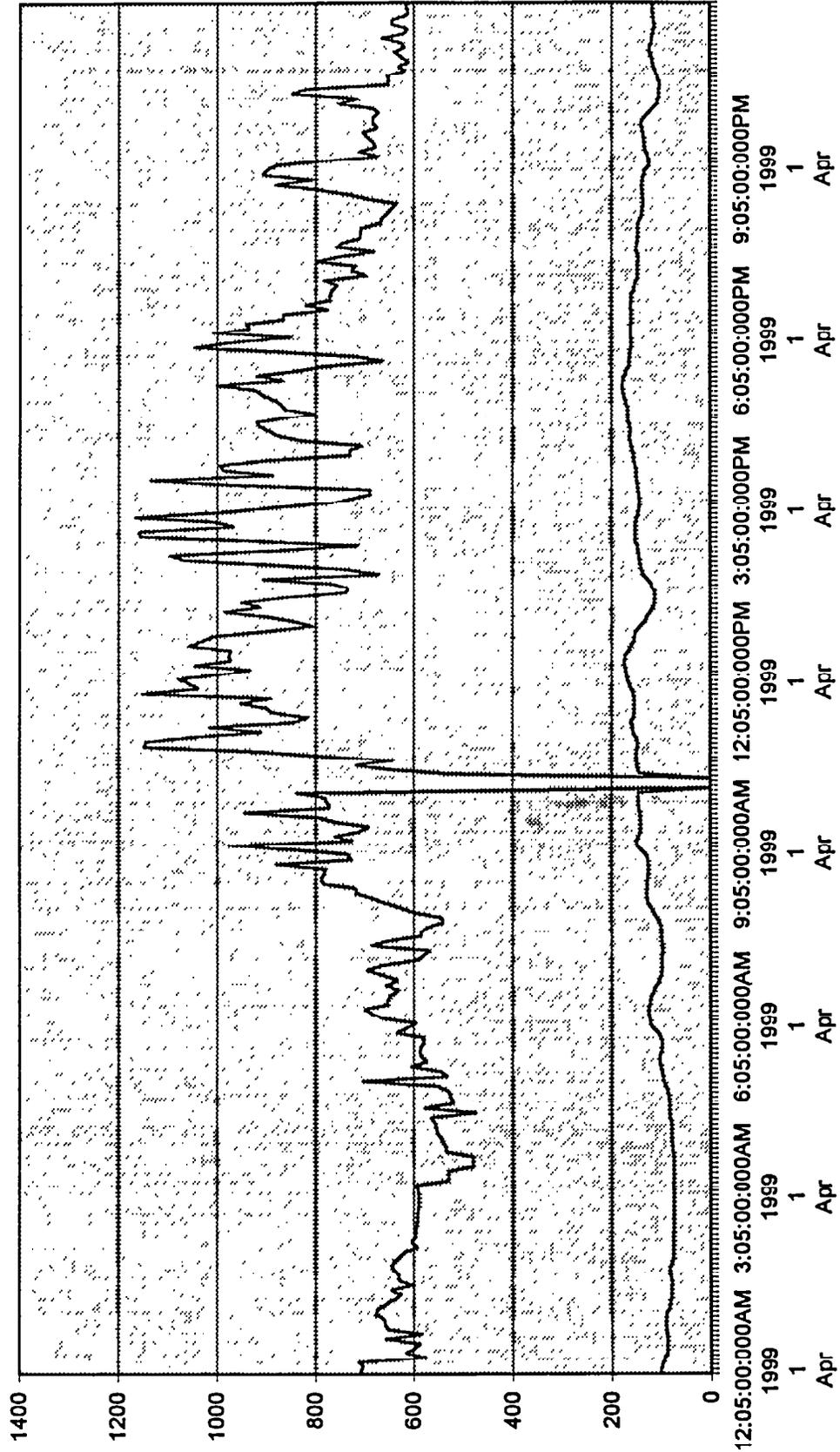
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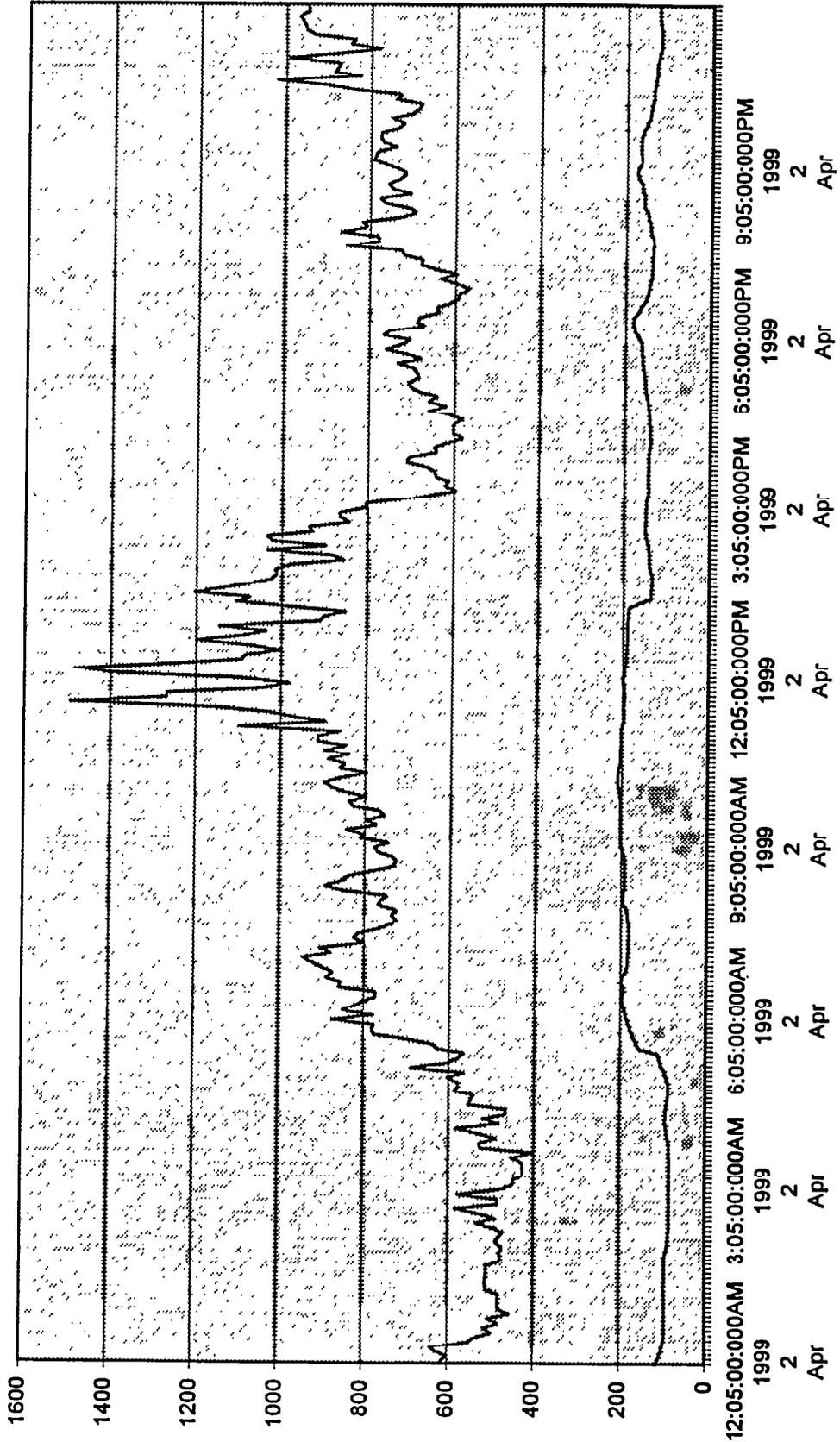
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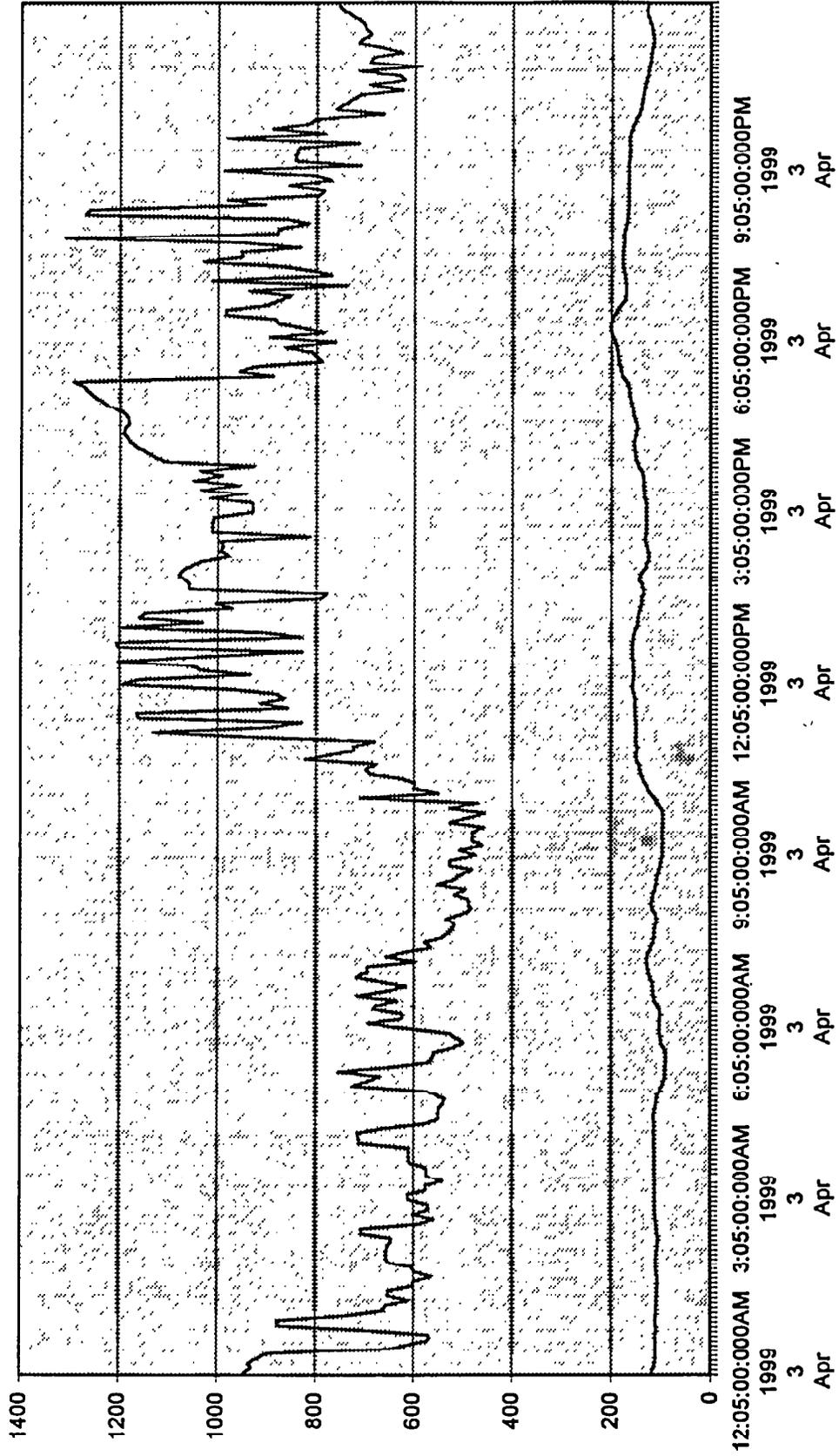
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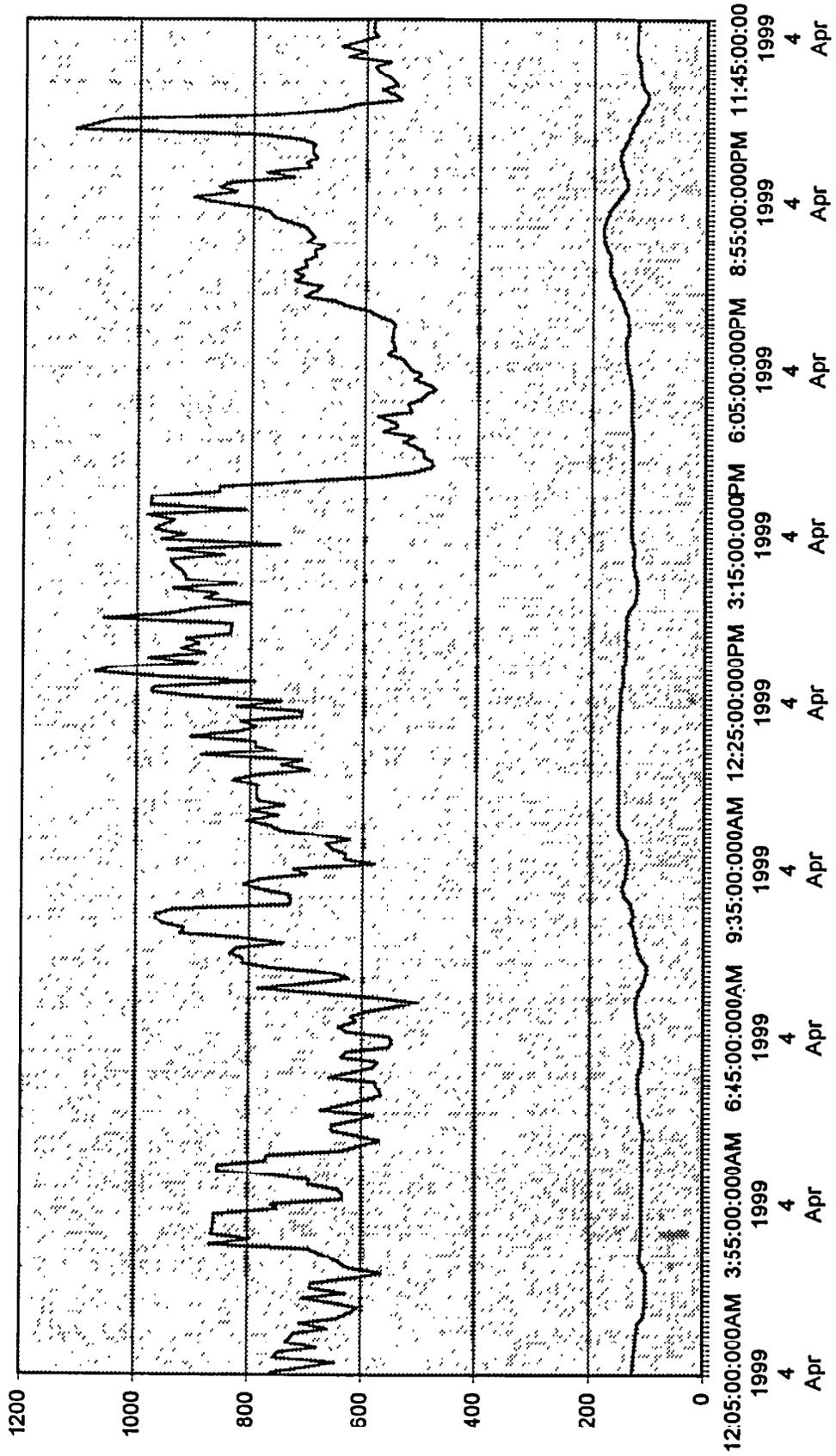
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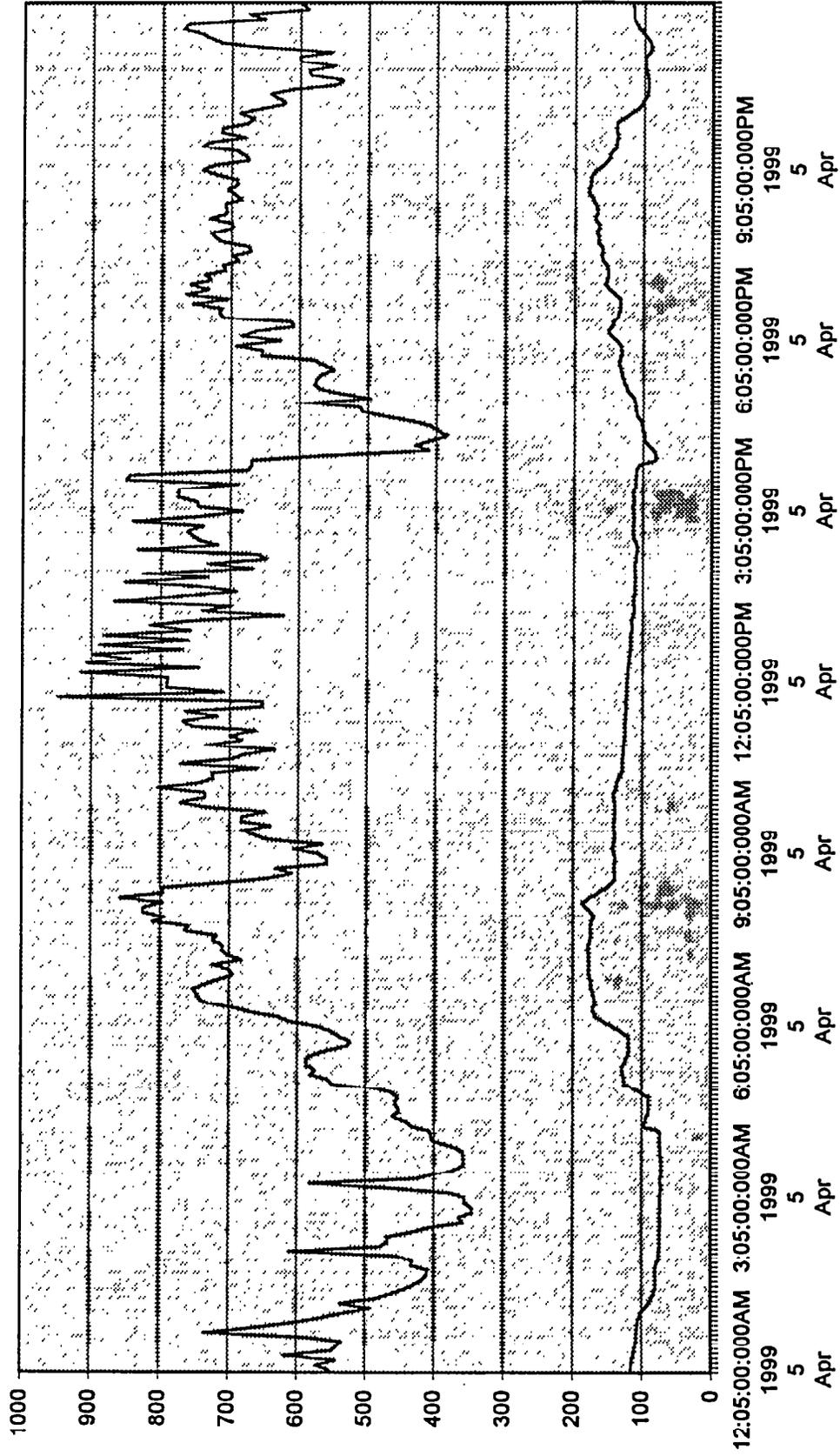
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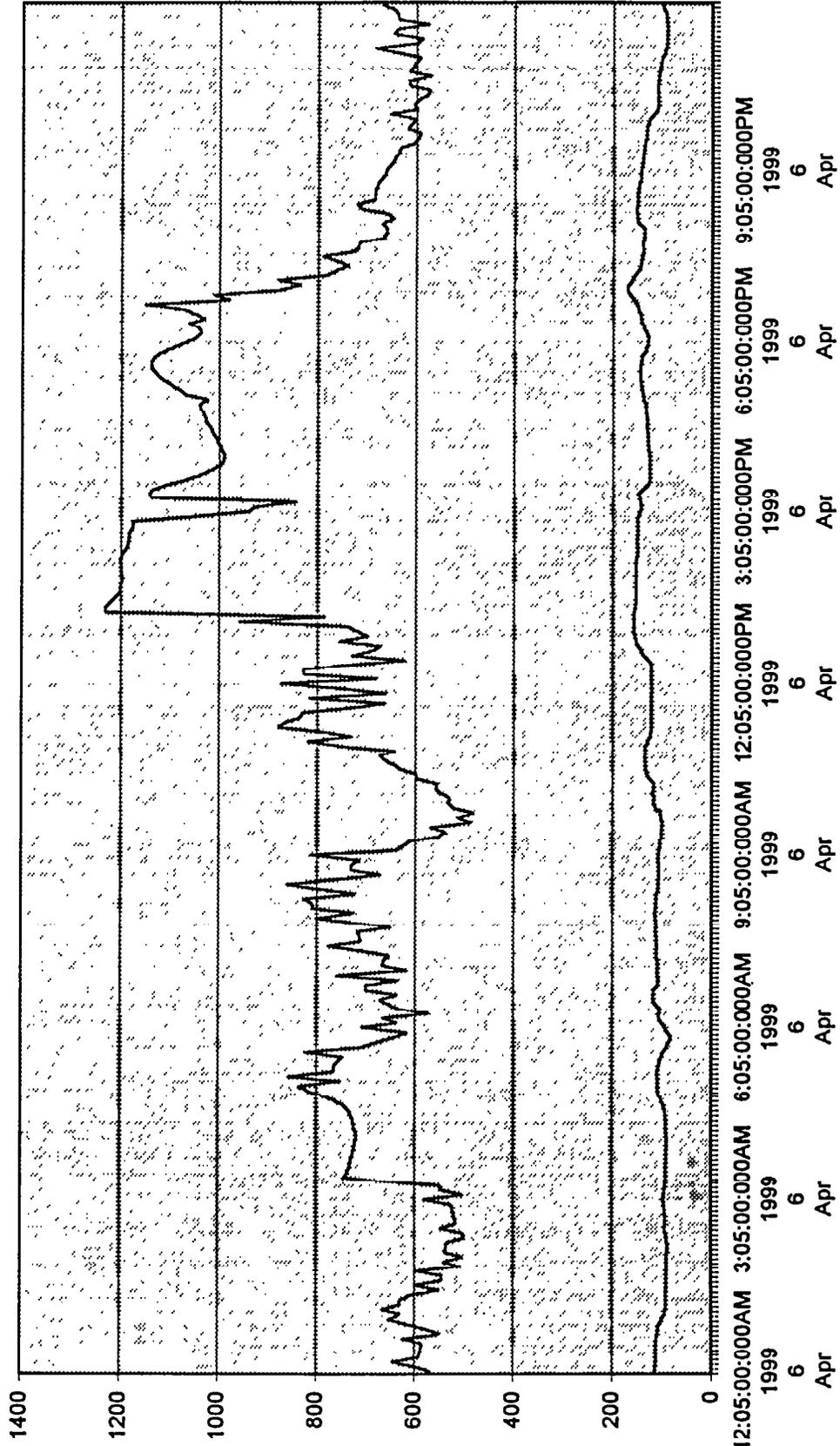
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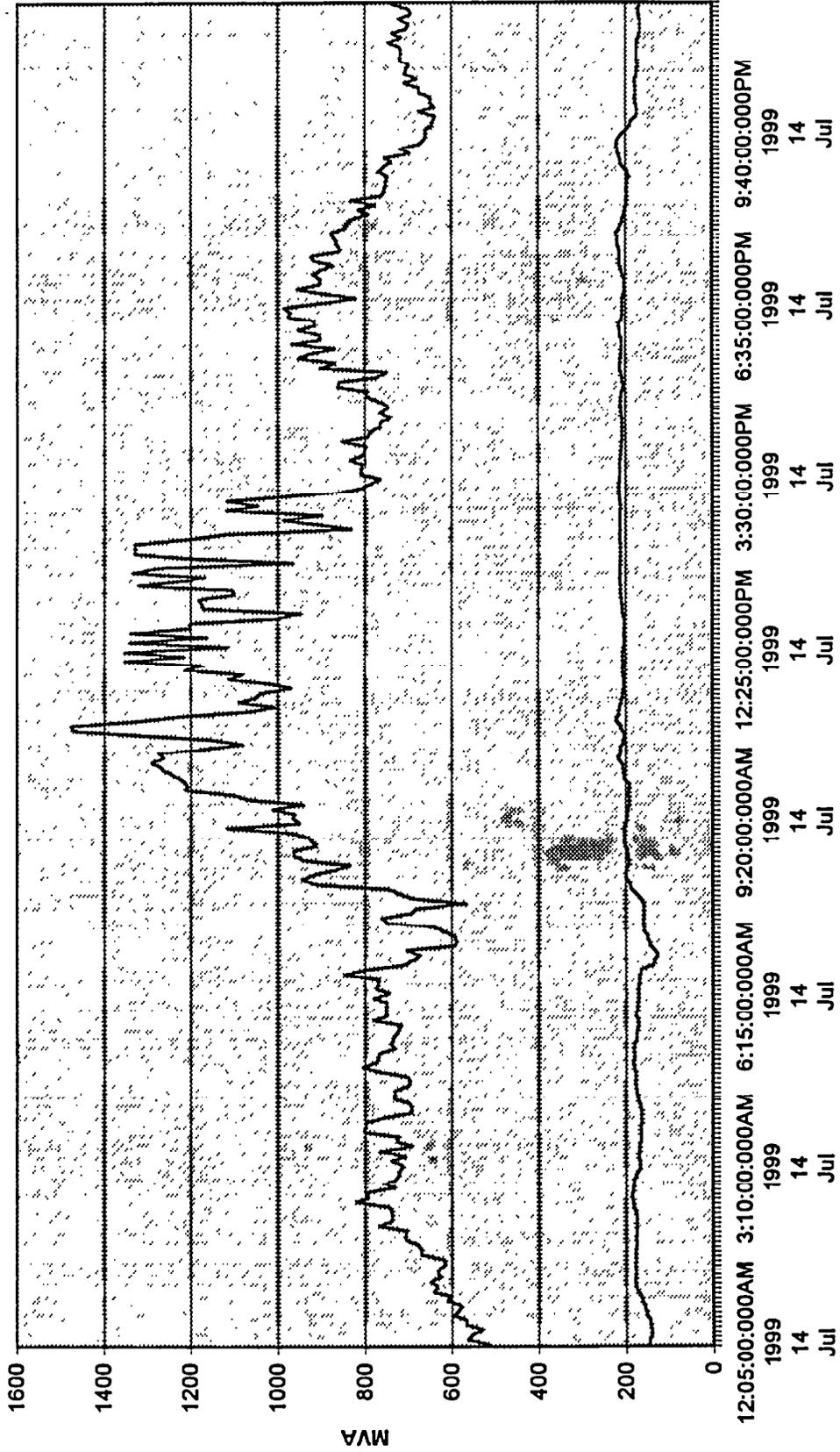
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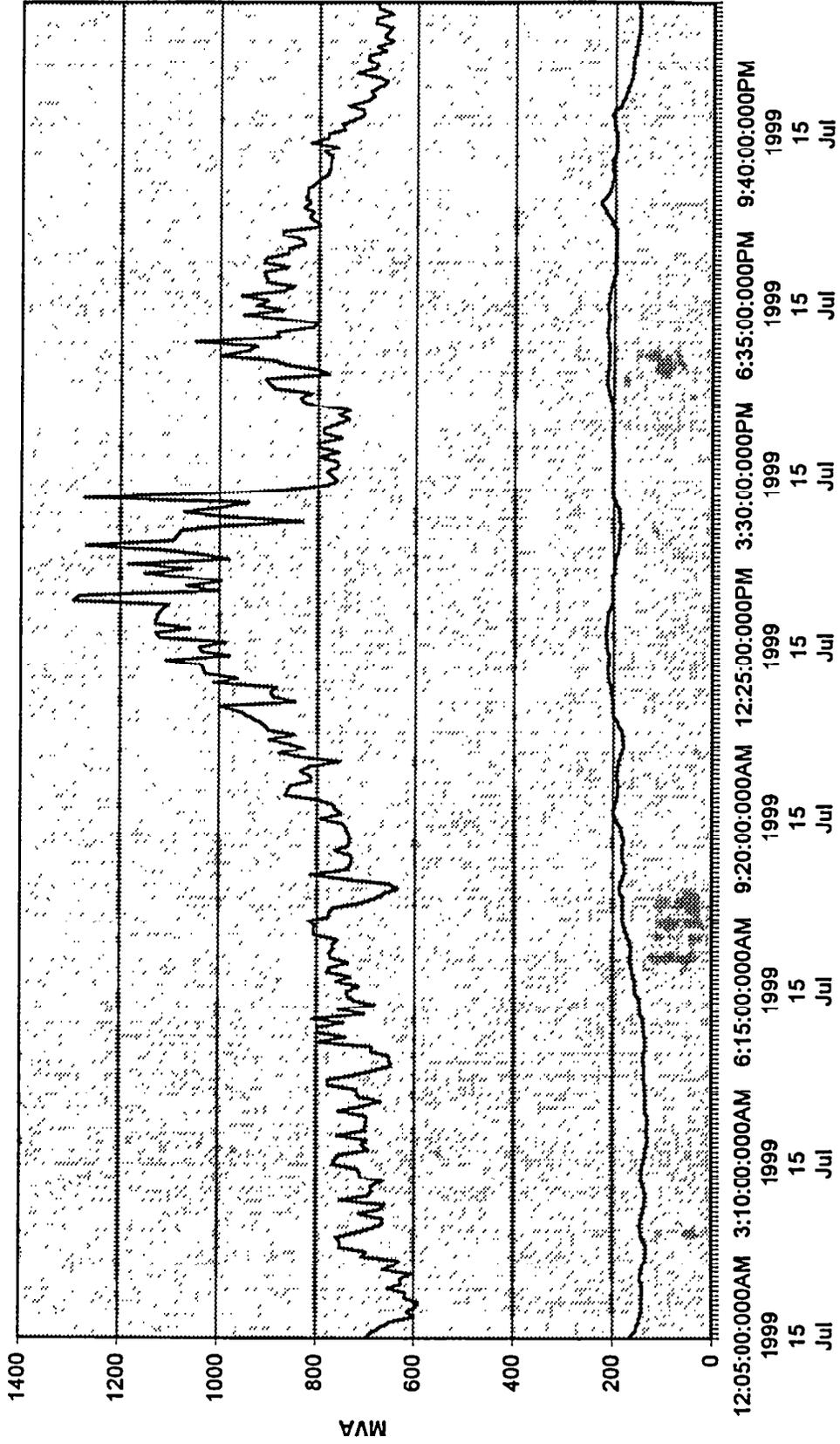
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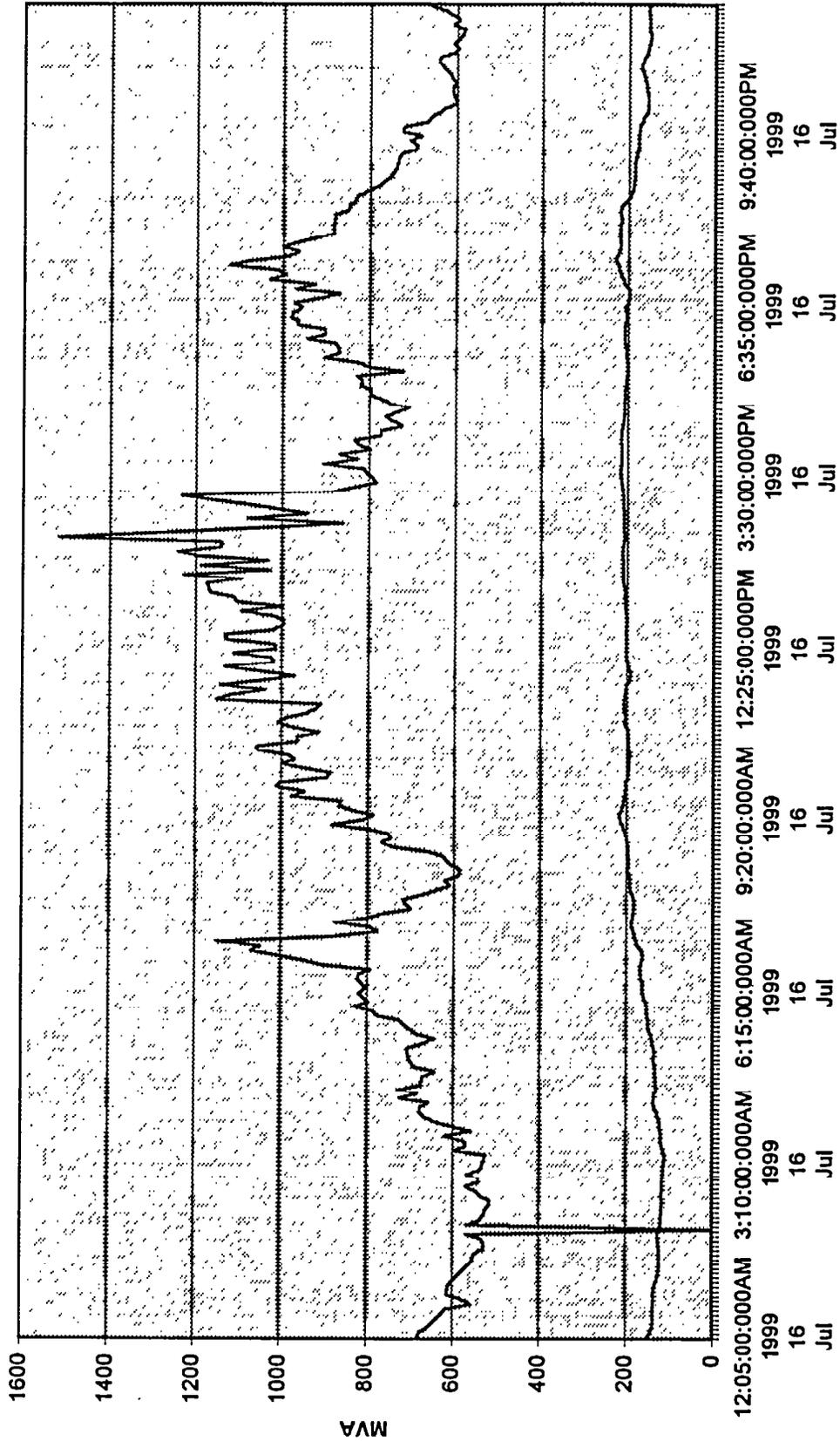
TL23052 DTCR Rating & Line Loading
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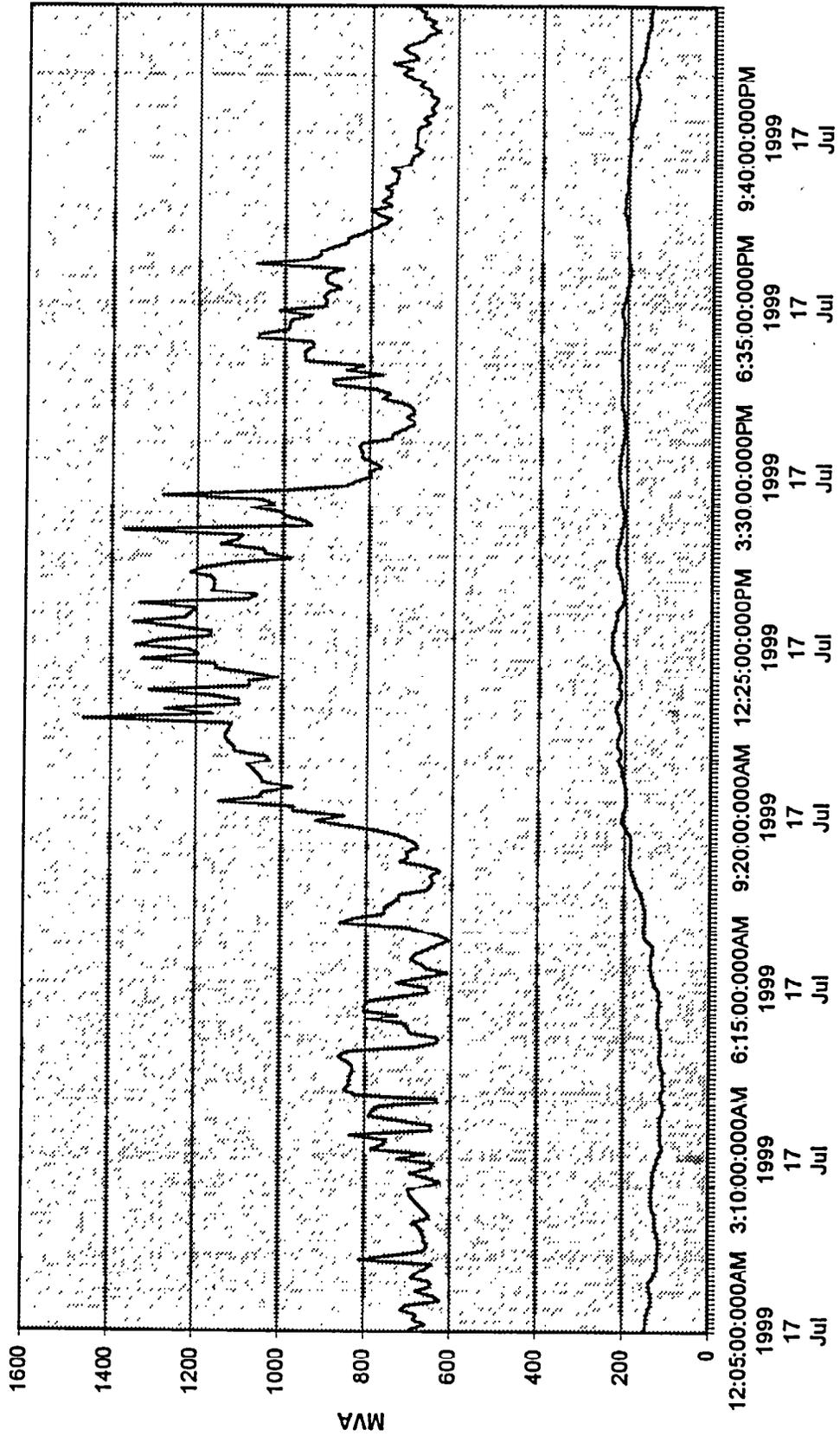
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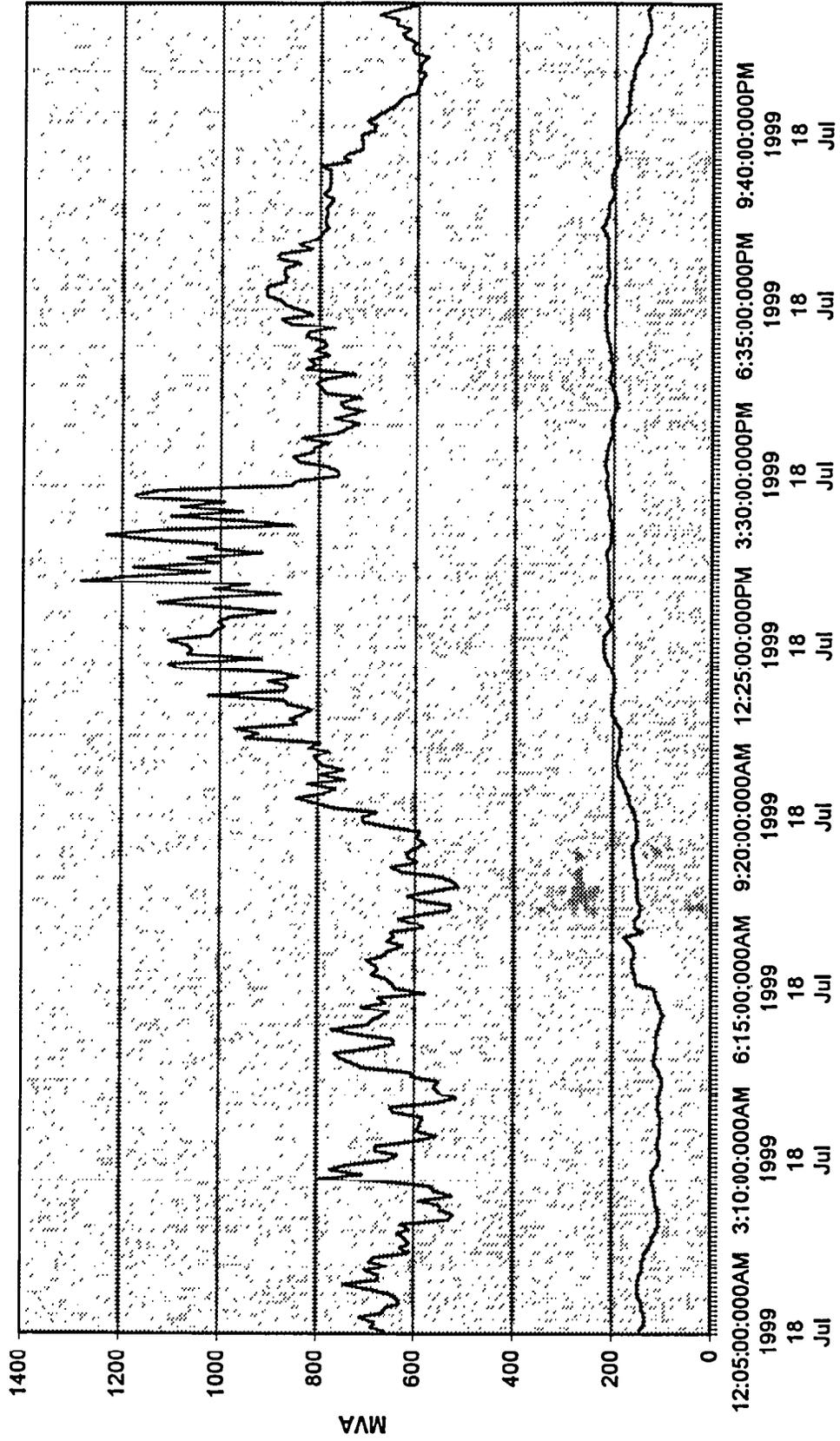
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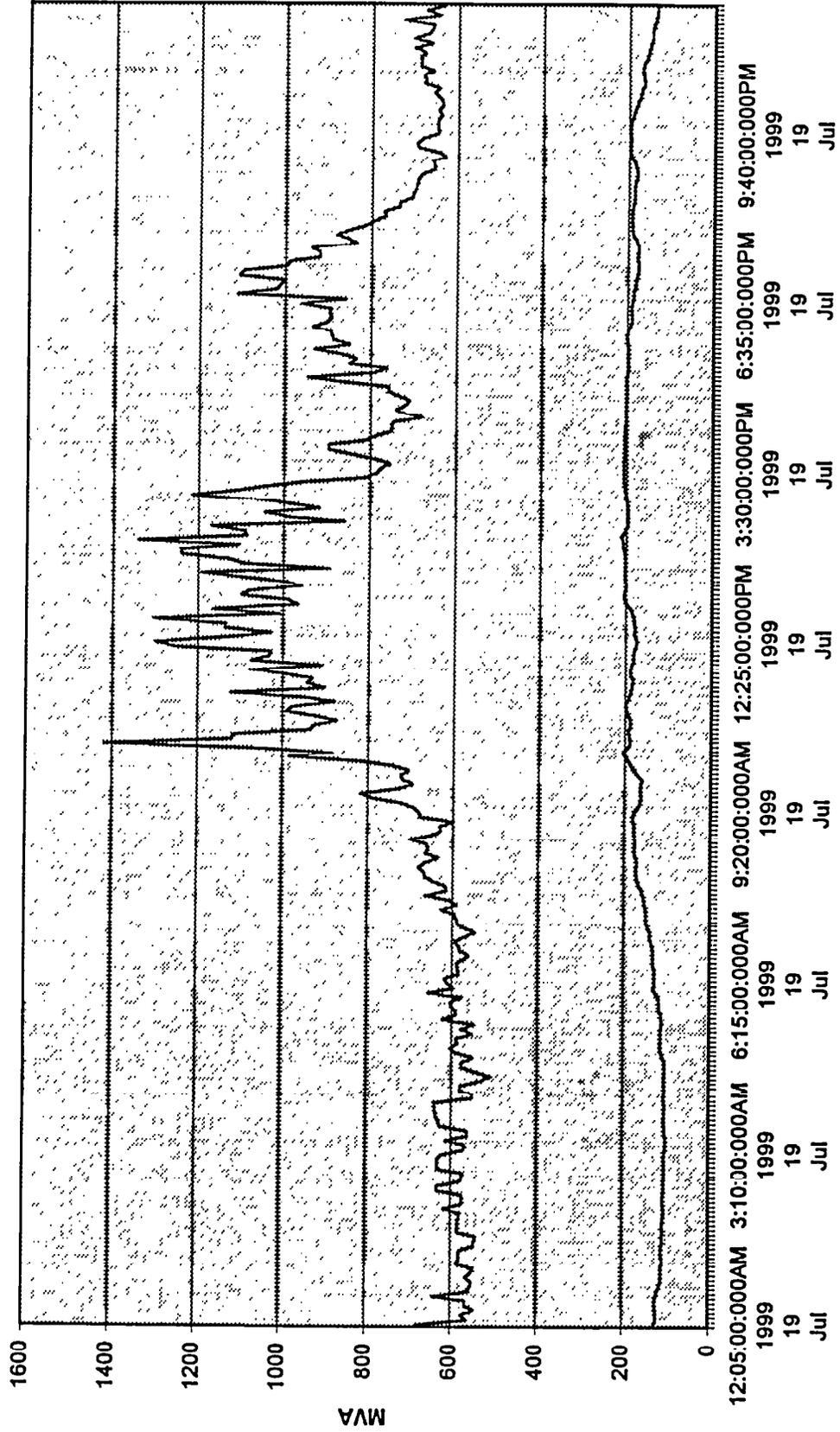
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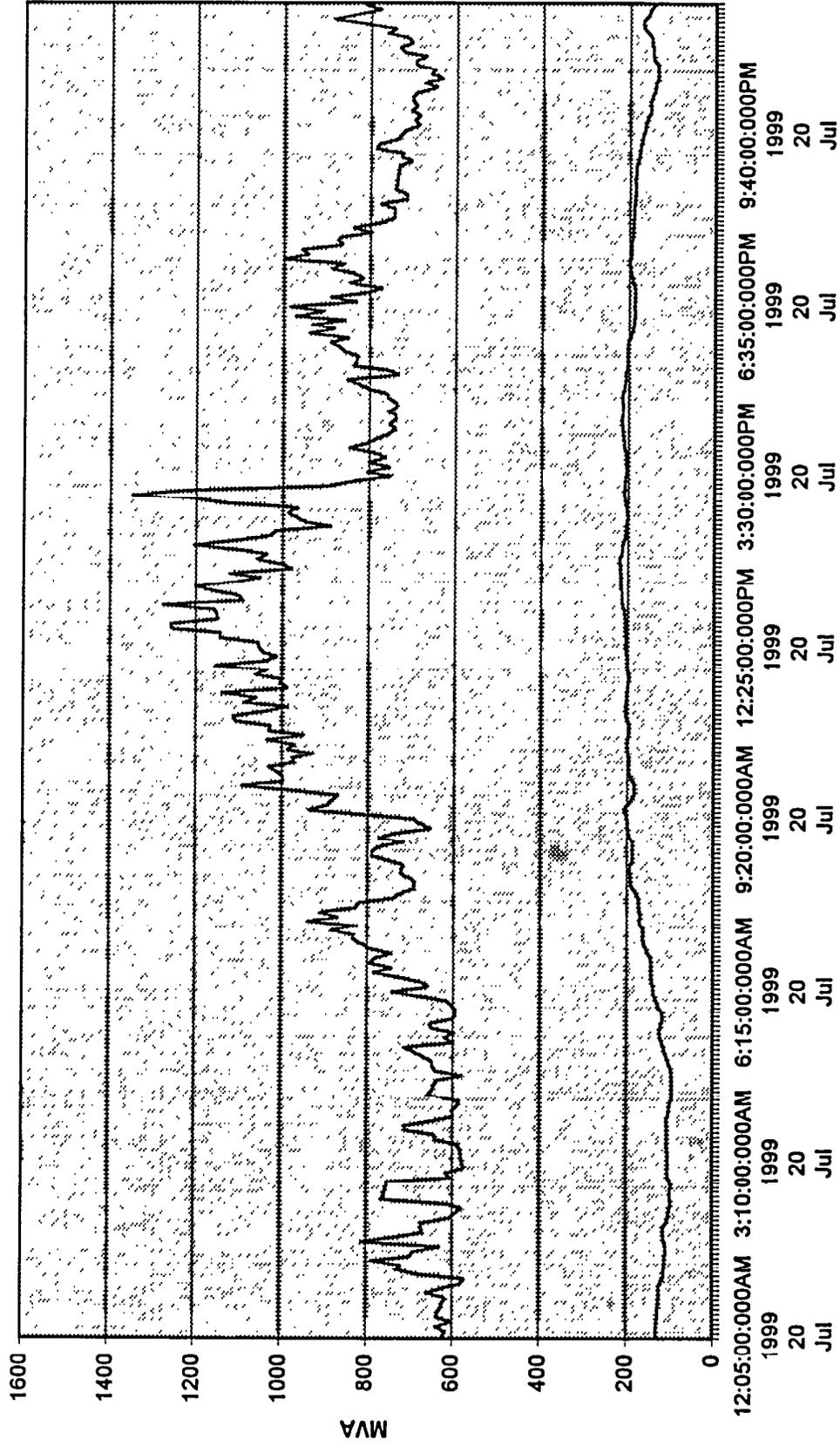
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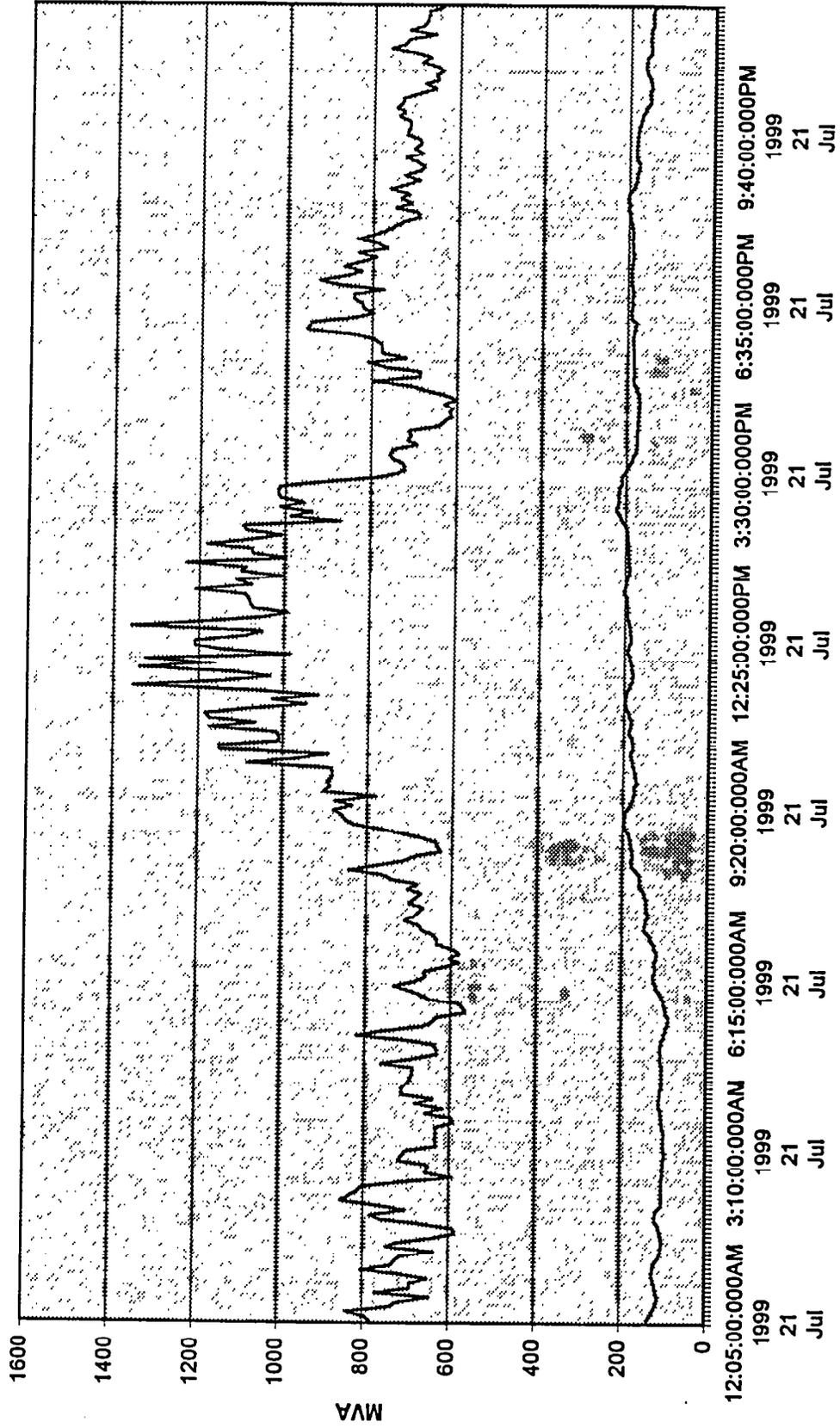
TL23052 DTCR Rating & Line Loading
July 19, 1999



TL23052 DTCR Rating & Line Loading
July 20, 1999



TL23052 DTCR Rating & Line Loading
July 21, 1999



Appendix B
Theory of Cable Tension Monitors and Related Technical Papers

"IMPROVING ASSET UTILIZATION OF TRANSMISSION LINES BY REAL TIME RATING"

Tapani O. Seppa, The Valley Group Inc., Ridgefield, CT

Decline of Transmission Capacity

Transmission lines can be classified by their transfer capability. A typical 115 kV line has a transfer capability of about 100 MW, or 0.1 Gigawatts, while the transfer capability of a 500 kV line is about 2 Gigawatts. These are the maximum amounts of power such lines are designed to carry. There are various reasons for these limits, but the most fundamental is the thermal limit, which always sets the maximum limit for a power transfer. At the thermal limit, called the thermal rating of the line, the conductors sag to a point beyond which they violate the safety clearances mandated by National Electrical Safety Code (NESC).

The NESC is deterministic. It states that lines may never be operated in violation of NESC clearances. For example, a 115 kV line crossing a road may never be operated at a clearance of less than 21 ft. above ground. Those who contemplate doing so better not leave a paper trail.

The transmission capacity of a transmission line can be determined by multiplying the capability of an individual line by its length. For example, a typical 20 mile long, 115 kV line has a transfer capacity of 20 miles x 0.1 GW, or 2 GW-mi (Gigawatt-miles). Similarly, a typical 50 mile long, 500 kV line has a transfer capacity of 100 GW-mi. The aggregate capacity of the whole transmission system is the sum of the individual line capacities.

If we divide the aggregate transfer capacity of the whole system by the coincident peak load, expressed in Gigawatts, the resulting ratio has a dimension of miles. This ratio represents the distance to which a typical generating plant could reasonably expect to sell power during peak load conditions. In many other industries, this would be called the "trade radius" of a given manufacturing facility. In this case, we can call it simply "ratio miles".

The importance of ratio miles becomes evident if we look at the developments of the past twenty-five years in the U.S., shown in Table 1.

TABLE 1.

Year	Transfer capacity GW-miles	Summer peak GW	Ratio miles
1974	64,000	338	190
1979	78,000	397	197
1984	96,000	451	214
1989	104,000	495	210
1994	107,000	550	195
1998 (est.)	116,000	648	178

Between 1984 and 1998, ratio miles declined from 214 to 178 miles, by 17%. Because the trade area is proportional to the square of the ratio miles, the average trade area of a generating plant is now less than 70% of what it was in 1984. In reality, the situation is even worse. The system is now strained to a much larger extent than before by wholesale trade and other third party transactions.

capital costs by \$200/kW, it is unlikely that any merchant plant owners would agree to such an amount.

Increasing System Utilization

If we cannot find the capital to physically increase the transmission system capability, what choices do we have? We can try to work the system harder. This requires both engineering solutions and procedural solutions.

The reliability and safety of transmission circuits can depend on voltage, stability, or thermal limits. Voltage and stability limits are deterministic to the degree that sophisticated network analysis programs can, with reasonable accuracy, calculate with the conditions to which reliability is endangered. Voltage and stability limits can also be enhanced, though at a relatively high cost, by use of capacitive or inductive devices, or by even more expensive FACTS-based devices.

Thermal limitations, which fundamentally affect every transmission line, are more complex. The basic limitation is that of line clearance from the ground and other objects. If the conductor is operated at too high a temperature, the increased line sag causes a violation of NESC mandated safe clearances. Operating a line in such a state can even result in fatalities. Knowingly operating a line under such conditions based on the "Risk Management Methods" presently in the vogue is neither responsible nor ethical. The applicability of Risk Management Methods ends at the conditions when people are killed and managers go to jail.

Actual thermal limitations depend on the weather. The most important weather variables are the wind speed and wind direction, as the lowest thermal capabilities occur when the wind speed is low and the wind is close to parallel to the line direction. High ambient temperature and solar radiation will also reduce the thermal capability of the line.

Unfortunately, wind speed and direction are local variables. Both are very unpredictable over even small distances. And the capability of a given line is limited by the lowest local wind speeds. So, if the average wind speed is 10 miles per hour along a 100 mile long line, but the wind on one line section of one mile length is 1 mph, the whole line is limited by this lowest local wind speed. As a consequence, line designers rate lines based on the statistically conservative assumption of a high ambient temperature, full sun, and a statistically low wind speed. A large number of studies have indicated that such traditional static thermal ratings are typically conservative between 95-99% of time, but are definitely not deterministically safe. So why have we not run into major problems before?

The reason is simple. Real thermal limitations occur only if :

- The line is loaded to or past the thermal limit, and
- Limiting conditions persist long enough for the conductor to heat up to its limiting temperature. This takes 30-45 minutes.

In the past, lines were very seldom, if ever, operated near their thermal limits. Most lines would expect such loads only under contingency conditions, typically for 1-3 hours each year, and chances were that weather conditions were benign at those times. Thus, statistically, a line might reach its limiting temperatures only once every ten or twenty years. The probability of a clearance violation was extremely low. This is no longer true today. If a utility posts a thermal limit of 200 MVA for a line, some power marketer or merchant plant is likely to assume that they can use that capability 24 hours a day, every day of the year. In many systems, this means a small but statistically significant possibility of clearance-related safety problems, because of a violation of NESC clearance limits.

- Real time ratings are 10-25% higher than the “book ratings” used by utilities, 95-98% of time.

Thus, we could expect to generate approximately a 10% increase in the real transmission capabilities - the equivalent of 10,000 GW-miles of construction - by equipping less than 10% of transmission lines with real time thermal ratings systems. This would have the equivalent effect of new construction worth \$10 Billion. As shown below, the cost of such rating systems for the required 20,000-30,000 circuit miles would probably be less than \$200 million.

This is obviously not a realistic expectation. A national, or even a set of regional, real time rating systems is not very likely under present political and economic conditions, in spite of its demonstrated technical feasibility. For now, real time rating is progressing through local initiatives, solving problems in locations where the economic payback is significant and immediate.

Real Time Tension Monitoring Systems

The following applications use real time rating systems based on conductor tension monitoring, details of which can be found in [1-6]. Over 150 of these systems have been installed for research, testing, and real time rating purposes. The latest such systems are directly linked to the utilities' EMS/SCADA systems and provide real time line ratings to operators. Data can also be used for planning and dispatch purposes. At present, 25 utilities have installed a total of 68 real time monitoring systems.

Typically, two monitoring locations are needed for a line of up to 20-30 miles in length, while longer lines may require three or four monitoring sites. The installed cost per circuit is typically \$60,000-\$80,000, but could be significantly less in larger volumes. The operating reliability of the present real time systems is exceptionally good. Maintenance intervals are 4-5 years. The systems are self-calibrating and have shown to retain their accuracy over time periods in excess of 5 years. Equipment failure rate is extremely low.

With an installed cost of \$2,000-\$5,000 per circuit mile, typically resulting in a capability increase of 10-25%, the method is obviously very attractive as shown by examples below.

Real Time Ratings at ENTERGY

Entergy is one of the major users of tension monitoring systems. “Initially installed for reliability on a heavily loaded 230 kV constraining link on the Entergy Amite South area, dynamic rating using line monitoring devices provided up to 20% more capacity increase over the summertime thermal rating. The additional capacity allowed Entergy to avoid load shedding during unplanned contingencies and enabled construction activities to take place without extended outages on the line” [4].

The latest applications at Entergy relate to lines connecting merchant power plants. In this case, the objective is to avoid curtailments during contingencies.

Contingency Action Avoidance

Presently, one of the most popular applications is avoiding unnecessary corrective actions during contingencies. As described earlier, most thermal “book” contingencies are not real. In the remaining cases, knowledge of actual real time ratings can be used to limit the necessary corrective measures or alternatively, to postpone corrective actions until they are absolutely necessary.

Note that most utilities base their line clearances on NESC limits plus a safety buffer. Safety buffers are necessary because clearances are subject to many unknown factors, such as creep, aluminum compression, and structural movements as well as construction and installation error

errors caused by the ruling span method [6].

A new application developed for Virginia Power was the annealing monitoring of an ACAR line section which was not clearance limited. Under contingency loading conditions, the conductor could reach temperature ranges where loss of strength was possible. Instead of a \$300,000 reconductoring, Virginia Power installed a \$25,000 tension monitor on the line section in 1994. Data from the installation is evaluated periodically and after any contingency load event. So far, the data shows that there has been neither loss of strength nor high temperature creep of the conductor [7].

Virginia Power has converted several of their systems to real time rating.

Experiences Outside the United States

TransPower New Zealand has been studying tension monitoring applications for over two years, with highly encouraging results. A recent report states: "The DLR rating provides 43% more capacity over static rating 60% of time, 70% more capacity for 40% of time and 100% more capacity for 20% of time" and "In general, we have observed that transmission line capacities can be increased during the hours of daylight which generally coincides with peak system times".

A large number of trials are in progress in six other countries.

Real-Time Ratings

At first glance, ratings on any specific line can look very confusing, as shown in Figure 1. Ratings can change quite rapidly, although a significant rapid decrease in ratings has a substantially lower probability than a rapid increase in ratings. As shown in Figure 2, rapid rating changes do not result in safety hazards in a short time. A rapid sag decrease is usually the result of rapid cooling caused by rain. On the other hand, rapid sag increases are very rare. Even if real time data were collected only every 15 minutes, as shown in Figure 2, the largest necessary clearance buffer would be less than 1 ft. And for data collected every 10 minutes, the necessary clearance buffer would only be about 6 inches.

Similarly, rapid load changes will not cause instantaneous sag changes because of the thermal inertia of the conductor; typical transmission line conductors have thermal time constants of 10-20 minutes. Note also that the real time rating systems can calculate transient ratings as well as static ratings and that tension-based real time rating systems can provide clearance warnings to the operators.

Predictive Ratings

While real time ratings are useful for system operators, additional benefits are realized when ratings can be accurately predicted for the next 24 hours. Such data can be applied for dispatch purposes as well as for line maintenance scheduling. In the future, such data could also be used for marketing interruptible energy, with reliable predictions of transaction risks.

If the ratings data is sorted out as probable values for time of day, as shown in Figure 3, the data becomes very useful for dispatch purposes. This is because at a given site, the daily temperature, solar radiation, and wind generally have specific statistical distributions. At most sites in the U.S., daytime winds commonly have much higher speeds, are more turbulent, and thus are more directionally random, than nighttime winds. For a large percentage of transmission lines, especially for those designed for temperatures over 80°C, this means that lines usually have significantly higher daytime ratings than assumed by "book" ratings.

References

- [1] T.O. Seppa, H.W. Adams, D.A. Douglass, N. Coad, A. Edris, P. Olivier & F.R. Thrash. "Use of On-Line Tension Monitoring for Real-Time Thermal Ratings, Ice Loads, and other Environmental Effects". CIGRE 22-102, 1998, Paris, France.
- [2] T.O. Seppa, "Increasing Transmission Capabilities by Dynamic Line Rating". T&D World Expo Conference Proceedings, November 12, 1997, Atlanta, GA.
- [3] T.O. Seppa, "Accurate Ampacity Determination: Temperature-Sag Model for Operational Real Time Ratings". IEEE Transact. on Power Delivery, Vol. 10, No.3, July 1995, pp. 1460-1470.
- [4] "How to get maximum value from existing transmission". Electrical World, August 1998, pp. 14-20.
- [5] D. A. Douglass & A-A. Edris, "Field Studies of Dynamic Thermal Rating Methods of Overhead Lines". IEEE T&D Conference Proceedings, Vol.2, pp. 842-851, April 15, 1999, New Orleans, LA.
- [6] W.F. Kelly & T.O. Seppa, "Clearance Assurance for Transmission Systems 'CATS' - Mt. Storm - Doubs 500 KV Line". SEE Meeting, Orlando, FL, May 26, 1995.
- [7] W.F. Kelly, Verbal Report, IEEE WG on Thermal Aspects of Bare Conductors and Accessories. 1998 SPM.

Figure 3.

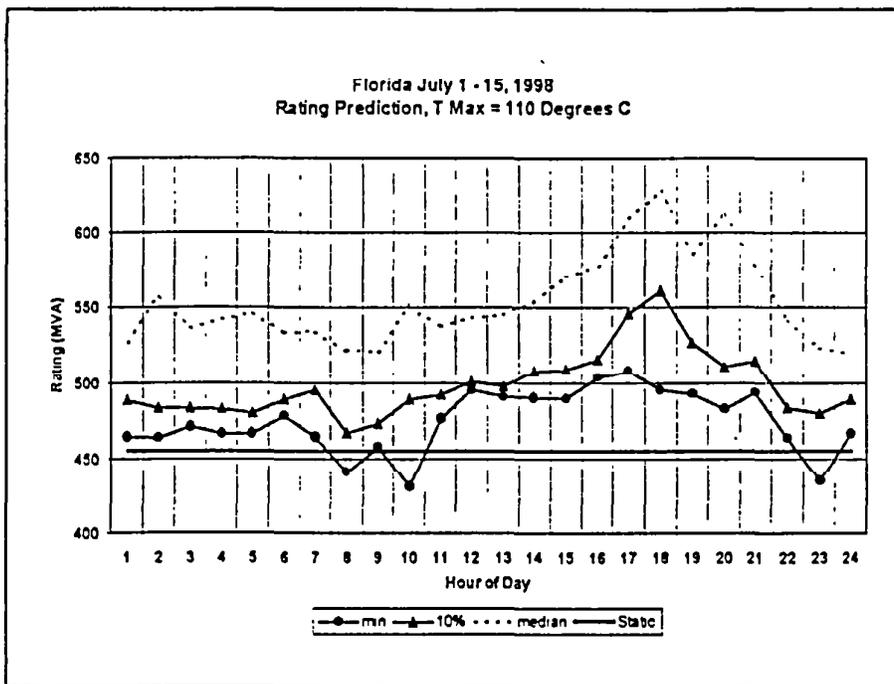
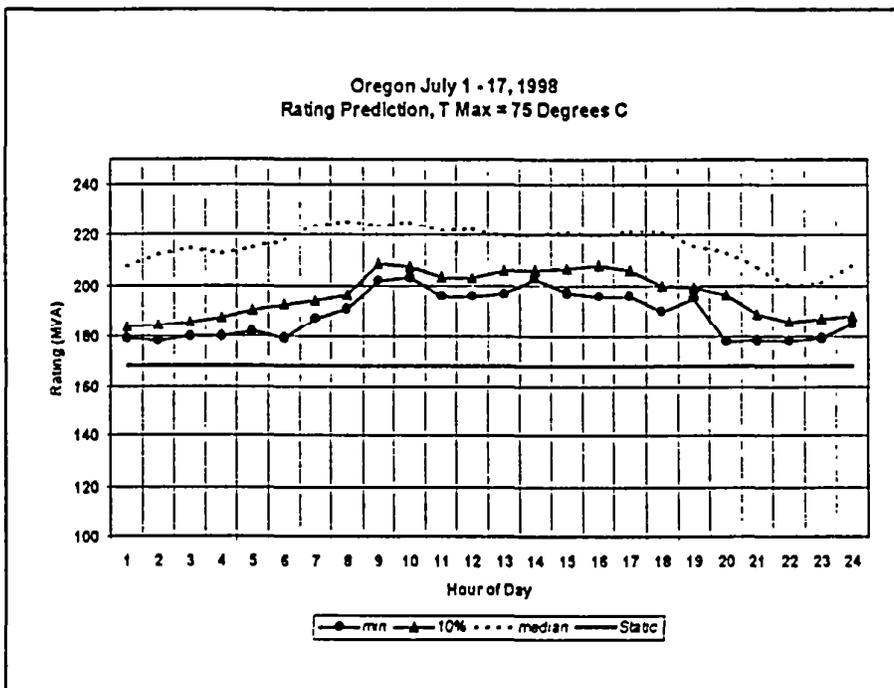


Figure 4.



**EPRI Workshop on Real Time Monitoring and Rating of Transmission and
Substation Circuits: A Technology Increasing Grid Asset Utilization
February 26-28, 1997 - San Diego, CA**

Real Time Rating Systems

Tapani O. Seppa, The Valley Group, Inc.

What is Real Time Monitoring ?

Real Time Rating systems currently in use

Rating of Overhead Lines in EPRI DTCR Project

Other Possible Applications of Tension Monitors in DTCR Project

160 installations

FERC NOPR
*RTO - Limit of Equip
Red. use*

Real Time Rating

Method	Error sources
--------	---------------

- | | |
|------------------------|--|
| 1. Tension monitoring: | Tension accuracy: 0.2-0.4%
Sag accuracy: 0.5-1.0% |
|------------------------|--|

Resulting error in the sag of a 1000 ft. span: 0.2-0.3 ft.

- | | |
|-------------------------|--|
| 2. Surface temperature: | $\pm 2.5^{\circ}\text{C}$ (sensors) [Foss]
$\pm 5-10^{\circ}\text{C}$ (variation in a single span) [Jerrel, Black]
$\pm 10-15\%$ of temperature rise within 1500 ft. distance [Seppa, Cromer, Whitlatch] |
|-------------------------|--|

Resulting error in the sag of a 1000 ft. span: 0.6-2.0 ft.

- | | |
|---------------------------|---|
| 3. Weather-based ratings: | $\pm 5-10^{\circ}\text{C}$ (near sensors) [Black]
$\pm 15^{\circ}\text{C}$ (1 mile distance) and
$\pm 30^{\circ}\text{C}$ (7 mile distance) [Jerrel, Black, Parker] |
|---------------------------|---|

Real Time Rating

Method	Additional error sources
--------	--------------------------

1. Tension monitoring:

Rating requires at least 3-4°C temperature rise.

2. Surface temperature:

Core temperature (which determines the sags) can be up to 10°C higher than the surface temperature.

For ACSR conductors, sags above 100°C have significant uncertainties because of aluminum compression.

Temperature sensors are "heat sinks". Heat sink effect depends on wind speed and wind direction.

Rating requires at least 3-4°C temperature rise

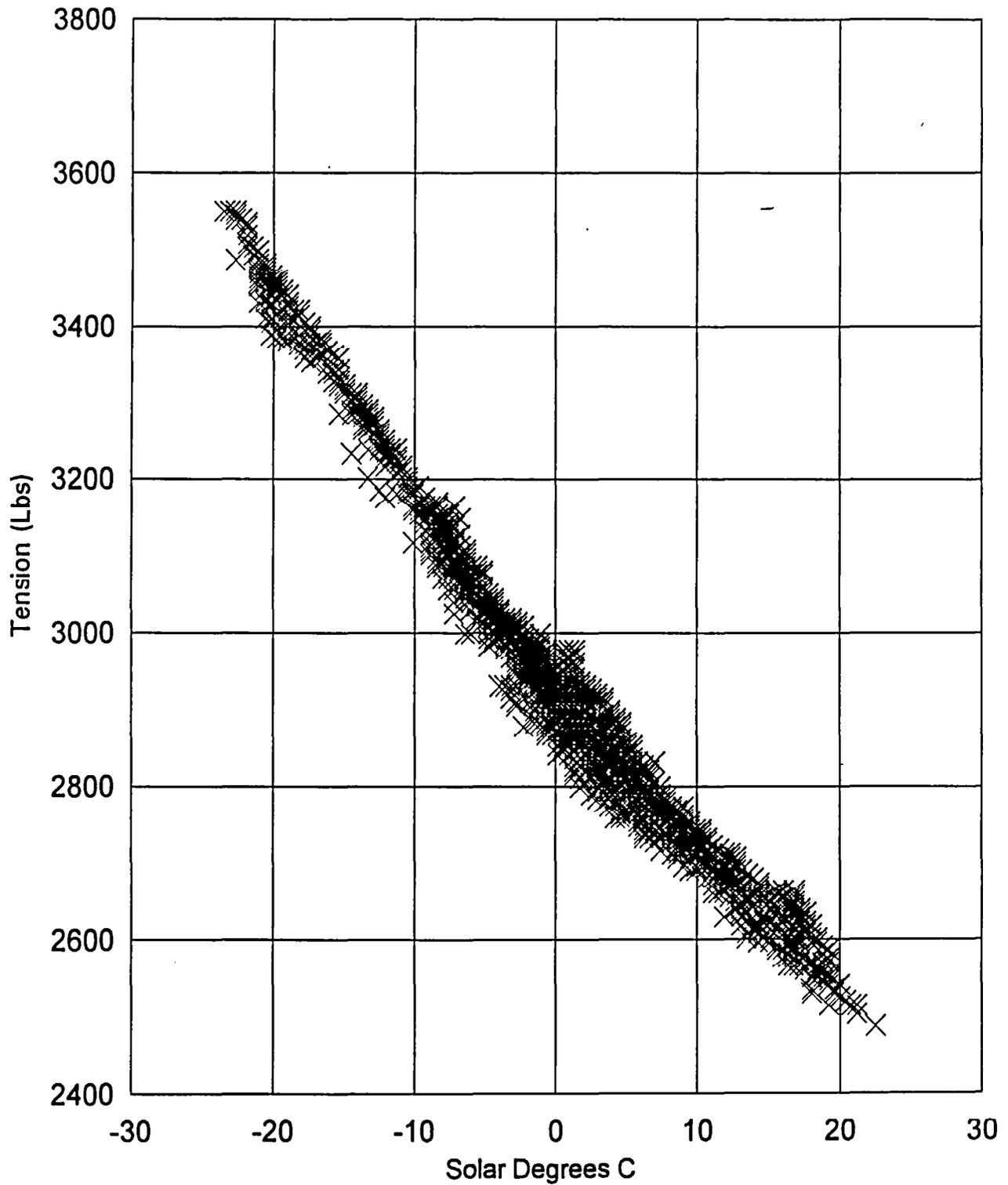
3. Weather stations:

Same error sources as for conductor temperature.

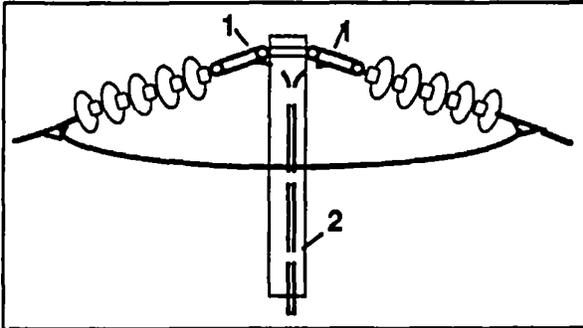
Inaccurate for the low wind speeds when the ratings are most important.

Weather sensors are maintenance-intensive.

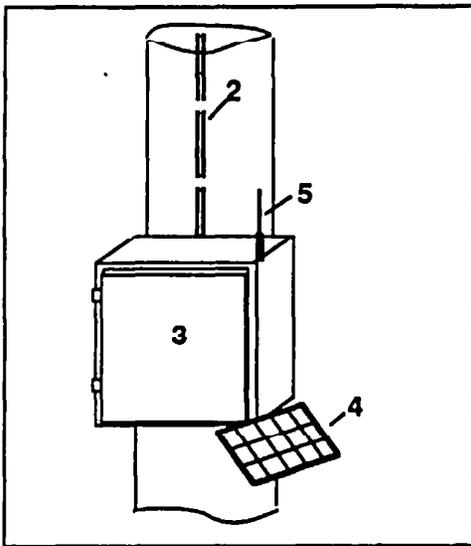
SN-228-94 01/26/97 to 02/21/97
Tension vs Solar Temperature - Port 1



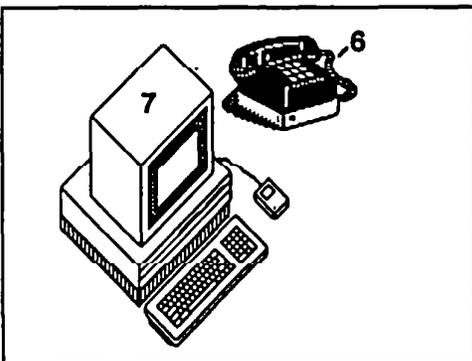
CAT-1 TRANSMISSION LINE MONITORING SYSTEM



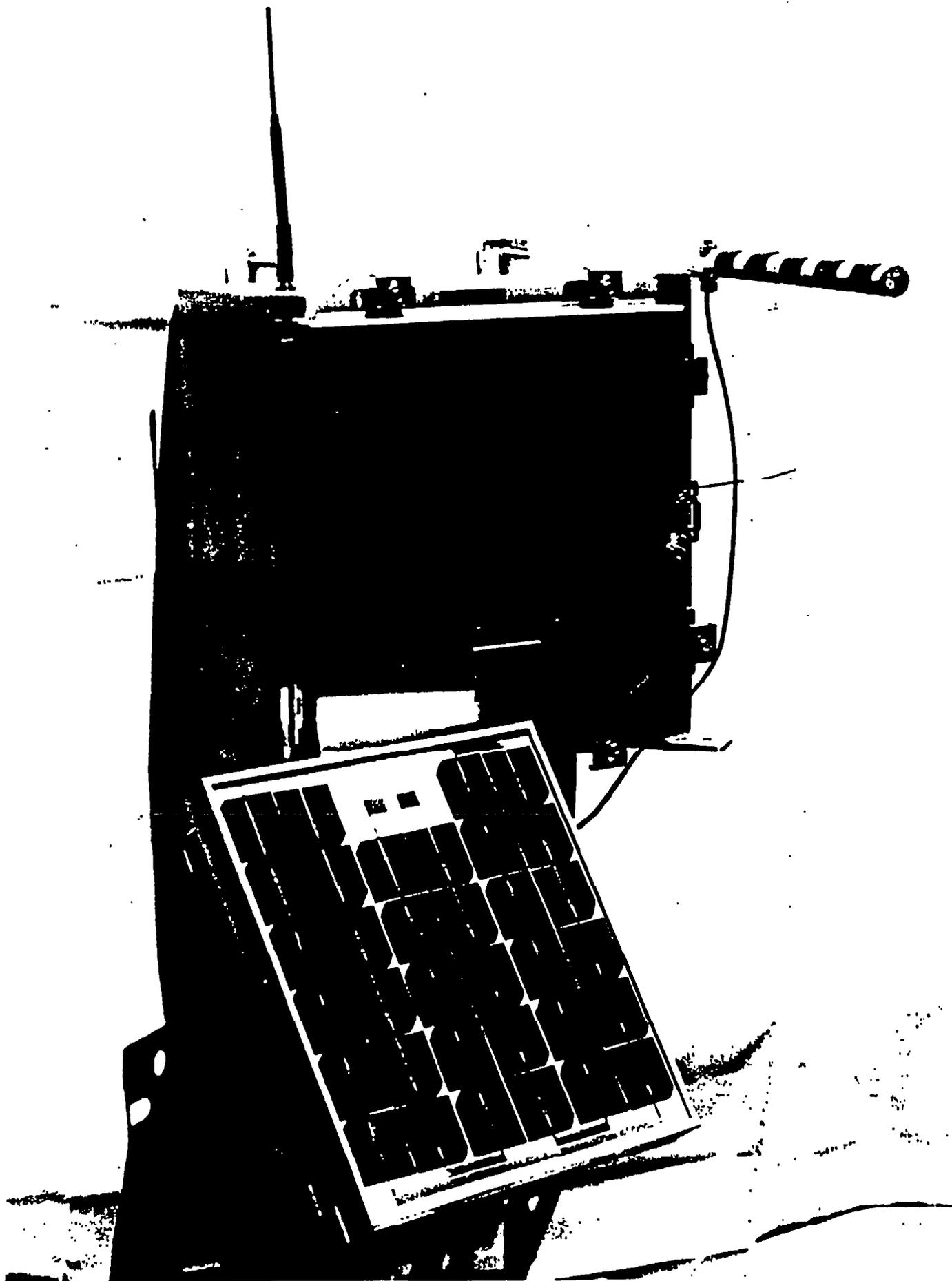
Load cells (1) are installed between the crossarm and the deadend insulators at both sides of a deadend structure. They are connected with shielded cables (2) to the CAT-1 main unit.



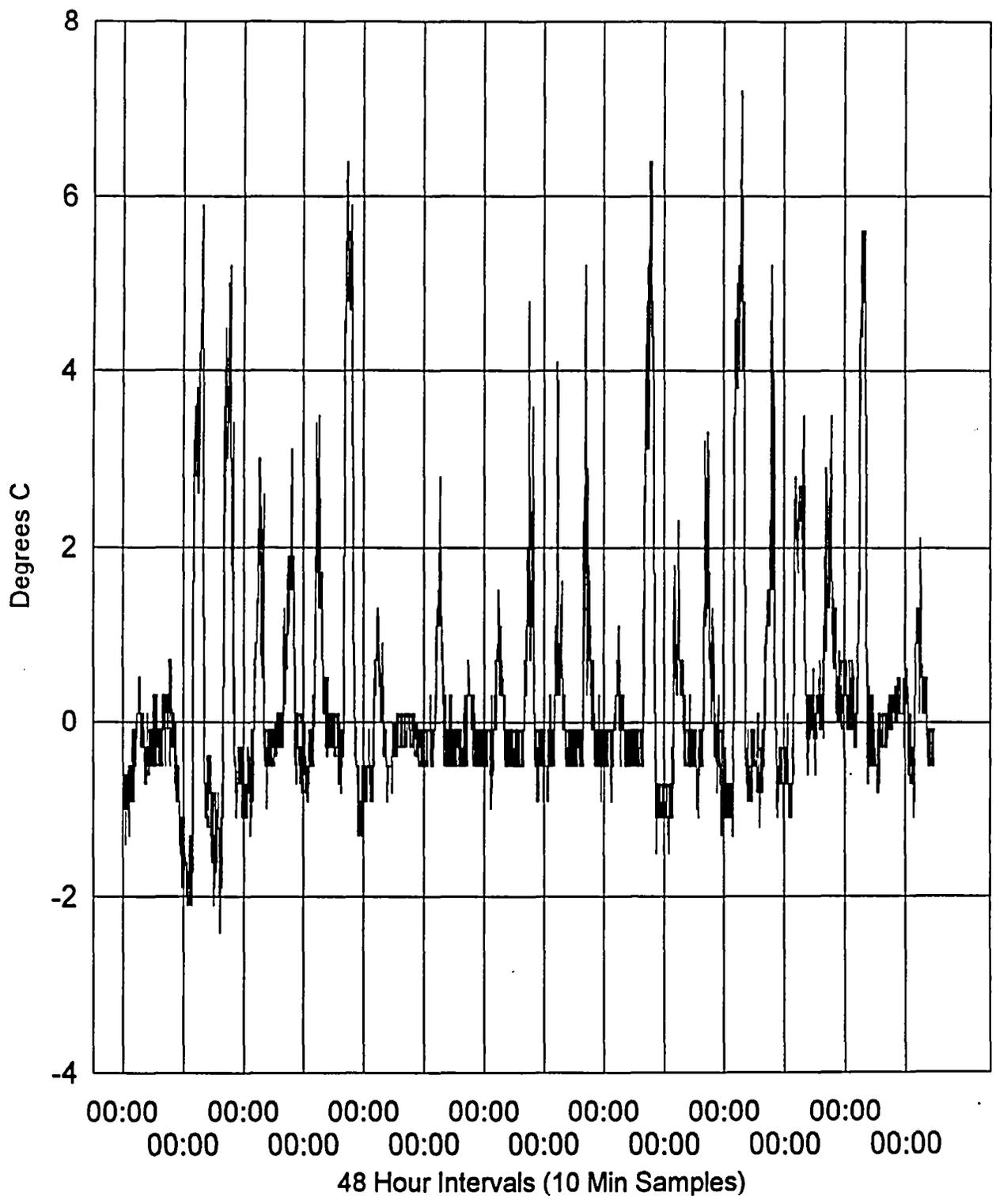
The CAT-1 main unit (3) contains the signal conditioners, the main CPU and the data logger. It is powered by a solar panel (4) with a backup battery. It communicates the data via cellular telephone (5) to a remote common carrier cell site. Other communications methods can also be used. The system can be programmed remotely.



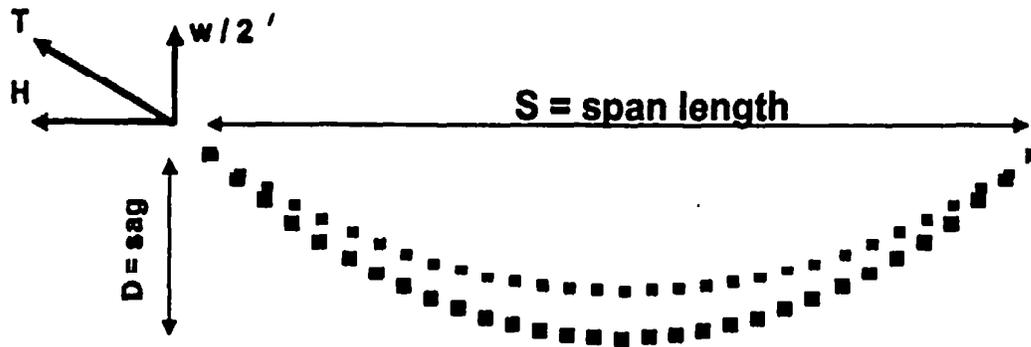
The data can be received at an engineering office via common carrier telephone line (6) and any MS-DOS PC with a modem (7). Alternatively, clearance alarm data can be sent either to the SCADA Master or to a RTU of the the SCADA system.



SN-228-94 01/26/97 to 02/21/97
Net Radiation Gain



TRANSMISSION SPANS ARE CATENARY CURVES



$$C = H/w_0$$

$$\text{Sag} = \text{Span}^2 / 8 C$$

$$\text{Slack} = 8 \cdot (\text{sag}^2) / 3 \cdot \text{span}$$

$$H = \sqrt{T^2 - (w/2)^2}$$

Slack is the difference of length of the suspended conductor and the length (cord) of the span

Other Possible Applications of Tension Monitors

- 1. Ice load monitoring and ice warnings
Already in use at two utilities**
- 2. Monitoring of bundle collapse (SRP)**
- 3. Monitoring of annealing (VEPCO, Illinois Power)**
- 4. High temperature sags of different conductor types
(Texas Utilities)**
- 5. Galloping studies (Southwire/CILCO)**
- 6. High-temperature sag/temperature relationship**
- 7. Creep (normal and high temperature), wind loads**

A PRACTICAL APPROACH FOR INCREASING THE THERMAL CAPABILITIES OF TRANSMISSION LINES

Tapani O. Seppa, Senior Member, IEEE
The Valley Group, Ridgefield, Connecticut

Abstract

The capability of most transmission lines is presently determined by thermal ratings. Ratings can be substantially increased if the overall ratings approach is based on recognizing that thermal ratings have three different aspects: Planning, Dispatch and Operations.

The general approach to transmission line ratings has been deterministic. The key reason is that transmission lines must be operated within safe clearances at all times. The proposed combination of a probabilistic planning approach combined with a deterministic operations view can pragmatically increase transmission capabilities by 20-30% with a 99% availability and a 100% safety.

This report proposes that transmission lines should be rated in the same way they are designed, i.e. based on the ruling span. The operating safety requirements that are based on clearances can be maintained by monitoring the tension of the conductor within the ruling span sections.

INTRODUCTION

Transmission lines are designed based on catenary equations. In a single catenary, i.e. a span with known end coordinates, the tension at the end of the catenary *exactly* determines the sag of the conductor at any point (Fig.1). It has also been known for a long time that if a transmission line consists of multiple suspension spans between two deadends and if certain basic constraints are adhered to, the sag of each span can be calculated using the "ruling span method." What the ruling span essentially means is that the span lengths do not vary so much that the suspension insulator swings cause a significant difference in the horizontal component of the tension of the conductor between the spans. As long as these conditions are adhered to, the sags of the section of the line between deadends can be computed from the ruling span formula.

The operating ampacity limits of most transmission lines depend on the available clearance of the spans. The National Electrical Safety Code (NESC) requires that these clearances are *always* maintained. In addition to clearances, some lines may also be limited by annealing or loss of strength considerations. Because these

limitations are also based on prolonged exposure to high conductor temperature, they are related to clearances and tension. Thus, if the tension or the average temperature of the conductor is maintained within prescribed limits, all safety considerations can be maintained.

This rating approach, based on the ruling span method used in transmission design, is significantly different from that discussed in prior dynamic line rating literature. The objective of many reports has been to identify the span in which the conductor temperature is the highest and to consider this the "critical" span. Yet, this approach leads to a substantial overestimation of the thermal risk because it does not take the equalization of thermal elongation between spans in a ruling span section into account. Further, such critical span methods can also lead to erroneous estimates of the location of the true sag-critical span, which may not be the one with highest temperature, but another span in the same ruling span section.

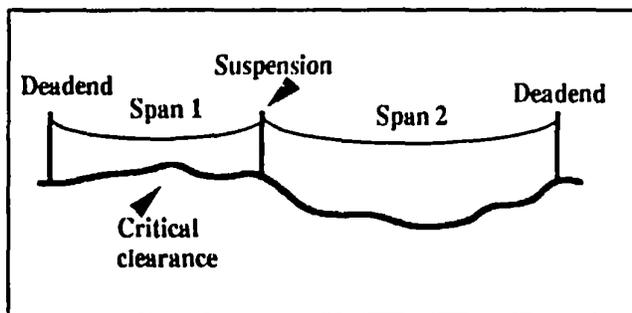


Fig. 1. A ruling span section of two spans of different lengths.

A simple two span section is shown in Figure 1. Assuming the line is designed to meet clearances at a conductor temperature of 100°C, the actual limiting clearance is in span 1. Because it is the shorter span, its relative sag varies more than that of span 2. The actual clearance limit of the line occurs when the *average* temperature of the two spans reaches 100°C. Because there is no actual clearance limit on span 2, a short term temperature over 100°C will not jeopardize the clearance of that span, but it might cause a clearance violation in span 1, even though the temperature of span 1 would remain below 100°C.

PLANNING, DISPATCH AND OPERATIONS

Within a utility, there are three fundamentally different points of view regarding the assessment of the capabilities of transmission networks: Planning, Dispatch and Operations.

The main concern for transmission planning is the reliability of the network and its overall operating economics. The planner builds the network plan on known probabilities of forced outages for generating facilities, on statistics of contingency situations and on statistically predictable load conditions. The planner designs the network to deliver the desired amount of power with a low reliability risk and with manageable contingency consequences for insufficient capability. The planning approach is fundamentally probabilistic.

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Thus, at most locations, it can be expected that the summer daytime wind speed is much higher than the summer nighttime wind speed. While this has the generally beneficial effect of increasing the ampacity of the line during the time when highest ampacities are most needed, it has the reverse effect at night. This means that the day/night ratings used by several utilities may not only result in an underestimate of their available daytime capability, but they may cause overestimates in their nighttime capabilities.

When do the most critical wind conditions occur? This topic is discussed in a report presented for IEEE publication (13). This report shows that there is a high probability that the winds are lowest immediately after sunrise and after sunset. In many locations, especially during hot summer days, there are two short periods each day when the wind dies down to close to zero speed.

WIND IS VERY VARIABLE

The wind is not only unpredictable, it is highly variable. It varies with space and with time. The time variation of wind speed is called turbulence or gustiness. The relative turbulence of the wind is indicated either by the standard deviation of the wind speed or the standard deviation of the wind direction. Because the turbulence, as explained below, is predominantly circular, a standard deviation of a wind speed of 50% means that the standard deviation of wind direction would be $\tan(0.5) = 27$ degrees. Thus, the more turbulent the wind is, the more variable it is in direction.

Data collected by numerous researchers clearly shows that:

- The lower the wind speed, the higher the relative turbulence. (7) shows that for wind speeds of less than 1 m/s, the mean variation of wind speed is over 35% (in Germany), while winds over 5 m/s have a variation of less than 10%. In White Sands, NM, daytime wind speeds of less than 1 m/s have a daytime gustiness (1/10min) of 2, while winds of over 5 m/sec have a gustiness of only 1.2 (10). While the measurement methods and data intervals are different, the data clearly indicates the trends.

- The higher the temperature, the higher the turbulence. A large amount of the turbulence of wind is generated by temperature differences. These are more pronounced during the daytime and when the temperatures are high. See (10) and (11), for example.

A wind front can be described as shown schematically in Fig 4. Travelling in a wind front of constant speed are three-dimensional circulating vortices. The typical summer daytime dimension of such turbulence is 300-800 ft (14). That means that in a typical 1000 ft. transmission line span, there are two vortices and in a typical transmission line section of 5-6 spans between deadends, there are about 10 such vortices. At any given location, the instantaneous wind speed is the vectorial sum of the speed of the wind front and the speed of vortex. Thus, during the time the vortex passes, the conductor experiences a wind gust, as shown in Fig. 5.

Using a simple example, assume that the average wind speed is the 2 ft/sec used in most ampacity calculations. Assume that we are in high daytime ambient temperature conditions, with a turbulence which causes a standard deviation of wind speed of 3 ft/sec and a 55 degree standard deviation in wind direction - which would not be unusual during hot summer days. At one point in the line (A), the wind varies from 3.5 ft/sec to 5 ft/sec during the passing of the

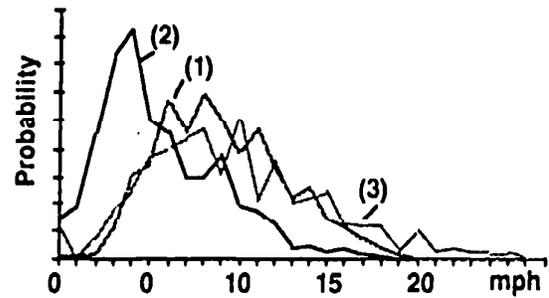


Fig. 2. Wind speeds in Florida (1), Michigan (2) and New York (3).

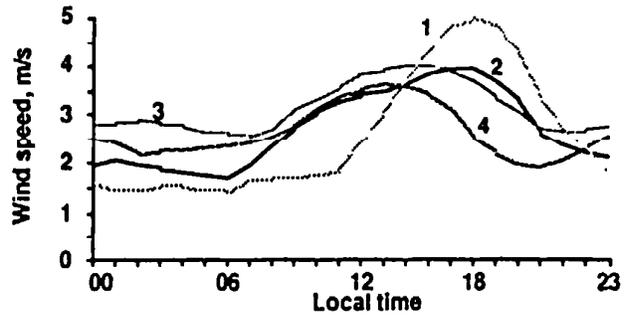


Fig. 3. Diurnal variation of summer wind speed in Fresno, CA (1), San Jose, CA (2), Helsinki, Finland (3) and in Rotterdam, NY (4).

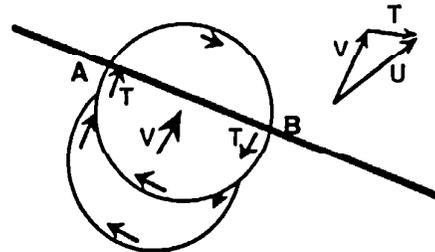


Fig. 4. Passage of a wind gust across a transmission line span. At a given location, the instantaneous wind velocity U is the vector sum of the average velocity V and the turbulence velocity T.

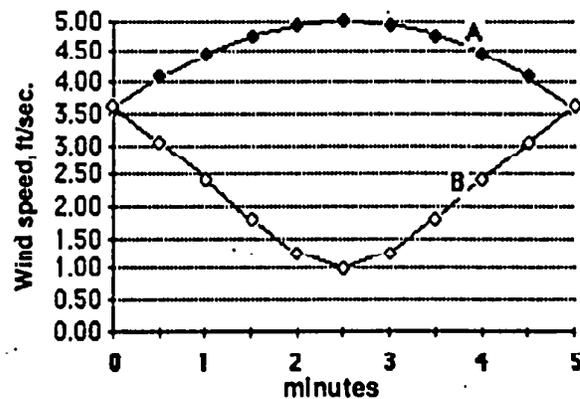


Fig. 5. An example of local wind speed variation. A vortex with a 3 ft/sec turbulence (T) and 600 ft diameter is superimposed on an average wind speed V of 2 ft/sec. Curve A indicates variation of wind speed at point A and curve B at point B in Figure 4. Note that because the wind angle varies, the "effective" wind speed is lower.

react to calm in different ways. Lines of higher voltage generally have larger conductors than lower voltage lines. Because of this, they react less and more slowly to periods of calm than lines with smaller conductors. Moreover, high voltage lines have longer spans and ruling span sections, which means that the probability of calm occurring over a substantial percentage of the ruling span is lower. Finally, higher voltage lines commonly have wider right of ways and are higher from ground. This means that the average wind speed seen by a higher voltage line is typically higher than that of a lower voltage line. Thus, a high temperature event caused by calm is a significantly less probable event for an EHV line than for a lower voltage line. This implies that the thermal planning ratings of EHV lines could be based on higher minimum wind speeds than lower voltage transmission lines. Also note that this means that using the same rating assumptions for distribution lines as transmission lines implies a higher risk.

OPERATION UNDER HIGHER AMPACITIES

From the evidence stated in this report, as well as from many earlier studies, e.g. (1),(3),(12), it is clear that most of the time, most transmission lines could be operated at significantly higher capabilities than what present ampacity calculations indicate. But, since operating safety requires operation within safe limits at all times, what operators need is a system that provides them assurance of line safety at all times.

There are two major operating considerations. The first and most critical one, is that of potential clearance violation. The second, less probable problem deals with the delayed effects of potential annealing and loss of strength of conductors.

The author's discussions with operating personnel in many utilities have most commonly resulted in the following two requirements:

- A real time line rating system should allow operators to operate their systems at higher ampacities without the continuous need for human interface and interpretation. The systems should provide advance warnings of impending clearance violations.
- The system should provide records of conductor temperatures or conductor tensions. These records could be used for refinement of planning and dispatch ratings as well as for determining the long term exposure of the conductor to annealing conditions.

Several solutions exist

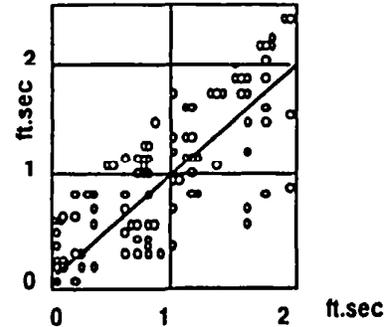
It is evident that the above tasks can be accomplished by using either sensors which measure average conductor temperature in the ruling span, conductor sag or conductor tension. Theoretically, each of these methods provides essentially equivalent information and the comments below indicate only the differences in practical application.

Conductor temperature sensors are mounted on the energized conductor. Because they measure the temperature at one location only, data from several sensors needs to be averaged at a base station. To determine the clearance, information is also needed about the ruling span section and the conductor creep. If the creep cannot be determined, the warning should be based on the assumed final creep.

There are no sag sensors commercially available, but several concepts have been developed in laboratories. Sag measured in a span can be applied to other spans in the same ruling span section.

Tension monitors operate as warning systems based on the known

Fig. 8. Simultaneous readings of low wind speeds from two anemometers near each other. Altitude 35 ft. One minute averages.



relationship between the tension and the sags in the ruling spans. For annealing calculations and dispatch purposes, the average conductor temperature can be calculated from the measured tension values, because the ruling span properties are known.

Each of the above systems only provides direct information on the ruling span section in which it is installed. One tension monitoring system can monitor two ruling span sections when it is installed in a deadend in the middle of a line. A single sag or temperature measuring base station can monitor temperatures within the radius of its radio communications, as long as sensors are installed in each ruling span. From a utility's point of view, the choice between the systems should be based on accuracy, reliability and cost.

How many systems are required per line?

There are many studies which have evaluated the variation of the temperature in either a single span or between individual temperature sensors at different locations in a line. There is no available published data which would shed definite light on the difference between the average temperatures of ruling spans of a long line.

The limiting condition is caused by calm or near calm. The crucial question which is not answered by the available wind statistics is: "Can a near-calm condition last over several time constants for a complete ruling span section while the wind in another ruling span section a several miles away is significant?" The comments of some researchers indicate that the variation of such average conditions may be less significant than the variation within shorter distances. This reflects the nature of the turbulence in the atmosphere, which tends to be dominated by events in the time domain of a few minutes, i.e. with a dimension of a few hundred to a few thousand feet. This has been shown by the excellent study of Van der Hoven (14). For a definite answer, the task can only be accomplished by performing measurements specifically designed for the purpose. The planned tension measurements at several sites along transmission lines, described below, are intended to answer this question.

PLANNED TRIALS

There are several trials presently under way, which are intended to shed light on the equalization of tension within the ruling span and on the variation of average temperature between different ruling spans in transmission lines. The participating utilities include Virginia Power, Public Service Company of Colorado and Imatran Voima of Finland. In each case, the utilities will monitor tensions in two or four ruling spans, at locations which are up to 15 miles apart.

Equipment used in the trials

The systems used for the trials are conceptually shown in

Table 1

Observations of the highest and lowest tensions and conductor temperatures on the Inkoo-Virkkala line

Date	Inkoo Newtons	Virkkala Newtons	Virkkala temperature
Lowest tension 01/03/92 at 2 pm	18,410	15,330	+7°C
Highest tension 12/25/91 at 2 am	20,670	18,260	-10°C

CONCLUSIONS

1. The planning, dispatch and operations aspects of thermal ratings of transmission lines should be considered separately. While probabilistic approaches are natural for planning ratings and acceptable in the dispatch environment, they are not applicable in the operating environment because of safety considerations.

2. The operation of transmission lines is governed by reliability and safety. Operation must be conducted under simple operating procedures. Clearance warnings, based on any suitable sensor system, can be used in a manner which is consistent with present operational practices.

3. The most significant thermal hazard for transmission lines is prolonged calm. It appears that the concern of prolonged calm is overestimated, indicating that transmission lines may be operated at significantly higher capabilities. What remains is to be investigated is the degree to which the worst cooling conditions in different ruling spans of a line are similar and coincident. A reasonable coincidence would mean that the number of required monitoring systems would be small.

4. Monitoring of the tension of a transmission line is a promising method for the maintenance of operational clearances. The tested systems have proven to be reliable in diverse operating environments.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valuable assistance of numerous persons at Virginia Power, Imatran Voima and Public Service of Colorado in the development and testing of the system and the method presented in this report. The author also wants to thank Mr. R. Swanson of PG&E for valuable advise on data analysis and comments on meteorological observations.

REFERENCES

- (1) M. W. Davis, "A new thermal rating approach: Part 1", *IEEE Transact. on Power Apparatus and Systems*. VOL PAS-96, May/June 1977.
- (2) M. W. Davis, "A new thermal rating approach: Part 2", *IEEE Transact. on Power Apparatus and Systems*. VOL PAS-96, May/June 1977.
- (3) S. D. Foss et. al., "Dynamic Thermal Ratings Part II", *IEEE 82 SM 378-8*, 1982.
- (4) W.Z. Black, R.A. Bush, "Conductor Temperature Research," *EPRI Final Report for Project 2546-1*, EL 5707, May 1988.
- (5) J.S. Barrett, "High temperature operation of ACSR Conductors", *Proc. Seminar on The Effects of Elevated Temperature*

- Operation on Overhead Conductors*, May 20, 1986, Atlanta, GA.
- (6) ESERCO Task Force Final report on Thermal Line Ratings, Albany, NY 1984.
- (7) M. Kraus et al., "Aeolian Vibrations; Wind Energy Input Evaluated from Measurements on an Energized Transmission Line", *IEEE 90 SM 346-7 PWRD*, 1990.
- (8) T. Seppa, "Transmission Line Vibration Intensity" *CIGRE CSC 22-70(SC)-01*, Helsinki 1969.
- (9) Seppo Huovila, "On the Structure of Wind Speed in Finland," *Finnish Meteorological Office Contributions*, 69, Helsinki 1967.
- (10) H.H. Monahan et al: "Gust Factor Variations with Height and Atmospheric Stability" *ECOM 5320*, Aug., 1970.
- (11) A-S. Smedman-Högström et al., "A Practical Method for Determining Wind Frequency Distributions for the Lowest 200 m from Routine Meteorological Data" *Journ. of Appl. Meteorology*, vol.31, Jan. 1982.
- (12) W.Z. Black, R.A. Bush, "Dynamp- a Real-Time Ampacity Program for Overhead Conductors", *Proceedings of Seminars on Real Time Ratings of Overhead Conductors*, Atlanta, GA., 1986.
- (13) T.O. Seppa, E. Cromer & W.F. Whitlatch, "Summer Thermal Capabilities of Transmission Lines in Northern California Based on a Comprehensive Study of Wind Conditions. Submitted for publication at IEEE-PES Summer Power Meeting, 1992.
- (14) I. van der Hoven, "Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour", *J. Meteor.*, 1957, 14.
- (15) W.Z. Black, "The Georgia Power Dynamic Thermal Line Rating System", IEEE-PES Summer Mtng., July 18-23, 1982, San Francisco.
- (16) T. O. Seppa & W. F. Whitlatch, "Wind studies show a low daytime thermal risk for transmission conductors." *Transmission & Distribution*, Vol. 44, No.5, May 1992.

Note 1:

The following statements are found on the record of the Panel discussion on Dynamic Thermal Ratings, at the 1982 IEEE-PES Summer Power Meeting, San Francisco:

Davis, Murray: "...we discovered...that if a sensor was placed each mile on 20 mile transmission line, the variations in the measured temperature within a span was greater than the variations among the spans."

Black, William: "the variations in conductor temperatures that we measured along the tests span - variations of 10, 15, 20°C between one point and another within the same test span..."

AUTHOR

Tapani O. Seppa (M'72-SM'75) was born in Lapua, Finland on December 29, 1938. He received his Diploma Engineering (MSEE) degree from Helsinki Technical University in 1962.

From 1960 to 1969 he was a research engineer at Imatran Voima in Finland. He held research and engineering management positions at Reynolds Metals from 1969-1970 and at Bundy Corporation from 1971-1975. From 1975-1981, he held several development and marketing management positions at Lapp Insulator. He was VP-Strategic Management at Clevepak Corp. from 1982-1985 and VP-Marketing of Nitech, Inc. from 1985-1990. In 1990, he formed The Valley Group, a consulting company specializing in advanced technologies for utility T&D systems. He has been active in a many IEEE task forces and has authored a large number of papers for IEEE, CIGRE and other organizations.

constant in all spans throughout the dead-end section. Would the author please comment on the limitations to this assumption? That is, under what conditions does he feel that the assumption of constant tension in all suspension spans may be invalid?

- (3) System operators are concerned with *circuit* capacities not with *line* capacities. In most transmission systems an increase in line capacity does not translate to an increase in circuit capacity because of unchanged thermal limitations on series equipment such as switches, power and current transformers, underground cables, and line traps. Simpler real-time rating schemes based on ambient temperature variations and wind monitoring allow the more modest but simultaneous increase in rating of both lines and other series components. Would the author care to comment on this aspect of practical operational real-time rating schemes?

Manuscript received August 4, 1992.

J. R. Meale, Y. Motlis (Ontario Hydro, Toronto, Canada): We congratulate the author for the interesting approach and extensive information on a topic which is of much current interest. We would like to inform the reader that Figure 1 and discussion on the application of the ruling span method are in support of our opinion that line profile is the major factor in determining line thermal rating, design or operational. That is, there is no need for an extensive and expensive instrumentation attempting to determine the "hottest" span as a "critical" one. The least clearance span is the "critical" span which can be determined from the line layout profile.

Some assumptions in the paper may be too generalized such as: "lines of higher voltage generally have larger conductors than lower voltage lines"; "higher voltage lines have longer spans and ruling span sections", "... and are higher from ground", and, therefore, "the average wind speed seen by a higher voltage line is typically higher than that of a lower voltage line."

In discussing temperature sensors the author indicated that if the creep cannot be determined, the warning should be based on the assumed final creep. For the example at IVO systems it is indicated that the maximum design sag has not been reached in 10 years because the maximum design ice load has not yet occurred. We assume in either case that it doesn't matter whether the maximum sag condition is due to long term creep or heavy ice loading conductor stretch. Could the author please explain further.

Would the horizontal tension measurement system proposed in the paper be applied to compact

lines with conductors rigidly clamped at each structure to line post insulators, for example.

The extensive discussions on wind effects and wind statistics by the author may be useful in the future when and if attempts will be made to apply reliability-based (RBD) method for line layout design.

Manuscript received August 5, 1992.

H. BRIAN WHITE, Consulting Transmission Line Engineer, Hudson, Quebec, Canada

It appears that Tapani Seppa is pursuing the better course of action in the matter of trying to determine the position of the conductor in space at any given time.

The real and ultimate objective is to determine the clearance to ground and, lacking the ability to measure this directly, the next best thing is to have the means to calculate the sag.

Thus it makes good sense to measure wire tension and use either parabolic or catenary functions and profile data to determine sags and from them, to obtain the clearances at critical points.

One tension measurement within a line section between dead end or strain structures is adequate because the tension throughout will be equalized as the wire behaves essentially according to the Ruling Span (RS) concept.

Mr. Seppa has correctly noted that the RS concept works as long as the span lengths do not vary so much etc but I think that he is being overly cautious and possibly overstating the problem of varying span lengths.

The RS rule of wire behaviour assumes infinitely long insulator strings and neglects the horizontal component of the loads in inclined strings.

At high temperature, which is our area of concern, spans that are shorter than the RS will have slightly more sag than those computed by the RS method and it follows that the tension in them will be slightly less or, more correctly, the tension will be slightly less than computed and thus the sags slightly more.

To qualify: as a problem span, the span probably has to be both a small percentage of the RS and must also be a very short span of no more than a 100m or so.

Furthermore, the insulator strings must be very short for the longer they are the more they approach the behaviour of the infinite strings. The problem usually disappears above 69 kV or at most 138 kV.

If the tension measuring device is installed in a span much shorter than the RS span, a low reading will be obtained and too conservative an operation will result.

S.A. Boggs, Underground Systems, Inc., Armonk, NY 10504. The author makes a convincing case for the assertion that most of the time, the available line ampacity is greater than the book rating. The problem is knowing when excess ampacity is not available to avoid dangerous operating conditions.

As the author points out, conductor temperature can vary within a span; however, properly averaged single point temperature data take care of gusts as discussed by the author. Local conductor orientation predictably accounts for much of the observed variation of temperature with span length. Thus, in terms of indicating average span conditions, such averaged temperature data are comparable to tension measurement on the span. The author is in error when he suggests that multiple point temperature measurements are required to provide data comparable to tension measurement. In fact, a single sensor is entirely adequate.

Insulator strings can swing in the direction of the line as a result of varying line conditions such as unequal span temperatures. At each insulator string, the net force must be zero. An insulator string which is not vertical implies a horizontal force on the tower approximately equal to $W/2 \tan(\theta)$, where W is the weight of the conductor spans on either side of the insulator and θ is the insulator angle from vertical. If we take two 1000-foot spans Drake conductor (at about 1.1 lbs/ft), the total weight of the conductor is about 2200 lbs. If the insulator string swings by 10° , then the horizontal force on the tower is about 200 lbs. This implies that the horizontal tension on one side of the insulator string is 200 lbs different from that on the other side of the string. A tension measuring device at the deadend cannot sense this change in tension which results from the force on the tower structure. Only if the temperature of all spans is the same and all insulators are vertical (i.e., the horizontal tension is uniform for all spans between deadends) does the tension measurement at the deadend represent the average condition of the line. However, this is a rare condition. Based on the assumption of such uniformity, a time-averaged temperature measurement anywhere along the line provides the same information as tension measurement.

To investigate the problem, we have undertaken some computations for a large number of conditions and have correlated sag in one span with the tension at the deadend. The sag vs tension data shown in Figure 1 are for a current of 1000 A passing through 16 spans of Drake conductor between deadends with wind speeds varying randomly between 0 and 10 ft/s at 20°C ambient for each span. Span lengths vary from 700 to 930 ft, the insulator string length is 6 ft, and horizontal tension at 30°C is 5000 lbs.

We present data for the fifth span from the deadend at which tension is measured. As one can see, the correlation between tension at the near deadend and sag in the fifth span is poor, especially for large sags (low tensions) which correspond to small clearances. The correlation appears to be good for small sags (large tensions) because this corresponds to high wind on all spans. Knowing only the line current and having computed Figure 1, one could predict that the sag would fall between 26.5 and 31 ft, a range of 4.5 ft. For tensions in the range of 3800 to 4200 lbs, knowledge of the tension narrows the range of possible sag to between 3 and 3.5 ft. Only for very high tensions (high wind on all spans) is knowing the tension of much value, but even for a tension of 4300 lbs, knowledge of the tension narrows the possible range of sag by only 1.5 ft. Thus over the full range of possible weather conditions, knowledge of the tension at the deadend contributes little to knowledge of the sag in this span. The correlation between tension at the deadend and sag is even worse for spans 6, 7, etc. as one progresses further from the deadend. Thus the value of such tension measurement must be questioned.

If field data and engineering experience demonstrate anything it is (i) nothing is "normal" when it comes to weather, (ii) if it can happen, sooner or later it will happen, and (iii) rare, extreme

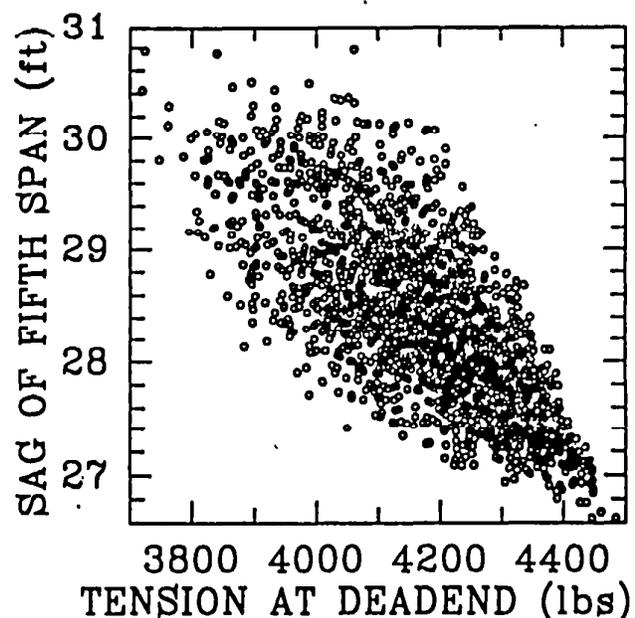


Figure 1. Sag at Span 5 of a 16-span line segment between deadends as a function of tension at the nearer deadend. Note the poor correlation of sag with tension at the deadend. The thermal expansion coefficient below 69°C is 1.9×10^{-5} and above 69°C , $1.2 \times 10^{-5}/^\circ\text{C}$. The maximum insulator swings are about 9° .

ment of average temperature of about 4-5°C. This is well within the needs of a practical thermal rating system. If even higher accuracy is desired, the calculations can be made with a correct vector balance method (see Figure 2, later). Using the vector balance calculation, the resulting error would then be less than 1%.

Mr. White is also correct in pointing out that the tolerances in conductor manufacture affect the ampacity values. "Typical" conductors have a diameter which is 1% larger than nominal and have a conductivity which is 1% higher than nominal. Together, these mean that a typical conductor has an ampacity which is about 2% higher than that calculated using "nominal" values.

Regarding Mr. Fink's and Mr. Douglass' question on capability prediction, the response is:

The transmission line monitoring system referenced in the article can calculate the ruling span sag compared to limiting sag and report it as "%sag", with 100% meaning the maximum allowed sag. This corresponds to the highest allowed average temperature of the conductor in the ruling span section.

The sag/temperature relationship of the conductor can be calculated from known line profile data. For reasonable temperature ranges, the relationship is linear and can be expressed in inches/°C. For example, the 1000 ft. span of Table 1 has a sag/temperature ratio of 0.64"/°C at 100°C. Thus, from a known tension, the average conductor temperature can be calculated quite accurately.

The Series 2.0 models of the monitoring system also incorporate ambient temperature sensors. The temperature rise over ambient can be calculated from the calculated temperature of the conductor and from measured ambient temperature.

Under normal convective cooling conditions, one can estimate that the conductor's temperature rise over the ambient is approximately proportional to the square of the current of the line. Although an exact calculation would require taking the radiation into account, such predictions are not very useful because the wind is the most important factor by far and is quite unpredictable.

Thus, if the data is reported to the SCADA system, it is quite easy to compute a capability estimate by using the simple formula:

$$\text{Present capability} = \text{Present MVA} \left(\frac{T}{T_{\max}} \right)^{1/2}$$

in which T is the present temperature rise over ambient and T_{\max} is the maximum allowed temperature rise over ambient.

Regarding Mr. Fink's comment on thermal risks, the author would like to make the following point: there are capability risks (planning risks), which can be considered acceptable for a utility, based on a financial valuation. On the other hand, there are safety risks, which should be treated with much greater concern.

Regarding Mr. Bush's comments; the author is in general agreement. For a complete ruling span, the vortex effects tend to be averaged out of consideration. But they will not be averaged out from calculations which are based on either one single weather station or one or a few conductor temperature sensors.

Also, while the effect of local sheltering has little effect on the sags of complete ruling span sections, the effect of wind direction is important, especially during sunset or nighttime conditions. Experiences at some of the monitoring installations, located at line angle points, have shown that the average conductor temperatures of two ruling span sections at 90° angles can differ substantially-

from each other, especially right after sunset. On the other hand, this effect is much less significant for daytime ratings [1].

Dr. Boggs presents a nice theoretical model, which unfortunately, as explained below, starts with inputs which bear no resemblance to real weather conditions and calculates an output which is only remotely related to a clearance warning problem. To indicate the error sources in assumptions, the author must first present the correct solution:

1. Statistics from reports [1-4] show that the difference in wind speeds (for 10-30 minute averaging periods), measured within a few miles, is normally distributed. The standard deviation for the important low wind speed range is typically 1-2 ft/sec. Temperature comparisons show that the standard deviation of temperature within a span is on the order of 10% of the temperature rise, with references [1] and [4] supporting the above conclusion.

2. Consider two 1000 ft spans of a 230 kV line of "Drake". Assume that the wind speed is low and that the standard deviation of temperature variation is high. The average temperatures of adjacent spans have a median difference of ±4°C (implying a standard deviation of ±6°C within a span). The temperature of one of the spans is 90°C and its tension is 4360 lbs. The temperature of the adjacent span is 94°C. Each 1°C temperature change changes its tension by 7 lbs., its sag by 0.7" and its slack by 0.13". If the insulator string is very long, the temperature difference of 4°C causes the suspension clamp to move 0.26". Both spans will have a tension of 4346 lbs. The sag of both spans is 30.2 ft. This means that the sag of one of the spans increases by 1.4" and the sag of the other span decreases by 1.4".

Because the typical 230 kV insulator string is only 72" long, the tensions will not equalize perfectly. The vectorial balance is shown in Figure 2. Calculation based on the above values yields a residual longitudinal force on the structure of 1.9 lbs. This means that the error between the sag measured in the second span compared to one calculated from the force measured in the first span is 0.2".

Using above statistical distribution for a six span section of 1000 ft. spans of "Drake" conductor, we can find that there is a 90% confidence that the sag in the sixth span will not differ more than 1.2 inches from the values calculated in the first span. The limit for 99% confidence is approximately 2.5".

We can now investigate Dr Boggs' assumptions:

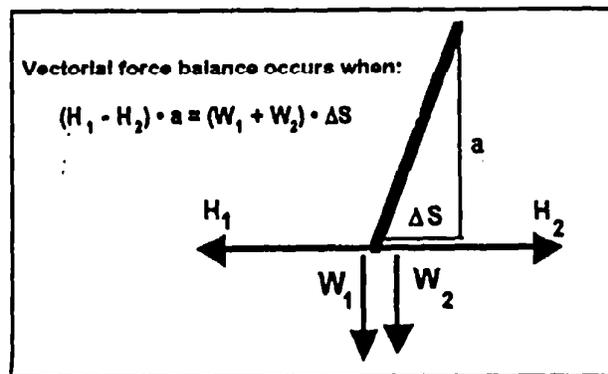


Figure 2. Vector force balance at the suspension point. Note that for practical situations $\Delta S \ll a$, meaning that $\Delta H \ll W_1 + W_2$.

failure-prone electronics. Moreover, each tension monitoring system monitors two ruling span sections, providing redundancy at a substantially lower incremental cost than that of additional temperature monitors.

Regarding the question of the equalization of the tension in a ruling span section, the author refers to the prior comments to Mr. White and Dr. Boggs. As a rule, well designed transmission lines meet tension equalization requirements. The main concern is the length of line over which the transmission line tension equalizes.

One way of looking at the question is to consider the line as a model consisting of tension springs (modelling the spans) and of compression springs (modelling the suspension points). Typically, the tension difference equalizes by 95% between spans of 1000 ft. length. This means that for one mile of line (five spans), the tensions should equalize by 75%. Thus, if the temperature of a span 1 mile distant from the deadend is 100°C and that nearest the deadend is 90°C, the maximum tension error should be equal to 2.5°C in temperature measurement. For a 2 mile long section, the similar calculated error would be 6°C.

The yet unresolved question is the following: If we know the average thermal conditions of a one or two mile section of the line, what are the conditions of the line 5, 10 or 20 miles away? Initial data indicates that the measurements will be valid for a 5-10 mile radius, but more experimental proof is needed.

Regarding the question of circuit capabilities, the author recognizes that there are other limiting elements. Some of these can be

changed with a low cost (e.g. line traps and switches). Other elements will require similar simplified means of monitoring as the proposed Clearance Assurance Method. Most of the critical elements have long thermal time constants and are more suited for ambient-based rating schemes than transmission conductors.

References:

- (1) T.O. Seppa, W.F. Whitlatch & E. Cromer, "Summer Thermal Capabilities of Transmission Lines in Northern California Based on a Comprehensive Study of Wind Conditions". *IEEE 92 SM 567-8, 1992.*
- (2) T.O. Seppa & W.F. Whitlatch, "Wind studies show a low daytime risk for transmission conductors". *Transmission & Distribution, Vol. 44, No. 5, May 1992.*
- (3) M. Monseu, "Determination of Thermal Line Ratings from Probabilistic Approach". *IEEE Conference on Probabilistic Methods applied to Electric Power Systems, London 3-5 July 1991.*
- (4) J.W. Jerrell, W.Z. Black & T. J. Parker, "Critical Span Analysis of Overhead Conductors". *IEEE 87 SM 560-6, 1987.*
- (5) S. Foss & R. Maraio, "Evaluation of an Overhead Line Forecasting Algorithm". *IEEE Trans. PWRD, Vol.4, April 1989.*
- (6) E. Brandt, "Ermittlung des Verlegerverhaltens von Freileitungsseilen" *Energiewirtschaftliche Tagesfragen 23 (1/2) 10-19, 1973.*

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Tension Monitoring - Rating the Lines like Their Designers Would

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Open network

Traditionally, transmission lines were designed as part of a utility's overall planning process. Their purpose was to move power from utility's own, strategically located generation facilities to the major areas of consumption within its service territory. Some lines were constructed as interties between utilities, to enhance seasonal or other operating economies, and to increase reserve margins. Transmission lines could be planned for very long economic lives.

When a line was designed for a 40 year economic optimum with a known source and cost of generation, line losses were a major part of the design considerations. Any line which was operated for a significant time at a high current was either replaced by a new circuit or upgraded for lower losses. The regulatory environment permitted and encouraged such practices. For a long period of time, transmission construction was the safest of utility investments. If the transmission line could be justified, it was built. The construction cost became a part of the rate base, with a guaranteed return. In such an economic environment, the pioneers of real time rating systems [1] often had a chilly reception at utility transmission line departments. The few exceptions were the cases where public pressure or environmental concerns made construction of new circuits impossible or undesirable.

The opening of the transmission network mandates the complete rethinking of transmission line limitations. Load no longer flows from predictable sources to known users. The cost of energy flowing over a given line can vary from 2 ¢/kwhr to 15 ¢/kwhr, depending on the source. The increased effects of cogeneration, IPP's, demand side management, and competition from other utilities mean that deterministic long-term load flow planning is no longer feasible. New opportunities are arising for profiting from transmission transactions. In August, the City of Jacksonville, Florida, was purchasing economy energy from the Los Angeles Department of Water and Power. At the same time, Virginia Power was selling energy to St. Louis. Even three years ago, no one would have dreamed of such transactions.

Operation of the transmission network is becoming more opportunistic and more real time oriented. While voltage and stability restrictions over the highest voltage lines are trimmed by the use of such technologies as FACTS, more lines are being operated closer to their thermal ampacity limits.

So what does the future have in store for you? Most likely, you will all be part of a transmission - or a "grid" company in two or three years. Your contribution to the company will be determined based on the return on assets, or equity, to this company. Or in simple terms,

$$\text{Return on assets} = \text{Sales margin} \times \text{Asset turnover}$$

Thus, to increase your value, you can try to increase your sales margin (i.e. price paid for moving a given amount of energy). But this will be tough. It seems much smarter to work on your asset turnover (i.e. ratio of sales to assets). If you can move more power with the same, or less assets, you are making money for your company.

Which way should you move in the new playing field? The rules are not fixed by FERC yet, but some of the possible options are shown in Table I. As you can see from the table, the fundamental rule for increasing profitability is increasing the power flow over your network. This means that you must use your transmission lines to their fullest capability, including their maximum thermal limits.

Thermal and elastic properties of ACSR conductors

Most transmission line conductors are ACSR, consisting of both aluminum and steel strands. The behavior of these conductors is quite complex, as aluminum has an elastic modulus which is only one third of steel, while the coefficient of thermal elongation of aluminum is twice that of steel. When the conductor is manufactured and put on a reel, there are no tensile stresses in either the aluminum or the steel. If the conductor is installed at the same temperature, the stress distribution between the wires can be calculated based on the known elastic properties of the materials. But when the temperature changes, the aluminum elongates more than the steel. Thus, for any ACSR conductor span, there is a temperature at which the aluminum strands have zero stress, while all the load is carried by the steel core. This transition temperature depends mainly on the ratio of steel to aluminum in the conductor [2-3].

For a 1000 ft. (305 m) span of 795 kcmil conductor, manufactured and installed at a temperature of 20 °C, the standard sag/tension programs assume the following transition temperatures [4]:

Conductor	Stranding	Steel/aluminum	Transition temperature
Macaw	42/7	5%	372 °F / 190 °C
Tern	45/7	7%	300 °F / 148 °C
Condor	54/7	13%	200 °F / 92 °C
Drake	26/7	16%	154 °F / 66 °C
Mallard	30/19	23%	91 °F / 33 °C

The traditional assumption which was used in sag/tension/temperature calculations was that above this transition temperature, the sag of the line changed less as a function of temperature, because it was assumed that the increase in thermal elongation depended solely on the thermal elongation of the steel strands. This model has been dubbed the "Teflon Model" by Dr. Dale Douglass, because the model assumes no interaction between the steel and aluminum above the transition temperature. There is significant evidence to question this classical model now. Tests [5] and [13] show sags which would be much better explained by the "Alumoweld Model" (Dale Douglass, again). Evidence from field tests with tension monitoring systems have also shown high temperature sags for ACSR which are significantly larger than those predicted by present sag/tension programs. Note that:

- For old lines, operated at 120 °F (49 °C) maximum temperature, errors are not apparent.
- The largest potential errors occur with 26/7 and 30/19 conductors, which are both widely used. Unfortunately, many such lines have now been uprated for 200-240 °F (90-110 °C) operation from old 120 °F designs.

Even if the "Teflon Model" was valid, there is still substantial uncertainty. Instead of the assumed manufacture and installation at 70 °F (20 °C), a conductor manufactured and installed during the winter in Canada may have a transition point which is 40 °F (22 °C) lower than assumed. A conductor made and installed during the summer in the Southern U.S. may have a transition temperature which is 30 °F (17 °C) higher. The magnitude of the potential sag errors is shown in Figure 2. Thus, one can conclude that:

- The temperature of a span of AAC, AAAC or ACAR conductor, and its sag and its tension is related to each other by exact mathematical relationships.
- The relationship between the temperature of an ACSR conductor to its sag and its tension are less well defined, unless more is known of the sag/temperature relationship of the particular installation.

Sags in a multiple span section of the line

Transmission lines are designed as multiple span sections of suspension structures between deadend structures. Traditional - and present - design methods assume certain important principles. One these principles is the assumption that the horizontal component H remains constant all along the Ruling Span section between two deadends structures. Thus, the sags of any individual span in the section can be calculated based on the Ruling Span formula [1]:

Local, circuit, and area ratings

Ampacity ratings can be calculated for local conditions (i.e. a single span, or a few spans close to each other), for circuits (i.e. a complete transmission line), or for areas (i.e. multiple lines in a large area). The larger the physical area to which the ratings apply, the more conservatism should be applied in the ratings, because the probability of weather and load conditions resulting in low ratings increases with the number of line sections and with the total extent of the weather conditions over the region.

For example, a single span crossing a waterway can sometimes be rated for a higher ampacity, because water crossings often have a lower ambient temperature and a higher effective wind speed. A single line in a unsheltered terrain can often be rated using a higher wind speed. A line at high altitude can often be rated higher because of lower ambient temperatures. And a line with an aged conductor can often be rated using a higher emissivity than a new line.

But for regional general ampacity ratings, the combination of worst rating conditions provides the most reasonable rating basis.

Clearance warning systems

Sometimes, rating studies indicate that thermal ratings cannot be changed without introducing a small, but finite, risk of clearance violation. In such cases, the Clearance Warning (CW) method provides an easy and straightforward option for increasing line capabilities.

Using the CW method, monitors measure conductor tensions and calculate RS sags. If a monitor detects that one of the RS sags is approaching its maximum allowed value, the monitor sends a warning message to the receiving PC. Based on the reported sags, sag rates of change, ambient temperature, and solar radiation, the receiving computer calculates the maximum allowable MVA rating which still maintains the minimum clearance. Typical alarm data, as it would appear on the operator's screen, is shown below:

```
Unit # 251 Line: I-161 Structure: 215
Sag 1 = 98.4 % Time to violation 10.5 min
Sag 2 = 98.0 % Time to violation 20+ min
Ambient temperature 25°C
Net radiation temperature 29°C
Time 06/24/95 15:45
Warning began at 06/24/95 15:30
Present load is 179 MVA
Safe load is 171 MVA
```

In this example, the operator would have 10.5 minutes to reduce the line load by 8 MVA.

One of the major advantages of the CW method is its ease of installation and operational simplicity. Because warning messages are very infrequent, cellular telephone can be used for communications. Thus, the same systems which are used for ratings studies can also be applied for CW use. The data received by the operator is easily understood. The base data consists of %sag (actual sag vs. maximum allowable sag, with 100% representing the clearance limit) and predicted time to clearance violation, making the report from each location uniform, independent of the line. The operator will know where the problem is, how soon to act, and exactly how much to reduce the load.

Real time monitoring systems

In some applications, operators want to operate certain lines up to their thermal limits very frequently, for example, if economy energy can be bought or sold at favorable rates. Under such conditions, operators prefer knowledge of the real time capabilities of limiting circuits. The main difference real time

be postponed by at least five years, with a present worth of \$1.8 million.

The utility plans to install three tension monitoring systems on the two circuits. Based on data collection over next year, it will have the following options:

a. If the wind speed and solar radiation assumptions can be changed based on actual data, the construction can be postponed for at least five years. The tension monitoring systems, with a total cost of less than \$70,000, can be moved to another location.

b. If the data shows that the change to the new rating assumptions is not 100% safe, the utility can use the systems as Clearance Warning systems and can proceed with a combination of the following options:

- Implementing demand side management in the suburban area.
- Negotiation of load curtailment agreements with major users. Note that in five years, such curtailments may amount to less than 5 hours per year.
- Making arrangements to use major customers' emergency generators or other distributed generation.

3. A utility has a 115 kV circuit, which is not clearance limited. Three miles (5 km) of this circuit consists of an ACAR conductor. Planning studies indicate that there is a possibility that under contingency conditions this line section may reach a temperature of 120°C. Because this is above the annealing threshold, planning has recommended reconductoring this line section, at a cost of \$250,000.

Instead of reconductoring, the utility can install a tension monitoring system on the line section, at a total cost of \$22,000. If contingencies occur, data from the monitor can be downloaded and the actual temperatures of the conductor can be calculated. From the known temperature/time of conductor, the actual amount of annealing can be calculated. It is most likely that annealing conditions will never occur, because it would require the coincidence of the worst possible cooling conditions with the contingency. If annealing is detected, the line can be recondored only when needed, and the tension monitor can then be relocated to another site.

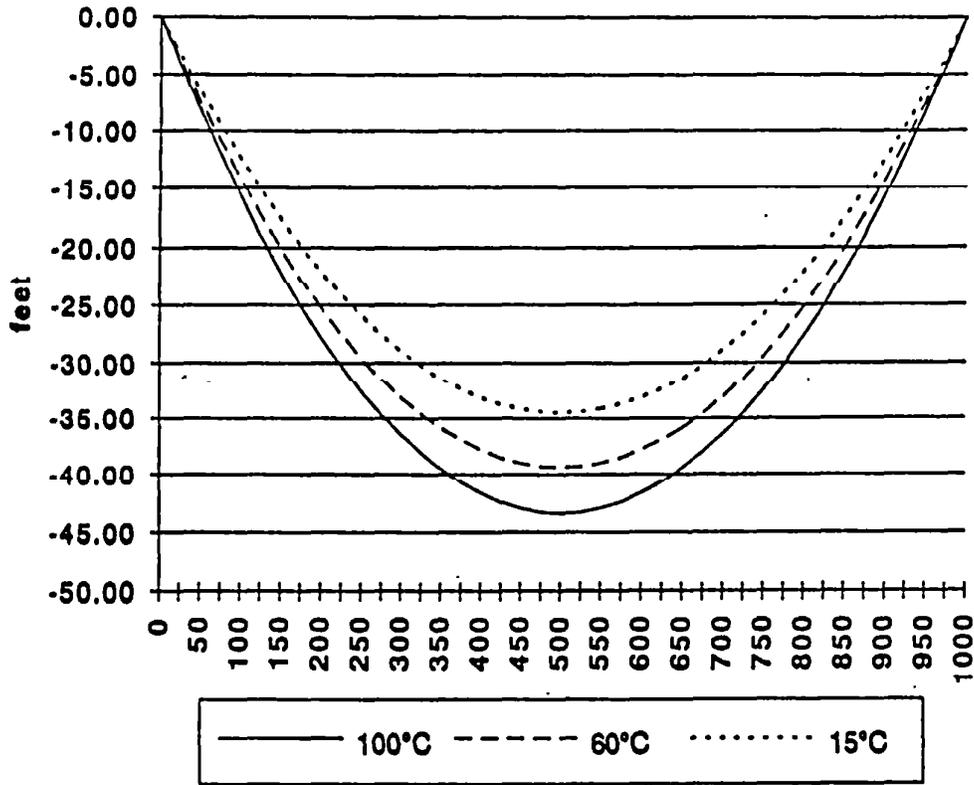
Other opportunities for savings from real time rating systems are shown in [12].

Conclusions

1. Tension monitoring rates the lines based on the same methods that transmission line designers use to design them. Thus, data from tension monitors is ideally suited for operating lines based on the most important of the thermal design criteria, that of maintaining safe clearances.
2. Tension monitors can be used for transmission line ratings studies. In this application, the systems provide data which allows utilities to accurately define the actual limiting rating conditions.
3. In real time use, tension monitors can presently be applied as clearance warning systems or as rating devices which provide continuous real time data to the utility's SCADA system.
4. The economic benefits of real time rating can be very significant and can allow utilities to increase the utilization of their transmission assets.

Figure 1.

Sags of 1000 ft. span of Arbutus



1000 ft. (305 m) span of Arbutus 795 kcmil AAC

Temperature °C	Slack		Tension (end)		Tension (H)		Sag	
	ft.	m	lbs.	kN	lbs.	kN	ft.	m
15	3.17	0.97	2726	12.13	2700	12.02	34.5	10.52
60	4.15	1.27	2391	10.64	2362	10.51	39.4	12.02
100	5.03	1.53	2178	9.69	2145	9.54	43.4	13.23

Table 1.

The most economic choices in the open network will depend on the rules of compensation...

If compensation is based on:

Postage Stamp Rate

Operating Principles

- Operate lines at maximum capability which is less than I²R losses.
- Take risks.

Capital expenditures

- Do not build unless all capital costs are guaranteed.
- Any other expenditure is speculative and requires a substantial price premium.

Financial / corporate

- Make deals with IPPs and local generators to allow you to use higher "opportunistic" ratings.
- Make deals to move power in opposite directions.
- Move maximum power over short distances.

If compensation is based on:

MW-Miles

Operating Principles

- Operate lines at maximum capability which is less than I²R losses.
- Take calculated risks.

Capital expenditures

- Build if reduction of I²R losses exceed the capital costs.
- Build if the construction gives you a strategic delivery advantage.

Financial / corporate

- Make deals with IPPs and local generators to allow you to use higher "opportunistic" ratings.
- Make deals to move power in opposite directions.
- Move maximum power over long distances.
- Look for more wheeling opportunities.

If compensation is based on:

Return on Equity (ROE)

Operating Principles

- Operate lines at maximum capability which is less than cost of ROE.
- Do not take risks.

Capital expenditures

- Build if the new construction increases your ROE (or reduces your key competitors' ROE).
- Build if it increases your sales without reducing your return on sales.

Financial / corporate

- Sell or scrap old lines which have low actual power transfers.
- Use cash flow to pay down debt to reduce leverage / pay down debt.
- Reduce your operating expenses.

Sags and Tension Equalization at High Temperatures
Presentation at 1996 Summer Power Meeting, Symposium on Thermal Rating
Tapani O. Seppa, The Valley Group, Inc.

Sags and tension in a single span

Transmission line spans are catenary curves. For practical purposes, individual spans can be usually approximated as parabolas.

Consider a single, level span of horizontal length S , conductor weight w per unit length with a horizontal component of tension H . The actual arc length of the span is L . The geometric shape of any such span is defined by the following equations:

Sag: $D = (w \cdot L^2) / (8 \cdot H)$ (1)

Slack: $L - S = (8D^2) / (3S) = (S^3 w^2) / (24H^2)$ (2)

Note that for a constant w/H , the slack is proportional to the cube of the span. Thus, the relative slack, defined as the slack divided by the span length, is:

$Slack\% = (S^2 w^2) / (24 H^2)$ (3)

For example, for an ACSR "Drake" conductor, the slacks and the relative slacks at 5,000 lb. tension and 3,800 lb. tension are:

		<u>Span length, ft.</u>				
Tension (lbs.)		500	800	1000	1200	1500
5,000	Slack, ft.	0.25	1.02	1.99	3.44	6.72
	Slack%	.050%	.127%	.199%	.287%	.448%
3,800	Slack, ft.	0.43	1.76	3.44	5.96	11.63
	Slack%	.086%	.221%	.344%	.496%	.776%

Thus, if the tension changes from 5,000 lbs. to 3,800 lbs. for these span lengths, the differences in the slack% are:

	<u>Span length, ft.</u>				
	500	800	1000	1200	1500
Δ Slack%	.036%	.093%	.146%	.210%	.328%

Conversely, if the slack changes by a given amount, the tension changes. Thus, a change in slack% of 0.146% in a 1,000 ft. span causes a tension change from 5,000 lbs. to 3,800 lbs. The same change in slack% in other span lengths causes the tension changes shown in the table below (initial tension 5,000 lbs.):

	<u>Span length, ft.</u>				
	500	800	1000	1200	1500
Initial slack, %	.050%	.127%	.199%	.287%	.448%
Final slack, %	.195%	.273%	.345%	.432%	.594%
Final tension, lbs.	2524	3416	3800	4072	4344

Ruling span based sag calculations

All present transmission line designs are based on the ruling span concept. The underlying assumption of the ruling span concept is that the movement of the insulator strings equalizes the tensions in adjacent spans. If the tensions equalize completely, the sags of the spans can be calculated from the ruling span sag:

Sag of span $i = D_i = (S_i / RS)^2$ (4),

in which the ruling span length RS is:

$RS = \sqrt{\sum S_i^3 / \sum S_i}$ (5)

Comparing equation (5) to equations (2) and (3) shows that the ruling span (also called the "equivalent span") is the length of an individual span which has the same relative slack as a line section. For example, consider a two span section with 800 ft. and 1,121 ft. spans of ACSR "Drake". According to (5) above, the RS for this section is 1,000 ft. At a tension of 5,000 lbs., the slacks of the spans are 1.02 ft. and 2.80 ft., while at a 3,800 lb. tension the slacks are 1.76 ft. and 4.85 ft. Thus, the tension change has increased the combined slack of the two spans by 2.79 ft. The relative slack of the line section has changed from 0.199% to 0.344%, i.e. the same change that would happen in a single 1,000 ft. span.

Note that the assumption of tension equalization requires that the suspension insulator string between the spans allows the suspension clamp to move longitudinally. If the insulator string is vertical at 5,000 lb. tension, at 3,800 lb., the string would be displaced longitudinally by 0.41 ft. towards the longer span. The ruling span assumption implies that this 5" movement does not cause a change in the tensions of the spans.

Force balance at the suspension clamp

The force balance of a suspension clamp between two level spans is shown in Figure 1. The vertical weight on the suspension clamp is:

$F = w (S_1 + S_2) / 2 + w_i / 2$ (6)

in which w_i is the weight of the insulator string. If the length of the insulator string is a , a longitudinal displacement of b of the suspension clamp results in a tension difference between the spans, which is:

$\Delta T = F (b / a)$ (7)

Thus, tension differences are largest when the conduc-

Figure 1.

Tension balance at the suspension clamp

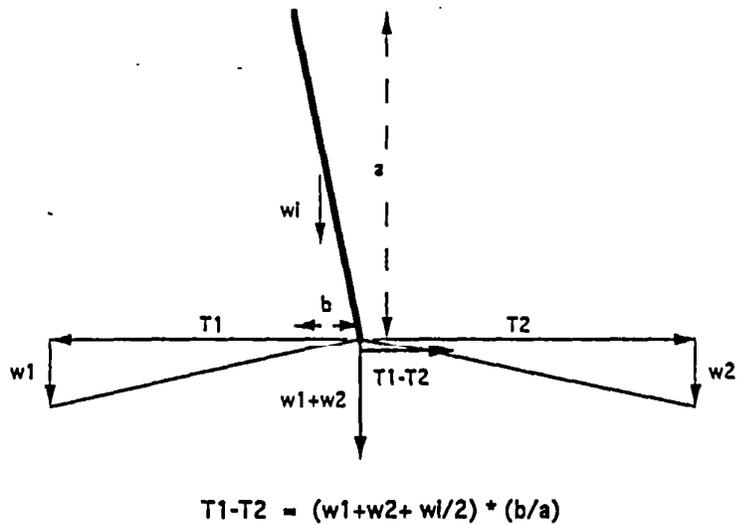


Figure 2.

Sag/temperature relationship of ACSR Drake, 1000 ft.

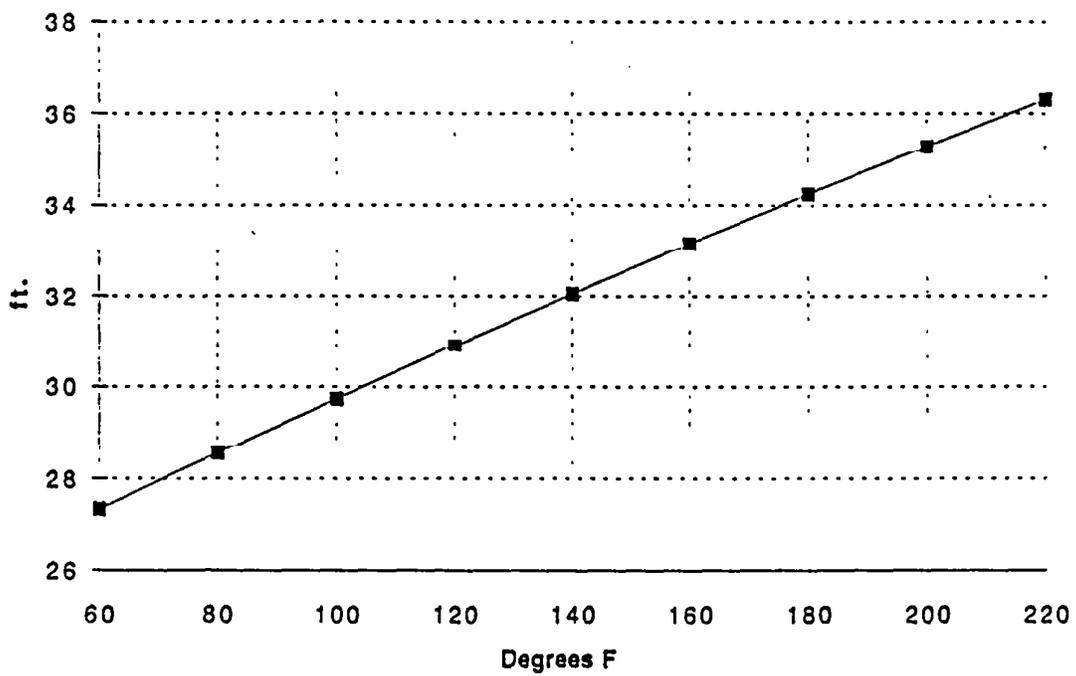


Table 3

Sag errors caused by a systematic variation of span lengths
Error = actual sag minus RS-based sag (clearance error)

Pair or pairs of spans									RS for Span 1
Span length	1121	1000	1000	1000	1000	1000	1000	800	1056
Sag error, ft.	-0.94	-0.39	-0.18	-0.02	0.14	0.33	0.62	0.66	
Span length	1000	1000	1000	800	1121	1000	1000	1000	994
Sag error, ft.	0.09	0.11	0.17	0.17	-0.11	-0.08	-0.06	0.00	
Span length	800	1121	800	1121	800	1121	800	1121	954
Sag error, ft.	0.44	0.23	0.23	-0.03	0.12	-0.22	0.00	-0.55	
Systematic variation									
Span length	800	800	800	800	1121	1121	1121	1121	854
Sag error, ft.	1.59	1.47	1.22	0.80	0.03	-0.90	-1.36	-1.55	
Span length	800	800	1121	1121	1121	1121	800	800	926
Sag error, ft.	0.73	0.50	-0.17	-0.72	-0.72	-0.17	0.50	0.73	
Span length	907	932	957	982	1007	1032	1057	1082	941
Sag error, ft.	0.73	0.65	0.47	0.23	-0.05	-0.35	-0.63	-0.84	
Span length	805	855	905	955	1005	1055	1105	1155	883
Sag error, ft.	1.25	1.22	1.01	0.63	0.11	-0.52	-1.16	-1.71	

Comments:

1. Pairs of spans which are within $\pm 10-15\%$ of RS do not cause major errors.
2. Systematic variation which causes the RS length at one end of the line section to be substantially different from average RS can cause significant sag errors.

Conductor Sag and Tension Characteristics at High Temperatures

Tapani O. Seppa and Timo Seppa, The Valley Group, Inc.

Presentation at the Southeastern Exchange Annual E/O Meeting, May 22, 1996 in Atlanta, GA

Background

Before 1970, most transmission lines were built for very low maximum conductor temperatures, in a time of fast growth of demand, easy availability of line corridors, and integrated long term planning. Economic calculations for a 30-40 year operational life of a line showed that operating temperatures of approximately 120°F resulted in optimum lifetime cost. As late as 1980, a report by the Swedish Power Board stated that "it is doubtful whether or not power lines should be designed for higher operating temperatures than 50°C".

Today's environment is quite different. Growth is minimal and new line corridors are not available. Network planning is now uncertain, because in the open access environment, generation dispatch uses the lowest cost source of power. The economic planning horizon has now become only 2-4 years. In most cases, the economy difference between generation costs is a magnitude higher than the cost of line losses to deliver the power. For example, during the first week of March 1996, surplus hydro power was available in the Washington/Oregon region spot market for 0.5-0.6¢/kWhr. Obviously, if the capability exists to transmit such power to Central California, where generation costs are 7-8¢/kWhr, line losses become meaningless.

Thus, it is not surprising that most utilities are looking for methods of uprating their existing lines at the lowest possible cost. The cheapest way is for utility management, or a committee, to declare a higher operating temperature. Many such committees have found that the line designs incorporate safety margins for clearance. For a committee consisting mainly of persons with little or no transmission experience, a safety margin is an obvious target to cut - "another example of engineering overconservatism".

What today's engineer must explain to management is that the safety buffers exist because we do not know everything. Present sag/tension calculation methods were developed at a time when a high operating temperature was an exception.

It is also important to emphasize that ruling span calculations are approximations. Even if these calculations are done on computers, resulting in sags and clearances computed with a resolution of one tenth of an inch, the data and the methods include unavoidable error sources, which necessitate the use of generous calculation buffers - or real time monitoring of the sags.

Error sources

Most electric utilities calculate the sags and tensions of their transmission lines using computer programs which simulate the "graphic method", originally developed by Varney [1], and later refined by a number of authors. An excellent description of this method can be found in Winkelman's classic paper [2]. The graphic method is based on a number of assumptions. The most significant are:

1. All wires of a given material have a uniform stress (i.e. which assumes that the conductor was manufactured under ideal conditions);
2. Conductor properties are equal to nominal catalog values;
3. The conductor was manufactured at a temperature of 20°C (68°F);
4. The elastic modulus E and the coefficient of thermal expansion α have constant values, equal to E at room temperature and α at a zero stress;
5. Aluminum and steel strands in the conductor behave independently, and there is no interaction between wire stresses caused either by hoop stresses or by gravity;
6. Conductor creep is shown by standard formulas (e.g. Aluminum Association average creep data);
7. The tensions equalize in a ruling span section between deadends at all temperatures. Thus, the sags of individual spans can be calculated based on the ruling span formula.

Recent data from several tension monitoring units brings the accuracy of high temperature sag calculations into question. Thus, each of the above assumptions needs to be investigated.

- At several sites with either AAC, AAC, ACAR, or ACSR conductor with a low steel percentage (e.g. 45/7), the agreement between calculated and measured sag-temperature relationships is much better. On the other hand, the actual sags of these conductors are generally higher than expected from design data, possibly indicating that creep is underestimated by standard calculations.

These findings are supported by earlier data. The 1981 report by O. Nigol and J.S. Barrett [5] described experiments that clearly showed evidence of larger than predicted sags of ACSR conductors. Yet, the theoretical mechanism they used to explain the data was not universally accepted; they predicted compressive stresses in the inner layer of aluminum of up to 1500 psi to explain their observed sag errors of about 4 ft. in a 1200 ft. span. One of their conclusions was that:

“Stress-strain and thermal elongation tests have demonstrated that the aluminum strands in ACSR conductors can support compressive stresses in the range of 6 MPa to 12 MPa. There is evidence from outdoor sag-temperature tests that the radial temperature gradients in the conductor, caused by wind, can increase the limiting compressive stress to 18 MPa or higher. This can account for excess high-temperature sags of roughly 1.5 m in a typical 300 m span”.

Discussion of this paper by J. Nick Ware and Harold W. Adams supported the author’s findings on compressive stresses.

In 1982, Georgia Power conducted simultaneous sag and temperature tests in a 213 m span of ACSR “Linnet”. The observed sag variation between 50°C and 90°C was substantially larger than that predicted by sag-tension calculations (see Figure 9 in [6]).

In 1994, EPRI conducted high temperature sag tests in a short laboratory span. The tests showed that high temperature sags of ACSR conductors were higher than anticipated. Unfortunately, there is no reference quality paper available. Verbal comments of the investigators indicate that the amount of excess sag was approximately equal to a 25°C temperature difference for 54/7 and 26/7 strandings.

High temperature sags of ACSR conductors are clearly larger than predicted by conventional methods. Thus, it is important to investigate some of the error sources in the sag calculations and the magnitudes of errors caused by these factors.

Lines may have substantial sagging errors or other installation errors, but this paper will assume that the line exists in an “as designed” condition. There are several other error sources to consider.

First error source: Conductor manufacturing accuracy

Even if you do not plan to operate your line at high temperatures, resulting in the additional errors described in the following sections, you need to recognize some basic limitations of sag calculations. “Transmission lines are not designed as Swiss watches”, nor are conductors made to similar tolerances.

- Generally, conductors are slightly oversized, typically having about a 1% larger than nominal cross section. The effect on sag calculation is of the same 1% magnitude.
- Conductor manufacturing temperatures are not controlled, and can vary by $\pm 20^{\circ}\text{C}$ between different manufacturing sites and times of year. If a 26/7 ACSR conductor is made at 20°C, sag-tension programs typically indicate a “knee point” at 55°C. Yet, if the same conductor is made at 0°C, the knee point is 35°C, and if it is made at 40°C, the knee point is 75°C. Thus, this can introduce a difference of ± 1 ft. in the 100°C sag of a typical 1000 ft. span (Figure 2).
- Individual wires do not have the same tension. Tests conducted by placing strain gages in individual strands show that the variation can be quite large. At a tension where the stress of aluminum wires of a 26/7 ACSR conductor were expected to be at 5800 psi, stresses in individual strands varied by ± 1800 psi [7]. Thus, the “knee point” becomes a curved region, instead of a single point. The uncertainty is of a magnitude of about 1 ft. in the 100°C sag in a 1000 ft. span. Also note that the wires in the inner aluminum layers of multi-layer ACSR are commonly tighter than the outer layers.

Combined, the manufacturing uncertainties alone suggest that a clearance buffer of at least 1.5 ft. should be used for transmission lines.

Compressive forces are likely to occur in the aluminum wires at high temperatures. The magnitude of such forces is open to discussion. Ontario Hydro has developed a computer program (STESS) which calculates the compressive effects based on Nigel and Barrett's compression hypothesis. Unfortunately, this program does not account for the other error sources described in the preceding paragraphs. Nevertheless, it is useful in identifying the potential magnitudes of sag errors.

What is the expected error magnitude? Ontario Hydro's tests on 400 and 1200 ft. spans showed sag errors of 2-4 ft. The compressive stress theory can only explain about one half of this amount, based on a compressive stress limit of 1000-1500 psi. Thus, observed sag increases were likely partially caused by the compressive stress, and partially caused by the high temperature changes in E and α . The compressive stresses alone can cause an additional error source of 1-2 ft. if ACSR conductors are operated above 80-90°C. Note that this error source will not affect AAC and AAAC, nor does it affect ACSR conductors of only one layer of aluminum or ACSR of less than about 7% steel.

Fourth error source: Ruling span calculations

Transmission lines are designed based on ruling span principles, which allow the calculation of the sags of individual spans based on the calculated "ruling span" of the line section. The underlying theory assumes that the horizontal component of the conductor tension equalizes in the line sections between any two deadends. The relative validity of this assumption depends on the suspension string remaining approximately vertical. Any significant inclination in the suspension strings causes a tension difference across the suspension structure.

The ruling span-based sag calculation is usually reasonably accurate. Major errors usually occur only when lines are uprated for higher temperatures. Errors can also be expected:

- When insulator strings are short and the span lengths are long;
- In line sections which have medium angles, especially if the structures are steel poles;
- In line sections where span lengths vary significantly. The largest errors occur in cases where the line sections consist of many spans and the span length varies systematically (the average span length of one line section differs significantly from the ruling span length).

Sag errors in individual spans can be calculated by using a computer program developed by The Valley Group, Inc. The program is used to determine sag-critical spans and tension limits for real time rating of lines where ruling span-based errors are substantial. Because the program, and field experience, show that the longest spans in ruling span sections typically have less sag variation than expected by the ruling span calculation, the results can often have a positive economic impact in line upgradings. On the other hand, the sag variation in the spans which are shorter than the ruling span length is typically larger than predicted by ruling span calculations. The results of the program have been verified by tension variation measurements from tension monitoring systems.

All present tower spotting and line optimization programs use the ruling span principle.

Fifth error source: Thermal rating calculations

The computer application of IEEE Standard 738-1993, along with programs such as DYNAMP, provide engineering tools which can calculate line ratings very accurately, but only if you select the correct input variables. Thus, the input selection for these programs is critical in obtaining the correct results.

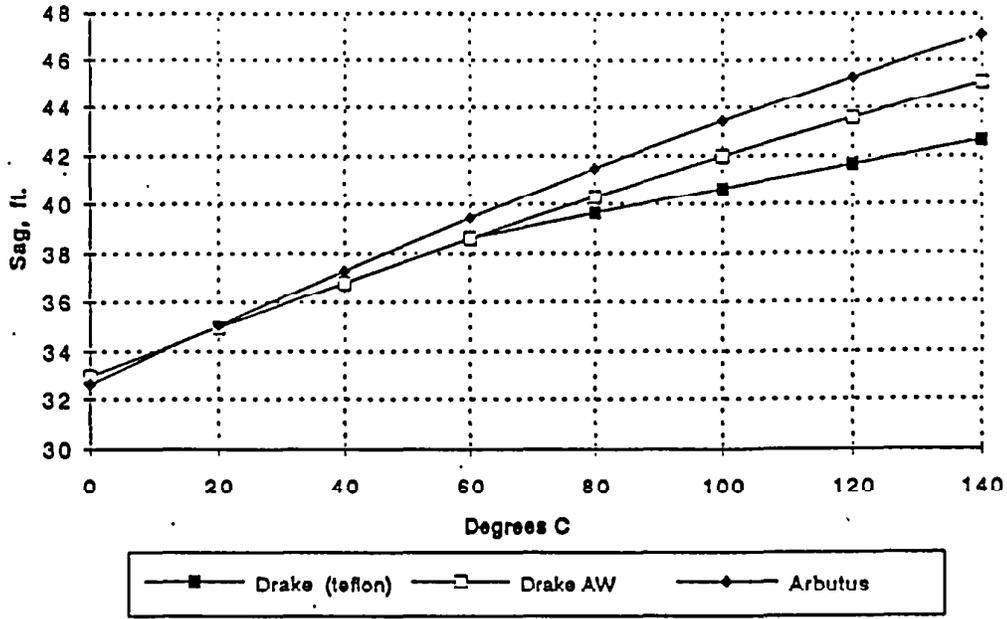
- Wind speed is the most important variable. Winds are much lower in sheltered transmission line corridors than at open weather observation sites, such as airports. At night, wind speeds can be close to zero. Data from tension monitoring systems has shown that the lowest real time thermal ratings often occur at night. And in today's aggressive transmission marketing environment, the highest loads are no longer guaranteed to occur in the afternoon, when the ratings are generally higher than at night. Unless there is solid evidence, it is not advisable to increase ratings based on higher wind speeds.

- Rating equations are based on the surface temperature of conductors. Yet, conductor sags depend either on the average temperature of the conductor, or for high temperature ACSR, on the temperature of the steel core, which can be several degrees higher than the surface temperature.

- Thermal rating devices measuring the conductor temperature measure the surface temperature of the conductor, and only at a single spot in the span. Yet, the temperature varies substantially be-

Figure 1.

Sags of 1000 ft. spans of Drake and Arbutus, assuming equal sags at 15°C



Tension of 1000 ft. spans of Drake and Arbutus, assuming equal sags at 15°C .

