6.9 AN APPLICATION OF REAL TIME METEOROLOGY TO MAXIMIZE THE CIRCUIT RATINGS IN THE PECO ENERGY TRANSMISSION LINE SYSTEM

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1. INTRODUCTION

One of the most important limitations on the maximum amount of power that can be transmitted by an overhead power line circuit is its thermal rating. The thermal limit is normally specified as that power flow which heats the conductors to their maximum allowable temperature under "worst case" weather conditions and is referred to herein as the line's "static" thermal rating. If the weather conditions along the line are monitored, it is possible to calculate the line's thermal circuit rating for these actual real-time conditions rather than for worst-case conditions. Thermal circuit ratings based on actual real-time weather conditions are referred to as Dynamic thermal circuit ratings (DTCR). The wind effectively cools the lines resulting in a direct relationship between wind speed and load capacity. Frequently, it is the assumed minimum wind speed that is the limiting factor which inhibits utilities from maximizing the transfer of electricity.

PECO Energy has begun a two-year pilot study to document real-time meteorological conditions along their transmission line corridors in Eastern Pennsylvania in an attempt to increase their transmission line ratings. At present, the rating of overhead transmission lines within the PECO Energy system is based on a fixed wind speed of 2.5 ft/sec. Preliminary data indicates that this wind speed is properly conservative for a static rating calculation but is normally exceeded during the day when power flows are at their maximum. Peco Energy has estimated that incrementally increasing this fixed wind speed to 3.5 ft/sec could mean a 10% increase in allowable power load, saving an estimated one million dollars annually.

Meteorological systems have been installed under and along transmission lines throughout Eastern Pennsylvania to measure numerous parameters including horizontal and vertical wind speed, wind direction, and ambient temperature. Additionally, real-time tension monitors have been installed to measure and model conductor temperatures. Data collected to date and over the next two years are being correlated with actual transmission line load data from PECO Energy with the goal of developing a model which returns the maximum electric transfer. This paper presents in detail the pilot program design, objectives and results to date.

2. LINE TRANSMISSION

During the past decade, it has become increasingly difficult for electric utilities to construct new facilities, such as transmission lines and substations. This is primarily due to escalating costs and public opposition. With an ever expanding demand for reliable electric power, utilities are finding it necessary to find alternative methods to increase the capacity of their power distribution network. The traditional methods for increasing the capacity of a particular network have been to either construct new generation facilities or to rebuild existing transmission lines and/or substations. Both solutions are cost prohibitive and undesirable.

An alternative low-cost method of increasing the capacity of the electrical network is to develop a system to recover any latent capacity that was previously unavailable. Such a method is the Dynamic Thermal Circuit Rating (DTCR) system which PECO Energy and the Electric Power Research Institute (EPRI) are jointly developing and installing on the PECO Energy power transmission system. The effect of wind speed on conductor temperature is the primary focus of this study.

As previously stated, the purpose of a DTCR system is to maximize the electrical capacity of power equipment by suggesting operating practices that bring the equipment to a utilization level which approaches the upper thermal limit of the device. The upper thermal limit or maximum operating temperature for a transmission line is based upon the peak electrical load and the worst case weather conditions. In many cases, often during peak demand periods, the maximum operating temperature has limited the capacity of the transmission line.

The PECO Energy study has the additional goals of first re-evaluating the static or normal operating parameters of transmission lines with respect to meteorological conditions, and secondly to develop a dynamic rating system which uses real-time meteorological data to instantly calculate a revised line rating.

When electricity is transmitted through a wire, or conductor, some of the energy is lost due to the resistance of the conductor. The lost energy is in the form of heat. In the case of an electric power transmission line, there can be hundreds of thousands of volts passing though the line at any particular time. As the electric load increases, the temperature of the conductor rises and the conductor expands, thus increasing the sag of the line. If the conductor temperatures are not actively monitored, it may be remotely possible to unknowingly exceed the ANSI guidelines for maximum allowable sag during peak loading periods.

Since a transmission line is suspended between transmission towers, there will always be some amount of sag (generally, line tension) in the conductor between any two towers. The amount of sag at any particular time is a result of the electrical load combined with environmental factors. These factors include the age of the conductor, the ambient temperature, solar heating and prevailing wind speed.

During the initial design phase of a transmission line construction project, the engineer models the performance of the line to insure proper sag. The result of this model is a data set which specifies the normal and emergency operating conditions for the line. Since there generally is a need to increase the capacity of the line, it is necessary to find ways of operating the line at higher levels.

By monitoring wind speed and line tension, it is thought that more power can be carried through the line than what current standards dictate. Because wind speed has historically been underestimated in constant terms, transmission lines have been underutilized, causing a significant loss of revenue during peak power demand times. Such peak times occur during severely hot weather with resultant high air conditioning loads lasting for extended periods of time.

While the sun heats the transmission line causing additional sag, the wind can alleviate this heating phenomenon by cooling the line and ultimately decreasing the sag. In areas now rated for maximum wind speeds of only 1-2 miles per hour, this study has begun to find that these same areas are electrically underrated causing an under-utilization of the transmission line. By re-rating and/or dynamically rating these lines, more power can be moved during heavy demand periods, thereby decreasing the need for off-system power generation. In other words, with line re-rating due to increased cooling from constant wind speeds, as discovered through this study, power companies can produce power locally and move it through their own proprietary lines without having to purchase it from elsewhere at significant cost.

With the specter of deregulation looming on the not-too-distant horizon, power companies will need to produce and move power through their own lines in order to decrease costs and increase efficiency, thereby retaining valued customers. A DTCR system is a powerful tool which provides a cost-effective solution to the need for increased line loading.

3. MONITORING PROGRAM

An extensive meteorological monitoring network has been installed across a 5-county area in Eastern Pennsylvania. This network includes eight sites which record wind speed, wind direction, and temperature at a height of 33 feet above ground level. This height corresponds to the approximate minimum sag height of transmission lines under normal conditions in the PECO Energy System. To determine the additional cooling affect of rising and sinking air, four of the eight sites also measure vertical wind speed. Since the primary interest of this study is centered on low wind speeds, Campbell Scientific wind anemometers capable of responding to wind speeds less than 1 foot per second were installed. Each of the eight sites also includes a Campbell CC-10 Data Logger, battery backup, modem, and phone line for remote interrogation.

One particular transmission line corridor was selected to study in detail the effects of wind, sun, and power load on line tension. An approximate 5-miles stretch of the 220kV transmission line between the Plymouth Meeting and Whitpain, Pa substations was selected because of it's importance during peak demand. Two of the Valley Group's CAT-1 Transmission Line Tension Monitors have been installed on towers along the right-of-way. Each CAT-1 monitor can transmit via cellular telephone instantaneous temperature, wind speed, wind direction, solar radiation, and line tension as recorded at the conductor level. In addition, two additional meteorological systems similar to the eight listed above, have been installed on 40-foot poles within the substation proper to measure the affects of the substation environment on the equipment. Table 1 summarizes the 12 monitoring sites currently operating in the study and a brief description of the parameters being measured.

Selecting the number of sites needed and where to place them in the PECO Energy Network has proven to be a significant challenge in this study. The PECO Energy Transmission Line Network includes the complex rolling terrain west and north of Philadelphia as well as the center city "Urban Heat Island". The wide range of vegetation, natural and manmade obstructions, and accessibility were all key factors determining the sites selected. Compounding the problem was the fact that some individual transmission line segments are suspended from towers on hill tops with the actual transmission lines dipping below the surrounding treetops in the valley below. This scenario is common in the western part of the Network and results in the transmission lines being subject to a variety of wind speeds, wind directions, solar insolation, and temperatures along the same segment.

The monitoring network is comprised of a balanced mix of sites which are either sheltered or open, and either in a valley, on a hill, or on flat terrain (Table 1). The sheltered valley sites would expect to provide the worst case scenario of light winds and higher daytime temperatures. The open hill sites provide the converse and are important in demonstrating the cooling affect of the wind on the overall line segment. It should be noted that most of the transmission line

TABLE I. PECO ENERGY METEOROLOGICAL MONITORING NETWORK

Site	Location	Parameters	Open	Shielded	Flat	Hill	Valley
1	Green Lane	WS,WD,T,VWS		X			X
2	Whitpain	WS,WD,T,VWS	X			X	
3	Plymouth Mtg.	WS,WD,T,VWS	X		X		
4	Bradford	WS,WD,T		X			X
5	Nottingham	WS,WD,T	X			X	
6	Buckingham	WS,WD,T,VWS	X				X
7	Grays Ferry	WS,WD,T	X		X		
8	Glenmore	WS,WD,T		X			X
9	Plymouth Mtg. (Substation)	WS,WD,T		X	X		
10	Whitpain (Substation)	WS,WD,T		X		X	
11	Plymouth Mtg. CAT	WS,WD,T,SR, TENSION	X		X		
12	Whitpain CAT	WS,WD,T,SR, TENSION	X			X	

KEY: WIND SPEED (WS), WIND DIRECTION (WD), TEMPERATURE (T), VERTICAL WIND SPEED (VWS), SOLAR RADIATION (SR), LINE TENSION MONITOR (TENSION) corridors are lined with fifty to sixty foot trees which approach within twenty feet of the lines. As a result, to accurately measure meteorological conditions along the lines, normal siting criteria could not be used when erecting these monitoring sites.

The thermal time constant of a typical overhead conductor is 10 to 15 minutes for wind speeds below 4 feet per second. To best represent this, fifteen minute averages of wind speed, wind direction, and temperature are stored in the network data loggers. Wind direction standard deviation are calculated and stored as well. In addition, due to the importance of low wind speeds, the minimum wind speed and frequency of wind speeds below the threshold value for each 15-minute period are recorded.

The overall success of the monitoring study is dependent upon the ability to obtain valid and continuous representative data. After the installation was complete in May 1995, each monitoring system was calibrated to design specifications. Over the next two years, regularly scheduled calibrations will occur every six months. Additionally, an aggressive emergency maintenance program has been established to minimize "down time". Complete sets of spare sensors have been procured, in the event of sensor failure or damage from hail, lightning, etc.

4. RESULTS TO DATE

Project personnel retrieve meteorological data from the ten network meteorological towers via modem twice-weekly. Fifteen-minute averages for the following meteorological data are archived for each of the ten sites: wind direction and standard deviation of wind direction, wind speed and standard deviation of wind speed, and temperature. Four of the sites are also equipped with a vertical wind-speed sensor.

Supplemental meteorological data are collected by PECO Energy at Plymouth Meeting and Whitpain, Pa, from the CAT-1 monitors located at intermediate points along the 220kV line.

Project meteorologists review and edited the meteorological data for reasonableness. This data review is enhanced by an understanding of the terrain and vegetation effects to the wind flow in and near each meteorological tower. The meteorologist's understanding of these local effects is supported through the use of topographic maps as well as routine visits to each site. The twice-weekly review of meteorological data is enhanced by a cross check of meteorological data from the PECO Energy Limerick Nuclear Generating Station and the Peach Bottom Atomic Power Station, both located in southeastern Pennsylvania, as well as data from the National Weather Service observation network.

An analysis of meteorological and power data from July 1995 follows.

4.1 Temperature Data

Climatological records for the Philadelphia Metropolitan Area have been maintained since 1871. Official observations have been recorded at the same location (Philadelphia International Airport) since 1941. The National Weather Service Office in Mount Holly, NJ currently maintains these records.

Temperatures across southeastern Pennsylvania were well above normal for the summer months of 1995. The mean temperature for the three-month period of June, July and August 1995 of 78.6°F was the warmest such period on record. As of September 18 there were forty-eight days in 1995 when the temperature reached or exceeded 90°F; the normal is 23 days. The mean temperature for the month of July was 81.5°F, which is the third warmest July on record; the normal mean temperature for July is 76.7°F.

Middle to late July was notable for an extended period of above normal temperatures. A summary of temperature averages for July 1995 across the PECO Energy meteorological tower network is provided in Table 2.

TABLE 2. AVERAGES FOR JULY 1995

Site	Temp. (°F)	Wind Speed (ft/sec)
1. Green Lane	73.8	2.3
2. Whitpain	76.3	6.8
3. Plymouth Mtg.	77.7	7.1
4. Bradford	73.6	3.3
5. Nottingham	75.7	7.1
6. Buckingham	76.5	5.0
7. Gray's Ferry	79.3	9.7
8. Glenmore	73.6	2.9
9. Plymouth Mtg. (Substation)	77.7	7.3
10. Whitpain (Substation)	77.7	7.3

There was a range of 5.7°F in the July mean temperature data across the PECO Energy data network. The lowest mean temperature, 73.6°F, occurred at both the Bradford and Glenmore Sites. The Bradford Site is located in a grassy field in a low-lying area, which is subject to optimal radiational cooling during the overnight hours. The Glenmore Site is located in a heavily forested area, where the daytime temperatures are affected by the vegetation. The highest temperature, 79.3°F, occurred at the Gray's Ferry location in the City of Philadelphia. The concentration of buildings, paved areas, and the lack of vegetation allow for maximum "Urban Heat Island" effects.

There was interest in determining how microscale meteorological processes impacted data in the environment of a substation. Substations are typically paved with stones and house power banks and power busses. PECO Energy installed an "in-substation" meteorological tower at each of the Plymouth Meeting and Whitpain Substations in addition to a meteorological tower located in the immediate vicinity of each substation. The mean monthly temperature at both Plymouth Meeting towers was 77.7°F. At the Whitpain "in-substation" tower the mean monthly temperature was also 77.7°F. At the Whitpain location, the tower in the field outside the substation recorded a mean monthly temperature of 76.3°F. On the warmest afternoon of the summer (July 15) the maximum average fifteen minute temperatures at the Plymouth Meeting meteorological towers differed by only 0.7°F. At the Whitpain meteorological towers the maximum average fifteen minute temperatures differed by only 0.2°F. In general, the impacts of the infrastructure associated with a substation had little impact on the temperature data.

4.2 Wind-Speed Data

A summary of wind-speed averages for July 1995 across the PECO Energy meteorological network is found in Table 2.

There was a range of 7.4 ft/sec in the mean monthly wind speeds for July 1995 among the ten sites. The minimum mean monthly wind speed of 2.3 ft/sec was recorded at the Green Lane Site. The Green Lane meteorological tower is located almost directly below the overhead transmission lines in a low-lying area, with dense forests of mature trees bordering the transmission line corridor. The maximum mean monthly wind speed of 9.7 ft/sec occurred at the Gray's Ferry Site in the City of Philadelphia, where the flat topography and lack of buildings in the immediate vicinity maximize the wind flow near the site.

TABLE 3. PERCENT FREQUENCY OF TEMPERATURES ABOVE 90°F AND WIND SPEEDS ≤2.5 AND ≤3.5 FT/SEC RESPECTIVELY

1. Green Lane	0.77	1.41
2. Whitpain	0.00	0.00
3. Plymouth Mtg.	0.10	0.10
4. Bradford	0.00	0.12
5. Nottingham	0.00	0.00
6. Buckingham	0.09	0.26
7. Gray's Ferry	0.00	0.00
8. Glenmore	0.00	0.13
9. Plymouth Meeting In Substation	0.07	0.10
10. Whitpain In Substation	0.00	0.00

In addition to the mean monthly wind speeds at each site, there is also an interest in the mean monthly wind speed across the entire meteorological network. A weighted averaging technique was used because there were some periods of missing data. The weighted average of wind speed for all ten meteorological towers in July 1995 was 5.9 ft/sec.

The current limiting wind speed for PECO Energy line rating is 2.5 ft/sec. The limiting wind speed, along with very high temperatures, now restricts the electrical current deployed through overhead transmission lines. The meteorological data for July 1995 was evaluated for the combination of high temperatures and low wind speeds. The results are provided in Table 3. The percent of observations with temperatures at or above 90°F and wind speeds less than or equal to 2.5 ft/sec is less than 0.1 percent at nine of the sites. Even at the sheltered Green Lane Site, this temperature and wind-speed criteria is met less than one percent of the time.

This analysis was repeated for the same temperatures but for wind speeds less than or equal to 3.5 ft/sec. These results are also provided in Table 3. The frequency using this criteria is less than 0.3 percent at nine of the sites. At the sheltered Green Lane Site, this temperature and wind-speed criteria is met for 1.41 percent of the observations. Given that July 1995 was the third warmest July on record at Philadelphia, the data from the PECO Energy meteorological tower network illustrate that the limiting wind speed of 2.5 ft/sec is extremely conservative.

4.3 Relationships between Meteorological and Power Data

There continued to be an interest in relating the meteorological data with power data. The 220kV line between Whitpain and Plymouth Meeting was used for this data analysis. Two tension monitors were installed at intermediate points of the 220kV line, as well as a sensor to measure the net solar radiation. For the initial phases of this project, a graphical presentation of the meteorological data was used. Therefore, software was developed to produce monthly plots of wind speed, line current, line tension, solar heating, and temperature for the Whitpain-Plymouth Meeting line. Monthly plots were produced for June, July, August and September 1995.

A sample of data plotted from July 15 is provided in Figure 1.

The series of plots at the top of Figure 1 are the wind speeds from the three wind-speed sensors at Plymouth Meeting (P) and the three wind-speed sensors at Whitpain (W).

The middle series of plots on Figure 1 include the current at Plymouth Meeting and Whitpain, and plots of line tension from two tension monitors at Plymouth Meeting and two tension monitors at Whitpain.

The lower series of plots on Figure 1 are the temperatures from the three temperature sensors at Plymouth Meeting and the three temperature sensors at Whitpain, as well as a solar radiation sensor at both Plymouth Meeting and Whitpain.

The following trends have been noted from plotting the data through the summer of 1995:

a. The limiting wind speed of 2.5 ft/sec occurred most frequently in the overnight hours.

b. The tension and current data frequently displayed diurnal variations. The diurnal ranges for both the tension and current plots displayed the greatest magnitude when there was a large diurnal temperature range. Days with large diurnal temperature ranges were generally clear and days with small diurnal temperature ranges were generally cloudy.

c. On clear days line tensions were greatest just before sunrise, between 0300 and 0500. Line tensions on clear days reached minimum values approximately one hour after maximum solar heating, generally between 1500 and 1700.

d. On a number of clear days the tension and current data were inversely proportional. That is, when the current data approached maximum daily values during the afternoon, the tension data concurrently approached minimum values for the day. The converse occurred during the overnight hours.

e. The period of June 14 through 20 was notable for a steady increase in maximum temperature with each successive day, from near 68°F on June 14 to 86°F by June 20. Overnight minimum temperatures also increased each day, from near 54°F on June 14 to approximately 66°F by June 20. We noted that the maximum line tension decreased steadily each successive morning of this period. However, the minimum line tension each successive afternoon did not decrease as steadily, despite the increasing demands on current. This we attribute to the cooling provided by the winds, which were generally above 5 ft/sec in the afternoons from 1200-1700.

5. CONCLUSIONS

Although only four months of this twenty-four month study have been completed, the early results have been promising. Helped by a very warm summer in Eastern Pennsylvania, the data demonstrate that during periods of extreme ambient temperatures, wind speeds of $\leq$ 2.5 ft/sec rarely occur, if at all, anywhere in the PECO Energy Network. In addition, line tension data when compared with temperature and wind-speed data, indicate that the cooling effect of the wind on transmission lines appears more than sufficient to counter any increase in line temperature and resultant sag due to increased current. Since this pilot study is ongoing, much more information will be obtained and analyzed over the next two years. However, the minimum wind speed rating of 2.5 ft/sec for the PECO Energy transmission line network is ultra conservative and inhibits using existing equipment to its full potential to meet power demand.

FIGURE 1. PLOT OF METEOROLOGICAL DATA VERSUS LINE TENSION AND CURRENT FOR JULY 15, 1995 ALONG THE PLYMOUTH MTG. - WHITPAIN 220kV LINE