NEW SOFTWARE PROGRAM FOR CALCULATING THE REVENUES FROM A MORE AGGRESSIVE LOADING POLICY AND THE SERVICE RELIABILITY OF POWER TRANSFORMERS

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INTRODUCTION

Several years ago, CPFL Maintenance group and CEMIG Operations group started to exchange experience and information on power transformer loading and life extension. This interaction helped the two groups to realize that a transformer operating with a dry paper and a nonacidic oil containing a low oxygen content could be more severely loaded. Also, it would operate more reliably than another with an acidic oil and a wet paper. In view of these possibilities, a more aggressive loading policy was introduced. As power transformer loading increased, the System Planning group of both companies decided to postpone investments in the construction of new substations.

We developed a software program ($CBL_{savings}$®) to evaluate the operational and economic advantages of the new loading policy. The information supplied by the program is the following:

- The savings obtained from postponing the construction of a new substation due to a more aggressive loading criterion.

- The end of operational reliability of power transformers based on its load and insulating system condition.

- The maximum load according to the utility's loading criteria such as top oil and hot-spot temperatures, daily loss-of-life of paper and the maximum per unit (p.u.) load.

- The top oil and hot-spot temperatures for checking temperature measurements of both electromechanical thermometers and electronic temperature monitoring systems.

PRESERVATION OF THE INSULATING SYSTEM

The maximum exploitation of power transformers can only be performed if they operate under good maintenance condition. Maintenance efforts must be oriented to minimize the influence of the factors which accelerate Kraft paper aging. The water content of Kraft paper, the oxygen content of insulating oil and its acid number must be kept very low as suggested in Table I[1]. Though these limit values are intended mainly to preserve Kraft paper, the insulating oil will be preserved as well. Transformers operating in a more critical condition cannot be loaded reliably to their maximum capacity. Bubbles can be formed at lower temperatures as the water content of paper increases. A survey of the insulating oil and Kraft paper preservation condition is valuable to determine the amount of critical transformers in service. The maximum temperature limits established in loading guides should not be reached in the case of poorly-maintained transformers. The loading guide limits are suggested for well-preserved units whose loss-of-life of paper is mainly caused by the heat due to loading.

TABLE I

SUGGESTED LIMITS TO PRESERVE KRAFT PAPER

TYPE OF TEST	LIMIT VALUE
WATER CONTENT OF KRAFT PAPER	< 1%
OXYGEN GAS CONTENT OF OIL	< 3,000 ppm
ACID NUMBER OF OIL	< 0.10 mg KOH/g

ECONOMIC ASSESSMENT

The loading criteria adopted by both of our companies until recently were based on technical parameters exclusively. In view of the changes faced by the electric power industry in Brazil, loading started to be assessed economicly. To accomplish such a task, we created the $CBL_{savings}$ software program. As a consequence of higher loads, it became feasible to change the criterion employed in planning the construction of a new substation. Both CPFL and CEMIG's criterion established that a new substation would be put in service when the load of transformers at an existing substation reached 100% of their rated capacity.

A new criterion for planning the construction of substations was introduced. It takes into consideration that both ambient temperature and load fluctuate all over the year for most transformers. Those operating in power plants are an exception since their load is almost constant. The fluctuations associated with the built-in thermal characteristics of transformers made available an extra capacity above the nameplate value. The extra capacity is calculated for each unit because of several individual factors involved. Calculation is made to determine the current obtained under real operating condition so that the unit reaches at least one of the limits established for design parameters such as top oil and hot-spot temperatures, daily loss-of-life of paper and p.u. load. Therefore, this calculated current became the new planning criterion for putting a new substation in service.

Table II shows an example of the input data referring to a substation with two transformers rated 138 kV and 25 MVA each. The data were useful for the assessment of the economic feasibility of the new planning criterion. The maximum daily current curve of the year - which was recorded in July, 1996 - was used in the calculation of the allowable daily current curve. Then, the maximum daily current curve of 1996 was used in the calculation to determine the year when its future values would reach the allowable peak current. The following parameters were also included in the calculation: the annual load growth rate, the ambient temperatures of a typical day of the month when the maximum daily current curve occurred, the transformer thermal characteristics, the top oil and hot-spot temperature limits, the maximum allowable load, and the maximum daily loss-of-life of paper. To make a comparable analysis, the cost to build a new 138-kV and 25-MVA substation was considered to be as an investment unit (IU). The cost of construction of the substation mentioned in Table II is equivalent to 1.65 IUs since two transformers will be installed in parallel.

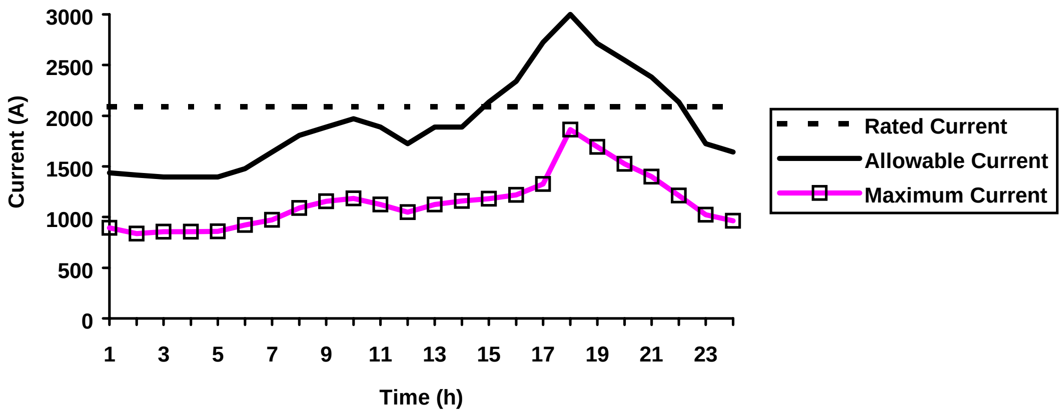
Figure 1 presents two daily current curves. The one at the bottom is the maximum daily current curve of the year. The other at the top is the allowable daily current curve calculated by the software program. The calculated peak current was 2999 A (Table II), which is 43% higher than the rated current (2092 A). Figure 2 shows that the maximum daily current curve of the year will reach the rated current in 1998. If the 100% loading criterion were still in use, 1998 would be year to have a new substation in service. As can be seen in Figure 3, the maximum daily current curve of the year will reach the allowable peak current only in 2005. The introduction of the new criterion postponed the substation construction for seven years. The expected savings are 55% of the 1.65 IUs that would be spent if the substation were built in 1998. These savings were obtained by calculating the amount of money to be deposited in a bank in 1998 so that an amount equivalent to 1.65 IUs would be available in 2005. If the annual interest rate were 12%, 0.75 IUs would have to be deposited in 1998.

TABLE II

INPUT DATA FOR ECONOMIC LOADING ASSESSMENT

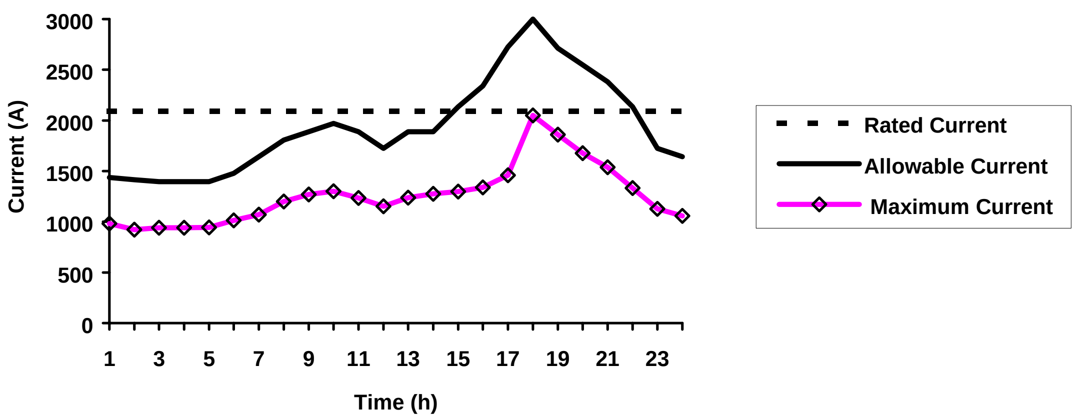
TIME (h)	AMBIENT TEMPERATURE (°C)	MAXIMUM DAILY CURRENT (A)	ALLOWABLE DAILY CURRENT (A)
1:00	6	892	1438
2:00	6	837	1413
3:00	6	857	1397
4:00	7	855	1397
5:00	8	858	1397
6:00	8	921	1479
7:00	9	972	1643
8:00	9	1091	1808
9:00	10	1155	1890
10:00	12	1184	1972
11:00	12	1123	1890
12:00	13	1048	1725
13:00	14	1124	1890
14:00	14	1159	1890
15:00	16	1181	2136
16:00	16	1219	2342
17:00	15	1327	2725
18:00	14	1864	2999
19:00	13	1691	2711
20:00	13	1526	2548
21:00	10	1399	2382
22:00	10	1213	2136
23:00	8	1024	1725
24:00	7	963	1643

SUBSTATION CHARACTERISTICS	OPERATIONAL LIMITS
Rated voltages: 138 - 13.8 kV	Daily loss of life: 0.0369%
Rated capacity: 2 X 25 MVA	Max. load in p.u.: 1.5
Rated current: 2 X 1046.0 A	Hot-spot temp.: 95°C
Cooling: NOFA1	Top oil temp.: 85°C
Winding rise temp.: 55°C	
Annual growth rate: 5%	
In service since: 1980	



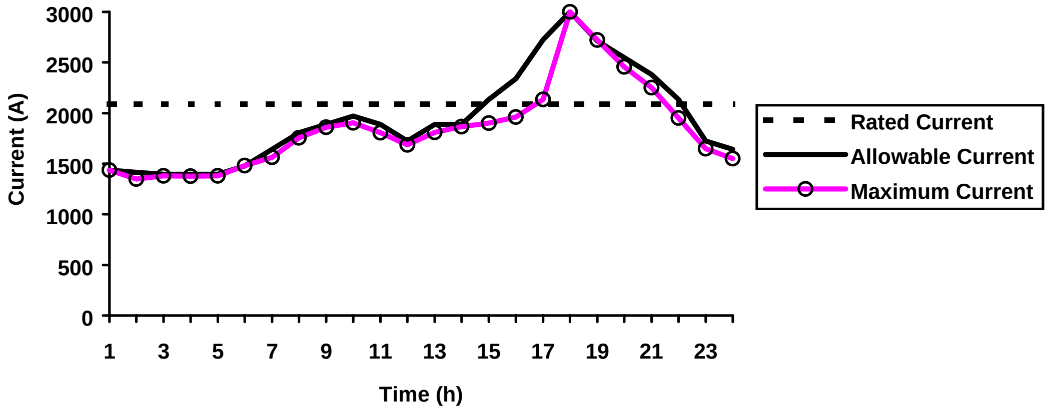
1996 MAXIMUM DAILY CURRENT CURVE AND ALLOWABLE DAILY CURRENT CURVE

FIGURE 1



1998 MAXIMUM DAILY CURRENT CURVE AND ALLOWABLE DAILY CURRENT CURVE

FIGURE 2



2005 MAXIMUM DAILY CURRENT CURVE AND ALLOWABLE DAILY CURRENT CURVE

FIGURE 3

Table III shows the savings expected to be obtained due to the new planning criterion only from the substations rated up to 138 kV and 25 MVA belonging to one of our companies. Once more for comparison analysis, the cost to build a new 138-kV and 25-MVA substation was considered to be as an IU. The utility has an equivalent asset of 35.51 IUs which correspond to 684 MVA. The new criterion made available an additional capacity of 147.43 MVA (22%) which is equivalent to the cost of postponing the construction of 17.04 IUs from 1995 to 1999.

TABLE III

SAVINGS TO BE OBTAINED FROM 138 kV AND 25 MVA SUBSTATIONS FROM 1995 TO 1999 DUE TO THE NEW PLANNING CRITERION

REGION	TOTAL EQUIVALENT ASSET (IU*)	EXPECTED SAVINGS (IU*)	PERCENT. OF SAVINGS (%)	INSTALLED CAPACITY (MVA)	ADDITIONAL CAPACITY (MVA)	PERCENT. OF ADDITIONAL CAPACITY (%)
CENTRAL	6.44	4.51	70	152.50	43.00	28
SE	1.66	1.00	60	39.50	6.12	15
E	6.84	2.65	39	151.50	13.23	9
N	3.89	1.26	32	57.00	16.07	28
TRIANGLE	5.68	1.90	33	130.00	21.08	16
W	7.26	3.09	43	106.00	28.61	27
S	3.74	2.63	70	47.50	19.42	41
TOTAL	**35.51**	**17.04**	**48**	**684.00**	**147.43**	**22**

* An investment unit (IU) is the cost to build a new 138-kV and 25-MVA substation

ESTIMATE OF THE END OF SERVICE RELIABILITY

$CBL_{savings}$ program was conceived to evaluate the end of service reliability of paper. Kraft paper is expected to take 7.42 years to reach 50% of its initial tensile strength, or 18.03 years to reach a degree of polymerization (DP) equal to 200[2]. Such a duration will occur if a thermally-upgraded paper is maintained at 110°C continuously. In the case of nonthermally-upgraded paper, the temperature is 95°C.

The water content of paper and the oxygen content of oil were included in the program calculation since they are accelerating factors of Kraft paper aging. The expected life of paper is reduced to the half when the water content of paper doubles[3]. The initial water content of paper adopted in the calculation was 0.5%. A high oxygen content of oil is considered to reduce the expected life of paper by 2.5 times[3]. In practice, oxygen is an important paper aging factor in free-breathing conservator type transformers. An easy solution to this problem was the development of a system consisting of a flexible bladder connected to the existing conservator tank, and filling both with nitrogen gas at a very low pressure[4]. Membrane-type conservator allows oxygen to permeate through the membrane, and should be carefully monitored to check for the increase of both oxygen content and acid number of oil. Transformers sealed with a nitrogen-cushion have not been considered to undergo an additional loss-of-life of paper because the oxygen content of their oil is usually lower than 3,000 ppm.

The evaluation of the service reliability of the paper of a poorly-maintained transformer is impaired because of much moisture contamination. In cases like this, it is even more difficult to determine the average water content of paper during the unit's lifetime. The availability of a DP test result can be very helpful to evaluate paper aging. In the case of operational transformers, the only feasible way to collect a sample from the windings is to use the paper microsampling technique[5].

Table IV shows the end of service reliability expectancies for the transformers mentioned in Table II. The load current curves used in the calculation were the average values measured during the first 16 years of service of the transformers. Simulations were made to establish the average water content of paper and oxygen content of oil during the service life of the two units since the real values were not available. The data in Table IV demonstrated clearly that water and oxygen accelerated paper degradation. Unit 1 is expected to reach 50% of the initial tensile strength of paper in 2008 and a DP of 200 only in 2019. In the simulation, the water content of its paper was 1% and the oxygen content of oil was below 3,000 ppm. Unit 2 must have 50% of the initial tensile strength of paper in 2001 and a DP of 200 in 2004. It is expected to arrive at the end of reliability in a shorter length of time because its insulating system was simulated as being poorly-maintained. The water content of paper was 2% and the oxygen content of oil was higher than 3,000 ppm.

TABLE IV

ESTIMATES OF THE SERVICE RELIABILITY OF POWER TRANSFORMERS

UNIT No.	END-OF-LIFE CRITERION	WATER CONT. OF PAPER (% in mass)	OXYGEN CONT. OF OIL (ppm)	YEAR OF THE END OF SERVICE RELIABILITY	YEARS IN SERVICE
1	**50% TENSILE STRENGTH**	1	< 3,000	**2008**	**28**
	200 DP	1	< 3,000	**2019**	**39**
2	**50% TENSILE STRENGTH**	2	> 3,000	**2001**	**21**
	200 DP	2	> 3,000	**2004**	**24**

The paper could have aged even more, but the average hot-spot temperature calculated for the two transformers will remain around 50°C from 1980 through 1998. Consequently, this low temperature will limit the loss-of-life of paper to very low values for this period of time. The loss-of-life of paper will increase significantly after 1998 as loads become much higher. If the water content of paper and the oxygen content of oil were the real values for the two transformers, the construction of a new substation foreseen for 2005 would have to be anticipated. Unit 2 will reach a DP of 200 in 2004 after 24 years in service. However, the accumulated loss-of-life of paper of unit 1 will be only 27% in 2005.

EVALUATION OF EMERGENCY LOADING CAPABILITY

The loss of a transformer due to an electrical failure may cause a power supply interruption of part of the load if there is no transformer available to take on the total load. When such an event occurs, fast decisions must be made. The right actions have to be taken as fast as possible because other problems may arise.

To facilitate the decision making under these circumstances, we developed the $CBL_{savings}$ program. It evaluated power transformer capability to supply loads under emergency condition. The calculation determined the allowable load to be carried by one of two units operating in parallel when the other is out of service for a certain length of time. This calculation is extremely important for the Operations group at utilities. If they are not sure the unit in operation can carry the load of the two units, the load of the unit out of service will have to be transferred to another substation in the area.

The software program takes into consideration several data such as the maximum limits for top oil and hot-spot temperatures, load currents, available capacity, ambient temperatures, and the thermal characteristics of the transformer. The calculation supplies a load current curve which tends to be as close as possible of the estimated emergency currents. The measured and estimated load currents to be carried by unit 1 is shown in Table V. As unit 2 was out of service from 4:00 PM (16:00) through 7:00 PM (19:00), currents were estimated for this period of time.

TABLE V

LOAD CURRENTS

TIME (h)	CURRENT (A)	TIME (h)	CURRENT (A)	TIME (h)	CURRENT (A)
1:00	577	9:00	854	17:00*	2050
2:00	556	10:00	847	18:00*	2200
3:00	556	11:00	854	19:00*	1944
4:00	568	12:00	881	20:00	924
5:00	602	13:00	895	21:00	927
6:00	721	14:00	919	22:00	741
7:00	748	15:00	922	23:00	668
8:00	813	16:00*	1862	24:00	588

* Estimated current

The analysis presented in Table VI indicates that the load current curve was limited by the top oil temperature. Figure 4 shows the load current curves calculated for different temperature limits. In Figure 4 (a), the limits were 100^{o}C for the top oil and 120^{o}C for the hot-spot temperature; while in Figure 4 (b), they were 110^{o}C for the top oil and 130^{o}C for the hot-spot temperature. The dotted lines in Figure 4 were obtained from the estimated emergency load currents. The black curves represent the allowed currents. The limit change enabled higher allowable load currents. A comparison between the currents during the emergency is shown in Table VII. As can be seen in the table, the higher temperature limits reduced current interruption.

THERMOMETER CALIBRATION

We estimate that around 70% of power transformers in service in Brazil have temperature measurement problems since all the installed thermometers are of electromechanical type. However, accurate temperature measurements become extremely critical when higher temperatures are reached at peak loads. Even small measurement deviations can cause false alarms and transformer trips when maximum temperature limits are reached. This may require to transfer load or to interrupt it partially.

Field surveys to check for thermometer measurement reliability showed that the conventional electromechanical thermometers need to be reset at least every two years. In many cases, however, calibration requires to take the transformer out of service because the thermometer hole is located near the bushings, and this prevents the thermometer bulb to be safely removed. Calibration is also time-consuming since it depends on the skill and experience of the technician at work.

TABLE VI

CALCULATION OF EMERGENCY LOAD BY $CBL_{savings}$ SOFTWARE PROGRAM

SUBSTATION CHARACTERISTICS		OPERATIONAL LIMITS
Substation: IBIRA	Rated voltages: 138 - 13.8 kV	Daily loss of life: 1%
Transf. company no.: 120	Rated capacity: 25 MVA	Maximum load in p.u.: 2.0
Manufacturer: BLC	Rated current: 1046.0 A	Hot-spot temperature: 120 C
Transf. Serial no.: 234	Winding rise temp.: 55°C	Top oil temperature: 100 C
Cooling: NOFA1		

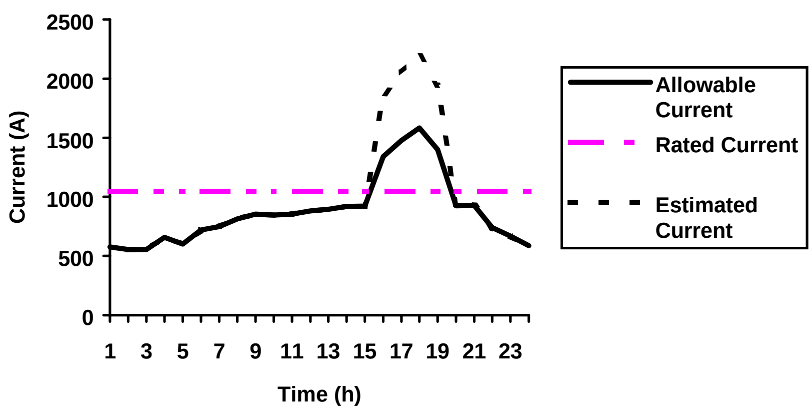
CALCULATION

TIME (h)	INPUT (A)	OUTPUT (A)	LOAD (p.u.)	MVA	TEMPERATURE (°C)			LOSS OF LIFE (%)
					AMB	TOP OIL	HOT SPOT	
1:00	577.00	577.00	0.55	13.79	30	49.4	53.3	0.0000
2:00	556.00	566.00	0.53	13.29	30	47.4	51.1	0.0000
3:00	556.00	556.00	0.53	13.29	30	46.3	50.0	0.0000
4:00	568.00	568.00	0.54	13.58	30	46.0	49.8	0.0000
5:00	602.00	602.00	0.58	14.39	30	46.1	50.3	0.0000
6:00	721.00	721.00	0.69	17.23	30	47.2	52.8	0.0000
7:00	748.00	748.00	0.72	17.88	30	49.5	55.5	0.0000
8:00	813.00	813.00	0.78	19.43	30	52.2	59.0	0.0000
9:00	854.00	854.00	0.82	20.41	30	55.0	62.4	0.0000
10:00	847.00	847.00	0.81	20.24	30	56.9	64.2	0.0000

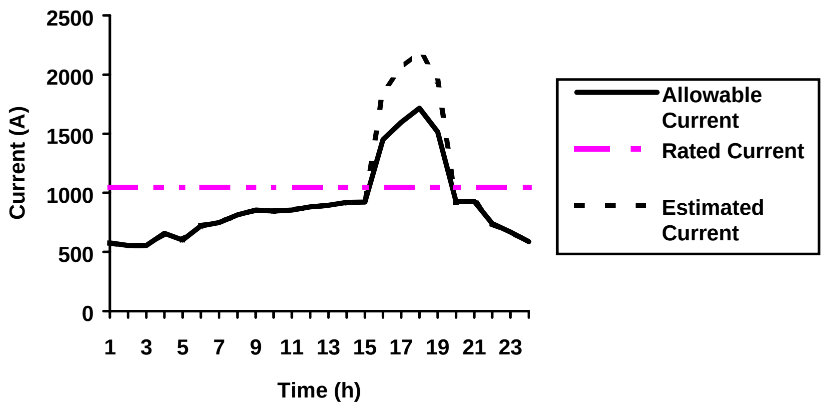
11:00	854.00	854.00	0.82	20.41	30	58.2	65.6	0.0000
12:00	881.00	881.00	0.84	21.06	30	58.8	66.6	0.0000
13:00	895.00	895.00	0.86	21.39	30	59.4	67.4	0.0000
14:00	919.00	919.00	0.88	21.97	30	60.4	68.7	0.0001
15:00	922.00	922.00	0.88	22.04	30	61.4	69.7	0.0001
16:00	1862.00	1340.48	1.28	32.04	30	65.1	80.3	0.0002
17:00	2050.00	1475.83	1.41	35.27	30	75.8	93.5	0.0013
18:00	2200.00	1583.82	1.51	37.86	30	89.3	109.1	0.0077
19:00	1944.00	1399.52	1.34	33.45	30	100.1	116.3	0.0168
20:00	924.00	924.00	0.88	22.09	30	97.1	105.4	0.0051
21:00	927.00	927.00	0.89	22.16	30	83.8	92.2	0.0011
22:00	741.00	741.00	0.71	17.71	30	68.8	74.7	0.0001
23:00	668.00	668.00	0.64	15.97	30	58.2	63.2	0.0000
24:00	588.00	588.00	0.56	14.05	30	53.7	57.8	0.0000

ANALYSIS

The load curve was limited by the top oil temperature	Maximum load in p.u.: 1,514 at 18:00 h Hot-spot temperature: 116.3 C at 19:00 h
Daily loss of life: 0.0327%	Top oil temperature: 100.1 C at 19:00 h



(a) LOWER TEMPERATURE LIMITS (120°C HOT SPOT)



(b) HIGHER TEMPERATURE LIMITS (130°C HOT SPOT)

ALLOWABLE DAILY CURRENT CURVE FOR UNIT 1 WHEN UNIT 2 IS OUT OF SERVICE FROM 16:00 TO 19:00

FIGURE 4

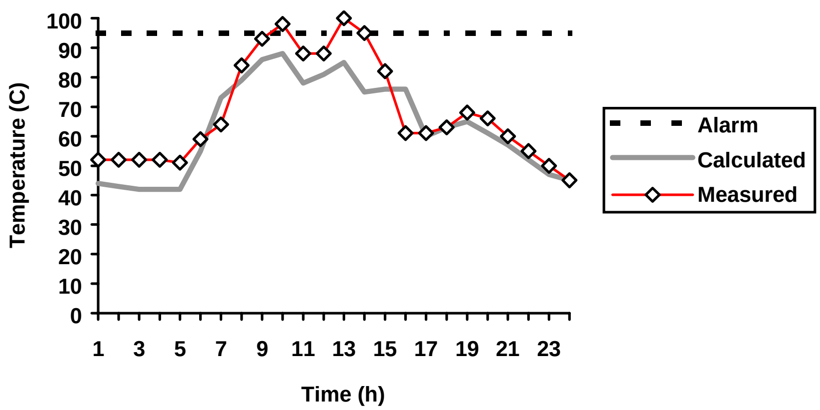
We developed the $CBL_{savings}$ to determine the reliability of temperature measurements. The program can also be used for setting temperature monitoring systems during their installation and for confirmation of their adequate operation. Ambient temperatures, load currents and the thermal characteristics of the transformer were used as input data. The program calculated the top oil and hot-spot temperatures for the currents and ambient temperatures supplied. A comparison was made between the calculated values and the thermometer measurements. After the introduction of this maintenance procedure, temperature measurements became more reliable, and thermometer calibration is performed at a shorter length of time.

TABLE VII

COMPARISON OF CALCULATED CURRENTS BASED ON DIFFERENT LIMIT VALUES

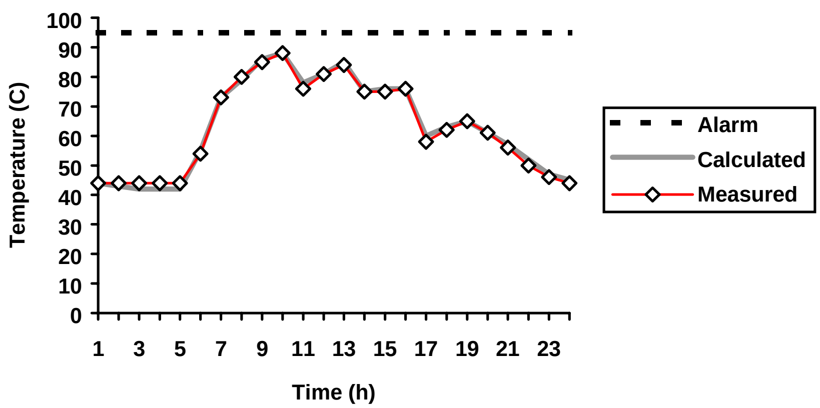
TIME (h)	ESTIMATED CURRENT (A)	CURRENT LIMITED AT 12O°C (HOT SPOT)	CURRENT INTERRUPTED AT 12O°C (HOT SPOT)	CURRENT LIMITED AT 13O°C (HOT SPOT)	CURRENT INTERRUPTED AT 13O°C (HOT SPOT)
16:00	1862	1340	**522**	1452	**410**
17:00	2050	1476	**574**	1599	**451**
18:00	2200	1584	**616**	1716	**484**
19:00	1944	1400	**544**	1516	**428**

Figure 5 shows a comparison between the calculated and measured hot-spot temperatures for the thermometer of a 138-kV and 15-MVA power transformer. As the hot-spot temperatures measured were very close to the alarm limit of 95°C, it was necessary to know if the thermal image thermometer measurements were reliable. Temperature discrepancies between calculated and measured hot-spot temperatures reached up to 15°C. This information helped to avoid load interruption. After the thermometer calibration, new data were collected to confirm temperature measurements for different currents and ambient temperatures. Figure 6 shows a temperature comparison after the problem had been solved, and a minimum discrepancy is seen. Discrepancies between calculated and measured temperatures range usually 1-3°C for electromechanical thermometers and 1°C for electronic temperature monitoring systems operating adequately.



COMPARISON OF CALCULATED AND MEASURED TEMPERATURES BEFORE THERMOMETER CALIBRATION

FIGURE 5



COMPARISON OF CALCULATED AND MEASURED TEMPERATURES AFTER THERMOMETER CALIBRATION

FIGURE 6

CONCLUSION

The maximum loading of power transformers can only be performed for units with a low water content of Kraft paper and a nonacidic oil with a low oxygen content. Otherwise, these factors will accelerate Kraft paper aging.

Temperature limits established in loading guides should not be reached in the case of poorly-maintained transformers. Loading guide limits are usually suggested for well-preserved transformers which age mainly due to heat from loading.

$CBL_{savings}$ software program was developed to validate a new criterion for planning the construction of new substations. The previous criterion established that a new substation would be built when the load of transformers at an existing substation reached 100% of their rated capacity. The new criterion proposes that a new substation must be put in service when the load current causes the transformer to reach at least one of the limits established for its design parameters such as top oil and hot-spot temperatures, daily loss-of-life of paper and p.u. load. The introduction of this criterion has enabled expected savings equivalent to postponing the construction of 17.04 substations rated 138 kV and 25 MVA from 1995 to 1999.

Power transformer capability to supply loads under emergency condition was included in the $CBL_{savings}$ software program. The program calculates the allowable load currents to be carried by a unit in service when another is out of service. This information is helpful to make fast decisions after an electrical failure of power transformers.

Top oil and hot-spot temperatures are calculated by $CBL_{savings}$ program for checking temperature measurements. Temperature discrepancies between calculated and measured hot-spot temperatures can be as high as 15°C. Discrepancies between measured and calculated temperatures range usually 1-3°C for electromechanical thermometers and 1°C for electronic temperature monitoring systems operating adequately.

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