Management of Available Power in Substation Transformers Based on Reliability

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Abstract **- This work presents a methodology for estimating the maximum power that can be extracted from distribution substation transformers based on (i) estimated values of future load, (ii) current temperature values measured at various locations within the transformer, and (iii) transformer reliability requirements. The final goal of the methodology is to provide a sensible means of controlling transformer overloads, especially at peak times during the daily load curve. The methodology has been implemented as a software tool running on computers in the Distribution System Control Center. The software makes use of real-time data acquired directly from the local loading control subsystem installed in two major distribution substations within the CPFL (Companhia Paulistra de Força e Luz) system.**

Index Terms**-- Load Forecasting, Neural Networks, Overloading, Power Transformer Loading, Substation Automation.**

I. INTRODUCTION

AT present, as utilities have been privatized, they've been forced to maximize their rentability by increasing gains on trade and by cost reduction through the optimized management of their assets. With the increasing implementation of digital control systems on substations, such optimization has been partially possible by the local processing capacity which allows the application of modern techniques for load forecasting and functions of automatic control of the installation's primary system. For such, this work proposes the application of a power transformer loading control system based on the transformer's reliability linked to a short term load forecasting system, able to treat the load's aleatory behavior in the transformers or in the primary feeder, in an optimized way and in real time.

Not until recently was the power transformer loading control based on the instant power running on the equipment in relation to the nominal. This restricted its better use, once, as more determining than the power, the oil and winding temperature are the most limiting factors of transformer loading. Nowadays, the loading came to be controlled through a hybrid process which involves the current and the oil and winding temperatures. Even so, the conventional limits adopted for the oil and winding overheating protections are conservative. Those great margins of security conventionally adopted between the thermal level of shutting-off and the respective real limit of operation are the result of little awareness about the transformer's operational conditions. Historical data on loading, climatic, maintenance, transformer's actual temperatures, and future estimated values on temperature and loading are not usually obtained in real-time, for each transformer individually, especially in the Distribution Control Center.

Therefore, some elements lack when the operator makes non-conservative decisions, in case the alarm level of some of the protections of a transformer is reached. On the other hand, one cannot disregard the operational criteria without any supervision, because operating a transformer with the winding temperature (of the solid isolation) above 95°C implies on life loss, besides the nominal, and just in case the winding reaches 140°C, it may favor the formation of oil bubbles, which may provoke the transformer to turn off by means of the gas relay.

Next, the description of the system being developed for the supervising of power transformer loading in real time is presented. It was implemented in two CPFL distribution substations in Campinas, SP. The tool forecasts the systemic use by the operators of available power of each transformer individually, the capacities for future use of each equipment being made available by the Control Center. This makes the optimized control for each transformer possible, in a coordenate way and monitored by an optimization system, going through the local tool of each substation, helping the operator on the decision making in the Control Center.

II. SYSTEM DESCRIPTION

The integrated system is made of several local systems, installed in each substation , connected to a managing system at the Control Center (CC). Each local system is responsible for load forecasting of substation transformers, calculating a set of possibilities for future use for each one, increasing the utilization factor, according to the operational conditions, on the equipment's history and its accessories characteristics, at the same time assuring the transformer's reliability whatever loading level.

Until now, two prototypes have been implemented, one at the Campinas Centro Substation (SECAM), which has three 30/40/50 MVA transformers and twenty 11,95 kV feeders, and another at the Andorinha Substation (SEAND), which has two 30/40 MVA transformers and ten 11,95 kV feeders. One

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of SEAND's transformers has been furnished with fiber optics sensors to monitor the internal temperatures of oil and windings. This procedure has allowed the development and adjustment of algorithms more precisely to figure out heating, that were extended to non-sensored transformers.

The local system's architecture and the management system are described as follows.

A. Local System's Architecture

In each Substation, the Local System consists of two networks, one with digital transducers (IEDs) for the feeders and another one with RTUs in order to acquire electrical and thermal variables of the transformers. Those networks are connected to two microcomputers operating in LAN, one working as SCADA System host and another processing the computational tool for real time load forecasting.

The computational tool consists of four interconnected modules, which are fed by the data acquisition platform in real time. Every 15 minutes a loading forecast is carried out up to 4 hours ahead (Module 1) which supplies information on future conditions for loading the transformer for the modules 2 and 3. The module 2 estimates the top oil and hot spot temperatures and the module 3 estimates the transformer reliability. Having such information, the system is able to calculate, for each transformer, available power figures which can be released within the next 4 hours (Module 4), taking into account the operational limits of the equipment. Follows a more detailed description of each module.

A.1. Module 1: STLF

The *Short Term Load Forecaster* (STLF) is fed by a real time data acquisition system, and carries out the forecasts using an Artificial Intelligence technique based on Artificial Neural Networks (ANNs), for all substation transformers and feeders. The forecast is divided into two parts: 1) Base Forecasting, which is a 24-hour ahead prediction carried out daily at midnight till the day after, with 24 time intervals. This procedure is used to define the general operational condition of transformers and primary feeders for the coming day; 2) Follow-up Forecasting, which supplies short term forecasts along the day aiming to provide a procedure which monitors occasional loading variations, and accommodates moderate variations along the day. This procedure aims at supplying more accurate conditions of the loading behaviour, every 15 minutes, for five future intervals - ¼ hour, ½ hour, 1 hour, 2 hours and 4 hours ahead. This module has been extensively studied [1], and has provided satisfatory results, which could still be improved.

A.2. Module 2: TOTE

The *Transformer Operation Temperature Estimator* (TOTE) processes the results of Module 1 loading forecasting, producing a thermal analysis of each power transformer in order to allow adequate operating conditions, which does not rely on monitoring devices only. Along the loading curve, expected within 24 hours and the short term forecasting, are calculated the expected temperatures for the top oil and the hottest spot of each transformer (checking if this is capable to bear the load), which form the major step for defining reliability and consequently the admitted loading limits.

For the good transformer thermal equationing, the CPFL has acquired a transformer with 8 internal temperature fiber optics sensors from SIEMENS, including the conventional sensors. Special tests on the plant have allowed to adjust the parameters of the thermal equations with higher precision, besides allowing to estimate an alternative methodology to calculate the temperatures, which associates the power flowing through the transformer to the ultimate oil and winding temperatures. Details about this study can be found in [2]. The recommended equations by IEEE Standard PC57.119 Draft 13.2 [3] were also applied.

A.3. Module 3: LTRA

The *Loading Transformer Reliability Analyser* (LTRA) is responsible for the application of the reliability criteria on the transformers and was implemented using a "pseudo fuzzy" process [4]. In this module, four independent evaluation criteria were adopted (or Blocks): Project, Maintenance, Operation and Accessories, with some input data in common. The output for each block presents a classification based on Risk, one on Alarms and another showing the limiting temperatures. If risks are acceptable, these temperatures are used as a basis for the calculation of additional power that can be released. This module presents the highest complexity among all the modules, either in the quantity of parameters involved, or the representative models of each parameter. The characteristics of each block are:

1) Project: it reflects basically the main technical constructive characteristics, such as technical competence of the manufacturer, measuring of the several parts (main tank, conservator, etc.), types of isolation, handling on transportation, stocking and oil fill up, etc.;

2) Maintenance: takes into account the equipment's historical life, through the reliability variables, such as oil physical-chemical analyses and cromatography, concentration of humidity on the oil and paper, concentration of gases, furfural content, mechanical rigidity and dielectric, etc.;

3) Operation: includes the operational conditions of the transformer on the field, such as: frequency and short-circuit level, keraunia level, humidity and ambient temperature in the transformer neighbourhood, etc.;

4) Accessories: the total equipment reliability takes into account the status of their accessories, such as HV and LV bushings, OLTC, VTs and CTs, etc.

These criteria are analysed individually and, in the end, through an algorithm which leverages grades and weights, an report is released on the general operational condition of the equipment. This result, added to the other modules, enables the establishment of power figure levels which might be released from the present moment until 4 hours ahead, taking into account the forecasted loading profile.

A.4. Module 4: TAPP

The *Transformer Available Power Predictor* (TAPP) calculates the short term Available Firm Power (AFP) values automatically, which supplies the power quantity (MVA) which can really be extracted from the transformer during the future loading conditions, without representing a dangerous operational condition in itself. As the AFP is calculated in a time window from ¼ to 4 hours ahead, the operator has an important information on the individual situation of each transformer. The previous knowledge about the AFP figure allows the operator to possess a much more optimized management strategy, supervising the loading at local and/or systemic levels, in order to preserve the transformer in use even in the most critical overloading operational conditions.

The short term AFP figures calculates the maximum power that transformers can bear in safe conditions, even overloading the equipment nominal limits according to the reliability variables. This procedure also takes into account the transformer's risk of failure, as a loading function and figures out the probable transformer's loss of life reduction on this overloading situation. One can also determine the maximum power figure in a certain interval (ex.: 0,25h or 2h) which may take the transformer's temperature (oil or winding) to its limit. Those figures are available to the operator who will find this overloading convenient or not. Once the overload is accepted, the system recalculates each quarter of an hour the AFP and the transformer temperatures, enabling the transformer performance to be monitored in the followingintervals.

Figure 1 shows the module TAPP main screen. It is composed of the measured demand curve, the load forecasted curve at 4 hours ahead, the 24 hour-forecasted curve and of the AFP figures for the following 4 hours. The curves are updated automatically every 15 minutes, as soon as these figures are recalculated.

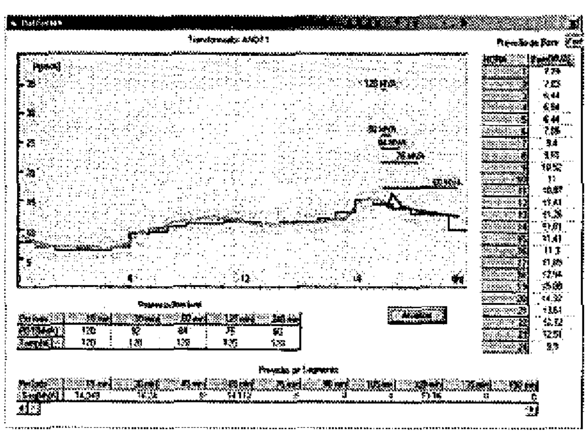

Fig. 1. Main screen of the Local Computing System

These last 2 modules, LTRA and TAPP, were implemented in a single computing module called LPTC due to technical implementation issues. But for conceptual reasons and for a better understanding of the system, the 4 modules are considered separately.

The local platform is being extended to a third substation, closing the biggest part of downtown Campinas. The characteristics of these 3 substations basically represent the CPFL's substations, being, by the end of the project, interconnected with the Control Center, validating the tool at the systemic level and giving meaning to the existance of local level tools.

The Integrated System's Architecture

The Integrated System or TLMS – *Transformer Loading Management System*, will be interconnected with the local processing platform of each substation (figure 2), and will be estimating the future loading conditions of the distribution system.

The TLMS gathers and makes available at the Control Center all information in real time or the equipment's history, measured or estimated (forecasted), of each substation transformer and feeder connected to it. This information can be:

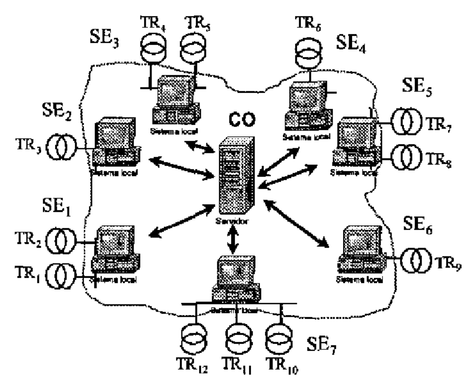

Fig. 2. Local Systems Systemic View integrated to the Control Center (indicated by CO).

- Traditional variables such as power, current, voltage, circuit breakers' status and protections etc. for transformers and feeders, top oil and winding temperatures, and ambient temperature figures in the substations, available every one minute;
- Non-conventional variables (in some transformers only) such as air temperature at the entrance of the oil ventilation vents, oil temperature at the refrigeration intake and exhaustion, winding and oil temperatures in the ducts (through the fiber optics), LV bushing basetemperature, air relative humidity at the substation, available every one minute;
- Forecasted power (MVA) for each transformer and forecasted current for each feeder, in short term intervals (from ¼ to 4 hours ahead) and 24 hours ahead, calculated by the STLF module every 15 minutes;
- Forecasted top oil and hot spot temperature for each transformer every 15 minutes, in short term intervals (from ¼ to 4 hours ahead), calculated by the TOTE

module;
- Available power figures and the associated risks up to 4 hours ahead, for each transformer, calculated every 15 minutes, based on the transformer reliability, calculated by LPTC (LTRA+TAPP);
- Warning alarms (and in some cases not releasing the available power) if some reliability variables reach critical levels, such as oil bubble formation temperature, oil power factor etc.).

Along with such information, the integrated system will allow the operator to visualize possible configuration topology of the distribution network in a more optimized way, both in expected contingency situations and in emergency ones (non-expected). The operator shall have, in real time, a set of configuration possibilities for future condition of power transformers being loaded above the nominal power for established intervals and limits, being able to obtain expressive gains both in the operation, planning and system expansion.

Using this extra power in the transformer, it is possible to, for example, not dispatching units to maneuver switches on the field, just transferring the block(s) affected by the contingency, switching buses at the substation , avoiding the load shedding(or minimizing it), improving the energy quality and reducing the system´s operational costs.

In the present conception, the system only supplies the operator with the system future loading condition, so that the operator itselfdecides the best strategy for the network configuration, i.e., the system does not make suggestions for configurations. In the future, this kind of help may be incorporated to this tool, suggesting configurations, taking into account not only the technical aspect, but also inputing economic variables to this decision, as for example, managing the equipment depreciation.

III. Conclusion

This paper presented a work which aims at developing an automated system for local use in Distribution Substations, in order to enable power transformer loading supervising in an optimized way and in real time from the Control Center, by means of a local tool from each substation. Besides that, this tool allows a more optimized distribution grid reconfiguration, with expressive gains for the operation planning and system expansion. Two CPFL substations had some prototypes implemented (and a third is being implemented), with very satisfying results.

The equipment monitoring and the implementation of automation platforms in substations tend to a less conservative limits of transformer loading. New and more reasonable loading practices, centered on the equipment reliability and on much more daring temperature limits have just come up. This is only more safely applicable before the implementation of a more precise transformer loading control process.

The developed local system has fully reached the expected aims. As a first analysis, the results have turned out to be satisfying, and the local system disposes a set of future possibilities of loading condition for each transformer individually, increasing the utilization factor, depending on the operational conditions and on the equipment's history.

It´s clear the great importance of loading control as a basis for automatic functions in substations. The final expected results are:

(i) Keep the transformer operating safely, most of the time;

(ii) keep under control the established loss of life ;

(iii) disconnect non-essential loads only when necessary, and in a minimal quantity;

(iv) avoid the risk of damage to the transformer being loaded in a maximized, continuous way, allowed in a certain time interval.

IV. References

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V. Biographies

José Antonio Jardini (M'66-SM'78-F'90) was born in São Paulo, Brazil, on March 27th, 1941. He graduated from Escola Politécnica da Universidade de São Paulo, Brazil, in 1963 (Electrical Engineering). From the same institution he received the MSc, PhD, Associate Professor and Head Professor degrees in 1971, 1973, 1991 and 1999, respectively. For 25 years he worked for Themag Engenharia Ltda., a leading consulting company in Brazil, where he conducted many power systems studies and participated in major power system projects such as the Itaipu hydro plant. He is currently Full Professor at Escola Politécnica da Universidade de São Paulo, where he teaches power system analysis and digital automation. He represented Brazil at SC-38 of CIGRÉ and was a Distinguished Lecturer of IAS/IEEE.

José Luiz Pereira Brittes was born in Ribeirão Preto, Brazil, on February 5th, 1959. He graduated from Universidade Estadual de Campinas, Brazil, in 1981 (Electrical Engineering). He received the MSc and PhD degrees in Electrical Engineering from Escola Politécnica da Universidade de São Paulo in 1996 and 2002, respectively. He has worked for Companhia Paulista de Força e Luz (CPFL), a Brazilian electricity utility, for 15 years, where he has conducted many power systems studies and participated in major power system projects. His research interests include the distribution automation and operational problems in electric power systems.

Luiz Carlos Magrini was born in São Paulo, Brazil, on May 3rd, 1954. He is graduated from Escola Politécnica da Universidade de São Paulo, Brazil, in 1977 (Electrical Engineering). From the same institution he received the MSc and PhD degrees in 1995 and 1999, respectively. For 17 years he worked for Themag Engenharia Ltda, a leading consulting company in Brazil. He is currently a researcher at Escola Politécnica da Universidade de São Paulo - GAGTD group.

Jorge Yasuoka (S'04) was born in Guarulhos, Brazil, on July 14th, 1974. He received the BSc. and MSc. degrees in Electrical Engineering from Escola Politécnica da Universidade de São Paulo, Brazil, in 1999 and 2002, respectively. He is currently working towards the PhD. degree at the same institution. Since 1997 he has been working in the field of load forecast and Artificial Neural Networks. His research interests include the application of

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Paula Suemi Dantas Kayano was born in Amazonas, Brazil, on July 9th, 1972. She graduated from Escola Politécnica da Universidade de São Paulo in 1995 (Electrical Engineering). From the same institution she received the MSc degree in 1998. She worked for Brazilian navy, participated in vessels electrical system projects. She is currently a researcher at Escola Politécnica da Universidade de São Paulo – GAGTD group. She is member Brazilina work group SC13.23 to CIGRE 54.

Josué de Camargo was born on April 28, 1958 in São Paulo, Brazil. He received his B. Sc. Degree in Electrical Engineering form the State University of Campinas (UNICAMP) in 1981. He worked at CPFL for 18 years in technical and commercial areas. Currently, he is the director of Expertise Engineering Co, working with Power Quality and as a researcher in the area of applied investigation into Power Distribution Systems.

Hernán Prieto Schmidt was born in Montevideo, Uruguay, on March 6th, 1960. He received the BSc and MSc degrees in Electrical Engineering from Escola Politécnica da Universidade de São Paulo in 1982 and 1989, respectively. In 1994 he received the PhD degree in Electrical Engineering from the University of London, UK. Between 1981 and 1990 he worked for E. J. Robba Consultoria & Cia. Ltda., a leading consulting company in São Paulo, where he developed computational models for power system analysis concerning composite generation/transmission reliability evaluation, automatic VAr sizing and location, and electrical and thermal analysis of underground power cables. Since 1985 he has been with Escola Politécnica da Universidade de São Paulo, where he teaches power system basics. His current research interests include the application of artificial neural networks in distribution systems and the development of GIS-based tools for the operation of electrical power systems.