AUTOMATED CONTROL OF EFFICIENCY OF LV GRID

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ABSTRACT

This paper deals with the new possibilities offered to Utilities for an automated control of the efficiency of electrical energy distribution. The accurate estimation of Technical Losses (TL) and Non-Technical losses (NTL) are linked to Fraud or energy diversion detection, this function is an aspect of the new challenges Utilities are facing today to efficiently manage decentralised energy generation, distribution and consumption.
Keywords: *Distribution Transformer Monitoring (DTM) Low Power Instrument Transformer (LPIT), Distribution grid efficiency, Smart Metering, Non-Technical Losses (NTL), Technical Losses (TL), energy diversion, tampering detection*

INTRODUCTION

This paper presents the benefits of a new generation of smart meters using non-intrusive LPIT current sensors, installed at the LV side of the MV/LV distribution transformer. The role of this meter is to coordinate its energy load profiles with those of residential smart meters installed at the junction of the grid and all residential loads and Decentralized Generation (DG). The objective is an automated detection of abnormal Non-Technical Losses (NTL). NTL are calculated in absolute value or as a percentage of the total energy circulating throw the grid. In case of abnormally high level of NTL estimation, the localization on the LV grid of the diversion can be obtained by the use of secondary non-intrusive smart meters collecting energy load profiles over given sub-sections of the LV grid.

DISTRIBUTION STATION METERING

The large deployment of Distribution Generation (DG) on MV and LV networks, based on renewable energy in parallel with introduction of new usage like Electric Vehicles, are the consequence to the increased demand to reduce carbon emissions. In this context, the MV/LV transformer becomes a critical node of the distribution grid. Utilities are more and more interested in monitoring the flow of energy on the LV side. This monitoring is first the metering of instantaneous active and reactive power and load profiles energies in the four quadrants over fixed time intervals , and also Power Quality indicators as voltage survey (sags, swells and cuts patterns, min/max excursion of the voltages, outage detection), THD, voltage and current waveforms and their harmonics content. Utilities are also interested in monitoring transformer load, load unbalancing, over-loading or under-loading periods of the transformer, and real time thermal behavior (Hot spot temperature) and ageing rate , because they are directly linked to loss of revenue for the utilities: Technical and Non-Technical Losses of the LV distribution grid are particularly interesting data.

Meter description

ACE7000 DTM meter is installed on the low voltage network, equipped with three LPIT current sensors connected to the meter. Current sensor technology (Rogowski) allows the safe commissioning of the meter, live, on an existing installation, whatever its power from 50kVA to 2MVA in outdoor or indoor MV/LV transformers.

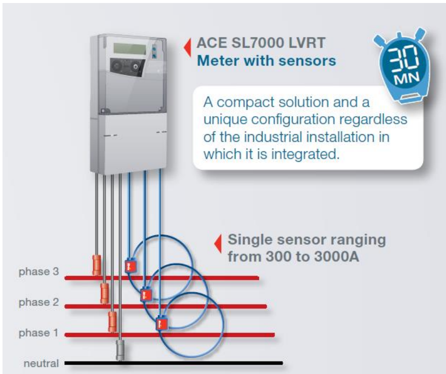

Fig.1 Distribution Transformer Meter (DTM)

ACE7000 DTM meter accuracy better than 0.5%, and largely better than conventional association of Class 0.5 meter and Class 0.5 inductive CT. The wide dynamic range (Istart < 1A and I max = 3kA) and large frequency bandwidth are key factors for precise energy diversion estimation and Power Quality analysis.

Fig.2 DTM meter in indoor and outdoor MV/LV station

Installation of DTM meter is possible on live network in indoor MV/LV station (160kVA -2MVA). Installation of DTM meter is also possible on live network in outdoor MV/LV station (50kVA – 160kVA).

Metrological linearity curves at PF=1 and at PF=+/-0.5 obtained with DTM meter are presented below on a dynamic between 0,3A to 3kA.

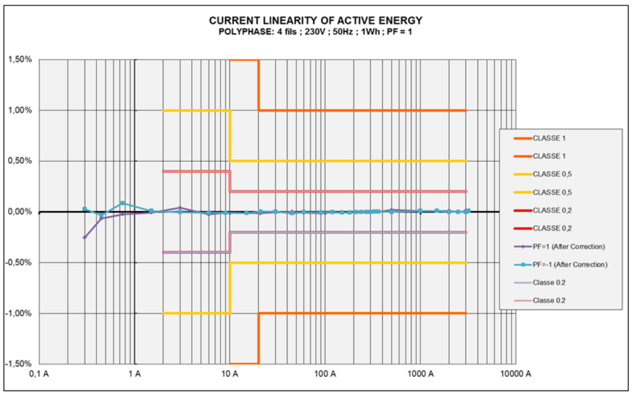

Fig.3 Linearity at PF1 and PF-1 (0.3A to 3kA)

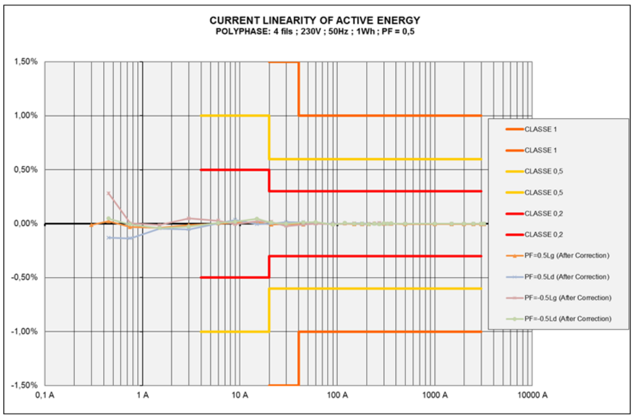

Fig.4 Linearity at PF 0.5 and PF -0.5 (0.5A to 3kA)

These unique linearity performances are resulting of nature of current sensor (Rogowski) and metrology firmware patented by Itron. Patent ref. WO2014117985 describes an innovative way to cancel the capacitive voltage coupling of the LV phase on the inductive current sensor signal , this allow accuracy even for the tiniest amount of energy , which is particularly relevant for TL and NTL reliable estimation .

LV residential Meter

Calculation of network losses (TL + NTL) implies that metering data must be acquired on each input and output of energy on the LV grid. Main export of energy to the grid comes from the secondary side of the distribution transformer, this energy is measured by DTM meter, all residential loads (import) and LV generation (DG) (export) are measured by single or poly phase residential smart meters. Metrological linearity curves at PF=1 and at PF=+/-0.5 of residential smart meters are presented below on a a range between 0.1A to 90A.

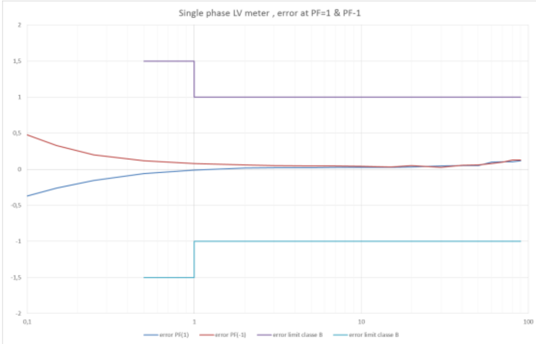

Fig.5 Linearity at PF+/-1 of smart meter (0.1A – 90A)

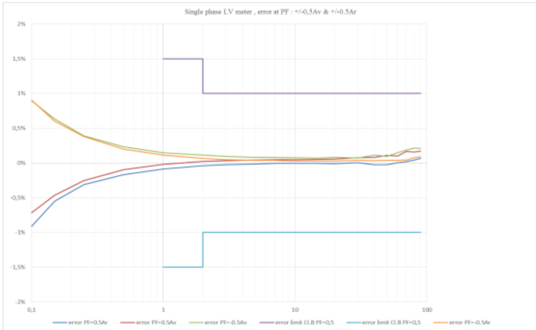

Fig.6 Linearity at PF+/-0.5 of smart meter (0.1A- 90A)

All the metering data of residential smart meter and DTM meter in active and reactive energy load profiles in the four quadrants are necessary and sufficient to estimate the sum of TL and NTL of the LV grid.
Inaccuracy in total losses measurement (TL + NTL) is given by calibration performance of residential smart meters (largely better than Class B (+/-1%) and DTM better than (+/- 0.5%).

Network losses Identification

For EU States, the average losses in distribution grids are between 2.3% and 13.5%. In MV grid, distribution transformers are the components presenting both fixed and variable losses. Typically, a third of the total system technical losses occur in transformers while fixed losses account for about two thirds of total transformer losses. In LV network, technical losses (TL) are variable depending on factors as: balancing on three phase loads, load power factor, too small section and lengthy conductor lines. Calculation of total network losses (TL +NTL) was complicated in the past, because losses were calculated and cannot be directly measured in most cases due to the diversity of electricity meter and difficulty to synchronize the load profiles manual readings.
The rollout of smart meters and DTM meter introduce a continuous and synchronized metering of all consumption and generation on the grid, this evolution allows now a direct measurement of distribution network losses.

LV network balancing.

Active energy balancing

All LV meters in Fig. 7 have synchronized load profiles over same interval of time. The total amount of active energy exported into the LV grid (Eexp (kWh)) by all the sources (MV/LV transformer + DG sources) is equal to the sum of the total amount of active energy imported by the residential loads (Eimp(kWh)) added to the total active losses L(kWh)

$$\mathbf{Eexp\ (kWh) = \sum Eexp(i)\ \ ,\ Eimp\ (kWh) = \sum Eimp(i)}$$

$$\mathbf{L(kWh) = TL(kWh) + NTL(kWh)}$$

$$\mathbf{\sum E\ exp(i) = \sum E\ imp(i) + TL + NTL}$$

$$\mathbf{NTL = (\sum E\ exp(i) - \sum E\ imp(i))\ \ - TL}$$

Above equation points that the calculation of NTL (kWh) depend of ($\sum$ Eimp(i) - $\sum$ Eexp(i)) calculation and TL estimation. For the term ($\sum$ Eimp(i) - $\sum$ Eexp(i)) the accuracy is only given by the meters linearity error , because all the meters are synchronized and integration of energies in load profiles are done during the same interval of time (error < +/-0,5%)

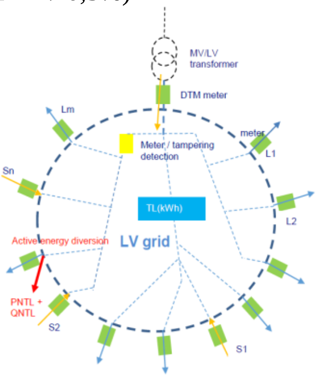

Fig.7: LV network with grid monitoring for NTL detection

Technical Losses (TL) estimation

Active losses of a conductor at main frequency are
$\mathbf{L = r.I^2 .dt}$, this formula can be generalized on each LV wire to : $\mathbf{L = (1/ PccN). \sum S^2\ exp(i)}$
Sexp(i): total apparent power of each sources exporting energy on the LV grid**.**
PccN: active power dissipated in the totality of LV wires in short circuit. This formula gives also the percentage of L compared to the nominal power of the transformer Sn(VA)
$\mathbf{(L/Sn)\ (\%) = (Sn / PccN). \sum(S\ exp(i) / Sn)^2}$
$\mathbf{L(W) = Sn.[(Sn / PccN). \sum(S\ exp(i) / Sn)^2]}$
Parameters of the above equation are:
Sn (VA) : Nominal apparent power of the transformer
Sexp(i) (VA) measured by DTM and other residential meters connected to DG.

Sn/ PccN = k (%) typical value is between 1% and 5%
$\mathbf{L = k(\%). Sn. (Sexp/Sn)^2}$
L is some percent of Sn (nominal power) multiplied by the square of the ratio of the total import over Sn. L is not a fixed percentage of Sn , if Sexp=Sn , then
L = k(%).Sn , and if Sexp=Sn/2 then L = (1/4).k/(%)

The TL energy is obtained by the integration of L in the load profile intervals of time:

$$\mathbf{L(Wh) = k\ Sn\ .(Sexp/Sn)^2\ .\Delta t}$$

Non-Technical Losses estimation

By injecting the formulation of TL in the equation of NTL a precise estimation of NTL energy can by formulated and calculated by the system at any interval of time.

$$\boxed{\mathbf{NTL = (\sum E\ exp(i) - \sum E\ imp(i)) - k\ Sn\ .(Sexp/Sn)^2.\ \Delta t}}$$

NTL can also be formulated in % of the total energy exported by all the sources to the grid.

$$\mathbf{NTL / \sum E\ exp(i)\ (\%) = 1 - \sum E\ imp(i)/ \sum E\ exp(i) - k.(Sn / \sum E\ exp(i)).(Sexp / Sn)^2.\ \Delta t}$$

NTL accuracy

$\sum$E imp(i) and $\sum$E exp(i) have the same inaccuracy +/- e% corresponding to the metrology error of the meters (e =+/-0,5%) .The major incertitude is on parameter **k(%)** in the formula of TL. In order to reduce the error on NTL, an identification procedure of parameter k is proposed consisting in calculating on a set of load profiles the equation of NTL for different values of k from 1% to 5% by step of 0.5%. For a LV grid where there is no diversion or theft of energy, k optimum value is obtained when NTL / $\sum$E exp(i) (%) is minimal by a least square criteria and equal to the uncertainty of metering +/-2.e% =+/-1%
For a LV grid where there is diversion or theft of energy, identification of k is more difficult, one possibility is to set k in the interval 1% to 5% to obtain for NTL / $\sum$E exp(i) (%) a load profile not correlated with Sexp , there is no evidence that the tampering load profile will be correlated with the total apparent power exported by the different sources on the grid while the TL are correlated with Sexp : $\mathbf{TL = k\ Sn\ .(Sexp/Sn)^2}$**.**

Active energy balancing

Whatever the load profile of the total active energy exported by the different sources to the LV grid , the ratio of NTL over the total amount of exported energy can be monitored and compared to alarm threshold : +/- 2%
Abnormally high positive ratios: **NTL / $\sum$E exp(i) (%)** can indicate active energy diversion or a customer meter presenting large negative metering error. At the opposite

abnormally negative ratios: **NTL / ∑E exp(i) (%)** indicate negative error of meter registering the sources.
When abnormally high ratio of NTL are detected, corrective actions will be launch to localize the significant Non-Technical Losses , this can be realized without any perturbation of the LV customers by putting live on the grid successively at different strategic positions a RT meters (RT = Rogowski Transformer) which will indicate to the system the total imported or exported energy of the downstream network. The calculation of the grid efficiency will no more take into account all the downstream meters but only the RT meters. When a satisfying balancing is found, the utility is sure that the cause of NTL is downstream to this RT meter.

Reactive energy balancing

Same calculations can also be done with reactive energies. These energies are exchanged between grid and sources and grid and loads, the sign (+/-) affected to each reactive energy depend of its inductive or capacitive nature. The balance between input and output is: Import reactive energy = export reactive energy

$$QNTL = \sum Q\ exp(i) - \sum Q\ imp(i) - QTL$$

QTL represent reactive losses of the network at main frequency is: $L\omega . I^2 .dt$, $QTL = (1/ QccN). \sum S^2 exp(i)$
Sexp(i) : Apparent power of all the sources exporting energy on the LV grid**.**
QccN: Reactive power dissipated in the LV wires in short circuit. Same development can be done for reactive energies than active energies.

MV network balancing

Calculation of energy balancing on MV network is identically obtained with accurate measurements of all active and reactive energies imported and exported on each MV feeder. DTM meter connected on the LV side embed an electrical and thermal model of the transformer and compute active and reactive energies dissipated inside the transformer, these energies are then added to the LV load profiles to finally deliver MV load profiles.

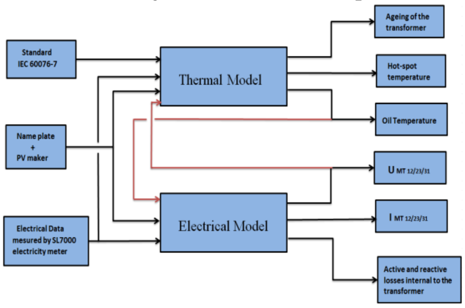

Fig.8 Block diagram of thermal and electrical coupled models embedded in DTM meter

Same calculations of TL and NTL done on LV side can be reproduced with all the energy quantities on the MV side.
The TL formula will be the same **k Sn. (Sexp/Sn)². Δt**
Sn being the nominal apparent power of the MV feeder, **Sexp** the total nominal apparent power of the sources injecting power on the MV grid, Δt : integration interval k (%) ratio of the active losses of the MV grid in short circuit under Un.

CONCLUSION

The smart metering roll out offers now to Utilities the possibility to calculate each day the Total Losses on their distribution networks LV, and on the MV network. The correlation between the Total Losses and the apparent energy injected on the grid will indicate clearly if these losses are only due to cooper losses (Technical Losses (TL) of few %) or if losses includes non-negligible Non-Technical Losses (NTL) due to tampering on meters or energy diversion.
The improved accuracy offered by residential smart meters and DTM meters , all of them synchronized and communicating their load profiles (RF , PLC) will help to pinpoint the poor efficiency ratio in the energy transfer from the sources to the loads. A mobile non-intrusive communicating RT (RT = Rogowski Transformer) meter with live installation on LV grid ,will also help to localize the significant Non-Technical Losses without any perturbation of the customers.

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