Technical analysis of the impact of smart meters' battery useful life on the management of a service company

De Carlo F.*, Navicelli A.*, Tucci M.*

**Dipartimento di Ingegneria Industriale (DIEF) – Università degli studi di Firenze, Viale Giovanni Battista Morgagni, bld.40 50134 - Firenze – Italy (filippo.decarlo@unifi.it, andrea.navicelli@unifi.it, mario.tucci@unifi.it)*

Abstract: The interest in tele-controlled meters (Smart Meter) derives from their diffusion, promoted by the European Union and regulated by law, in the industrial sector of utilities distribution (light, gas and water) with different power supply technologies. In the electricity sector, these are supplied by the mains, in the gas and water sector, it has focused on battery power, becoming the critical element for the reliability of meters. In this context, the following study aims to evaluate, through a case study, the economic impact caused by the early replacement of the battery pack or the entire meter, which causes an increase in operating and plant costs in addition to the non-amortization of the meters. The methodology adopted starts from the evaluation of the correlation between data transmission and battery discharge using deep learning. Afterwards, starting from the knowledge of the probability distribution function of the transmitted data for each connection, different consumption profiles were simulated with the Monte Carlo method to identify the remaining useful life of the batteries. The comparison of the estimated useful life with the nominal lifetime of the meter, which is required to manufacturers by tender specifications, made it possible to assess the economic impact of the extraordinary maintenance operations required. The results made it possible to evaluate the strategic importance of the meters' batteries, whose incorrect functioning has a strong influence on the entire company management.

Keywords: Management, reliability, utilities management, Deep Learning, Monte Carlo

1.Introduction

The European Directive 2009/73/EC, concerning common rules for the internal market in natural gas, and the 2012/27/EU, on energy efficiency, require EU Member States to ensure the implementation of 'smart metering systems' that assist the active participation of consumers in the energy market. These directives are part of the Horizon 2020 Research and Innovation project, the European programme whose main objectives are to improve overall energy efficiency to 20% by 2020.

Smart metering is the term used to describe systems that enable remote reading and management of electricity, gas and water meters. The switch from mechanical to electronic meters has led to the problem of powering them, necessary for remote management and telemetry. This problem, easily solved for the electricity sector, where meters are connected to the mains, is more difficult to solve for the gas and water sector, for which an external battery power supply is used. In the water sector, the process of replacing old meters is still being defined and not largely carried out as for the other sectors of public utilities; therefore, since the purpose of this study is to assess the useful life (UL) of smart meters batteries and their impact on business management, we will focus on the gas distribution sector.

The replacement of traditional gas meters has been started with the larger flow meters, and in 2013 it was extended to smaller calibre meters such as those for domestic use. The first directive on this subject is the resolution ARG/gas 155/08, dated 2008, with which the Authority for Electricity, Gas and Water System indicated a set of due dates for the replacement of the old gas meters with remote reading and management meters provided by the entity responsible for the measurement service. This timetable provides the replacement of 100% of the meters larger than measurement class G6 (nonhouseholder users) by 31 December 2012, and a gradual renewal of the lower measurement groups (household users) with the objective of exceeding 80% of installations by the end of 2016. Over the years, the Authority has updated the plan for replacing gas meters several times, considering the implementation difficulties. Currently the reference resolution is 631/2013/R/gas of 27 December 2013, which provides for the installation of 50% of smart meters class G4-G6 by 2018, and the complete installation of meters of the higher classes (Di Castelnuovo and Fumagalli, 2013).

Traditional household gas meters are membrane meters, also known as deformable wall meters. The operating principle consists in separating the gas volume into two measuring chambers with a capacity equal to the measuring volume. The measurement is correlated to the counting of the cyclical operations of filling and emptying the two chambers due to the differential between inlet and outlet pressures; a crank mechanism transmits the motion generated by them to a pinion that causes the tambourines to advance on the totalizer, where the updated consumption is displayed (Pearman et al., 1990).

The reliability of electronic meters is determined by the operating status of both mechanical components and all electronic components, depending primarily on the state of charge of the power supply batteries. There are in fact experimental failure data showing that early discharge of batteries is the main cause of malfunctions and alarms that occur in new generation meters. Such a system can be schematically represented as a series of two elements, respectively represented by the metrological component of the device and by its electrical component. This configuration works if and only if all its components work, therefore its reliability is determined by the least reliable component (Di Bona et al., 2016). An effective battery life shorter than the nominal one declared (and guaranteed) by the manufacturer, therefore implies a strong correlation between the RUL (Remaining Useful Life) of the power supply system and the RUL of the measuring device before maintenance is necessary (Van Gerwen et al., 2006).

In this regulatory context, triggered by the technological evolution of instruments for measuring natural gas consumption, the question arises whether it is possible to assess the impact of the useful life of the batteries used to supply the remote-controlled meters, in terms of cost, for the organisation and execution of extraordinary maintenance activities of these devices (Digiesi et al., 2012); furthermore, on the basis of the case study analysed, it is possible to give general indications on the behaviour of meters' batteries installed in Italy.

2.Methods

The wide use of batteries supply in many applications nowadays has made essential to accurately estimate their RUL. This, in fact, would lead to an improvement of the system in terms of both performance and reliability, allowing to avoid sudden interruptions in the operation of the device and to subject the battery to overcharging or over-discharging states that may compromise the internal structure. The existing techniques for the calculation of RUL can be categorized according to the different typology of approach to the problem. Are identified:

- experimental techniques;
- techniques derived from consumption trends;

Among the experimental techniques, methods requiring measurements of the physical quantities that govern the discharge phenomenon of a battery are identified. These approaches are based on the estimation of the state of charge (SoC), defined as the available capacity (in mAh) expressed as a percentage of the nominal capacity. This parameter can be considered as a thermodynamic quantity able to evaluate the potential energy of the battery in a given moment of time. The two methods mainly used to estimate the SoC are presented below:

- Coulomb counter
- Voltage measurements

The Coulomb counter, also known as Ampere hour counting and current integration, is the most common technique for SoC calculation. This method uses readings of the current delivered by the battery, which are integrated over the time interval of use to obtain the value of SoC, given by:

$$SoC = SoC(t_0) + \frac{1}{C_{rated}} \int_{t_0}^{t_0+\tau} (I_b - I_{loss}) dt \qquad \textbf{Eq.1}$$

where $SoC(t_0)$ is the initial charge state, C_{rated} the rated capacity, I_b the battery current and I_{loss} the current consumed by leakage reactions.

The Coulomb counter calculates the residual charge of batteries by evaluating the charge transferred inside or outside the battery. The accuracy of this method depends primarily on the accuracy of current measurements and estimates of the initial SoC. Once the capacity is known, which can be declared or initially estimated by operating conditions, the state of charge of a battery can be calculated by integrating the discharge current (or charge) over the working period. However, the charge released is always less than the charge stored in the charging and discharging cycle. These processes are characterised by the presence of losses. These losses, together with the self-discharging phenomenon, cause the overlapping of several errors, which make the result less reliable. Considering these phenomena, periodically recalibrating the SoC and not neglecting the decrease of the capacity available over time, are important factors contributing to a greater accuracy of the estimate (Murnane and Ghazel, 2017).

With voltage measurements, however, the SoC of a battery, i.e. its residual capacity, can be determined by a discharge test under controlled conditions. This method converts a reading of the battery voltage into the equivalent state of charge by means of its characteristic discharge curve (Volts vs SoC). However, the voltage is significantly affected by the current intensity, due to the typical electrochemical kinetics of the battery, and temperature.

A more accurate estimate is obtained by correcting the measurement with a current-proportional term and using Open Circuit Voltage (OCV) reference tables as a function of temperature. The need for a stable voltage range for the correct functioning of the battery makes this method difficult to implement. Finally, it should be noted that, unlike the current measurements used by the Coulomb meter (online method), during the voltage measurement it is necessary to interrupt the system power supply (offline method), a further limiting requirement in practice (van Schalkwijk and Scrosati, 2007). The traditional techniques derived from the consumption trend are intended to determine the RUL of a battery from a set of data that associate a specific battery level with a specific time reference. The battery level can be expressed by relative indices, such as SoC or Depth of Discharge (DoD = 1-SoC), or by autonomy indicators, such as the number of days or hours of operation remaining at the corresponding time. Once the set of points to be considered has been defined, it is possible to study the problem in statistical terms and to define the distribution trend outside the definition domain. Data are processed using self-regressive forecasting methods, the variable being under examination exclusively based on time, both on a multi periodic basis, where the same weight is given to all historical data, and on an aperiodic basis, where the most recent data are of greater importance. The choice of the model to be used is strongly correlated to the type of data distribution. Finally, confidence bands identify the reliability of the result. The main limitation of these methods is due to the strong dependence between the accuracy of the estimate obtained and the accuracy of the available data. In fact, these are often provided by the powered system itself, and it is not always possible to know how they were recorded. The techniques derived from the consumption trend, although lacking in accuracy of the estimate of RUL compared to some experimental techniques, are still of considerable importance as they are cheaper and decidedly faster, especially when the number of batteries under consideration is very high. In addition, accelerated test methods can be applied (De Carlo et al., 2014; Tucci et al., 2014). In this study, an approach to estimating residual life was adopted based on an analysis of the consumption history provided by the internal algorithm of the device. The innovative methodology adopted integrates the use of neural networks to Monte Carlo simulation according to the conceptual model represented in Figure 1:

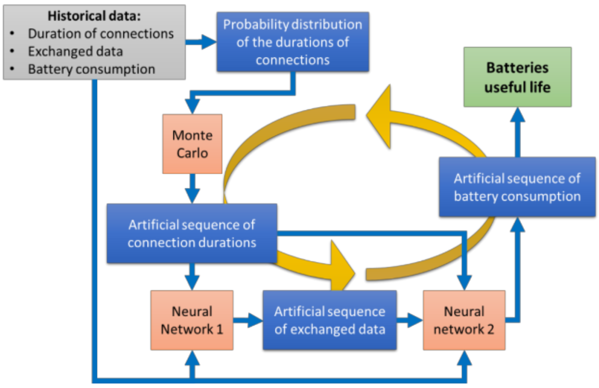

Figure 1: Neural network and Monte Carlo simulation model for estimating the useful life of the meter battery

Based on the data of:

- Duration of connections with the central acquisition system (SAC);
- Amount of data transmitted and received with the SAC;
- Battery consumption.

Two neural networks are trained to perform different functions in calculating the residual life of the analysed battery. Both the neural networks used Deep Learning algorithms with 2 hidden layers and 50 neurons for each layer. The training set of the neural network 1 is composed by an attribute, the duration of connections, and as label the exchanged data. Instead the neural network 2 used a training set with 2 attributes, the duration of connections and the exchanged data, the label is the battery consumptions. Therefore, the first Neural Network is trained to associate to each connection duration value the corresponding value of exchanged data quantity; the second is trained to forecast the battery consumption associated to each pair of connection duration values and exchanged data quantity.

Starting from the probability distribution function of the duration of the recorded connections, a Monte Carlo simulation model is implemented to provide an artificial sequence of this parameter; subsequently, neural network 1 associates the corresponding amount of data exchanged with the central acquisition system (SAC) with this value; afterwards, neural network 2 associates to the pair of values the battery consumption estimated based on historical data. Iterating the procedure from the average UL value estimated by the algorithm inside the meters until reaching the null RUL value for a large sample of cases, we obtain the probability distribution function of the number of connections necessary to completely discharge the batteries. Knowing the frequency of connections that is usually regular and configured on the device, you can estimate the UL probability distribution function of the batteries of the meters.

Based on the analysis carried out, it is also possible to evaluate the economic impact of any discrepancy between the result obtained and what was agreed in the tender, using the classic techniques of equivalent annual cost (EAC) to compare two cost scenarios with different time horizons.

3.Results (Case of study)

The analysis carried out takes into consideration the study of batteries for the supply of remote-controlled natural gas meters installed by a big Italian company that deals with natural gas transmission, distribution and sale of natural gas. With many thousand kilometres of proprietary networks, it is positioned as one of the main operators in Italy. The company, which started the massive replacement of traditional metrology devices in 2015, has in fact found numerous malfunctions caused by the early depletion of the power supply batteries, although the minimum duration guaranteed by the supplier was 15 years.

The meters used by the company are of the single battery pack type, which supplies both the communication apparatus with the SAC and the measuring apparatus; given the important function performed, the battery pack is sealed with metrological seals, so it is not possible to replace it by the operator, otherwise the fiscal value of the measure will be lost. The data used to carry out the study in question were acquired by a multi-service software system for the automation of telemetry and remote management processes of gas meters. The available data are transmitted by 1294 integrated meters, and the available information is summarised in the table below:

Table 1: Structure of the data used

Data	Description
Source	Return point identification code (pdr) on which the meter is installed
Date	reference connection date
Duration	Duration of reference connection in seconds
RxPackets	Number of data packets received in the reference connection
TxPackets	Number of data packets transmitted in the reference connection

Corrector Battery	RUL in hours of charge remaining for the meter's metrological battery

A first overview of the problems was carried out analysing the failure data registered by the SAC. As show in the following figure there are a part of meters that stopped to communicate whit the SAC in their first 3 years of functioning and a sampling inspection performed by the company, carried out that over the 90% of them is caused by the completely discharge of battery supply system.

This troubling result confirms the need for a statistical study to estimate the UL of the meter supply batteries. Based on the data in the database, with reference to Figure 1, the following probability distribution function presented in Figure 2 was obtained and used for Monte Carlo simulation:

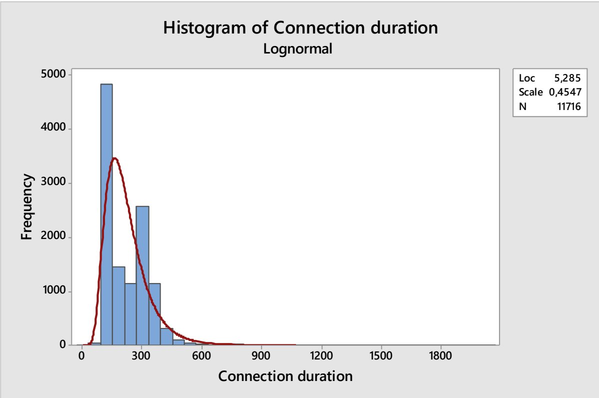

Figure 2: Lognormal probability distribution function of connection duration for Monte Carlo simulation

The choice of the lognormal fitting function is justified by the high value (0.952 on a maximum of 1) of the correlation coefficient calculated with the least square method as shown in Figure 3:

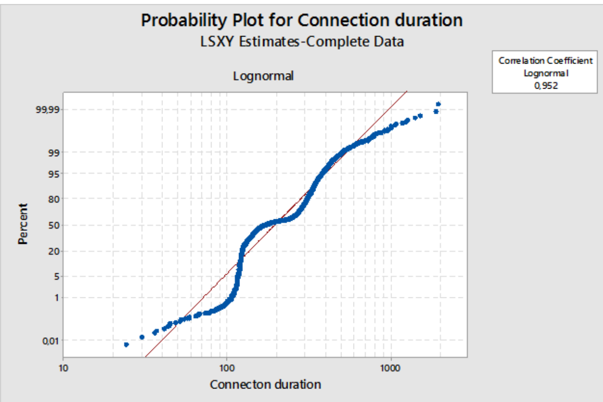

Figure 3: Goodness analysis of the fitting of the lognormal distribution to the historical data of connection duration

The procedure shown in Figure 1 was then iterated and 10000 samples of the estimated UL of the batteries were obtained and its probability distribution function is plotted as shown in Figure 4:

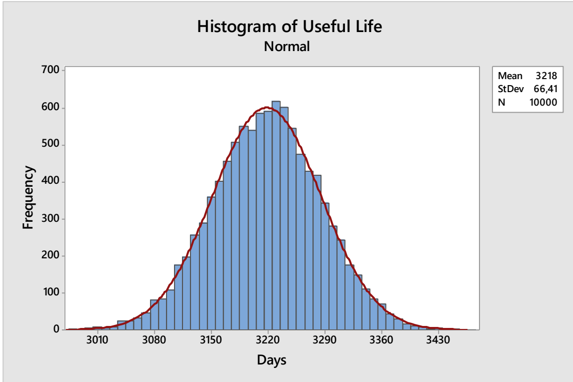

Figure 4: Probability distribution function for Monte Carlo simulation

The Useful Life of the battery pack analysed has an average value of 3218 days, equal to approximately 8 years and 10 months with a standard deviation of 66.41 days; this value is much lower than the 15 years guaranteed by special tender specifications.

After the simulation we implemented an economic analysis of the damage suffered by the company, comparing the cost profile of the simulation model with that guaranteed by the dealer.

Since these are metrological batteries, they are not replaceable, otherwise the fiscal value of the instrument will be lost; consequently, the discharge of this type of battery coincides with the change of the meter itself. The cost items used for the analysis are therefore:

- Labour costs for the replacement of meters;
- Cost of materials;
- Travel costs for replacement;
- cost of non-amortisation.

The two cost profiles compared are the following:

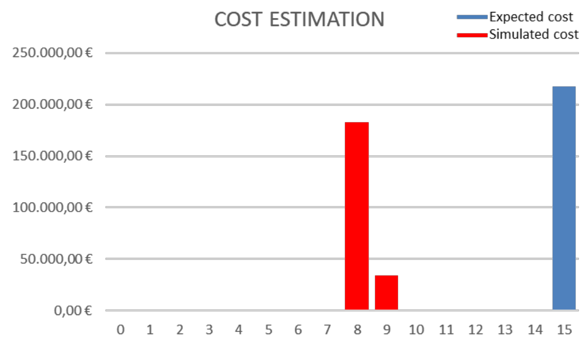

Figure 5: Analysed cost profiles

As a result of the simulation, 84% of the batteries are exhausted in the eighth year and the remaining 16% in the ninth year, characterizing the profile shown in red in the figure. The costs were calculated on the number of meters installed by the company (1294 units). Because of the different time horizon of the two costs, they were valued using the EAC with the following result:

Table 2: Equivalent annual cost

Description	Value

Simulated EAC	31.413,50 €
Expected EAC	12.323,20 €

As shown in the table, the cost of replacing meters has increased compared to what was expected by about 155%, causing high economical damage to the company.

4.Discussion & Conclusions

The result of applying the simulative model has allowed to evaluate the useful life of the gas meter batteries, leading to the conclusion that the malfunctions found are not the result of anomalies, but all the installed meters do not respect the useful life limits expected during the design of the devices. The proposed model also led to an economic evaluation of the damage suffered by the company case study resulting in an increase in costs of about 155% which highlights the strategic importance of the batteries for the reliability of the devices.

The study was carried out using forecasting techniques based on the historical estimates of RUL calculated by the software installed on the devices; a possible widespread malfunction of the estimation algorithm would therefore invalidate the results of this study. It is therefore considered necessary to perform an experimental study by accelerated testing to validate the data used.

References

De Carlo, F., Borgia, O., Tucci, M., 2014. *Accelerated degradation tests for reliability estimation of a new product: a case study for washing machines.* Proc. Inst. Mech. Eng. Part O J. Risk Reliab. 228, 127–138.

Di Bona, G., Silvestri, A., Forcina, A., Petrillo, A., 2016. *Reliability target assessment based on Integrated Factors Method (IFM): a real case study of a sintering plant.* J. Fail. Anal. Prev. 16, 1038–1051.

Di Castelnuovo, M., Fumagalli, E., 2013. *An assessment of the Italian smart gas metering program.* Energy Policy 60, 714–721.

Digiesi, S., Mossa, G., Rubino, S., 2012. *Sustainable order quantity of repairable spare parts.* IFAC Proc. Vol. 45, 181–186.

Murnane, M., Ghazel, A., 2017. *A Closer Look at State of Charge (SOC) and State of Health (SOH) Estimation Techniques for Batteries.*

Pearman, A.N.J., Hunter, G.D., Woessner, M.A., Gilman, R.E., 1990. *Electronic gas meter.* US4918995A.

Tucci, M., De Carlo, F., Borgia, O., Fanciullacci, N., 2014. *Accelerated life tests as an integrated methodology for product design, qualification and production control: a case study in household appliances.* Prod. Manuf. Res. 2, 112–127.

Van Gerwen, R., Jaarsma, S., Wilhite, R., 2006. *Smart metering.* Leonardo-Energy Org 9.

van Schalkwijk, W., Scrosati, B., 2007. *Advances in lithium-ion batteries.* Springer Science & Business Media.