Failure Analysis of Current and Future Electricity Meters and their Components in Relation to the Costs of Ownership

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Abstract. *Among other aspects, the reliability of electricity meters is important for securing energy supply and other Smart Grid (SG) functions and services. This paper analyses the reliability of functions and services provided by electricity meters in relation to reliability of individual electricity meters and their components. The increasing reliability requirements lead to higher complexity and manufacturing cost of electricity meter. On the other hand, purchase price pressure may cause increased failure rate of an individual meter, drop in overall reliability of SG environment, and finally can increase operating costs. Thus, Total Cost of smart meter Ownership (TCO) is associated with the failure rate (reliability). While seeking optimal TCO/reliability ratio, a contribution of each individual component to the overall failure rate of an electricity meter was investigated. Expected development of selected components reliability parameters and its influence on failure rate of meter and metering system was also estimated.*

Keywords

Electricity meters, failure analysis, smart grid, smart metering, total costs of ownership.

1. Introduction

In many countries, Smart Grid concept [1], [2] and [3] is linked with smart meters development and Advanced Metering Management (AMM) systems roll out. The Czech Republic has been considering its attitude to scope and functions of an AMM implementation since 2006. A few pilot projects, analyses, and studies were carried out or are underway. Many of them deal with communication issues, especially with data exchange among meters and data centers and tools for load control, such as [4] and [5]. This paper contributes to the analysis of the electricity meters and components reliability that was introduced in papers [8], [9] and [10]. Reliability of electronic systems, communication systems, and special systems in utilities (measurement, regulating, switching and monitoring systems) is a key area because it is crucial to secure a supply of energy in today's society [6], [7] and [11].

To evaluate development of the whole AMM system, it is necessary to look comprehensively at electricity meters and related infrastructure. The very basic function of the electricity meter still is to measure and record customer's consumption. Development towards smart technology extends basic functionality and offers new possibilities like data transferor power load control at supply point and other.

Reliable function of the complex smart metering infrastructure must be supported by reliable and balanced function of all parts and components:

- basic metering functions,
- extended metering functions,
- communication interface,
- data concentrators,

- communication network,
- data center including interface to other systems.

However, in this paper, we only deal with reliability of electricity meter itself, we will not evaluate effects of other related components (e.g. meter service failure due to communication loss, while electricity meter itself is fully functional).

First, a general component model is analyzed. Then, a specific matrix of the component model is presented, quantifying the risk of failure of specific components and deriving influence on individual functions.

The cost of installing and operating electricity meters is then analyzed. Balance between the cost of achieving a certain rate of failure and the cost of recovering broken devices is sought.

In the last part of article, the electricity meters and their components development are estimated for near future. The influence of electricity meters construction on failure rate is discussed.

2. Reliability Analyzes and Component Model of the Electricity Meter Layout

Reliability analyzes of electricity meters is important for finding balance between production cost and failure rate. Higher reliability leads to higher cost of electricity meter. Lower purchase price may lead to lower quality of components, consequently to higher failure rate and higher operating costs.

2.1. Reliability of Electricity Meters

The system reliability is dependent on failure rate (intensity of failures) of its individual components. The aggregation of individual components can be made for the steady state (the bottom of the bathtub curve). Based on the serial model of the system, it is evident that failure of each component causes a system failure. The failure intensity of the individual elements is based on the manufacturer's data or from standardized catalogs of elements. Subsequently, a computational model is applied including various deteriorating influences (e.g. temperature, humidity, pressure, vibration, etc.) described in the guidances, such as MIL-HDBK-217-F Notice 2 (1995), Telcordia SR332 Issue 3 (2011).

The reliability of electricity meters and their components is discussed in [9] and [10]. The main evaluation criteria for the electricity meter functionality during its lifetime is the measurement trueness and accuracy. After the warranty period, the meters are removed and subjected to an inspection in state-approved testing laboratories. This represents a complicated logistical problem. To simplify this, the remote calibration with secure data channels can significantly reducethe complexity of the process. The electricity meters can remain without the need to disassemble at the supply point.

The electricity meters need to be highly reliable. The tests of devices with low intensity of failures are time consuming and expensive. The Accelerated Degradation Tests (ADT) for the prediction of reliability are more effectively and easily in some cases [11].

This paper is based on reliability analyses of the electricity meters components and expert knowledge from longtime statistics of electricity meters operation.

2.2. Component and Function Matrix

To analyze the failure rate, we designed a matrix based on the influence of the components on the required functions and on the risk assessment of the components from the failure point of view. The M_{ij} is the element of matrix $\mathbf{M}$. The effect of the i-th component failure on the j-th function of the meter is evaluated in value M_{ij}.

We can calculate the component's criticality as a vector $\vec{C}$ based on matrix $\mathbf{M}$ and vector of functions significance weights $\vec{W}$.

$$\vec{C} = \mathbf{M} \cdot \vec{W}. \tag{1}$$

Next, we introduce the vector $\vec{R}$, which is an estimation of the element's risk.

The corrected vector of criticality $\vec{C'}$ is obtained as a product of the corresponding elements of vector $\vec{C}$ and $\vec{R}$.

$$\vec{C'} = \vec{C} \cdot \vec{R}. \tag{2}$$

The vector $\vec{C'}$ calculation indicates most critical elements with high risk of more functions failure. In this context, it can be deduced that those circuits which support functions for more functional blocks, are at higher risk.

2.3. Components and Features

Meter can be divided into separate components. We clustered the components into several homogenous groups from C_{11} to C_{46} for purposes of this study:

- Basic blocks for measuring, processing and storing data – components of the C_{1x} group:
  - current sensors - C_{11},
  - voltage sensors - C_{12},
  - A/D (Analog to Digital) converters - C_{13},
  - control processor - C_{14},
  - memories - C_{15}.
- Blocks for interacting with HAN (Home Area Network) interface - components of the C_{2x} group:
  - display - C_{21},
  - optical pulse indication - C_{22},
  - pulse output (S0 interface) - C_{23},
  - IR (Infra-Red) interface circuits - C_{24},
  - load control switching relays and tariff inputs - C_{25},
  - control buttons - C_{26},
  - LAN (Local Area Network) communication circuits (M-bus, ZigBee) - C_{27},
  - WAN (Wide Area Network) communication circuits (PLC - Power Line Communication, RF - Radio Frequency, GSM - Global System for Mobile) - C_{28}.
- Support circuits and components - components of the C_{3x} group:
  - supply circuits (overvoltage protection and circuit-less voltage) - C31,
  - power circuits (stabilizers) - C_{32},
  - power backup batteries and real-time clocks - C_{33},
  - real-time circuit - C_{34}.
- Mechanical and electromechanical components - components of the C_{4x} group:
  - high-current clamps - C_{41},
  - breaker - C_{42},
  - other terminal blocks - C_{43},
  - covers - C_{44},
  - mounting elements for installation - C_{45},
  - sensors (opening contacts, magnetic field sensor) - C_{46}.

We can assume the following critical points in terms of reliability based on our experience from operation and expert evaluation of components and their fitting into the functional architecture of the electricity meter:

- Mounting points and mechanical fasteners - they are a weak point especially in relation to vibration and mechanical stress and more frequent manipulation.
- Power clamps - they are a weak point especially in relation to increased humidity and other corrosion-promoting effects even when are used more often.
- Power circuits - an extremely power and voltage-stressed part, contains electrolytic capacitors that typically have a lower life span than other elements.
- Memory, integrated circuits with high level of integration and programmed circuits.
- Displays.
- Interface circuits that can be affected by improper handling, overvoltage, and intentional attack.

Based on importance for business processes, following functional blocks were defined:

- Key features - F_{1x}:
  - measurement of energy consumption and processing of measured data - F_{11},
  - load control - F_{12},
  - disconnecting the supply point - F_{13},
  - local management - F_{14},
  - remote meter reading and control - F_{15}.
- Important Features - F_{2x}:
  - tariffs - F_{21},
  - status and consumption indication - F_{22},
  - display of consumption - F_{23},
  - local controls (buttons) - F_{24},
  - tariff pulses - F_{25},
  - tariff input function - F_{26},
  - local interface function (HAN) - F_{27}.
- Other features - F_{3x}:
  - homogeneity and compactness of the device - F_{31}

2.4. An Example of the Component Criticality Determination

Based on the previous analysis of the components, functions, expert risk assessment, and the effect of the components on the functions, we have compiled the following matrix that puts the entities into context.

Tab. 1: Estimated contribution of individual components to the failure of the electricity meter - the **M**-matrix with the elements at the intersection of the components $\vec{C}$ and the function F with the given vector $\vec{R}$ and the resulting calculated $\vec{C}'$.

	R_i	F_{11}	F_{12}	F_{13}	F_{14}	F_{15}	F_{21}	F_{22}	F_{23}	F_{24}	F_{25}	F_{26}	F_{27}	F_{31}	$\vec{C}_i'$
C_{11}	2	3			2	2		2	2	1	2	1			0.6
C_{12}	1	3			2	2		2	2	1	2	1			0.3
C_{13}	2	3			2	2		2	2	1	2	1			0.6
C_{14}	2	3	3	3	3	3	3	3	3	3	3	3	3	3	1.5
C_{15}	3	2	3	1	3	3	3		2	2		2	2		1.5
C_{21}	3								3					2	0.2
C_{22}	1							3							0.0
C_{23}	3										3				0.1
C_{24}	3				3									1	0.3
C_{25}	3		3			2	3					3		1	0.7
C_{26}	3								2	3				1	0.2
C_{27}	2					2							3		0.2
C_{28}	3	1	2	3		3	1				1	1	1	1	1.1
C_{31}	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3.8
C_{32}	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3.0
C_{33}	5	2	2		2	2	2		2			2	2	1	1.8
C_{34}	3	3	3		3	3	3		3			3	2	2	1.6
C_{41}	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3.8
C_{42}	3			3		2								1	0.5
C_{43}	3	3	3	3	2	3	3	2	2	3	3	3	3	3	2.1
C_{44}	2	1	1	1	1	1	1	1	1	1	1	1	1	3	0.5
C_{45}	4	1	1	1	1	1	1	1	1	1	1	1	1	3	1.1
C_{46}	3	1	1	1	1	1	1	1	1	1	1	1	1	3	0.8

The input and output values in defined vectors and matrix are shown in Tab. 1. Example of calculation is demonstrated on real data based on the expert knowledge.

We used a scale of 1 to 5 to estimate the risk of an element in the first column (vector $\vec{R}$), where 5 is the highest risk of component failure. We chose a scale of 0 to 3 (elements of the **M** matrix) to evaluate the individual component failure effect on the meter's functions, where 0 is not displayed (empty element of the matrix) and indicates zero, negligible or unintended influence in this analysis, whereas the effect of 3 is fatal. The **M** matrix consist of elements at the crossing of the meter function F_x and the type of component C_x.

The criticality of components (vector $\vec{C}'$ in the last column of the table) was calculated as the weighted average of the matrix rows. The key functions are counted with a double weight (vector value $\vec{W}$). Higher values indicate more critical components of the electricity meter.

The result of the calculation confirms the assumption that the most critical elements which most functions depend on have a high risk of failure. Therefore, the assumption is that the circuits supporting more functional blocks are at higher risk. For specific inputs, the most critical components are the power supply and the high-current terminals, the microprocessor control, and the memory.

3. Cost Analysis

From the economic point of view, operational costs (caused by failures) and the purchase price of the electricity meter are closely related to the failure rate. Increase of the reliability may lead to higher costs of electricity meter, but also to lower operating costs.

The Total Cost of Ownership (TCO) of electricity meters may be used as a transparent indicator and it will be related to the failure intensity (or failure percentage). The objective should be to achieve failure rate with lowest TCO.

3.1. Assumptions

For following considerations, we assume that the intensity of the failure is constant (the steady central part of the bathtub curve) at the considered time of operation of the electricity meter (typically 12 years).

The resulting faults are considered to be fatal, so after fault identification, the electricity meter needs to be removed, discarded and replaced by a new meter.

3.2. Cost Model to Increase Reliability

We assume that the production cost of the electricity meter depends on the reliability class and is related to the different failure intensity.

We have established an empirical relationship that models the cost increase with decreasing intensity of the failure based on analysis of components and construction. The cost dependence coefficient can be modeled as:

$$K_c = k_1 + \frac{k_2}{k_3 \cdot \lambda^{k_4}}, \tag{3}$$

where k_1, k_2, k_3 and k_4 are the coefficients of the model proposed in this analysis according to Tab. 2.

Tab. 2: Value of the coefficients.

Parameter	k_1	k_2	k_3	k_4
Value	0.8	0.01	4.75	0.8

The modeled dependence is illustrated by the graph in Fig. 1. Initial slow rise of the curve from right to left is partly due to the higher cost of components with lower failure rates (better performance, typically with higher temperature range, margin in boundary parameters, etc.) and due to careful and more systematic test functions in the output control. A dramatic cost rise for failure rate below 10^{-3} year^{-1} is caused by the introduction of sub-circuits and modules redundancy in the device to achieve a low failure rate (not achievable by a simple design).

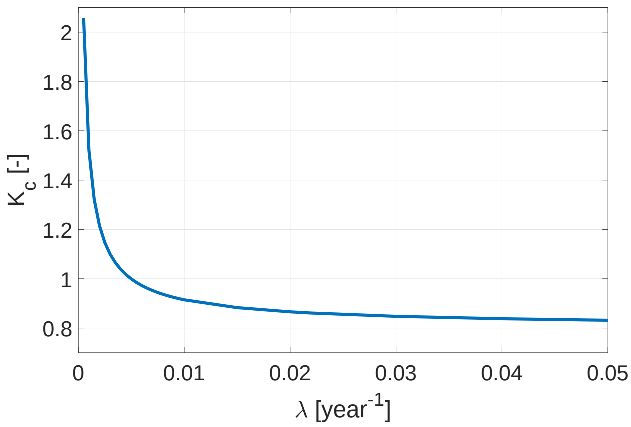

Fig. 1: Relative price dependence on failure intensity (failures per year).

3.3. Example of TCO Calculation

For the purposes of the indicative calculation, we estimated the following data:

- the average purchase cost of an electricity meter is 60 EUR,
- the number of electricity meters in the Czech Republic is 5,750,000 pcs,
- the additional operational cost associated with failure is 80 EUR.

Total TCO are calculated as the sum of capital and operating costs.

$$TCO = CAP + OP. \tag{4}$$

Capital costs are calculated from unit cost CAP_{0i} for each N_i device multiplied by the function according to Eq. (3) and the operating costs are defined as the cost of replacing the damaged pieces,

$$TCO = K_c \sum_{i=0}^{n} (N_i \cdot CAP_{0i}) + \lambda \sum_{i=0}^{n} (N_i \cdot OP_{0i}). \tag{5}$$

The TCO calculation for the case of varying fault intensity at a constant purchase price is shown in the graph in Fig. 2 (green curve). The red curve illustrates the dependence of the device price on the failure intensity according to the model Eq. (3).

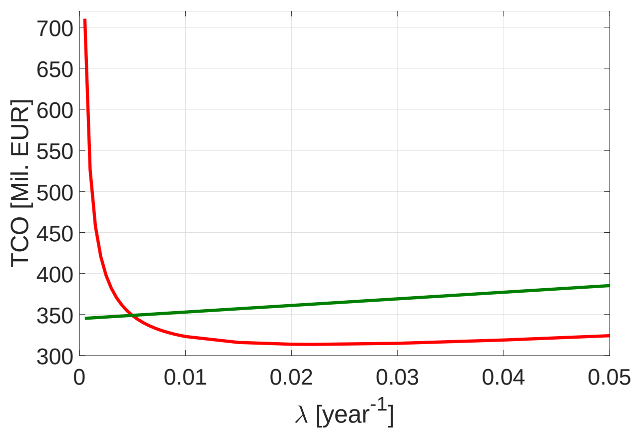

Fig. 2: Dependency of the cost on failure intensity (failures per year) - TCO without the intended price increase at lower failure rate (green line), total TCO (red line).

The cost minimization point is obtained for the first derivative of the cost function equal to zero. Based on the proposed parameterization of the model Eq. (3), the minimum TCO is reached at a failure intensity of approximately $2.25 \cdot 10^{-2} \cdot$ year^{-1}. However, such failure rate may not be acceptable from business perspective, for example with respect to the image of the company (not only manufacturer of electricity meters but the distribution system operator mainly).

The sensitivity of TCO to changes in failure rate and additional operational costs is very low, the TCO sensitivity to the purchasing cost is high, but nonlinear.

A specific example of the TCO calculation was presented. However, the model is parameterized and extensible in general, e.g. for the needs of a particular distribution system operator or for other distribution areas.

Tab. 3: Estimation of the future design of electricity meters - basic blocks for measurement, processing and storage of data.

Components	Current typical design	Estimated design in the future	Expected risks in terms of durability
The general trend is towards single board design			A smaller number of modules and components increases durability. However, accumulation, miniaturization and higher integration increase the risk of failure.
Control processor	Microcontroller (MCU) universal or specialized chip(SoC)	Performance increase, miniaturization, integration of security features can take over some of the communication features	Increased integration density leads to reduced durability.
Memory	Integrated in MCU or SoC, optional external memory EEPROM, FLASH	Full integration into MCU/ SoC	

Tab. 4: Estimation of the future design of electricity meters - Interaction blocks.

Components	Current typical design	Estimated design in the future	Expected risks in terms of durability
The general trend is to reduce the number of interface types, increase versatility, and use wireless communication with smart devices			
Display	LCD display, usually with backlight	Graphic color displays or their absence (data transfer to another device that takes care of their visualization)	New trends can lead to increased reliability compared to today's situation, while under pressure to reduce the price, on the contrary, increasing the failure rate.
Optical indication of pulses	LED	In the long run, they will probably disappear	Transition to store and display data in the cloud Direct communication interface between the meter and home automation systems
Pulse output $S0$	Galvanically isolated opto-coupler	In the long run, they will probably disappear	
IR interface	IR LED with driver and photodiode with preamplifier	In the long run, it will probably be replaced by PAN wireless communication	
Tariff inputs	Galvanically isolated opto-coupler	In the long run, they will probably disappear	
Switching relay for load control	Usually a mechanical relay	It will be replaced by a semiconductor relay or wireless communication with the Smart Home controller	Increasing reliability by eliminating an electromechanical element
Control and test buttons	Microswitches usually directly on the printed circuit board	In the long run, they will probably disappear	
WAN communication circuits (PLC, RF, GSM ...)	Interface type design as a detachable module, motherboard module inserted during production, or part of the motherboard.	Enhanced Circuit Integration, some of the functions may take over the MCU / SoC. Increasing the share of SW defined circuits.	SW definition allows easy update / upgrade functions, butit is a source of error.

4. Assumptions for the Design Development and the Impact on Failure Rate

In general, we can estimate higher integration of electricity meter through reduced number of components. Dramatic design changes cannot be expected, but following trends could significantly affect the architecture of AMM systems:

- Reduction of the measuring system to only voltage and current sensors (IoT - Internet of Things) with direct communication to data center (cloud computing), data will be processed in real time and be available for further use (display, home automation, network control, etc.).

- Increased density of microprocessor units could significantly shorten microchips lifespan and also shorten the innovation cycle.

- Accelerated technical development can lead to shorten innovation cycle.

Tab. 5: Estimation of the future design of electricity meters - Support circuits.

Components	Current typical design	Estimated design in the future	Expected risks in terms of durability
Power circuits	It includes overvoltage protection, transformer, precipitating capacitor or converter, rectifier, filter capacitor, stabilizer.	The tendency of reducing own consumption and thus the possibility of miniaturization. The development is directed to construction using high-efficiency inverters.	We can expect a slight increase in reliability compared to today's situation, while under pressure to reduce the price, on the contrary, the risk of increasing the failure rate.
Sensors	Typically mechanical opening contacts, electromagnetic magnetic field sensors, temperature sensors, etc.	Replacing mechanical contacts Replacing mechanical with fully electronic elements, an increase in the number of states and quantities can be expected.	
Breaker / Limiter	Breakdown components (breaker) and supply limitations (limiter) executed by the command from the control center (via the communication module).	In the long run, the use of external elements appears to be effective. This will require a change in power distribution and intelligent appliances.	

5. Conclusion

It is clear that reliable function of the complex metering system must be ensured by balanced reliability of all system components. However, in this paper, we only deal with the electricity meter itself.

The failure analyses in this paper are based on reliability of the electricity meter components and expert knowledge from longtime statistics of electricity meters operation. The component and function matrixes are defined in the Sec. 2.

The electricity meter is built from logical parts with specific design and manufacturing process (architecture, components). These technical parts and blocks determinate key performance indicators for functions of the meter. The result of the analyses confirms the assumption that the most critical elements which most functions depend have a high risk of failure. The Sec. 3. outlines options for cost optimization based on TCO analysis at typical price dependence on failure intensity (see Fig. 2).

Major changes in the design of electricity meters cannot be expected in the near future. Common supporting elements and circuits are likely to remain risk points, especially power circuits including filtration or mechanical design of heavy-current clamps.

In the long-term perspective, more dramatic changes in the concept of the whole metering system are expected due to dominance of remote reading and control, as well as interconnection to home control and regulation systems.

In the future, the number of components will be reduced and the element density on the chips will be increased. We can expect the Solution with One Chip (SoC) accompanied with necessary set of discrete components. A smaller number of modules and components increases durability. However, accumulation, miniaturization and higher integration increase the risk of failure.

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