A SMART GRID APPLICATION – STREET LIGHTING MANAGEMENT SYSTEM

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Eficientizarea consumului de energie electrică, prin utilizarea unor tehnologii inovatoare, este un concept cheie pentru „smart grid". Această lucrare prezintă un sistem de management al iluminatului public, bazat pe utilizarea contoarelor de energie electrică, cu funcționalități extinse, pentru comandarea şi monitorizarea iluminatului public. Sistemul ajută la economisirea de energie electrică, reducerea numărului de defecțiuni în rețeaua de iluminat public şi scurtarea timpilor de defect.

Increasing the efficiency of electricity consumption, by using innovative technologies, is a key concept in "smart grid". This paper presents a street lighting management system, based upon the use of electricity meters, with extended functionality, for control and monitoring of street lighting. The system provides energy savings, decreases the number of faults in the street lighting network and mitigates down-times.

Keywords: efficiency**,** lighting, meter, smart, grid, management, control

1. Introduction

A smart grid integrates innovative products and services together with intelligent monitoring, control and communication technologies in order to [1]:

- facilitate grid integration of electricity producers of all sizes, regardless of the technology they use
- have better informed consumers, capable of choosing their suppliers
- significantly reduce environmental impact of the power system
- provide high reliability level of power supply

Street lighting is a low voltage power distribution sub-system, important for the quality of life and even safety of each of us [2], yet, in a sense, less prone to catastrophic failures then other power system elements. That and the inherent visibility it enjoys make the street lighting a good place for development and implementation of new and innovative technologies that will lay the foundation of the future smart grid.

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2. Using the Smart Grid

The existing electricity grid has 200 years of intelligence invested in it. It isn't smart; it is clever and even intelligent:

- Analogical and digital relays protect power installations
- Artificial intelligence is used for electrical related processes, like load forecast
- Expert system help operators make real-time decisions
- SCADA (*Supervisory Control and Data Acquisition*) ensures remote control and monitoring of all power-related processes, etc.

The grid can become smart in the way nowadays phones are smart, search engines are smart and operating systems are getting smarter. They all are able to quickly understand and anticipate the moves of their users; they make decisions for them and sometimes make mistakes – without dramatic consequences.

A smart grid should not be a more expensive one, on the contrary, smart means doing more with less. New ideas and lateral thinking should be the drive for smart grid development.

Under the casing of the meter – designed to respond to many legal requirements [3] – there is enough space to integrate more than metering functionality, with small costs compared to the overall cost of the meter.

Existing meters, considered by their manufacturers "*smart*" are endowed with a simple PLC-like (*Programmable Logical Controller*) logic.

The few input and output contacts the meter is fitted with can be used in the PLC logic, together with metering data and other specific features [4].

This was designed with the purpose of replacing simple automation with meter optional functionalities, where meters were needed anyway. Of course it adds to the price of the device, but is cheaper and more reliable than using a meter and a PLC.

3. Street Lighting Metering System

3.1.The Control System

An example of using extend meter capabilities together with a specially designed software solution is the ***Street Lighting Management System***, which can be regarded as smart grid application for the following reasons:

- It embeds smart metering capabilities (metering, monitoring and control) using only a "*smart meter*" and adequate software
- This solution helps reduce energy consumption by provided extended real-time information and full control over the moments when the lights go on or off

- It is ready for flexible tariff agreement
- The system helps identify burned lamps location and network events in extended real-time, thus reducing congestion times and improving service quality.

An application of this project was successfully implemented for the street lighting of Pitesti City, Romania [5]. Pitesti Mayor's Office decided to buy, from the distribution company, the public lighting electrical distribution system. This was done mainly with the purpose of improving the service for the citizens, controlling and reducing costs – by power savings, theft reduction, etc. – and becoming eligible consumer.

To achieve that, about 250 meters were installed in distribution and control boxes of the public lighting system. The meters were connected to the central station mainly by broad band Ethernet (fiber optic) and communicate to the central platform metering and control application mainly via a VPN (*Virtual Private Network*) over the internet (a few remote metering and control points were equipped with GSM/GPRS communication units, as Ethernet link was not available). The meters that were used have the following important features [6]:

- 15 minutes load profile recording for active and reactive
- Instrumentation measurements: instantaneous current, voltage, power factor and frequency *rms* values
- 12 configurable seasons
- Recording of electricity network and self-diagnosis events (over/undervoltage, over/undercurrent, power up/down, phase failure, meter fault, etc.)
- Configurable tariffs
- Interchangeable communication units (Ethernet, GSM/GPRS, etc.)
- Input/output solid-state relays.

Although the main purpose of a meter is to measure energy consumption, in that project the meter became an RTU in a *pseudoSCADA* (*Supervisory Control and Data Acquisition*) system.

The meters are parameterized with 2 x 12 different lights on and lights out timed triggers – for each of the 12 seasons. At configured times the meters send the appropriate command to relays that turn city lights on and off.

The meters can also be controlled from the central station, via communication inputs. Thus, the authorized operator can turn lights on and off at any time – depending on the weather, city events and so on. Also, a more flexible "*time of use*" may be used to automatically turn on/off the lights at a different time every day, increasing thus power savings.

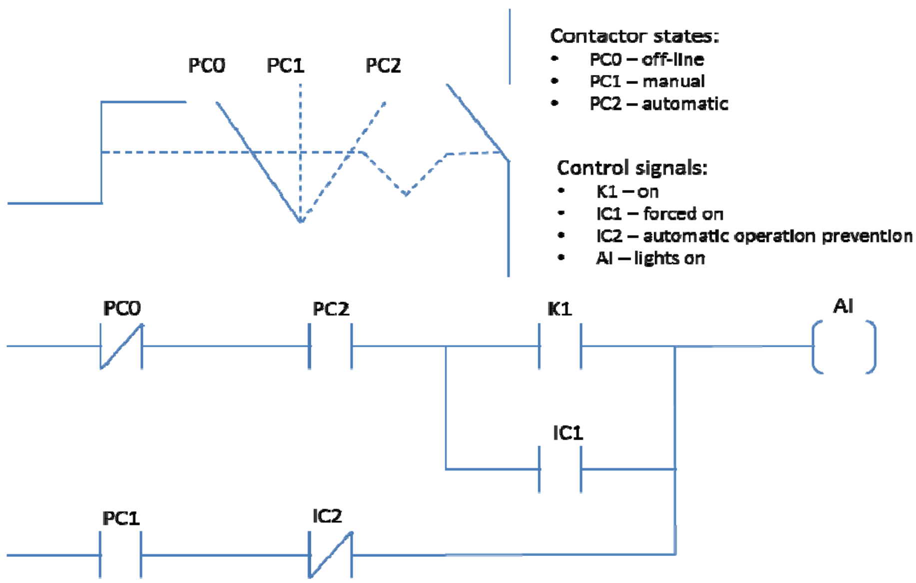


Fig. 3.1. Automation ladder diagram for street lighting control

Fig. 3.1 depicts the contactor possible states and the automation ladder diagram, the logic behind the automated and manual control of the street lighting system.

The automation schema can be implemented in the meter, in a manner similar to a PLC (Programmable Logical Controller) configuration – Fig. 3.2.

In normal operation (automatic), the signal defined, in Fig. 3.2., as "TOU-E1" will control the street lighting based on the meter "time of use".

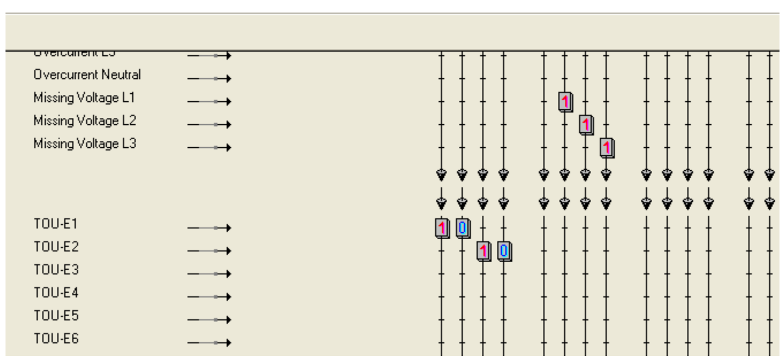


Fig. 3.2. Meter internal control logic

In manual operation, remotely controlled from the system HMI, signal "K1" – coming as "communication input", in Fig. 3.1., will overwrite the value of signal "TOU-E1", changing it form "0" to "1" and thus, the meter control steady-state relay sends an on/off signal to the lighting control relay.

Communication inputs are sent to the meter via Ethernet or GSM/GPRS, using DLMS protocol.

3.2.Identifying Burned Lamps

A major advantage of the solution is the automatic identification of burned lamps capability. The control system points-out to the operator the lighting point name (distribution box) and the phase on which one or more lamps are off-line.

For the identification algorithm it was taken into account the variation of power (consumed by the lamp) with voltage, which can have significant weight due to:

- Increase of supply voltage during the night,
- Differences between voltages applied to the each lamp, on long supply lines, due to voltage drop on the supply wire.

Based upon metering data, a power quality analysis and after studying dedicated literature on the subject [7, 8, 9, 10, 11] the following hypothesis and remarks were formulated:

a. Power Factor

Significant drops in power factor are the result of a malfunctioning compensation capacitor. The dependency between absorbed active power and the power factor is "modest", with small values for the correlation coefficient R^2 = 0.074 [7, 12].

For a high pressure sodium vapors lamp (SON), having a rated power of 70 W, a decrease of the power factor from 0.95 to 0.5 will result in an increase of the absorbed power of approximately 10 % [13].

Such a dramatic drop of the power factor will be properly indicated by the *Street Lighting Management* System as a stand-alone event and will be ignored by the burned lamps localization algorithm.

Small variations of the power factor don't have a measurable effect on the consumed active power [13] and will be, thus, consider constant.

b. Lamps Aging

Voltage drop on a lamp increases along with its aging [8, 12], and thus, the absorbed active power increases proportionally. As the dependency between absorbed active power and voltage is the very purpose of the presented algorithm, lamps' aging is not considered, distinctly.

c. Mismatch Between Lamp and Ballast

For the burned lamps localization algorithm, inductive ballast is considered, working at rated frequency of the network, with a stable voltage/current ratio, uninfluenced by current, temperature and magnetic fields variations, according to EN 60923:1996 [14]. Also, it is considered that the ballast from one manufacturer was not connected to a lamp of a different one.

Thus, the influence of the lamp ballast, upon the variation of the absorbed active power, can be ignored.

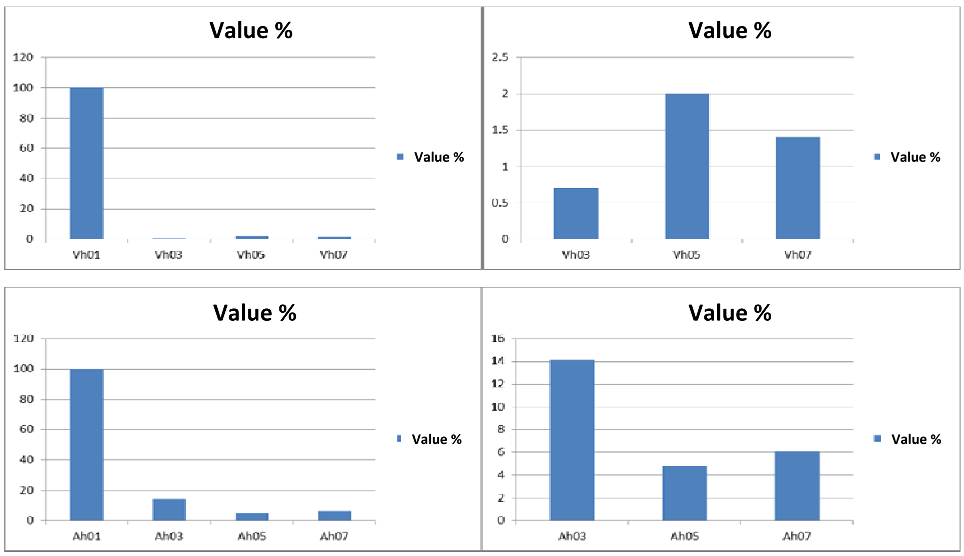
d. Thermal Effects

The lamp temperature may increase, as a result of inserting it into a luminaire, which can lead to reflecting the radiation back to the discharge tube. Lamp temperature may also vary with the environmental temperature. Increased temperature leads to an increase of voltage drop and thus, to an increase of the absorbed active power [13].

As a consequence, temperature variation is not considered separately, but is included in the active power variation with voltage.

e. Power Quality Analysis

By measuring and studying some power quality parameters – such as even voltage and current harmonics, power factor including *THD* (Fig. 3.3) or network frequency – in some supply points of the considered network, no influence of those factors, upon active power variation with voltage, was noted.



(a) *(b)*

Fig. 3.3. Harmonics 3,5 and 7, voltage and current, percentage of the fundamental (a); comparison between 3, 5 and 7 voltage and current harmonics (b)

f. Frequency of the power grid was considered constant, at rated value.

The variation law of the active power (P_L) with voltage supplied to the lamp, can be provided in the lamp datasheet or can be experimentally determined.

A general variation formula of lamp power consumption with supply voltage is given by (1).

$$P_L = P_N \cdot (K_1 + K_2 \cdot \Delta U \ [\%]) \tag{1}$$

where:

P_N – rated active power of the lamp at rated phase voltage (at $U_N = 230$V) [kW],

P_L – lamp active power adjusted according to voltage [kW],

ΔU – voltage drop of the cable connected to the lamp [V],

K_1, K_2 – are constants provided by the lamp manufacturer or empirically deducted. Voltage drop quota, in percentage is written as follows:

$$\Delta U[\%] = \frac{\Delta U}{U_{spl}} \cdot 100 \tag{2}$$

where U_{spl} is the actual supply phase voltage of the network.

Voltage drop formula [15] is considered:

$$\Delta U_{p1} = \frac{r_1 \cdot P + x_1 \cdot Q}{U_{spl}} \tag{3}$$

where:

r_1 – specific resistance [Ω/m],
x_1 – inductive reactance [Ω/m],
P, Q – active and reactive phase power [kW], [kVAr].

Considering a constant power factor *cos φ* for every P_k, Q_k it can be written:

$$\frac{Q_k}{P_k} = \frac{Q}{P} = tg\varphi \tag{4}$$

Using (4) and (3),

$$\Delta U_{p1} = \frac{P(r_1 + x_1 \cdot tg\varphi)}{U_{spl}} \tag{5}$$

For the first lamp, (1) becomes:

$$P_{L1} = P_N \cdot (K_1 + K_2 \cdot \Delta U_{p1}[\%]) \tag{6}$$

Power losses in the lamps power supply line [16] are computed:

$$\Delta P_{pl} = \frac{r_0 \cdot l \cdot (E_a^2 + E_r^2)}{(U_{spl} \cdot T_{\text{int}})^2} \tag{7}$$

where:

ΔP_{pl} – are power losses of the supply wire [kW],

r_0 – specific resistance [Ω/m],

l – length of the supply wire [m],

E_a – measured active energy consumed during the integration period of the meter (15 minutes=900 seconds) [kWh],

E_r – measured reactive energy consumed during the integration period of the meter (15 minutes) [kWh],

T_{int} – integration period (15 minutes) [s].

Considering the small percentage represented by overall power line losses and in order to simplify the computation algorithm, equal power losses for each segment of the supply line are assumed and thus, for *n* lamps, it can be written:

$$\Delta P_{psegment} = \frac{r_0 \cdot l \cdot \left(E_a^2 + E_r^2\right)}{n \cdot \left(U_{spl} \cdot T_{\text{int}}\right)^2} \tag{8}$$

For the next lamp (or segment) it can be written:

$$\Delta U_{p2} = \frac{\left(P - P_{L1} - \Delta P_{psegment}\right)\left(r_2 + x_2 \cdot tg\varphi\right)}{U_{spl}} + \Delta U_{p1} \tag{9}$$

and similarly,

$$P_{L2} = P_N \cdot (K_1 + K_2 \cdot \Delta U_{p2}[\%]) \tag{10}$$

In general, for any lamp current number *k,* having *k>2,* (9) becomes:

$$\Delta U_{pk} = \frac{\left(P - \sum_{i=1}^{k-1} P_{Li} - k \cdot \Delta P_{psegment}\right)\left(r_k + x_k \cdot tg\varphi\right)}{U_{spl}} + \Delta U_{p(k-1)} \tag{11}$$

and (1) becomes:

$$P_{Lk} = P_N \cdot (K_1 + K_2 \cdot \Delta U_{pk}[\%]) \tag{12}$$

Resistance *r* and inductive reactance *x* for each segment can be written:

$$r_i = r_0 \cdot l_i \tag{13}$$

$$x_i = x_0 \cdot l_i \tag{14}$$

where: l_i – the length of the cable segment between lamps

Using (13) and (14), (11) becomes:

$$\Delta U_{pk} = \frac{\left(P - \sum_{i=1}^{k-1} P_{Li} - k \cdot \Delta P_{psegment}\right) \cdot l_k \cdot (r_0 + x_0 \cdot tg\varphi)}{U_{spl}} + \Delta U_{p(k-1)} \tag{15}$$

and replacing (2) and (15) in (10), results in (16), representing the actual power consumed by each lamp:

$$P_{Lk} = P_N \cdot \Big(K_1 + K_2 \cdot$$

$$\cdot \frac{\left(P - \sum_{i=1}^{k-1} P_{Li} - k \cdot \Delta P_{psegment}\right) \cdot l_k \cdot (r_0 + x_0 \cdot tg\varphi) + \Delta U_{p(k-1)} \cdot U_{spl}}{U_{spl}^2} \Big) \tag{16}$$

As active power consumed by each lamp is different, the metered power is the summation of power consumption of each lamp:

$$P = \sum_{j}^{n} P_{Lj} \tag{17}$$

In the case of Pitesti *Street Lighting Project*, phase active energy is recorded by meter, with 15 minutes integration period (configurable from 1 – 60 minutes).

Thus, using (1) it is considered that one or more lamps are burned when the difference between mean active power – resulted from measured active energy (12) – and the total computed active power per phase is higher the rated active power of a lamp (11).

$$P_{fN} - \sum_{j}^{n} P_{Lj} < P_N \tag{18}$$

From the active energy provided by the meter, per phase, mean active power is calculated:

$$P_{fN}[kW] = E_a[kWh] \cdot \frac{60[\min]}{p[\min]} \tag{19}$$

where p=1,3,5,10,15,30,45,60 – is the configured integration period.

Similarly, from metering data, the average power factor per integration period is computed, using active and reactive power:

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} \tag{20}$$

Using a general variation law for high pressure sodium vapors lamp [17], it can be written:

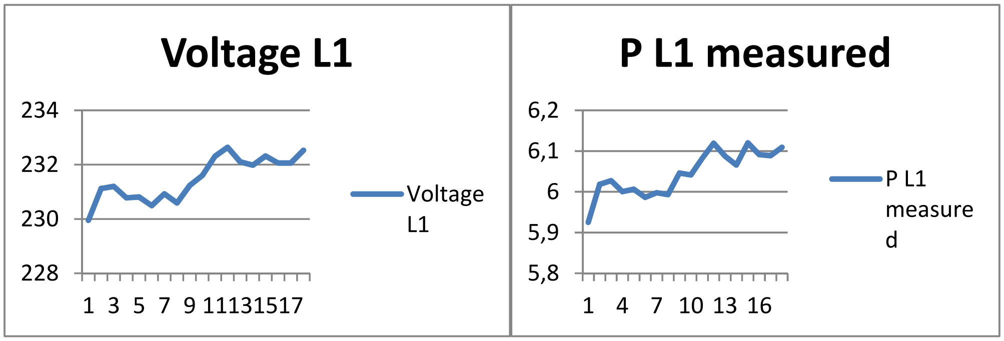
$$P_{Lk} = 1.1 \cdot P_N \cdot (2.5 + 1.5 \cdot \frac{\left(P - \sum_{i=1}^{k-1} P_{Li} - k \cdot \Delta P_{psegment}\right) \cdot l_k \cdot (r_0 + x_0 \cdot tg\varphi) + \Delta U_{p(k-1)} \cdot U_{spl}}{U_{spl}^2}) \tag{21}$$

Using (21), actual consumption of the lamps is computed, from metering data and rated constants.

To prove the validity of the theoretical model, the voltage and active power variation, as resulted from metering values, is analyzed, in a monitored area of the street lighting system – no lamps were burned during the monitored period. The monitored area had 24 lamps with a rated power of 250 W for each lamp. Same interval of similar days was used for the analysis.

In the Figs. 3.4 (a) and (b), measured voltage and active power values are displayed.

In Fig. 3.5 active power values calculated based on (21) are shown.



(a) *(b)*

Fig. 3.4. Measured phase voltage (a); Measured phase active power (b)

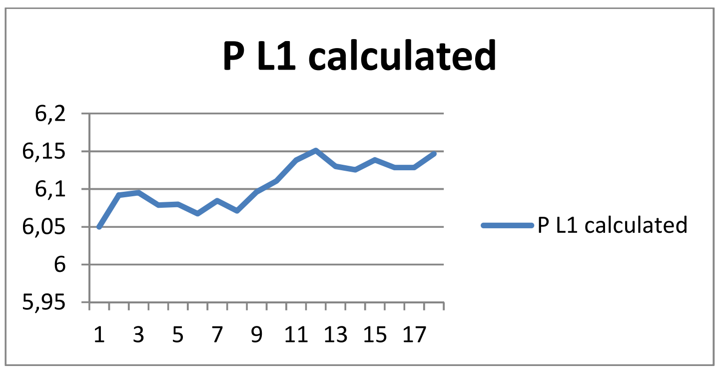


Fig. 3.5. Calculated phase active power

In both measured and calculated values, large active power consumption variations are noted, with a maximum power variation of approximately:

$$\Delta P_{\min-\max} = 0{,}2 \ \ [\text{kW}]. \tag{22}$$

This value (22) is closed to the rated power of a regular street lighting lamp (250 W) and higher than the dimmed rated power for the same kind of luminary (150 W).

The result shows that using a simple comparison between measured active power values, from the monitored area, in different days, would have resulted in a false **positive result** indicating a **burned lamp**.

Using the proposed algorithm, expected power consumption of each lamp is computed based on measured values for each reference interval, taking into account voltage variation. The software application of the "*Street Lighting Management System*" sends a "**burned lamp**" message only if the measured active power drops below the expected consumed active power with more than the rated power of a lamp, thus avoiding false positive results.

As shown in Figs. 3.4 (b) and 3.5, calculated and measured active power curves follow the same trend. The differences between calculated and measured values will not change the overall result, as the margin for error is quite high, being linked to the lamp active power.

However, using the chosen function describing how power varies with voltage (21), there are notable differences between calculated and measured values, although for the chosen period the system remained unchanged.

To compensate for disregarded conditions that influence power variations, a statistical method – like linear regression – is used for computing expected power values, based upon measured data.

Fig. 3.6 shows the full algorithm used in localizing burned lamps, in two stages:

- Computation of normal power absorbed by the lamp, based on the power variation with voltage law,
- Estimation of absorbed power, with all the lamps in operation, using a linear regression method – also following the variation of power with voltage, empirically.

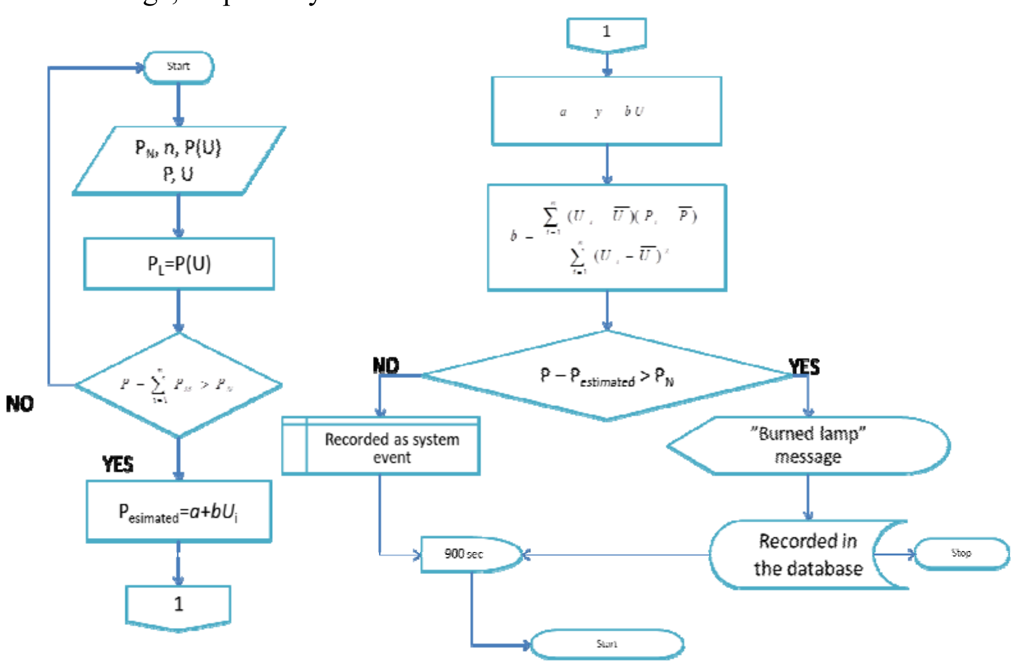


Fig. 3.6. Burned lamp localizing algorithm

The analyzed dataset shows that the difference between measured and estimated values (expected values) is below the active power of a lamp, when all luminaires are operational. When a lamp is burned, the result of the estimate points this out, through the maximum value of the calculated differences.

3.3.Energy Savings

From empirical data, collected from one of the metering points of the analyzed system, phase power (P_f) variation, with supply phase voltage (U_f [V]), follows the following trend-line:

$$P_f = 0.0932 \cdot U_f - 13.6 \text{ [kW]} \tag{23}$$

In normal operation, for the studied supply point, voltage varied from 229.8 V to 239.7 V and the corresponding active power consumptions from 7.83 kW to 8.76 kW.

Commonly used 250 W SON lamps can stay lit, for an input voltage down to 172 V [18]. Considering that the supply voltage of the lamps will be reduced to 190 V, using (23) the power absorbed be the lamps is reduced to 4.11 kW.

This translates into energy saving of around 50 %. However, is has to be considered that reducing normal illumination level can be applied in general, between 11 p.m. and 5 a.m., that is, outside the busy hours. The actual power savings are thus reduced to around 25 – 30 %. This percentage is confirmed by various vendors of voltage stabilization and mitigation equipment (e.g. Schneider Electric [19], General Electric, Romlux Lighting etc.).

Reducing supply voltage will result in an illumination level dimmed accordingly. It must be considered individually, for each set of circumstances, whether the resulted lighting is sufficient.

From an economic perspective, is has to be taken into account the fact that the interval 11 p.m. to 5 a.m. is entirely covered by the low tariff rate, for a night-day tariff. Thus, although energy savings may be significant, economic indicators, like return of investment, internal rate of return etc., have to be considered carefully. On the other hand, a complete economic analysis will take into account the increase of lamps life span, due to stabilized and reduced voltage usage [12].

6. Conclusions

Using the infrastructure needed for metering – meters, communication paths, servers and metering software – much more functionality can be obtained by adding relatively inexpensive hardware and creating adequate software.

SCADA specific functions like control and monitoring can be performed, for certain non-critical power installation by unconventional equipment – "*smart meters*", using Ethernet and/or GPRS for communication.

The *Street Lighting Management System* helps reduce power consumption by providing the operator with means to optimize illumination period and helps improve service by reducing congestion and fault times.

Lamps life time can be increased and power consumption can be mitigated by analyzing data provided by the system – mainly voltage and power – and act accordingly – e.g. by installing voltage reduction equipment, change and/or rearrange lamps, etc.

Although it doesn't deal with renewable energy or actual flexible-load consumers, for helping reduce power consumption and congestions, for using meters in a smart way and for bringing the power grid closer to "unconventional" operators – like the city hall department for public services – the *Street Lighting Management System* can be regarded as a "*smart grid*" application.

The system as such can be implemented in any public lighting system. Results and principle from this project can be used and improved in more complex "smart grid" applications.

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