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Smart light control in buildings

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***Abstract*— The light system is considered among the large consumers of energy in residential buildings. Thus, this paper develops a light control loop whose inputs are smart data based on the triptych three Vs which are volume, velocity and variety. This control loop aims to predict an objective parameter related to the energy consumption. It depends on the reference luminosity fixed by the occupant. This parameter is provided to human in readable form in order to motivate him to make the appropriate perspective analysis that has a great potential on energy savings. This smart light control loop is applied to dimmable fluorescent light and tested in locals of the National Engineering School of Tunis.**

Keywords—residential buildings; smart light control; smart data; energy consumption; objective parameter

I. Introduction

Energy consumption is absorbing interest of many researchers around the world. Various aspects of this research domain have been investigated so far. Indeed, it is increasing exponentially in the current decades. According to the report of the International Energy Agency [1], energy consumption for the year 2013 is equal to 13541 Mtoe (157.482*10^{12} kWh). The energy requirement is provided mainly by the use of fossil fuels that ensure 80% of demand. The oil is considered among the main consumed resources with 31.1%, followed by coal with 28.9%, then natural gas 15.1% and finally nuclear 4.8%. As Tunisia belongs to the Africa continent, fig. 1 illustrates the annual energy increase for the period 2000 – 2014. This

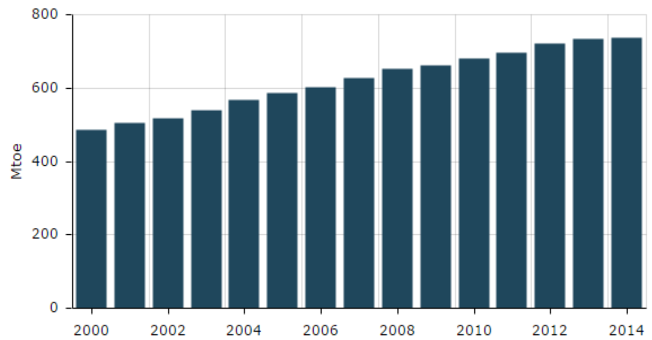

Fig. 1. Energy consumption in Africa for the period 2000 - 2014

significant increase in energy demand is responsible for a transitory phase full of concern about environmental problems: CO_2 emissions, depletion of world energy reserves, excessive heating…

Buildings as among the prominent consumer of energy have an important role in electrical grids. Thus, introducing intelligence in buildings in the sense of efficient and optimized usage can save a considerable amount of energy.

Recently, researchers emphasize that enormous attention should be paid to the sector of buildings. They try to develop sustainable strategies and technologies under the vision of smart buildings [2, 3, 4].

A new approach that can have a great potential of energy saving is highlighted in this paper. It is based on:

- Descriptive analysis that aims to identify the causes of the significant increase in energy consumption.

- Projection that aims to project on the future the historical data.

- Predictive analysis that aims to extrapolate new information on the basis of contextual settings (constraints, variables, assumptions …).

- Perspective analysis that aims to take appropriate decisions that would decrease energy demand.

To follow this approach, smart control loops for each measurement parameter (heating, cooling, light…) can be introduced inside the building. To have reliable and accurate results, several environmental settings must be provided to these loops such as heat transfer coefficient, heat capacity, ambient luminosity… The light's control loop is highlighted in this paper.

Smart control loops need smart input data based on the triptych three Vs which are volume (measurement data for each small sampling period), velocity (data provided in near real time) and variety (thermal parameters of the building, data provided by sensors, variable parameters…). These three properties add a value to the smart control.

The smart control loop provides as output an objective parameter [5, 6] given to the occupant in a readable and understandable form. This parameter incites the human to make appropriate actions.

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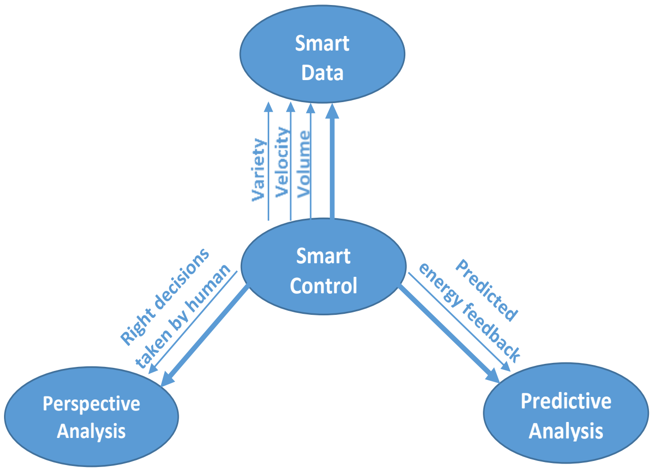

Fig. 2. Smart control

The definition of smart control in smart building is depicted in fig. 2.

II. STANDARD CONTOL AND SMART CONTROL

The standard control and the smart control have the same objective which is energy optimization. The difference between them (fig. 3) is explained in the following.

In the standard control:

- There is a standard regulation loop whose inputs are the measurements provided by sensors and the output is the computing of the power.

- The energy feedback loop is absent. The standard control is an open loop.

In the smart control:

- There are several regulation loops, for each building's appliances, whose inputs respect the triptych three Vs (Variety, Volume and Velocity). This allows to bring intelligence to data.

- The energy feedback loop is added [7, 8]. The smart control is a closed loop since it provides occupants with fast analyses in order to make the appropriate actions and respect the energy and comfort trade-off.

III. LIGHT CONTROL LOOP

Energy in building is consumed for different purposes such as light, appliances, cooling, heating… A balance of power study, done in National Engineering School of Tunis (ENIT, an example of building), showed that the light is considered among the large consumers of energy. Its consumption percentage is estimated to 31%. Therefore, it's interesting to invest on developing on sustainable strategies and technologies under the vision of smart light control loop [9].

The objective of this light control loop is to keep the inner luminosity constant and equal to the occupant preference while taking into account the ambient luminosity variation. To do so,

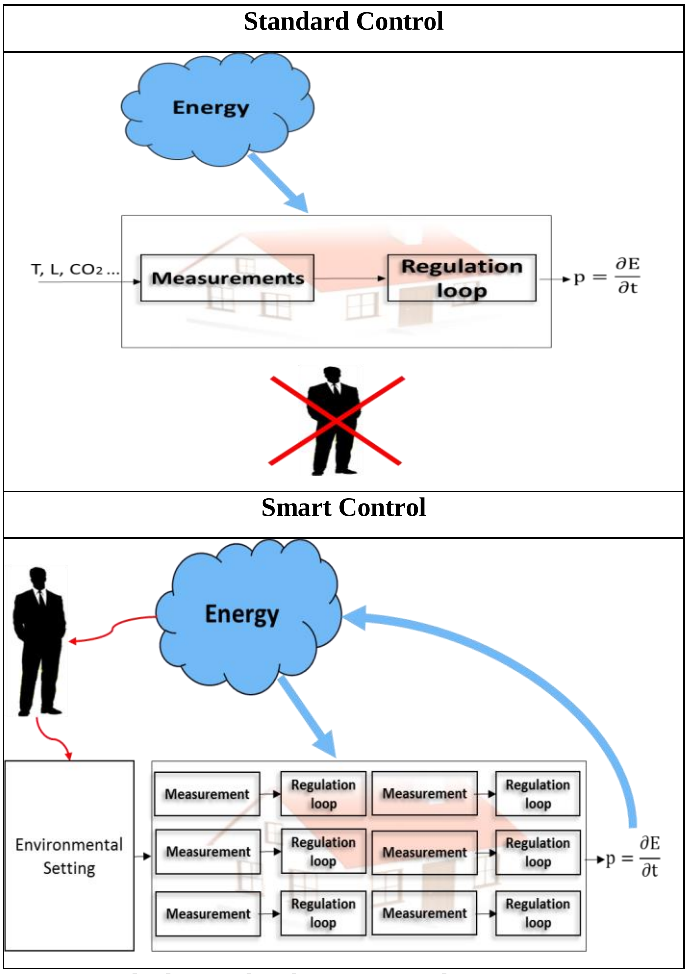

Fig. 3. Standard control and Smart control

we have disposed:

- a luminosity sensor that measures the inner luminosity and

- a control unit that sends commands (ON, OFF and Dimming) to the lamp. This command is modeled by a duty cycle which function is the variation of the luminosity by acting on the voltage's mean value (fig. 4).

The duty cycle is given by (1):

$$N = \frac{t_c}{T} \tag{1}$$

The average output voltage $V_{out,average}$ is related to the average input voltage $V_{in,average}$ via the duty cycle (2):

$$V_{in,average} = N \times V_{out,average} \tag{2}$$

The value of the duty cycle is deducted after computing the adequate average output voltage using a regulation loop based on PI controller. It's explained in the following.

The PI function is written as follows:

$$F_{PI} = \frac{V_{linear}}{e} = K_p + \frac{K_i}{s} = \frac{1+sT_n}{sT_i} \quad (3)$$

Where V_{linear} is linear voltage and e is error.

$$K_p = \frac{T_n}{T_i} \quad (4)$$

$$K_i = \frac{1}{T_i} \quad (5)$$

As the objective is regulating the light system, the open-loop function is given by (6):

$$F_{open\_loop} = \frac{G_o}{1+sT_o} \quad (6)$$

Where G_o is the open-loop gain and T_o is the open-loop time constant.

As the regulation is carried out for dimmable fluorescent lamp which is equivalent to RL electrical circuit, the voltage V is expressed as:

$$V = RI + L\frac{dI}{dt} \quad (7)$$

Where R is the lamp resistor, L is the lamp inductor and I is the current.

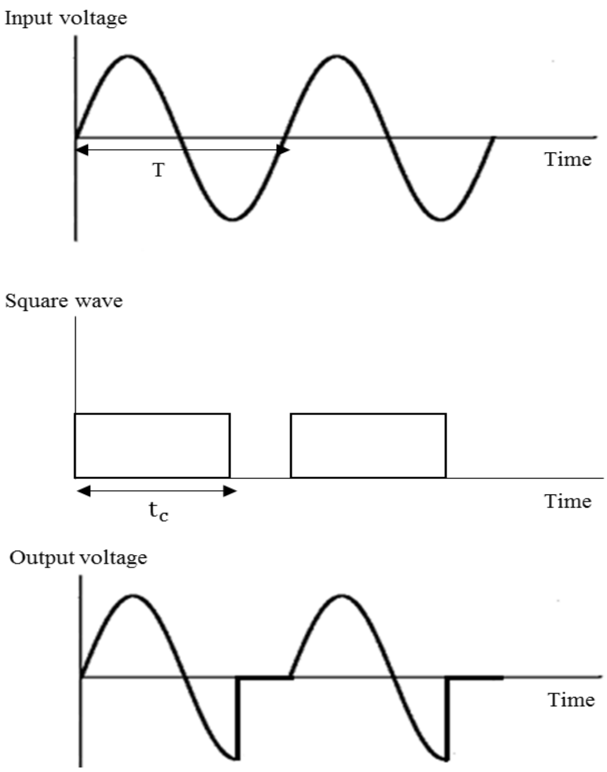

Fig. 4. Duty cycle principle

To avoid a large amount of calculation, we suppose that the relationship between the luminosity Lum and the current is linear. So, it's given by (8):

$$I = a \times Lum + b \quad (8)$$

Where a and b are empirical constants.

The voltage consists of two components: linear V_{linear} and nonlinear $V_{nonlinear}$. They are given by (9) and (10):

$$V_{linear} = R \times a \times Lum + L \times a \times \frac{dLum}{dt} \quad (9)$$

$$V_{nonlinear} = R \times b \quad (10)$$

The transfer function is deduced from the linear voltage. The nonlinear voltage will be added by compensation. The transfer function is written in the form (11):

$$F_{open\_loop} = \frac{Lum}{V_{linear}} = \frac{1/(R \times a)}{1+(L/R) \times s} \quad (11)$$

So, the open loop parameters are expressed as follows:

$$G_o = \frac{1}{R \times a} \quad (12)$$

$$T_o = \frac{L}{R} \quad (13)$$

The next step is the computing of the PI controller parameters. It's detailed in the following. To do so, the closed-loop transfer function must be calculated. The first order has been chosen due to its stability. So, the closed-loop transfer function F_{closed_loop} is given by (14):

$$F_{closed\_loop} = \frac{G_c}{1+sT_c} = \frac{1}{1+sT_c} \quad (14)$$

Where G_c is the closed-loop gain and T_c is the closed-loop time constant. The gain is equal to 1 so that the output follows the reference set point. The closed-loop time constant is expressed as:

$$T_c = k \times T_o \quad (15)$$

Where k is a constant. It's chosen smaller than 1 in order to improve the convergence speed of the closed-loop.

On the other hand, the closed-loop function can be rewritten as follows:

$$F_{closed\_loop} = \frac{F_{PI} \times F_{open\_loop}}{1+F_{PI} \times F_{open\_loop}} \quad (16)$$

In order to obtain the first order system, we have recourse to the compensation via (17):

$$F_{PI} \times F_{open\_loop} = \frac{G_o}{sT_i} \tag{17}$$

Therefore the PI parameters can be calculated. They are expressed as:

$$T_n = T_o = \frac{L}{R} \tag{18}$$

$$T_i = G_o \times T_c = \frac{k \times T_o}{R \times a} \tag{19}$$

The parameters K_p and K_i can be deduced directly from T_n and T_i via Eq. (4) and Eq. (5).

The inverse Laplace transform of PI controller is given by (20):

$$\frac{dV_{linear}}{dt} = K_p \times \frac{de}{dt} + K_i \times e \tag{20}$$

To discretize the PI controller, the following discretization method is used:

$$\frac{dx}{dt} = \frac{x(k) - x(k-1)}{T_{sp}} \tag{21}$$

Where T_{sp} is the sampling period.

Therefore, Eq. (20) can be written again as follows:

$$V_{linear}(k) - V_{linear}(k-1) = K_p \times (e(k) - e(k-1)) + K_i \times T_{sp} \times e(k) \tag{22}$$

Summing the equation described by (22) while using the discretization method given by (21), the Eq. (23) is obtained:

$$V_{linear}(k) = K_p \times e(k) + L(k)$$
$$L(k) = L(k-1) + T_{sp} \times K_i \times e(k) \tag{23}$$

Once the reference luminosity, selected by the occupant, is fixed, an objective parameter can be added to the control loop.

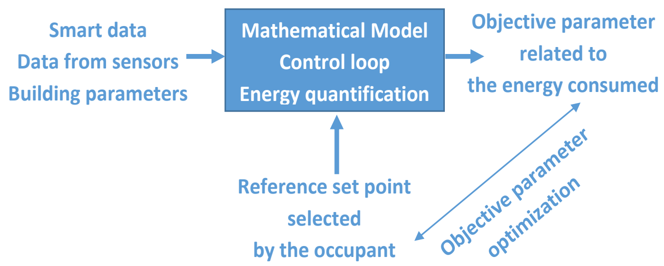

Fig. 5. Human control

This parameter is readable and understandable by the occupant. It can be deduced from the amount of energy consumed. This parameter is used in order to motivate the concerned person to react and take the appropriate actions. This is called the human control [10].

For the light system, we can propose as an objective parameter the daily cost of the energy consumed by the occupant [5, 6]. Since it's derived from the energy quantification, the computing of the light energy consumption during a day is detailed in the following.

In order to estimate the daily energy consumption, it was assumed that the ambient luminosity without the artificial luminosity Lum_{amb} follows a normal distribution given by (24):

$$Lum_{amb}(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(t-\mu)^2}{2\sigma^2}} \tag{24}$$

Where σ is the standard deviation and μ is the mean. They can be determined from measurements.

For reasons of simplicity, we supposed that the ambient luminosity is constant during a sampling period; the discretization of the Eq. (24). Therefore, the artificial luminosity $Lum_{art,k}$ during each sampling period Δt is described in the following:

$$Lum_{art,k} = Lum_{ref} - Lum_{amb}(k\Delta t) \tag{25}$$

Where Lum_{ref} is the reference luminosity fixed by the occupant.

The Fig. 6 explains how the artificial luminosity is computed during each sampling period while taking account the ambient luminosity variation.

For each sampling period Δt, the artificial luminosity's

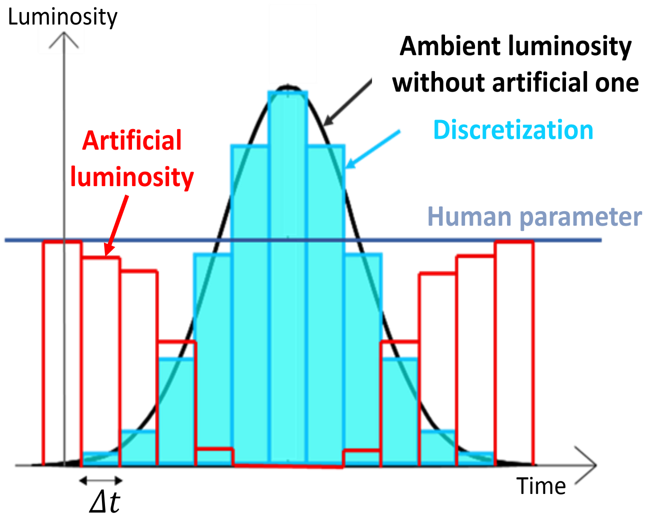

Fig. 6. Computing of the artificial luminosity

power $P_{art,k}$ can be determined by Eq. (26):

$$P_{art,k} = \frac{Lum_{art,k} \times S}{U \times n \times eff} \quad (26)$$

Where S is the room's surface, U is the utilance factor, n is the luminosity performance and eff is the luminosity efficiency.

Since the energy is defined as the integral of the power during a period t, the artificial luminosity's energy consumption during a day $Energy_{art}$ is given by (27):

$$Energy_{art} = \sum_{k} 2 \times pres_k \times P_{art,k} \times \Delta t \quad (27)$$

Where $pres_k$ is a binary parameter indicating the occupant's presence during the sampling period Δt. The number 2 is added due to the artificial luminosity's symmetry. The integer k vary between 0 and $\mathrm{E}\left(\frac{t_1 - 0.5\Delta t}{\Delta t}\right) + 1$.

Where E is the floor function and t_1 is given by (28):

$$t_1 = \inf\left\{Lum_{amb}^{-1}\left(Human\_parmeter\right)\right\} \quad (28)$$

IV. CONCLUSION

The smart control, which relies on predictive and perspective analysis, requires as inputs smart data based on the triptych three Vs (Volume, Velocity and Variety). Since it highlights the human control, its output is an objective parameter related to the occupant's energy consumption. This parameter must be provided to human in readable and understandable form. It's chosen intelligently so that it can highly influence the occupant behavior.

Unlike the standard control, the smart one proposes several regulation loops for each building's appliances. Since the light system presents among the dominant energy consumption in building especially in ENIT considered as case of study, its regulation and energy prediction are highlighted in this paper.

The light regulation loop consists in fixing the reference luminosity, selected by the occupant, via varying the light's voltage. The command is applied via sending the adequate duty cycle to the dimmable fluorescent lamp. The next step was energy quantification in order to predict the daily cost of the energy consumed by the occupant, chosen as an objective parameter.

In perspective, this control will be extended and applied to other appliances. The challenge in this work is how to replace all objective parameters related to each building's appliance by just one objective parameter that can intelligently change human behavior.

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