Logical Design of the E-Cig for a Fine Control of the Inhaled Nicotine for the Reduction of the Damage from Tobacco

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Abstract: The Electronic Cigarette (e-cig) is increasingly recognized as a pharmaceutical/medical device because the digital smoke appears helpful in reducing the nicotine addiction and the reduction of damages from tobacco. However, to this aim, it is not enough to know the nicotine concentration in the liquid digitally smoked, because there is no notice about the quantity of liquid digitally smoked, until the liquid tank of the e-cig is empty. This means that there is no notice about the equivalent of one cigarette has been smoked because there is no end-cigarette control in the e-cigs commercially available. Therefore, in this paper, criteria are proposed, implemented and simulated for a fine control of the inhaled nicotine based on a notice of end-cigarette given to the smoker. It is proposed a logical design of the e-cig with the end-cigarette control: the logic model is implemented in a digital circuit model, useful to design the e-cig for a fine control of the inhaled nicotine. The fine control of the nicotine is necessary to reduce the addiction from tobacco and related damages.

Keywords: Electronic cigarette, E-cig, Pharmaceutical device, Medical device, Nicotine.

1. INTRODUCTION

The great diffusion of the electronic cigarette (e-cig) is a relatively recent phenomenon even if already in the year 1963 Herbert A. Gilbert filed the first patent [1]. However, the most significance contribution to the birth of the e-cigis due to HonLik that in the year 2003 has patented a design of the e-cig with ultrasound technology [2]. Although today the majority of electronic cigarettes do not use this system in favor of the use of the vaporizer, the Chinese patent was the basis for the continue development of electronic cigarettes designed to meet all the needs of smokers [3].

The e-cig has a modular structure composed of seven main components: Nozzle, Vaporizer (or Atomizer), Liquid Cartridge, Sensor airflow, Micro-Controller, Lithium Battery and LED Indicator, as can be seen in Figure **1** [4].

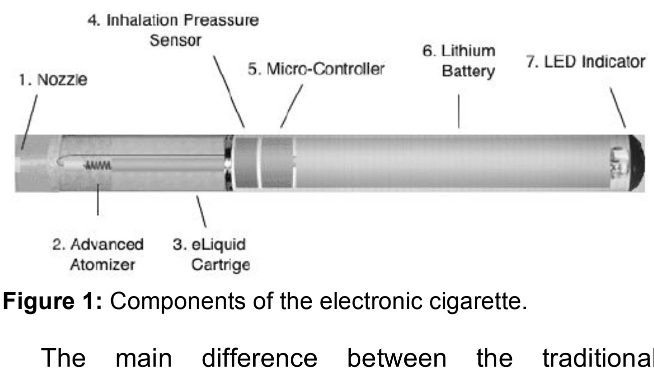

Figure 1: Components of the electronic cigarette.

The main difference between the traditional cigarette and the e-cig is that in the latter there is no combustion. This is why people speak about digital smoke.

In fact, the operation of the e-cig lies in heating a composed liquid contained in a small tank or in a cartridge to produce a steam that is inhaled by the user. This vaporization process is performed using sensors and power supply (battery), and is managed by a control unit. The steam inhaled, is the digital smoke.

The main advantage of the e-cig compared to the traditional cigarette appears to be the healthiness due to the lack of combustion.

In fact, by smoking a traditional cigarette, due to the combustion, the user inhales more than 4000 chemicals of which at least eighty are carcinogens such as carbon monoxide, tar, nicotine, ammonia, arsenic, polonium 210 and many other according to the International Agency for Research into Cancer [6].

In the e-cig there is no combustion and the steam produced is mainly composed of substances apparently not harmful to health:

Propylene Glycol (PG): a liquid colorless, tasteless, humectant and hygroscopic; it has bacteriostatic properties and can be stored for many years without alteration. The propylene glycol enhances the hit of nicotine.

Vegetable Glycerin (VG): a colorless, thick, viscous, sweetish, humectant, hygroscopic liquid. The vegetable glycerin is the substance that gives the steam the appearance of the smoke.

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Water**:** it is an approximately 10% of the liquid.

Nicotine**:** this substance, while not necessary for the creation of the steam, it is extremely important because it is present in the tobacco and is addictive.

Aromas**:** are common food flavorings, giving the flavor to the liquid. Aromas generally make up from 3% to 10% of the liquid.

Concerning the damages due to the digital smoke, the scientific community is divided into two groups clearly distinguished. There are people approving the digital smoke [7] and judges the liquid of the e-cig not dangerous for the health, and, instead, there are people absolutely contrary to the electronic smoke, considering it dangerous for the health[8]. Really, there are no appropriate data, coming from scientific tests, allowing to determine if the electronic cigarette is able, to what extent and for how long, to detoxify from the abuse of the tobacco. Moreover, there are no studies proving the safety of products used, including studies of any long-term damages.

Then, it is not proved that the e-cig is the ideal solution for the people who want to stop smoking the traditional cigarettes for the sake of the health. However, it is sure that the e-cig gives million tobacco users an opportunity to reflect about dangers due to the traditional cigarettes. It is also sure that as a result of the combustion of the traditional cigarette, there are over 4000 substances of which at least eighty are also carcinogens, while in digital smoke there are only a few chemical substances that are inhaled by the smoker.

In most cases, the nicotine is responsible for the addiction, even if small doses are useful to avoid the crisis of abstinence in the strong smoker, and to prevent from returning to tobacco. In this respect, the e-cig appears useful for the reduction of the damage caused by the tobacco addiction because it simulates the smoke but it does not contain tobacco and no combustion occurs, although smokers maintain the gestural pleasure and can inhale a controlled dose of nicotine.

Therefore, the e-cig is increasingly recognized as a pharmaceutical/medical device because it appears helpful in reducing the nicotine addiction.

However, to use the e-cig for this purpose, it is not enough to know the nicotine concentration in the liquid because there is no notice about the amount of liquid vaporized (smoked) until the liquid tank is empty. It is not given the smoker any notice about the equivalent of one cigarette has been smoked (end-cigarette control).

Therefore, in this paper criteria are proposed, implemented and simulated, for a fine control of the inhaled nicotine based on a notice of end-cigarette to the smoker. The end-cigarette control allows the e-cig to alert the user when he has inhaled a quantity of nicotine equivalent to one traditional cigarette. Then, it is proposed a logical design of the e-cig with the end-cigarette control, and it has been implemented in a digital circuit model, useful to design the e-cig for a fine control of the inhaled nicotine.

Therefore, in Section II is studied, through the flow chart, the control logic of the commercially available e-cig. In section III the criteria for the end-cigarette control, are proposed. In section IV, there is described a digital circuit model implementing the logic design of the e-cig. In section V, simulation results are discussed, accounting for the end-cigarette control method proposed and implemented. Final remarks are in Section VI.

2. LOGIC MODEL OF THE E-CIG

The operation of the e-cig is described in the block scheme in Figure **2.** The signals managed by the control unit are highlighted through dashed arrows.

When the user does not inhale the e-cig is in standby mode.

When the user inhales, the airflow sensor detects a pressure difference and sends a signal to the control unit. Suddenly, the e-cig is located in the “on" mode [9].

In the “on” mode, the control unit checks the temperature into the vaporizer by an inside temperature sensor. If the temperature detected is high enough to reach a threshold value T_{Break}, the control unit interrupts the power supply to the resistance of the vaporizer (cut-off) by opening an inside electronic switch, in order to prevent damages to the e-cig. At the same instant, the control unit drives the LED to warn the user about the high temperature through a series of flashes. Finally, after a certain time, the temperature in the vaporizer is once more checked and when the temperature $T < T_{Break}$ the operation mode becomes “on” again.

The control unit, by closing the electronic switch provides power supply to the resistance (coil) of the vaporizer to heat the liquid and causing the production of the digital smoke. At the same time, the control unit drives the LED to light up with the aim of simulating the combustion that occurs in a traditional cigarette while smoking.

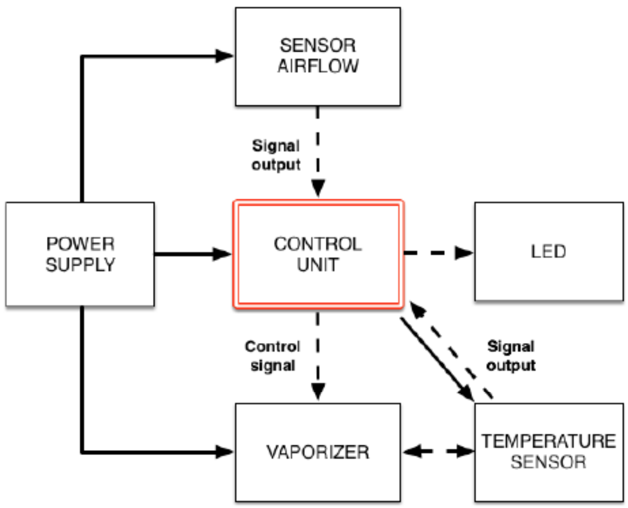

Figure 2: Block scheme of the e-cig.

When the control unit detects a low battery charge level, usually below 10% as compared to the nominal full charge level, it drives the LED to flash in order to alert the user that the battery charge is low and that a recharge is required. Conversely, if the charge level of the battery is high, the control unit waits for the user inhalation in order to put the e-cig in its on mode.

One of the improvements needed in the use of the e-cig is to notify the user how much digital smoke, *i.e*. how much liquid in cartridge, match a classic cigarette in terms of the amount of nicotine inhaled. Without this kind of control can happen that the user, who smokes digital, hires more nicotine than if he smokes the traditional cigarette.

Clearly, this risk depends primarily on the concentration of nicotine in the liquid inside the cartridge (or in the tank) of the e-cig, which concentration can be 24 mg/ml, 18 mg/ml, 16 mg/ml, 12 mg/ml, 8 mg/ml, or 4 mg/ml, but also depends on the amount of liquid consumed in a session of digital smoke, and this is currently not fine controllable. In fact, there is a notification to the user only when the liquid in the cartridge is exhausted but there is no way to know when the user has inhaled the same quantity of nicotine as if he smokes a classical cigarette.

Therefore, it is necessary to perform the statistical estimate on the consumption of nicotine in order to define criteria to quantify the nicotine inhaled and implement a control mechanism based on these criteria in order to give warnings to the user. This is exactly the aim of this paper.

The fine control of the inhaled nicotine is called in this paper “the end-cigarette control” because the most useful information for a smoker is not just the quantity of nicotine assumed but the number of cigarettes smoked, and these quantities clearly are strictly related each other.

3. END-CIGARETTE CONTROL CRITERIA AND RELATED LOGIC MODELS

It is reasonable to estimate that the average number of shots necessary in order to smoke completely a normal cigarette is about ten even if it depends on the concentration of nicotine and from the duration of the inhalation act (depth of inspiration).

It is also important to know how much is the nicotine contained into the liquid in order to figure out how many traditional cigarettes correspond to a given amount of liquid consumed. In a commercial bottle of liquid for e-cig the typical concentration of nicotine is 24 mg/ml.

In this respect, one milliliter of liquid for e-cig equals approximately 20 drops; using a vial of 24 mg/ml of nicotine, there would be 1.2 mg of nicotine per drop. Therefore, to smoke three drops of liquid correspond to an average consumption of 3.6 mg of nicotine, as three classical cigarettes quite strong.

So, comparing a liquid for the digital smoke having a concentration of nicotine of 24 mg/ml, with a classical cigarette with 1.2 mg of nicotine (per cigarette), results that:

- One drop of liquid contains the same nicotine as a traditional cigarette.
- One milliliter of liquid contains about the same nicotine as 7 traditional cigarettes.
- Three milliliters of liquid correspond to about a package of traditional cigarettes.

It is noteworthy that these proportions theoretically make it possible to control the amount of nicotine inhaled, but only after exhausting the cartridge: there is no way to quantify the exact amount of liquid evaporated before it runs out.

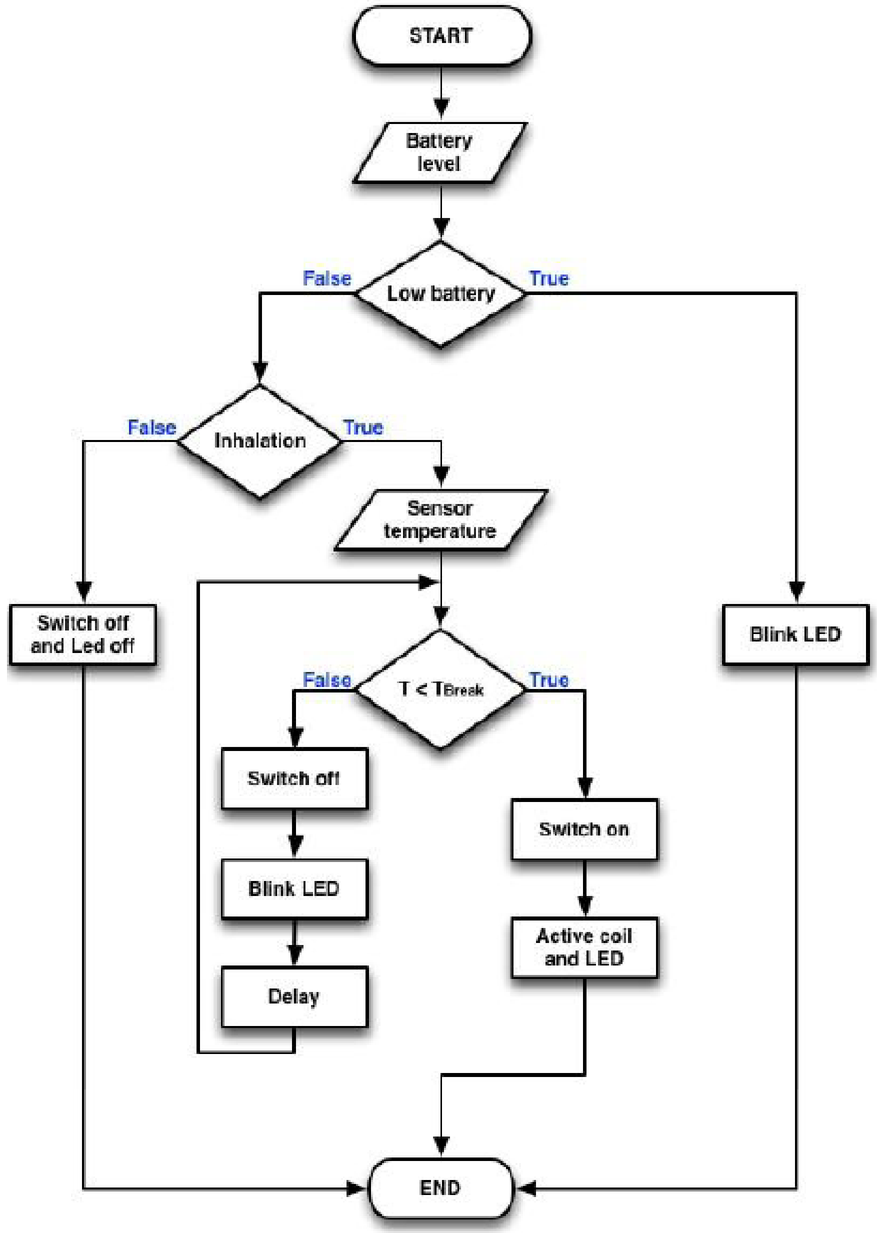

Figure 3: Flow chart of the e-cig logic.

Also, it must be taken into account that the absorption of nicotine depends also on other factors such as the frequency and duration with which the user smokes and how deeply inhales [10].

On the basis of the above considerations, has been implemented by the authors a fine control of the inhaled nicotine by a control of end-cigarette. In fact, it is notified to the user when it has assumed an amount of nicotine almost equal to that which would take by smoking a traditional cigarette, so allowing a fine control of the amount of the inhaled nicotine. The criteria adopted to implement the end-cigarette control are the following:

- Control the number of shots made by the user
- Control the time elapsed from the first inhalation

Both criteria have been implemented. They have been also implemented in a very effective, combined form.

The flow chart relevant the combined implementation of the two criteria is splitted in Figures **4** and **5**

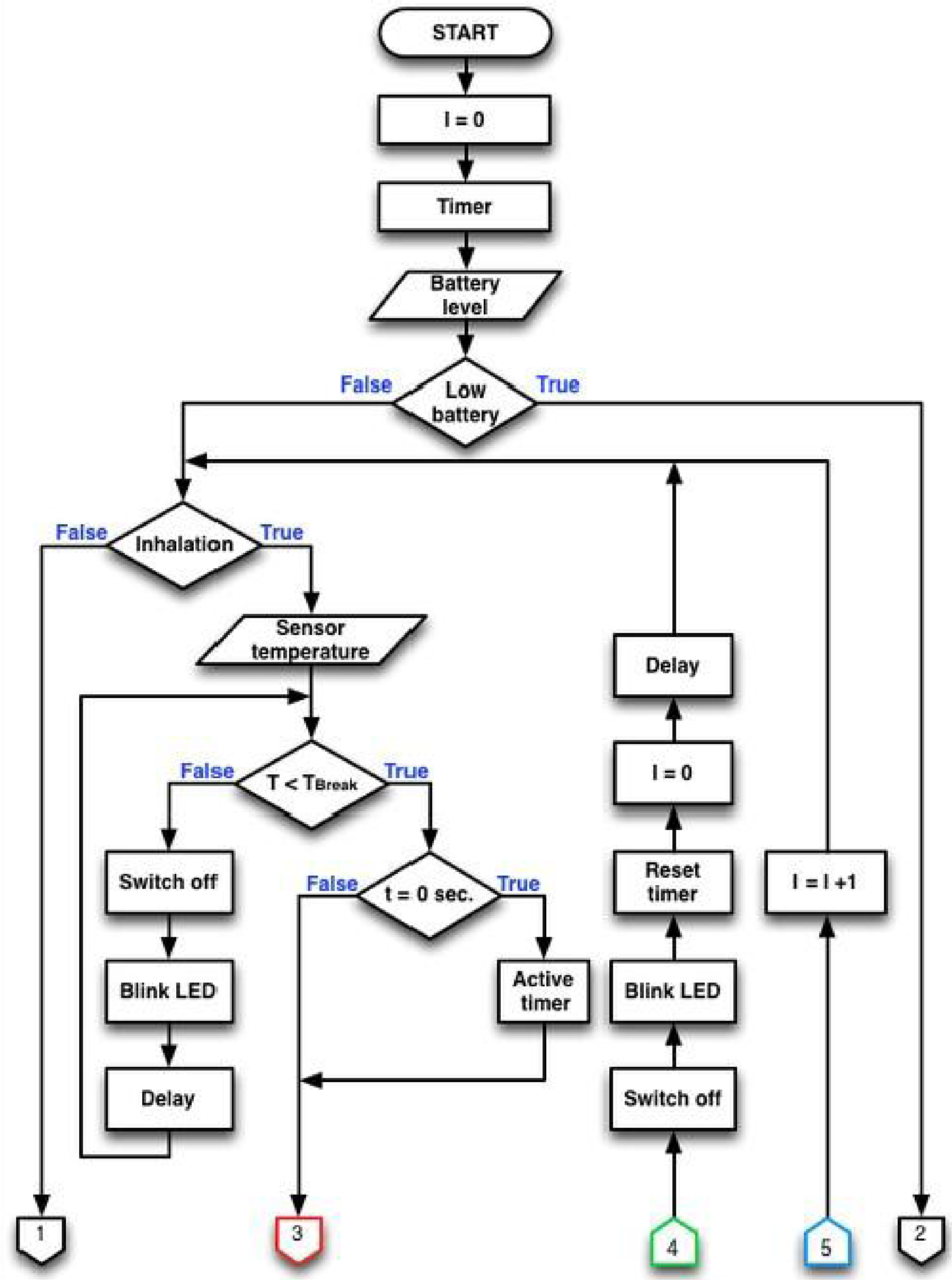

Figure 4: Flow chart of the e-cig logic with combined end-cigarette control, on the number of shots and in time – first part.

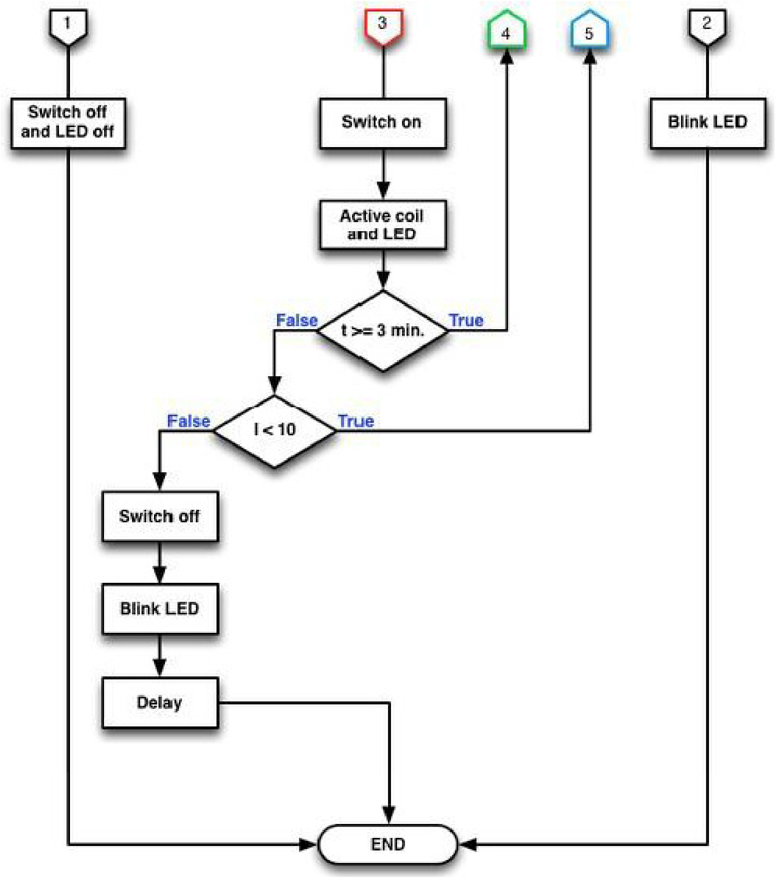

Figure 5: Flow chart of the e-cig logic with combined end-cigarette control, on the number of shots and in time – second part.

To implement the end-cigarette control combining the two previously defined criteria, two steps are necessary.

Firstly, is defined a variable, **I**, initialized to zero, in order to check for the number of inhalations carried out by the user. Then, it is implemented a timer (counter) initialized to zero and initially turned off, in order to count the amount of time that elapses starting from the first inhalation by the user.

At the beginning of the smoking session, if the control unit detects a low battery level, drives the LED to flash in order to alert the user that the e-cig needs a recharge. Conversely, if the battery charge level is high, the control unit waits for the user attempts the inhalation in order to put the e-cig in its "on" mode.

If the battery's charge level is high and the user inhales, the variable "I" that monitors the inhalation condition is set "true" and the control unit checks for the temperature through the sensor in the vaporizer.

If the sensed temperature is close to the breaking limit temperature, T_{Break}, the control unit opens the electronic switch (switch off) and at the same instant drives the LED to warn the user that a high temperature condition occurs. Finally, after a certain time, the control unit again evaluates the temperature of the vaporizer in order to exit from the warning mode when the temperature is less than T_{Break}.

When the user inhales and the sensed temperature is less than T_{Break}, the control unit activates the counter (timer) counting for the time elapsed from the first inhalation. Then, the electronic switch is closed, providing power supply to the resistance inside the vaporizer and to the LED simulating the combustion.

The control unit monitors the timer constantly.

If the elapsed time from the first inhalation is less than or equal to three minutes, the control unit checks the variable "**I**" that counts for the number of inhalations/shots. If the number of shots is less than ten, the control unit increases by one the value of the variable "**I**".

On the contrary, if the number of shots is ten, in the assumption that the amount of the elapsed time from the first inhalation is less than or equal to three minutes, the control unit opens the electronic switch to interrupt the power supply to the vaporizer. At the same time, the control unit drives the LED to flash in order to notify the user that in less than three minutes has already carried out ten shots.

The "on" mode of operation of the e-cig remains interrupted for a few tens of seconds and, then, the control unit resets the e-cig and starts again the "on" mode of operation.

If the elapsed time from the first inhalation reaches three minutes and the number of shots is less than ten, the control unit opens the electronic switch to interrupt the power supply to the vaporizer. At the same time, the control unit drives the LED to flash in order to notify the user that the time elapsed from the first inhalation is that enough to smoke a traditional cigarette even if the assumed nicotine is poor due to the reduced number of shots.

Then, the control unit resets the timer by initializing it to zero and resets the variable "**I**" to zero. Once more, the "on" mode of operation of the e-cig remains interrupted for a few tens of seconds and, then, the control unit resets the e-cig and starts again the "on" mode of operation, from the beginning.

Having defined the logical model of the e-cig operation, accounting for the end-cigarette control, it is necessary to implement a circuit model in order to verify by simulations the effectiveness and in order to make it useful for the design of the e-cig.

Therefore, follows the description of the digital circuit model of the e-cig with the end-cigarette control.

4. DESIGN OF THE CIRCUIT MODEL OF THE E-CIG LOGIC

Implementing a circuit model means to translate the flow chart in terms of logic gates.

Following the logic in the flow chart in Figures **4** and **5**, the circuit specifications are:

- Notification during the inhalation
- Control of the charge level of the battery
- Control of the temperature inside the vaporizer
- Control of the number of shots
- Control of the time elapsed from the first shot

The actions carried out are:

- During the inhalation is provided the power supply and is activated the LED to light up in green color
- If the battery is discharged the LED flashes 5 times (green light)
- If the temperature of the vaporizer $T \geq T_{Break}$ is interrupted the power supply to the vaporizer and is activated the LED to light up in red color
- If the user made 10 shots or spent 3 minutes from the first inhalation, the power supply is interrupted and are issued 3 flashes of green color by the LED

The inputs and the out puts are summarized in Figure **6**:

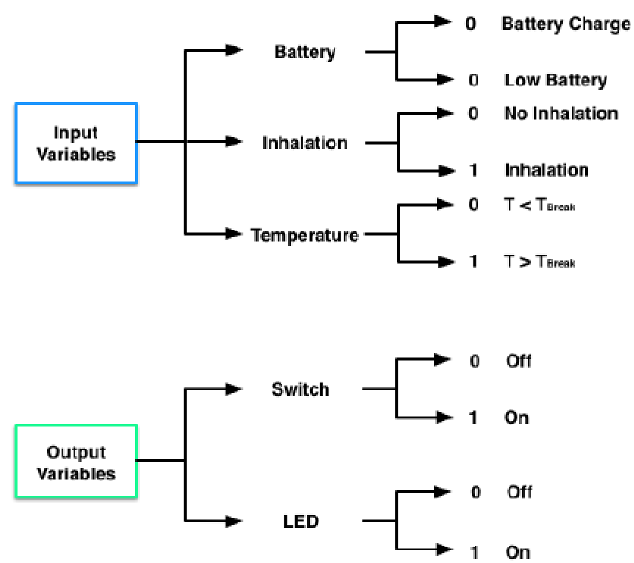

Figure 6: Inputs and outputs for the e-cig digital circuit model.

Figure **7** shows the schematic of the digital circuit model of the e-cig with the end-cigarette control combining both of them the previously described criteria.

The circuit model has been developed in order to simulate the e-cig operation with the software Multisim.

The circuit consists of a dip switch S1, a demultiplexer, two 555 timer, a voltage driven switch S2, two SR latch, a BCD decoder, a 7-segment display,

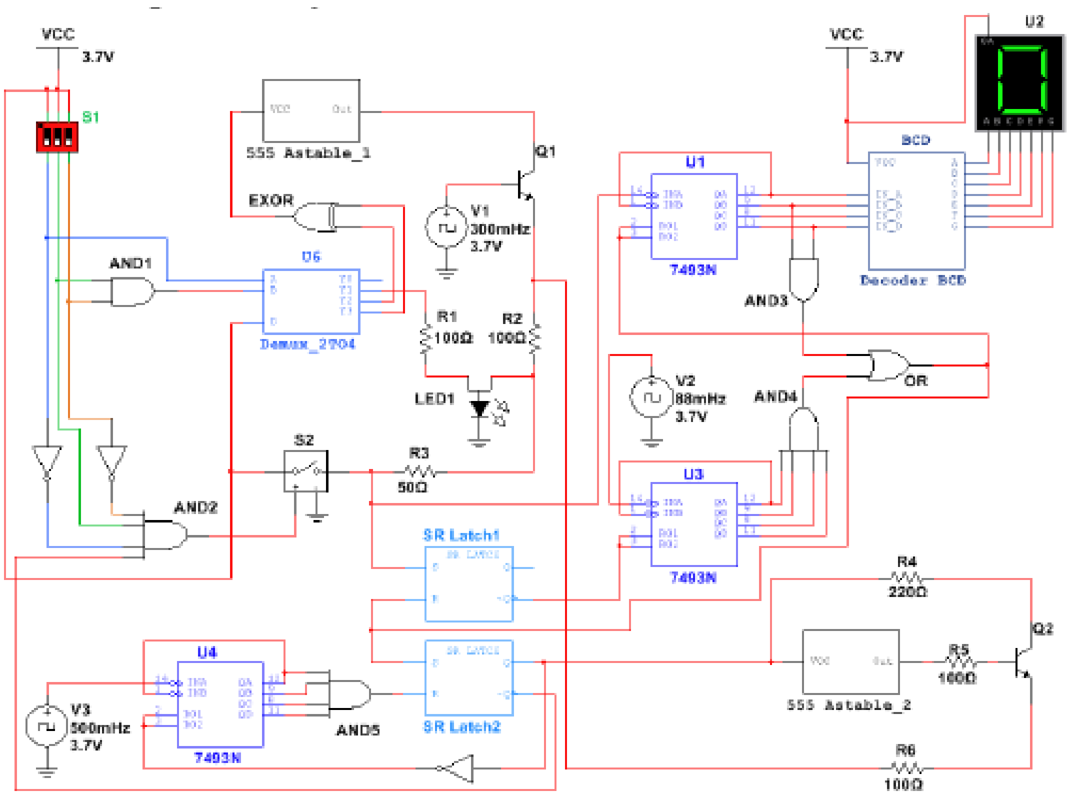

Figure 7: Logical schematic of the e-cig with combined control of the number of shots and of the time elapsed (in time control)

three module-16 asynchronous counters (U1, U3 and U4),a two-colour LED (red and green), and finally by some logic gates and analog components useful to switch on the whole circuit.

The dip switch S1 consists of three switches encapsulated in a single package and is used to generate the combinations of the input variables, *i.e.* the test-input waveforms. The switch on the left refers to the variable "battery", the central one refers to the variable "inhalation", while the switch on the right refers to the variable "temperature".

Demux_2TO4 manages the warnings relevant to the discharged battery and the high vaporizer's temperature through the flashes of the LED.

The blocks 555 Astable_1 and 555 Astable_2 generate the square waves driving the LED to flash if any warning occurs, and, finally, the BCD Decoder manages the 7 segment display used only for simulation purposes in order to view in real time the simulation results.

The counting of the time elapsed from the first inhalation carried out by the user, is entrusted to a module-16 asynchronous counter,that counts for the pulses that are supplied by the pulse generator V2.The period T of the square wave generated by V2 is dimensioned so that when arrives the sixteenth pulse is spent a time interval equal to three minutes, according to the established criterium for the end-cigarette control. Therefore it results:

T × 16 ≈ 180 sec and then T= 1/0.088Hz=11,36 sec. meaning that the frequency of V2 is f = 88mHz.

At the beginning of the simulation, if all the switches of the dip switch S1 are open,there are no signals relevant to the battery's charge level, to the inhalation act and to the vaporizer temperature and then the e-cig is in standby mode. In this case, the ripple counter U3, that counts for the elapsed time from the first inhalation by the user, and the asynchronous counter U4,that maintains active the warning of end cigarette, are disabled.

In fact, as Figure **7** shows, the Q output of SR Latch1 which is at a high logic level, is connected to the reset inputs of U3.

Similarly, U4 is also disabled. In fact, the output of the OR gate in Figure **7**, which is at a low logic level, is connected to the input S of the SR Latch2, thus forcing the Q output of the SR Latch2 at a low logic level. Therefore,U4 is in the reset state,because of the Q output of the SR Latch2 which is connected through an inverter to the reset inputs of U4.

When the switch relevant to the battery charge level is closed, it is simulated the situation of low charge detected. In this situation, the green LED performs a series of five flash to notify the user that a recharge of the e-cig is required, and this happens regardless of the state of the other input variables.

When the switch relevant to the battery charge level is open (*i.e*. the battery is charged enough) while the switches relevant to the inhalation and to the temperature are closed, the LED will light up in red color to notify the user that the temperature of the vaporizer is high. Then, follows a period of switch off of the e-cig.

On the other hand, when the switches that simulate the state ofthe battery and of the vaporizer's temperature are open (battery enough charged and temperature below the threshold value), while the switch that simulates the inhalation act (shot) is closed,the e-cig is in the condition of normal operation ("on" mode). In this case, the switch S2,in the circuit model shown in Figure **7**, closes and activates the LED to light up in green color for the entire duration of the shot. At the same time, the asynchronous counter U1 counts the first clock pulse, *i.e*. the first shot,and the number on the display in Figure **7** changes from 0 to 1. Moreover, it is also activated the asynchronous counter U3, because of the high logic value at the input S of the SR Latch1, which brings its output Q to a high value, while the output Q' switches from a high value to a low value.

When the user makes the tenth shot and the time elapsed from the first inhalation is less than three minutes, the output of the gate AND3 in Figure **7** is brought to a high logic level and, consequently, also the output of the OR gate switches to a high logic level, which is used both to reset the asynchronous counter U1 (that counts the shots), and to reset the asynchronous counter U3 (that counts the elapsed time from the first inhalation by the user) through the SR latch1. This is because of the R input of the SR Latch1 has a high logic level and then the output Q' switches at a high logic level.

In addition, considering that the high logic level of the output of the OR gate has a very short duration, is used the SR Latch2 in order to store it. Then, the output Q of the SR Latch2 switches to an high logic value and is used both to supply the block 555 Astable_2 (for the notification through the green LED), and, once inverted through the NOT gate, to activate the asynchronous counter, U4.

Then, after a time interval of 32 seconds during which by the LED alerts that the end-cigarette event has occurred, the output of the gate AND5 is at a high logic level and is connected to the R input of the SR Latch2, whose output, Q, switches to a low logic value. Consequently, both the asynchronous counter, U4, and the block 555 Astable_2 are disabled, so the e-cig returns in standby, again.

Conversely, if the user makes less than ten shots, and the time elapsed from the first inhalation equals three minutes, the output of the AND4 gate switches at a high logic level. Therefore, also the output of the OR gate is at high logic value, and is used to reset the asynchronous counters U1 and U3, involved in the counts of the number of shots and of the elapsed time, respectively.

The output of the OR gate is stored by the SR Latch2, whose output Q is at a high logic level and is used to supply the block 555 Astable_2 and, inverted by a NOT gate, to activate the asynchronous counter, U4.

After a time interval equal to 32 seconds during which occurs the alert of end-cigarette by the LED, the output of the gate AND5 is at a high logic level and it is connected to the R input of the SR latch2, whose output, Q, switches to a low logic level. Consequently, both the asynchronous counter, U4, and the block 555 Astable_2 are disabled and the e-cig returns again in standby.

5. SIMULATION RESULTS

In Figures **8** and **9** are shown the waveforms coming from the simulations associated with the warning of end-cigarette, when they are carried out ten inhalations in less than three minutes.

In detail, in Figure **8** the channel A of the virtual oscilloscope provided by the simulation software, is connected to the voltage driven switch S2,that detects the inhalations by the user, and the channel B is connected to the Q output of the SR Latch1. In Figure **9**, channels A, B, C, and D are respectively connected

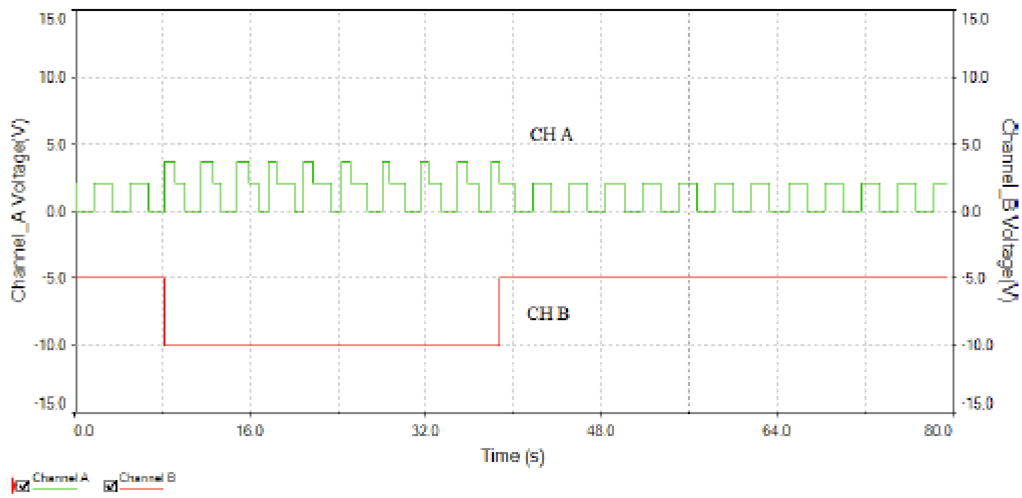

Figure 8: Waveforms simulating the control of end cigarette starting due to the number of shots.

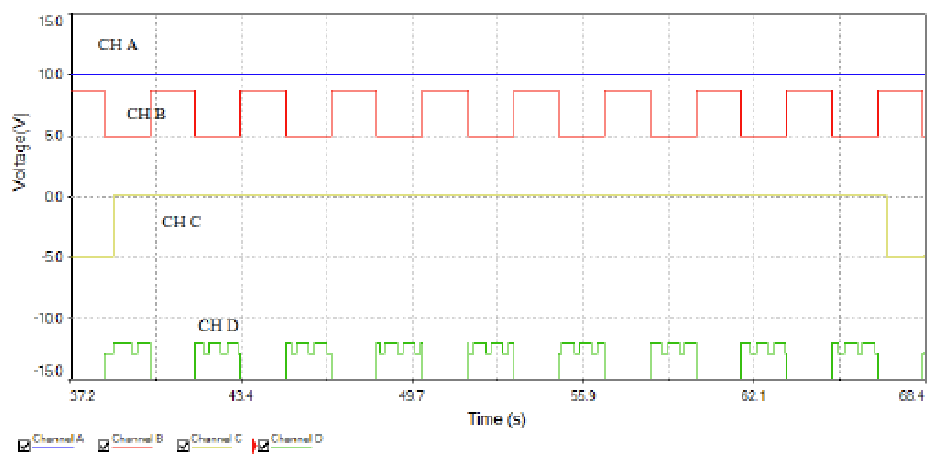

Figure 9: Other waveforms simulating the end-cigarette control starting due to the number of shots.

to the clock generator V1, to the output Q' of the SR Latch1, to the Q output of the SR Latch2 and to the emitter of the transistor Q1.

When the user inhales for the first time, the waveform detected from the channel A (upper curve)in Figure **8**, reaches a high logic level and causes the output Q' of the SR Latch1 to switch to a low level, as it can be seen in the channel B (lower) curve in Figure **8**. Therefore,it activates the asynchronous counter, U3, counting the time elapsed from the first inhalation by the user.

Subsequently, in the simulation more shots are made, and when it occurs the tenthshot in less than three minutes, it starts the warning by the end-cigarette control logic,due to the number of shots.

In this situation, it may be noted that the output Q of the SR Latch1 returns to a high logic level in order to reset the counter U3 and, at the same time, the counter U1,which counts the number of shots, is reset.

Figure **9** shows that at the tenth shoot, the Q output of the SR Latch2 switches to an high logic value, as can be seen from the channel C curve (the second curve counting from down), which allows to activate the asynchronous counter U4, that holds the end-cigarette warning signal active for 30 seconds. In this time interval, the LED performs a series of three flashes, as it can be seen from the channel D curve (lower curve) in Figure **9**.

In Figures **10** and **11** are shown the waveforms coming from simulations when the shots are less than ten but it elapses a time equal to three minutes starting from the first inhalation by the user (criterium of the end-cigarette control based on the time interval the cigarette is in the “on” mode).

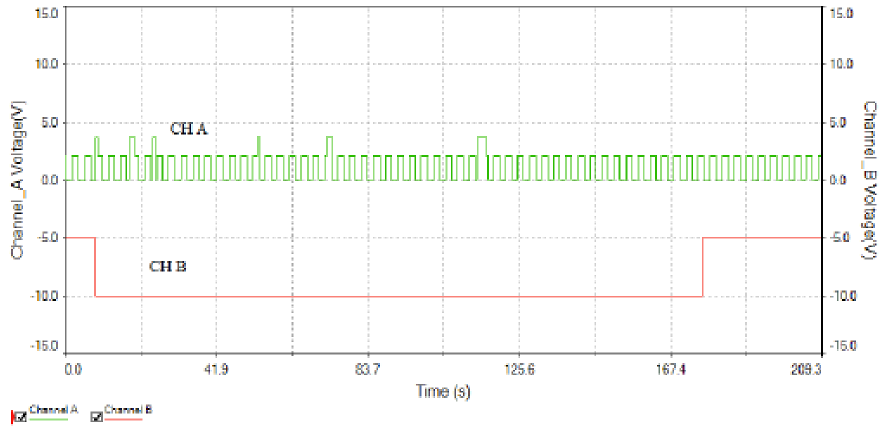

Figure 10: Simulated waveforms of the channels A and B during the end-cigarette control warning, due to the time elapsed from the first inhalation.

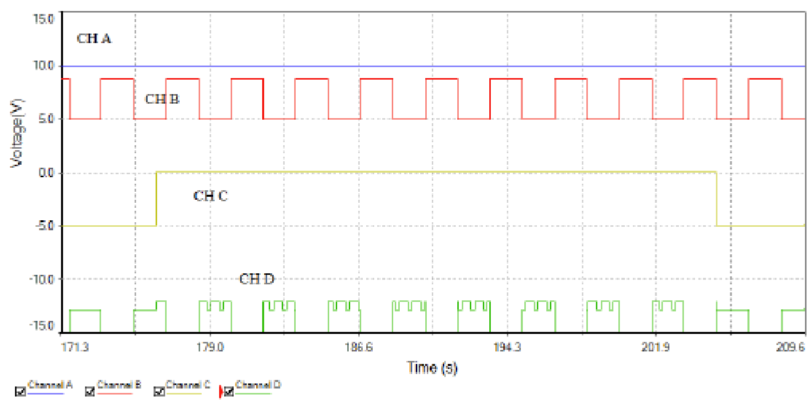

Figure 11: Other simulated waveforms of the channels A, B, C, D during the end-cigarette control warning, due to the time elapsed from th first inhalation.

In detail, in Figure **10** the channels A, B, C, D are the same as in Figure **9**, and in Figure **11** the channel A is connected to the voltage-driven switch, S2, that simulates the inhalations/shots by the user, and the channel B is connected to the Q output of the SR Latch1.

When the first shot occurs(see the channel A curve, at the top of Figure **10**) the output of the SR Latch1 enables the counter U3 (that counts the time elapsed from the first inhalation by the user), as can be seen from channel B (lower) curve in Figure **10**.

Then, other shots are carried out in the simulation, and after a time interval of three minutes, the end-cigarette control is enabled bringing the output Q' of the SR latch1 at a high logic level and disabling the counter U3, as it is possible to observe from the (lower) channel B curve of Figure **10**.

As can be seen in Figure **11**,in this situation the Q output of the SR latch2 switches to a low logic value, as it can be seen from the channel C curve (the second curve counting from down), thus allowing to activate the asynchronous counter U4, which maintains active the warning signal of end-cigarette for about thirty seconds. In this time of thirty seconds,the LED performs three flashes for notifying purposes, as can be seen from the channel D (lower curve) in Figure **11**.

6. CONCLUSION

In this paper it has been discussed about the fine control of the nicotine inhaled by a user with the digital smoke, using the electronic cigarette. Moreover, two criteria have been presented in order to notify the end-cigarette condition to the user and thus obtaining a fine control of the inhaled nicotine.

The criteria aim at determine and notify to the user, in a session of digital smoking, the condition in which the user has inhaled the same nicotine as by smoking a traditional cigarette.

Moreover, logic and circuit models have been presented, implementing the end-cigarette control.

Finally, the simulation results validate the logic model of the end-cigarette control, thus making the model useful in order to optimize the design of the e-cig with a fine control of the inhaled nicotine.

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