



Design, fabrication, and testing of an electronic device for the automatic control of electrochromic windows



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ABSTRACT

In this study, an electronic apparatus for transmittance control of electrochromic windows is presented. The system is based on a microcontroller that, combined with a suitable interface, allows the user to choose among different operating modes. In addition, either voltage or current control can be performed, counting six different modes in total. Silicon photodiodes are used for sensing both the incident radiation and the transmittance of the window. Furthermore, the electronic device can be re-programmed to perform different tasks, providing a versatile tool for real time testing of electrochromics in outdoor conditions. The proposed controller can be combined with different electrochromic devices, regardless of their fabrication method or size. To test the controller, an electrochromic prototype 10 cm by 10 cm was used as a load. The experimental set-up has been tested in real time outdoor conditions and the system stability was verified, regardless of fluctuations of the incident radiation, partial shading of the system and ion diffusion effects. For the electrochromic window tested, a transmittance change from 60% to 10% or vice versa lasts approximately 210 s with voltage control, while the same operation lasts 600 s with current control, as in that case, the applied current is limited to 2.5 mA.

1. Introduction

Heating, cooling and lighting of buildings require considerable amounts of energy and there is a global trend towards improving energy efficiency in the building sector. Of all building components, windows can be regarded as the weak link, since they allow heat losses to the environment and admit excessive solar irradiation. To rectify this situation, a large range of heat insulating windows have been developed and are commercially available [1]. However, seasonal and diurnal variations of weather conditions require dynamic control of the building heat load for optimum operation. To this end, smart windows, characterized by their ability to change their optical properties in response to external stimuli, have emerged in recent years. Their use may lead to reduced heating and cooling loads and, in some cases, to a reduced demand for electric lighting [1,2]. Electrochromic (EC thereafter) windows belong in the extended category of smart windows and have the potential to become the leader in fenestration industry. The advantages of EC windows and their superior performance compared to other similar technologies have been demonstrated over and over again, through modeling and experiment [3–7].

1.1. Generic electrochromic device design and equivalent circuit

In general, an EC device consists of two conductive glass pieces, one with an EC thin film, the other with an ion storage and/or protective film, laminated by an electrolyte (solid, liquid or gel), which usually contains Lithium ions (Li^+) [2]. Tungsten oxide (WO_3) is the most promising EC material, widely used in smart windows. The transmittance of WO_3 films can be altered by the intercalation/de-intercalation of small cations (H^+ , Li^+ , Na^+) into the film. The reversible EC effect in the case of tungsten oxide and Lithium ions can be expressed as a redox reaction [8]:



Given the aforementioned structure of an EC device, it is concluded that all the individual layers should be considered when designing an equivalent circuit. Thus, the structure and the equivalent circuit of a small EC device are presented in Fig. 1.

The transparent conducting electrodes and the ionically conducting electrolyte are modeled as resistances, while the working electrode (EC layer) and the counter electrode (ion storage layer) as impedances. Those impedances are diffusion controlled, since they are both functions of the charge state and are described by the Randles equivalent

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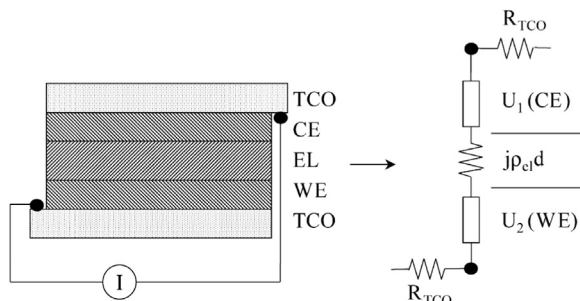


Fig. 1. Structure and equivalent circuit of a small EC device, where TCO is the transparent conducting oxide, WE is the working electrode, CE is the counter electrode, and EL is the electrolyte [9].

circuit (parallel combination of a capacitance and an impedance of a faradaic reaction) [9,10]. In addition, a voltage-dependent capacitor was utilized to represent the impedance due to the EC processes. This capacitor has a charge dependence on voltage fitted to the response of a small EC device.

Therefore, the applied control strategy should be adapted to the aforementioned equivalent circuit of the load in order to design a robust and reliable system. More precisely, the instantaneous current of the device will be connected with the instantaneous rate of the voltage change over time. Therefore, the greater the rate of the voltage change over time the higher the current from the supply to the EC device is. However, high currents through an EC device could reduce its life expectancy and, thus, they should be regulated.

1.2. Control systems and strategies for EC windows - state of the art

As already mentioned, the operation of a building is connected with the demand for cooling, heating and electric lighting, while the integration of EC windows aims to reduce the total energy consumption and improve the indoor visual quality. Even though some recent publications [1,11] summarize the main characteristics of the commercially-available EC windows, they lack details about the characteristics of the control system used by the manufacturers, as they are proprietary items [2]. Nevertheless, in Ref. [12,13] commercial EC windows were used along with the controllers supplied by the manufacturer for extended field test to assess the performance of both the window and the controller.

In the past, two prototypes for automatic control of EC windows were presented in Ref. [14,15]. Both electronic control systems consisted of a general-purpose microcontroller, the user interface, light sensors and an unknown drive circuit for the EC device. The authors did not describe the control systems in detail, since their aim was to assess the performance of the EC device. To the best of our knowledge, there are no more published papers on the subject.

In Ref. [14], the performance of a test cell was evaluated in simulated “real working conditions” using a filament lamp as radiation source, while photodiodes, sensitive to the red part of the spectrum, were utilized to measure the transmittance of the cell. In Ref. [15], a test-cell was equipped with a number of sensors and was evaluated under real weather conditions. In contrast to the previous reference, the light sensors had a spectral response curve adapted to the human eye sensitivity. The system could operate in manual and automatic mode, implementing both static and dynamic control strategies.

In buildings, large area EC windows must satisfy specific performance indicators, with regard to their electrical, thermal and optical properties, to accomplish the benefits of energy efficiency and indoor comfort. These indicators have been identified in Ref. [16] along with their desirable values. However, the performance and energetic benefits of an EC window in a real situation depend to a large extent on the operation strategy of the device [17]. This is clearly illustrated in the simulation results of [18,19], where it is demonstrated that an

advanced control strategy, based on the occupant presence, could enhance the advantages of EC windows.

It is therefore of paramount importance for researchers to possess a versatile tool, able to perform various control strategies for the experimental evaluation of EC windows of different properties [2].

1.3. Proposed control system for electrochromic windows

The present paper aims to cover the aforementioned void in knowledge and, thus, a laboratory prototype for both static and dynamic control of EC windows is presented. Both the circuit synthesis of the electronic device and the implemented control strategies are described with adequate detail, so that the system can be reproduced for research purposes. Nevertheless, the device can be re-programmed to perform different tasks, according to the users' needs.

Contrary to other studies, the main goal of this work was the evaluation of the EC response with regards to the proposed control system. To that end, preliminary experiments of the fabricated electronic device, driving an EC window prototype, were carried out under real time outdoor conditions. Additional experimental results are required to evaluate the response, the lifetime, and the durability of the EC window in real functioning conditions under the proposed control scheme. However, this approach is out of the scope of the current work and will be considered in a forthcoming publication in order the proposed controller to be compared with other static and dynamic controllers. Nevertheless, from the evaluation of the preliminary results it was concluded that the system can automatically adjust the transmittance of the EC window at the desired level within the range of fully colored to fully bleached state.

2. System overview

2.1. Electrochromic window

An EC window prototype fabricated in the Renewable Energy and Environment Laboratory of the Department of Physics, University of Patras, has been used as load. The prototype consists of five layers, namely Glass/SnO₂:F/WO₃/1 M LiClO₄-PC-PMMA/SnO₂: F/Glass. As substrates, 10 cm by 10 cm pieces of a commercial SnO₂: F coated glass (trade name K-Glass) have been used. K-Glass is produced by spray pyrolysis with a thickness of 200–500 nm [20]. Tungsten oxide thin films 550 nm thick were prepared by electron beam gun deposition at room temperature. The gel electrolyte consists of Poly-methyl-methacrylate (PMMA, MW: 120.000) dissolved in a solution of 1 M LiClO₄ in propylene carbonate (PC). The resulting gel had a 18% w/w concentration in PMMA.

The fabricated films and electrolyte were incorporated into EC devices as follows: The EC WO₃/SnO₂:F/Glass sheet and the SnO₂:F/Glass piece were arranged facing each other. They were sealed peripherally by a thermoplastic material (PV 5414, Dupont, with thickness 0.5 mm), that also served as a spacer. The electrolyte was poured into the device with the use of two small holes, 1 mm in diameter each, drilled close to the edges of the SnO₂:F/Glass sheet prior to the device assembly. A detailed account of the materials and the device fabrication is presented in Ref. [21], together with transmittance spectra for the coloration and bleaching of the EC device and the corresponding photographs.

2.2. Electronic controller

2.2.1. Basic design principles

The basic principles of the designing process were the implementation of a low cost, portable and robust electronic device to automatically control the transmittance of an EC window. Thus, previously performed coloration and bleaching experiments with laboratory equipment [21,22] were used to assess the response of the EC window prototype and to determine the hardware requirements. In

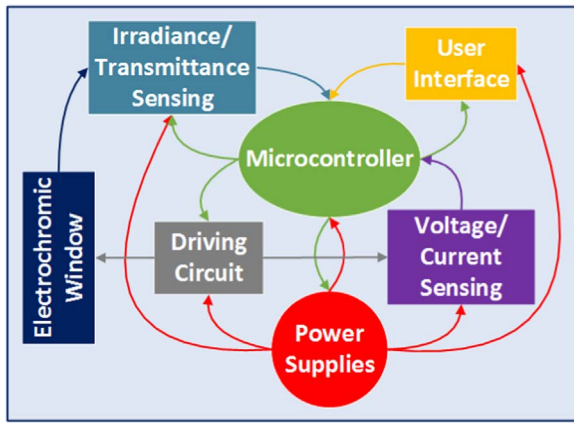


Fig. 2. Block diagram of the system.

addition, the majority of the selected elements for the electronic device were of such a small scale, that it was still possible to be soldered with typical hand equipment, and consequently the size of the electronic device was reduced to 14.5 cm by 15 cm. A simplified block diagram of the designed system is given in Fig. 2.

2.2.2. Microcontroller

The operation of the electronic device was based on a general-purpose microcontroller to administrate all the input and output signals and eventually to control the transmittance of the EC window. The STM32L151RBT6 was selected for this purpose, which belonged to the family STM32L15xxx of ARM Cortex-M3 microcontrollers characterized by low power consumption, and was programmed in C.

2.2.3. Driving circuit

The dynamic behavior of an EC window could be achieved by controlling both the amplitude and the polarity of the applied voltage, while typical values, as recorded in the literature, were 3–5 V DC [2,22]. However, the amplitude of the current was another crucial parameter, which had to be taken into account during the switching processes, in order to achieve a long-term cycling durability. Given the aforementioned restrictions, a DC-DC converter with a full bridge topology combined with a variable output power supply was considered as a suitable and efficient topology to automatically control the transmittance of an EC window.

The aforementioned DC-DC converter allows the reversal of the polarity across the load and the control of the average output voltage, which make it suitable for many applications. In addition, this converter combines small volume, low weight and cost, high efficiency and requires minimal maintenance [23]. Such an ideal DC-DC converter consists of two branches, each of which has two switches with an anti-parallel diode connected to them, as it is shown in Fig. 3.

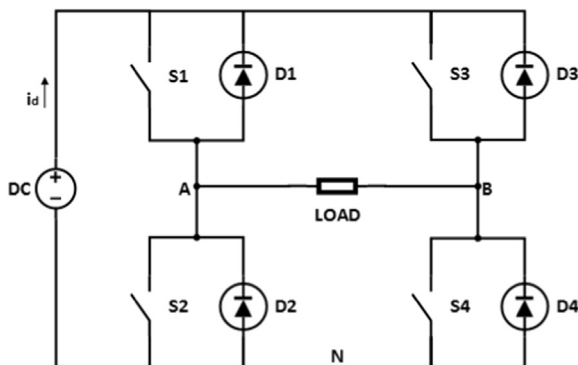


Fig. 3. Ideal DC-DC converter with full bridge topology.

The forward bias of the load is implemented by actuating the switch pair S1 & S4, while the pair S2 & S3 is connected with the reverse bias of the load. More precisely, when S1 is closed and S2 open, the voltage between terminals A and N is equal to the voltage of the input source. In the other case, when switch S1 is open and S2 closed, the voltage between terminals A and N is zero. Likewise, the same principles apply to the second branch and terminal B. Therefore, the state of the switches affects the output voltage of the converter, which is equal to the differential voltage V_{AB} .

However, a real converter consists of semiconductor switches, which are controlled by an appropriate driving circuit to change their state from open-circuit to short-circuit. Using the Pulse Width Modulation technique (PWM), the average output voltage can be controlled. Consequently, the voltage difference between terminals A and N, and V_{BN} correspondingly, derives from the following equation.

$$V_{AN} = \frac{V_{in} t_{on} + 0 \cdot t_{off}}{t_{on} + t_{off}} = \frac{t_{on}}{T} V_{in} \quad (2)$$

Nevertheless, during the implementation of the PWM technique the amplitude of the instantaneous output voltage remains as high as the input voltage of the DC-DC converter and, given the characteristics of the load, high current spikes could be measured. Therefore, it was preferred to combine the converter with a controlled voltage source as input. This dynamic topology enabled the control of the amplitude, the polarity and the width of the pulses of the output voltage.

One drawback of the DC-DC converter was the minimum required supply voltage. Therefore, the monolithic digital IC LB1930MC-AH was selected, since it combined a wide operating low voltage range, low cost and small scale. In addition, the logic, the power circuit and a built-in thermal protection circuit were included in the package. Due to the open circuit memory of the EC device, a considerable voltage exists across its terminals in any coloration state. Thus, the EC device should be isolated from the rest of the circuit, when the latter is unenergized, for reliability issues. The isolation was achieved by utilizing a low power relay.

Small scale EC windows require ultra-low supply voltages, since it is of the utmost importance to maintain the current as low as possible. Due to the low power demands of such a case, a current regulator was used in an alternative driving circuit for the EC device. In contrast to the DC-DC converter, which operated as a variable output voltage source, the current regulator operated as a direct current source of predefined amplitude at 2.5 mA. Through a set of DPDT (Double Pole Double Throw) relays, the terminals of the window were automatically transferred from one driving circuit to the other, changing also the polarity, if this was necessary. In addition, current pulses of pre-determined amplitude but variable width could be applied to the EC device, since a semiconductor switch was utilized in this circuit.

Another advantage of this low power current source is that it could be used for the regeneration of the EC device. In [24] it was demonstrated that ion-trapping-induced degradation, which is commonly believed to be irreversible, can be successfully eliminated by constant-current-driven de-trapping. To this aim, WO_3 films degraded by continuous coloration-bleaching cycling could be forced to return to their original state by current loading at $1 \times 10^{-5} \text{ A cm}^{-2}$ for 20 h. Therefore, the application of a “regeneration” current through the devices, during night hours, could prevent their degradation in the long term.

2.2.4. Power supply

The proposed system was supplied from the electric grid and a linear power supply was preferred so as to reduce the implementation cost. The designed power supply had multiple outputs, such as two fixed and one adjustable voltage output combined with a fixed current output. The adjustable output voltage was controlled by the digital to analogue peripheral (DAC) of the microcontroller and a circuit of operational amplifiers. Thus, the output voltage could be adjusted at any

value within a predetermined range, which was selected by considering the hardware limitations and the properties of the EC device.

2.2.5. Voltage and current sensing

The voltage and current measurement was achieved by amplifying the voltage difference across two points, where those points were either the terminals of the EC window or of a sensing resistor. For this purpose, the instrumentation amplifier MCP6N16-100E/MS was selected. Sensors based on the Hall effect were not used due to their high cost, the low values of the measured quantities and the non-isolated driving circuit from the circuit of the microcontroller.

2.2.6. Irradiance and transmittance sensors

In order to automatically adjust the transmittance of the window in a wide range of fully bleached to fully colored state, the use of suitable sensors was inevitable, since no equivalent model was taken into account to predict the optical behavior of the window. The connection between the physical and the control system was achieved through light sensors and silicon photodiodes were selected.

Photodiodes are sensors which produce voltage or current as an output, when the p-n junction is irradiated. Key features of those sensors are the linearity to the incident light, the large bandwidth, the low volume and weight as well as their robustness and long-life. However, their dark current is a crucial parameter in light measuring applications [25].

Since there was no need for incredibly fast response but there was an indispensable need for negligible error at low light conditions, it was chosen to use the photodiodes in photovoltaic mode (unbiased). In addition, a linear response of the output signal of the sensor was desired. Thus, photodiodes were combined with a transimpedance amplifier to convert the short-circuit current of the sensor to an analogue voltage. As it can be seen in Fig. 4, one terminal of the selected feedback resistor is on a virtual ground potential and the measured voltage at the other terminal is equal to the short-circuit current of the sensor multiplied by the value of the feedback resistor. The selection of the operational amplifier is a crucial parameter and high precision operational amplifiers are suitable for this application [25].

Since the system should be able to operate in both high and low light conditions, the implementation of programmable gains in the photodiodes circuits was mandatory. Using different resistors combined with an analogue switch or a resistor with programmable value, the maximum operation range could be achieved. The second analogue switch, shown in Fig. 4, was utilized to eliminate the error due to the ON-state resistance of the first one. Consequently, the output voltage was measured at the terminal of the selected resistor and not at the output terminal of the operational amplifier [25].

The VTB8440BH photodiodes were selected since they incorporated an infrared rejection filter and their spectral range was of 330–720 nm, with the peak of the spectral response at 580 nm. Consequently, those sensors simulated the human eye and were suitable for the implementation of a daylight control strategy. Using a Kipp & Zonen CM6b

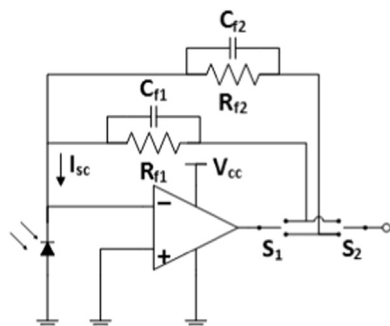


Fig. 4. Transimpedance amplifier with programmable gains.

pyranometer, the short-circuit current of the photodiodes was calibrated against the incident solar irradiance. As expected, a linear relation was observed. The low cost but high precision operational amplifier MCP6032-E/SN was combined with the analogue switch TS3A44159PWR to convert the short-circuit current of the photodiodes to an analogue voltage and also to achieve an extended operation range according to the incident radiation level. Due to reliability issues, when the circuit is unenergized, the photodiodes were isolated from the remaining circuit by a low power relay.

2.2.7. User interface

The controller must communicate with the user of the system; therefore, a suitable interface was designed. This interface included switches, buttons and LEDs. With the implemented interface the user could choose between the different operating modes, but also could be informed about the state of the system.

2.3. Experimental prototype

At this point, it is worthwhile to mention that the proposed prototype did not operate only with a specific EC window. Since the window was treated as a “black box”, the controller could be used with any available EC window with some minimum software adaptations, if necessary. The aforementioned peripheral circuits are presented in Fig. 5, a and b, where the top and the bottom view of the proposed controller are illustrated, respectively.

As already mentioned, both the incident radiation and the transmittance of the EC window were estimated from the signals of the photodiodes. More precisely, for the estimation of the transmittance two different approaches were used, which were evaluated under real time outdoor conditions, so that the most suitable and reliable approach could be identified.

In the first case, two sensors, one on the external surface and one adjacent to the internal surface of the window, located as close as possible, were utilized to sense the transmittance of the EC window. This approach was based on the incident solar irradiation on both the sensors and, consequently, the external photodiode was also utilized for the estimation of the incident radiation. As for the transmittance of the window, it was estimated by the rate of the output signals of the sensors:

$$T = \frac{I_{sc}^{internal}}{I_{sc}^{external}} * 100\% \quad (3)$$

where T is the estimated transmittance, $I_{sc}^{internal}$ and $I_{sc}^{external}$ are the short-circuit currents of the internal and external photodiode, respectively.

The other case was independent from the solar radiation, since a second internal photodiode was irradiated only by a LED of fixed and known luminous intensity. The LED and the photodiode were placed on either side of the EC window and more precisely at a permanently dark sector of the window (e.g. in the frame) in order to minimize the error caused by the diffuse solar irradiance. Thus, the sensor output was directly related to the transmittance of the EC window. Moreover, the output of the sensor circuit was calibrated according to the transmittance of the EC window at 550 nm (peak of the human eye sensitivity), measured by a Perkin-Elmer Lambda 650 UV/Vis spectrophotometer at different coloration states in the range of fully bleached to fully colored. The final form of the experimental set-up is presented in Fig. 6, where the test-cell, with the EC window and the light sensors, as well as the electronic controller are shown.

3. Control strategy

The implemented control strategy is analyzed by presenting the flow charts of the most important functions. In general, the system was able to operate in three different modes, namely a constant internal daylight

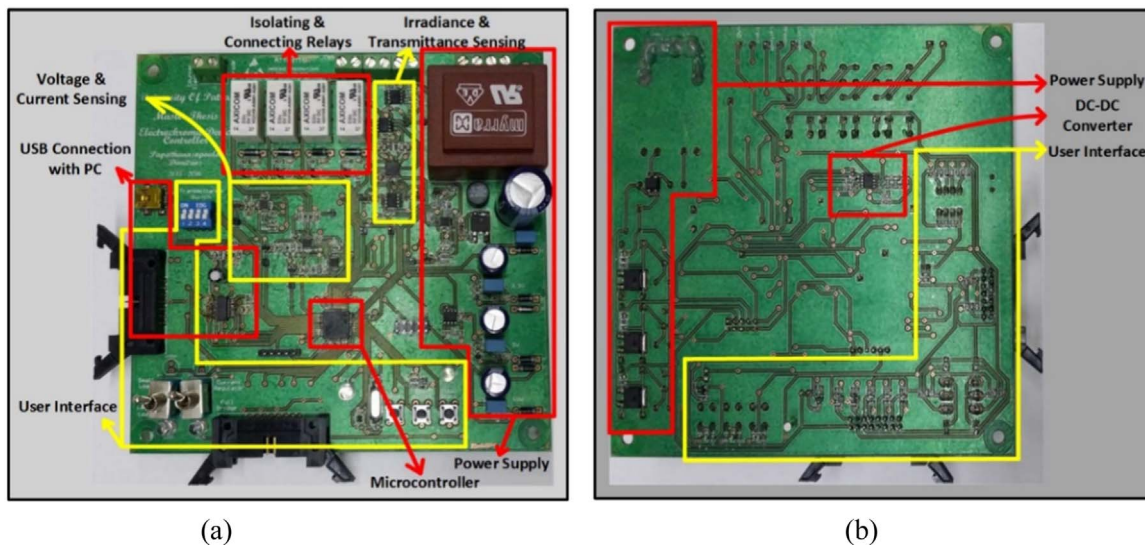


Fig. 5. Top (a) and bottom (b) view of the controller.



Fig. 6. Experimental set-up with the test-cell and the controller, where (1) is the external light sensor, (2) is the internal light sensor and (3) is the LED with the second internal sensor (covered during operation).

mode, a constant transmittance one and a manual mode. At each one of those modes, different functions could be performed based on the control technique and the scale of the load combined with protection functions, such as those analyzed below.

3.1. Functions to extend the life expectancy of the EC window

The control system should be characterized by a predefined inertia, since the continuous change of the optical properties of the EC window might reduce its life expectancy. Therefore, an idle period was implemented every time the desired transmittance was achieved. Moreover, a new process could be enabled only if the difference between the actual and the desired transmittance was greater than 1% in absolute value. The idle period combined with the transmittance tolerance were necessary to allow some time for the “relaxation” of the EC window and to permit the even distribution of lithium ions within WO_3 .

It is well known [2,22], that Li ions diffuse rather slowly within the matrix of tungsten oxide, with diffusion coefficients in the order of $10^{-11} \text{ cm}^2/\text{s}$. Thus, during a fast coloration process, a considerable ion concentration gradient occurs along the depth of the film. Furthermore, random deviations in the conductive oxide electrical resistance affect the applied electric field and give rise to uneven coloration across the

surface of the window, with darker and brighter spots. Once the coloration process ceases and the device remains in open circuit, these non-uniformities are evened out by diffusion of Li ions. This phenomenon (to be called “ion diffusion effect” thereafter) manifests itself as a gradual change in the open circuit voltage of the device (see for example Figs. 11, 12, 14). Similar effects (in the reverse order) appear during bleaching.

Since the transmittance of the EC device is altered during ion diffusion effect, the controller will continuously try to rectify that change. The one-minute delay was found appropriate (by trial and error) in order to achieve a stable operation, according to the measured transmittance, and a uniform appearance of the window. It should be noted that for large area EC windows higher delay times may be required and, thus, appropriate adjustments to the control parameters may be needed.

Extra care was needed at real time outdoor conditions, due to the fluctuation of the incident radiation. Thus, the average value of the incident radiation, during a period of one minute, was utilized. However, the time interval for the average radiation calculation can be altered according to the desired inertia of the system. At the beginning of each idle period, the calculation of the average radiation was re-started. An updated value of the average radiation was indispensable at the end of the idle period, since at this instant the type of the new process had to be decided.

3.2. Constant internal daylight mode

In constant internal daylight mode, the signals of the light sensors were combined in order to achieve a fully automated process. As illustrated in the flow chart of Fig. 7, the appropriate transmittance of the EC window was defined in accordance with the radiation level.

Given the radiation level on the external sensor, the desired transmittance was automatically calculated by the microcontroller, since at this mode the goal was to maintain the incident radiation on the internal sensor at a predetermined level. The target value was selected at 200 W/m^2 , similar to the one used in Ref. [19], but can easily be varied to any other value. For the protection of the window due to possible construction restrictions, if the radiation level, measured at the external photodiode, was lower than 330 W/m^2 then the desired transmittance was kept constant at 60% and, consequently, the window was maintained at a bleached state.

For the implementation of this mode at least two light sensors are required, since both the incident radiation and the transmittance of the window have to be measured. However, this set-up does not always ensure constant irradiation within a room, as it does not account for the

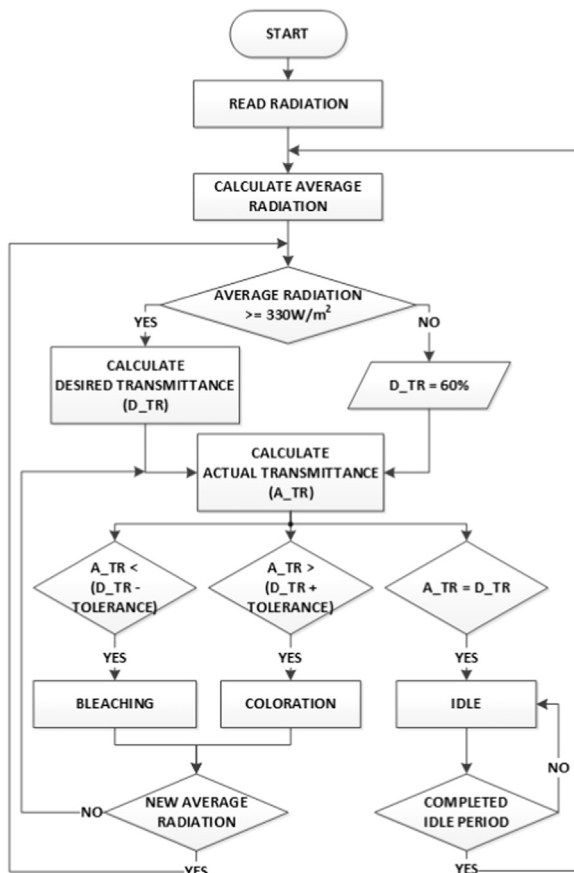


Fig. 7. Flow chart of constant internal daylight mode.

solar height and for shading or reflection effects. For a better result, additional sensors could be mounted at different positions of the room in order to measure internal daylighting and to assess its uniformity. However, given the small size of the test-cell, this approach was not considered necessary for the preliminary implementation and evaluation of the proposed control system. As for large scale experimental setups, the incorporation of additional sensors, such as luxmeters or video luminance meters, is mandatory for a reliable estimation of the desired constant internal daylighting.

3.3. Constant transmittance mode

Even though constant transmittance mode is based on the occupant's visual comfort to determine the desired transmittance, this mode can be still characterized as an automated mode, since the light sensors are used to measure the actual transmittance and the microcontroller to determine the type of the process and its completion. Therefore, the user had only to choose among the eight different available states, in the range of 10–60%, regardless of the incident radiation level. The implementation of the programmable gains at the photodiode circuits was mandatory in that mode, since the user might desire to alter the state of the window in low light conditions. In this case, the short-circuit currents of the light sensors, connected with the solar radiation, would be extremely low and, consequently, special treatment had to be taken. The flow chart of the constant transmittance mode is illustrated in Fig. 8.

3.4. Manual mode

In the manual mode, the incident radiation and the transmittance of the window were still measured, but did not affect the whole process, since this mode was completely based on the user's will. As illustrated in Fig. 9, the manual mode could be activated through an override switch

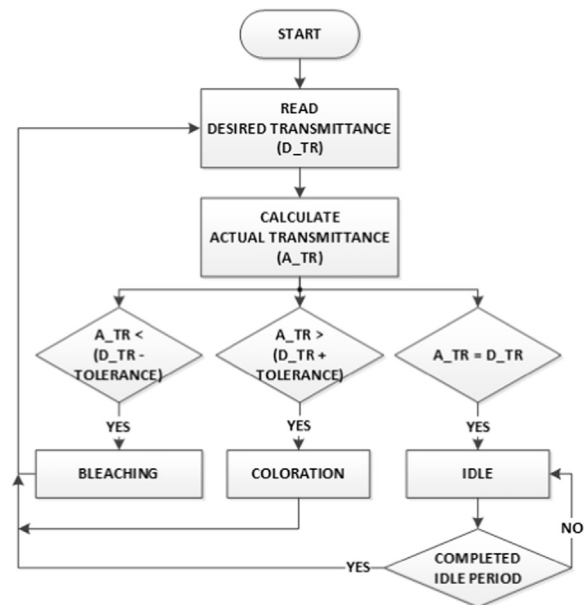


Fig. 8. Flow chart of constant transmittance mode.

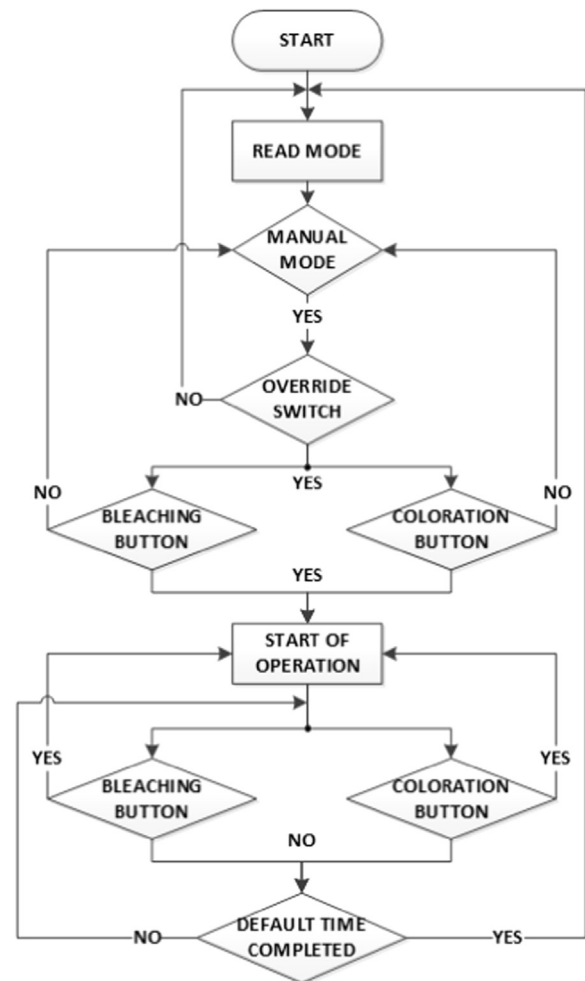


Fig. 9. Flow chart of manual mode.

and then by pressing the bleaching or coloration button. The manual process was automatically completed after a period of one minute, in order to protect the window from overuse due to user's negligence. In case the user would desire an operation time for more than one minute,

he had to press the corresponding button again. Consequently, the process would start over for one more minute, regardless of whether an operation was already in progress or not.

3.5. Voltage or current control

In each one of the aforementioned modes, the user could choose between constant voltage or current control. The voltage control was connected with the DC-DC converter and the adjustable voltage output of the power supply. This voltage output was determined in correspondence with a current threshold, which was a parameter of the software and was based on the scale of the load. Therefore, there were two values of the current threshold determined at 4 mA and 20 mA for the small and the large-scale load, representing a 10 cm by 10 cm and a 40 cm by 40 cm EC prototype respectively, but can easily be set at any other value. When an operation was in progress and the measured current was measured below the current threshold value, then the voltage was increased, based on predetermined steps, in the range of 1.5–5 V. In case the next process was the opposite of the previous one (bleaching-coloration), the voltage level was restarted and the new process started with the lowest voltage, to protect the EC window from relative high currents. If current control was chosen, the load would be automatically connected to the current regulator circuit. In this case, there was no difference for the loads, since the output current was fixed at 2.5 mA and its amplitude could be altered only by changing the hardware characteristics. However, changing the pulse width, it was possible to change the average value of the current flowing through the EC device and also to achieve small relaxation periods, enabling the ion diffusion effect to be performed. The flow chart of the two possible control techniques is presented in Fig. 10.

4. Experimental results

The designed system was evaluated in real time outdoor conditions and the preliminary experimental results of the two automated modes for both constant current and voltage control are presented in the following. The protection of the EC window from excessive use was achieved by the idle period, the transmittance tolerance, and the average radiation.

The fluctuations of the incident radiation were compensated by the software implementation of the average incident radiation over a time interval of one minute. At the initialization stage, the average radiation equaled the instantaneous one, since there were no available previous data. Thus, the instantaneous radiation level compared to the average radiation of the previous minute are illustrated in each of the following figures.

In addition, the two different approaches for the estimation of the transmittance of the EC window are presented to identify the most reliable approach. The variable “Transmittance – Case 1” refers to the case with the two light sensors (external and internal) and Eq. (3), while the variable “Transmittance – Case 2” refers to the light sensor irradiated only by the LED. The latter approach was selected during the presented outdoor experiments and, consequently, the variable “Control Transmittance” equals the variable “Transmittance – Case 2” during an ongoing process. When the desired transmittance, determined by the selected mode, is achieved, then the “Control Transmittance” equals the “Desired Transmittance”, during the idle period of one minute, for the implementation of the control. In that time interval, the actual transmittance (either case 1 or 2) can be compared to the transmittance considered by the software and the error to be evaluated.

Moreover, the time intervals of the ongoing processes and the idle periods are also presented for clarification purposes. However, the variables “Ongoing Process” and “Idle Period” are not always complementary. When they are both equal to zero, the controller is in standby mode, since there is no need for a new process, either due to the available transmittance tolerance or an unchanged radiation level.

Finally, based on the circuit of the DC-DC converter, which is presented in Fig. 3, the anode (WO₃ film) and the cathode of the EC device were connected to the terminals A and B, respectively. This

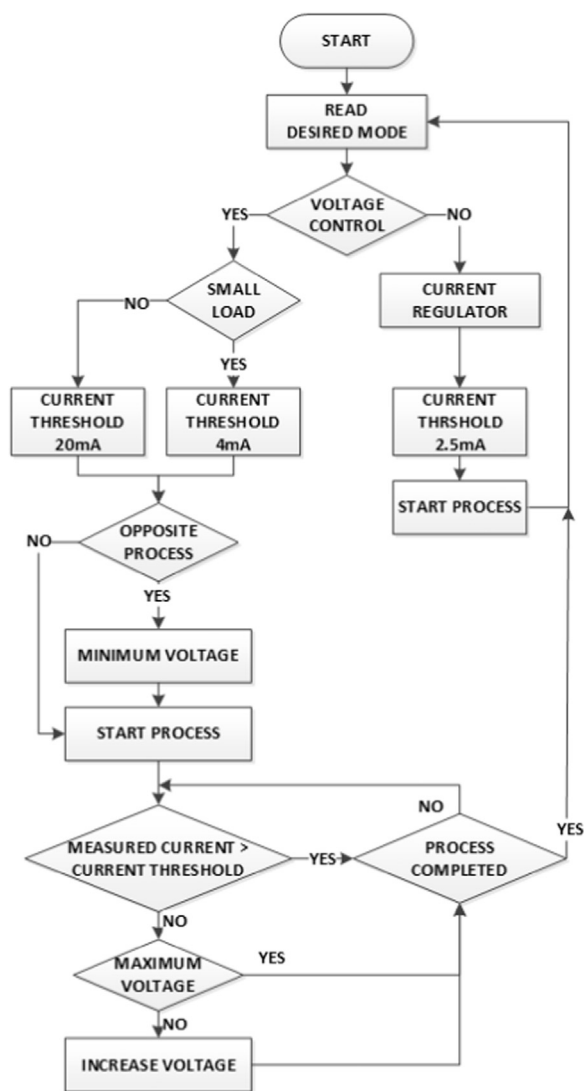


Fig. 10. Flow chart of voltage and current control.

configuration was also related with Eq. (1). Therefore, the reverse bias of the EC device and the coloration process is achieved by the activation of the switch pair S2 & S3. Accordingly, the forward bias of the load (switch pair S1 & S4) causes the de-intercalation of the cations from the WO₃ film and the bleaching of the EC device. As a consequence, the negative measured currents are related to a coloration process, while the positive currents are related to a bleaching process.

The operation of the system under the constant internal daylight mode and constant current control is presented in Fig. 11. Considering the average radiation level for the control implementation, the system is immune to abrupt changes of the radiation and, consequently, a smoother transition and fewer changes of the desired transmittance are observed. At this point, it is worthwhile to mention that there is a difference between the two measured values of the actual transmittance of the EC window. The first approach is prone to unequal radiation levels on the two sensors, given their distance and the constant diffuse and reflected radiation levels. Moreover, the sensors could be unequally shaded by an obstacle resulting to a higher or lower estimation of the actual transmittance. Thus, it was inevitable that the measured transmittance of the first approach was prone to errors. In the contrary, the second approach was independent from the solar radiation and was not affected by light fluctuations or shading issues. The reliability of the latter approach can be verified by observing the negligible difference of the variables “Control Transmittance” and “Transmittance – Case 2” during the idle periods.

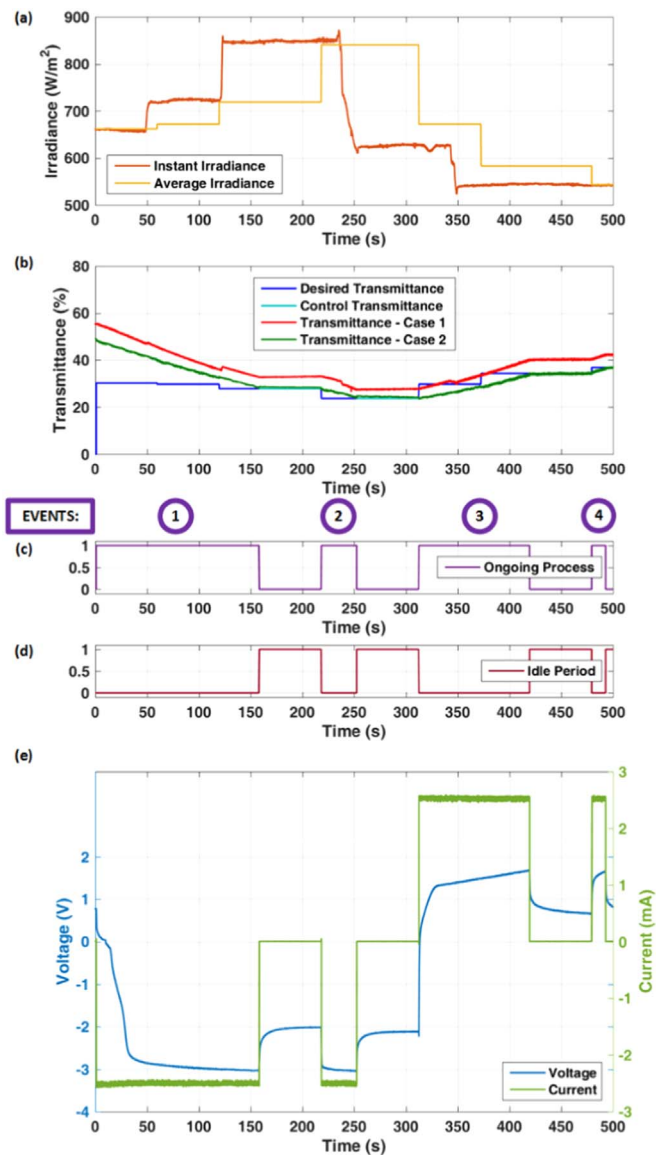


Fig. 11. Time dependent operation of the system under constant internal daylight mode and current control. (a) Instantaneous radiation compared to the average radiation of the previous minute. (b) Desired transmittance compared to actual one - Two different approaches. (c) Ongoing process indicator - Coloration: Events 1,2. Bleaching: Events 3,4. (d) Idle period indicator. (e) Voltage and current characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A relative high radiation level can be observed in Fig. 11 and, consequently, a coloration process was performed (event 1) to satisfy the constant internal daylight. During the first event the desired transmittance changed twice due to the increasing radiation level. After the completion of the first idle period, a second coloration process of smaller duration is observed (event 2). The events 3 and 4 relate to a bleaching process, since the measured irradiance was decreased. Even though the polarity of the applied current was changed between the events 2 and 3, its amplitude remained constant due to the selected control technique. The EC device was open circuited during each idle period and the ion diffusion effect can be observed from the time dependence of the open circuit voltage of the EC device, since it varies exponentially and converges asymptotically to a final value. This was the main reason for not using the instantaneous value of the V_{oc} to

estimate the transmittance of the window with “dead reckoning”, preferring instead the implementation of the light sensors.

The system operation under constant internal daylight mode and voltage control is presented in Fig. 12. Due to the increasing level of the average radiation, five coloration processes (events 1–5) of small durations are observed. The amplitude of the applied voltage at the first two events remained constant at the lowest predetermined value, while it was increased for the events 3–5 in order to maintain the current above the threshold value (4 mA). At the end of the fifth idle period the new desired transmittance was higher than the actual one, due to the decreased radiation level, and two bleaching processes are observed (events 6–7). Therefore, the applied voltage should be changed in both polarity and amplitude to force the de-intercalation of the cations from the WO_3 film and simultaneously to maintain the current as low as possible.

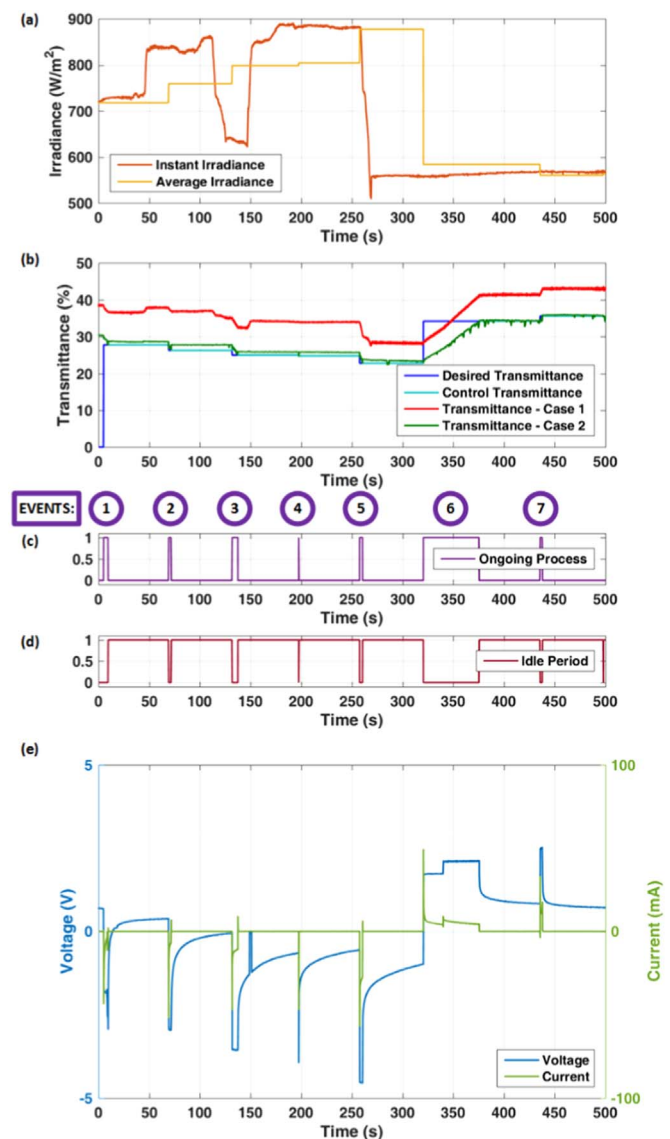


Fig. 12. Time dependent operation of the system under constant internal daylight mode and voltage control. (a) Instantaneous radiation compared to the average radiation of the previous minute. (b) Desired transmittance compared to actual one - Two different approaches. (c) Ongoing process indicator - Coloration: Events 1–5. Bleaching: Events 6,7. (d) Idle period indicator. (e) Voltage and current characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

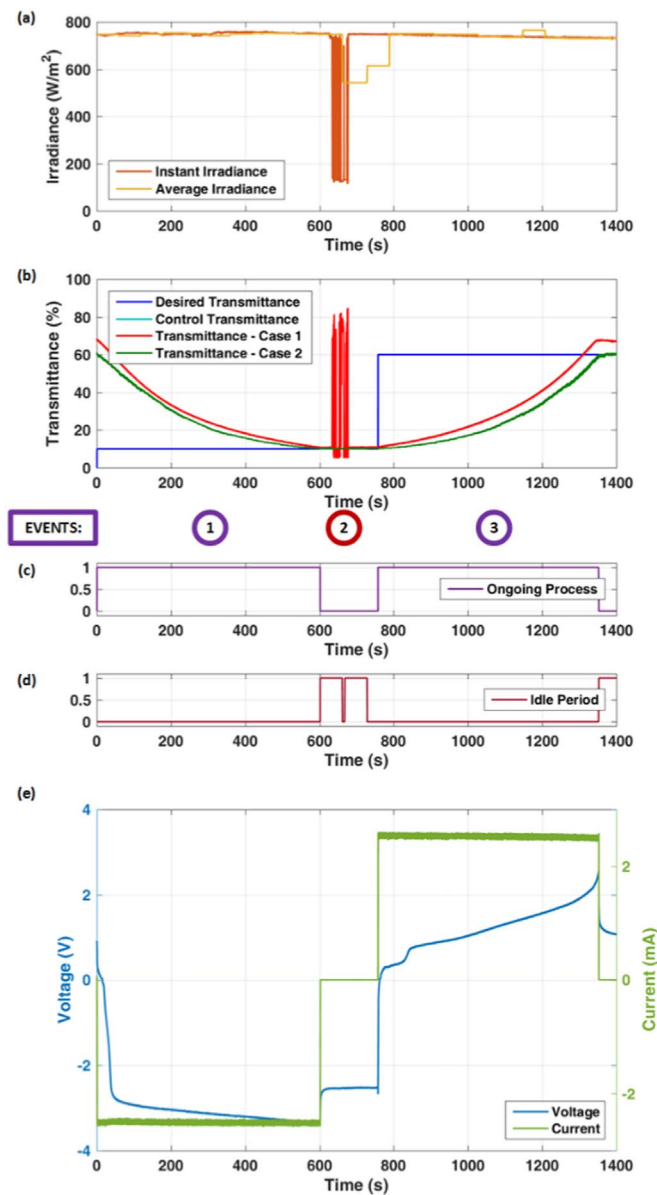


Fig. 13. Time dependent operation of the system under constant transmittance mode and current control. (a) Instantaneous radiation compared to the average radiation of the previous minute. (b) Desired transmittance compared to actual one – Two different approaches. (c) Ongoing process indicator – Coloration: Event 1. Bleaching: Event 2. (d) Idle period indicator – Forced idle period: Event 2. (e) Voltage and current characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The system operation in the range of fully bleached to fully colored state and vice versa is presented in Figs. 13 and 14 under constant transmittance mode and constant current or voltage control, respectively. Since the desired transmittance was based on the occupant's will, two different cases are presented. In Fig. 13 the incident radiation is high and the user demands a change from 60% to 10% and vice versa. The duration of the coloration process (event 1) was 601 s, while the bleaching process (event 3) lasted 595 s. During the idle period between the events 1 and 3, the measured irradiance had a high repeated ripple caused by the shading of the light sensor. The control system identified the error and forced a second idle period (event 2) to prevent the EC window from unnecessary change of its optical properties, until the fault was mitigated. In addition, it is verified that the first approach for the transmittance sensing is unreliable, while the second is immune to shading issues. Finally, the difference between the two approaches for

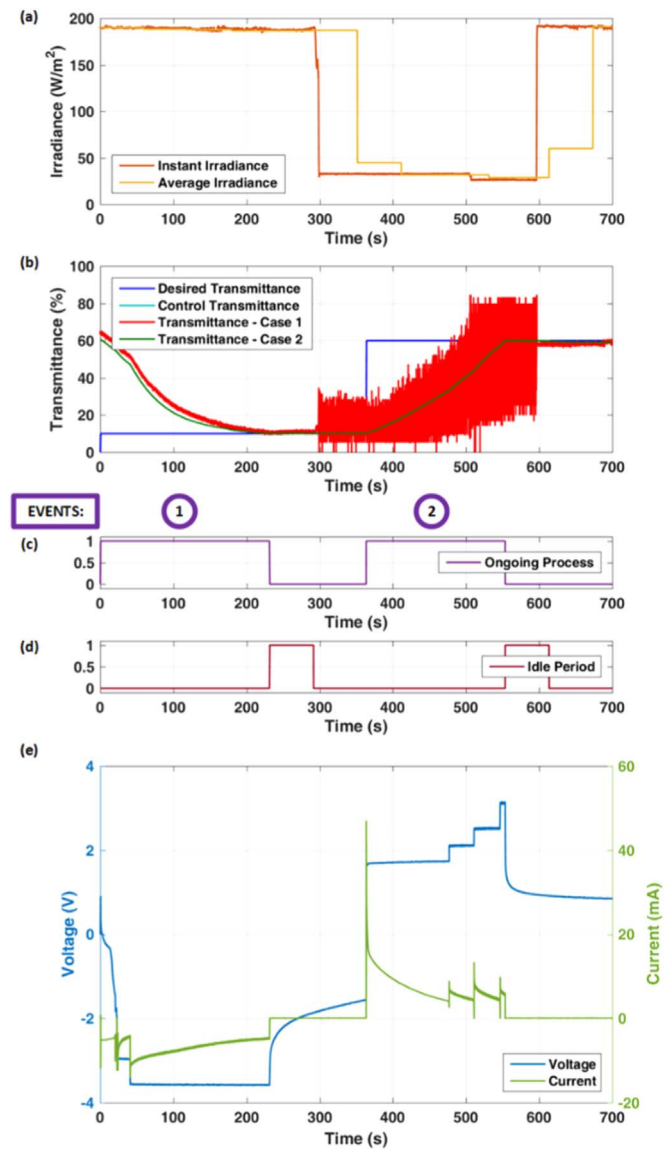


Fig. 14. Time dependent operation of the system under constant transmittance mode and voltage control. (a) Instantaneous radiation compared to the average radiation of the previous minute. (b) Desired transmittance compared to actual one – Two different approaches. (c) Ongoing process indicator – Coloration: Event 1. Bleaching: Event 2. (d) Idle period indicator. (e) Voltage and current characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the transmittance sensing decreases as the transmittance of the EC window decreases. In the case presented in Fig. 13 only the internal sensor output varies. Thus, the error relates to the internal sensor, its position and the total radiation level.

Contrary to the previous case, the operation of the system in both low and ultra-low light conditions is presented in Fig. 14. In low light conditions, both transmittance sensing techniques can be characterized as reliable. For ultra-low light conditions (e.g. irradiance < 50 W/m²) however, Case 1 suffers from significant noise (within the time interval of 300 s to 600 s in Fig. 14), while Case 2 is free of noise. Thus, the supremacy of the second approach is undeniable. Consequently, the system is able to operate in a wide range of the incident radiation, satisfying the user's will either for visual comfort or for privacy reasons.

In the case illustrated in Fig. 14, the change from 60% to 10% and vice versa was implemented under constant voltage control. The duration of the coloration process (event 1) was 230 s, while the bleaching process (event 2) lasted 190 s. Consequently, faster

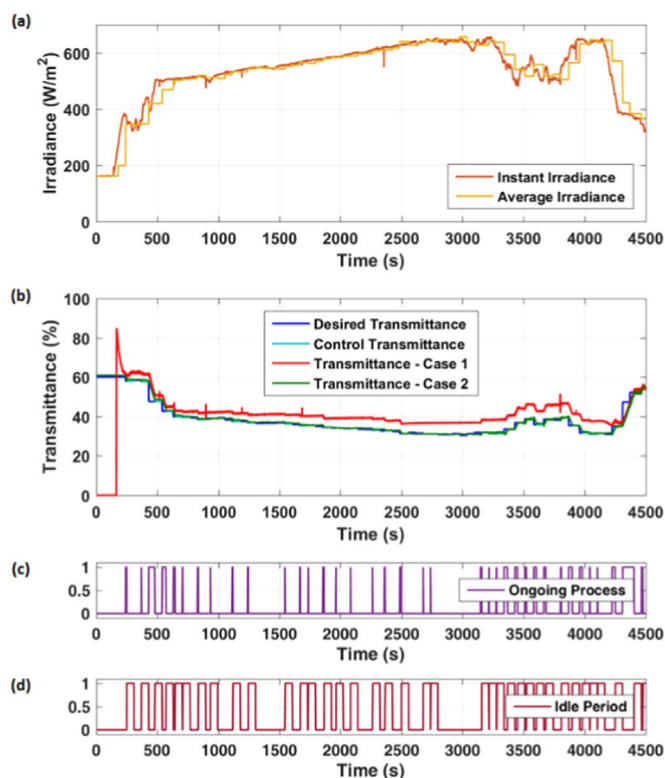


Fig. 15. Extended operation of the system under constant internal daylight mode and current control. (a) Instantaneous radiation compared to the average radiation of the previous minute. (b) Desired transmittance compared to actual one – Two different approaches. (c) Ongoing process indicator. (d) Idle period indicator. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adaptation to the desired transmittance can be achieved by the implementation of the constant voltage control, but the life expectancy of the EC window will be decreased, due to the high spike of the current at the change between a coloration and a bleaching process. Even though the applied voltage at the beginning of the second event was only 1.5 V (limited due to hardware restrictions of the DC-DC converter), the measured spike of the current was relative high. The high rate of the voltage change over time, related to the V_{OC} of the previous state, and the characteristics of the EC window are the main reasons of this current spike.

The response of the EC window and the controller, in real functioning conditions, was evaluated during an extended experiment under different sky distributions, which is presented in Fig. 15. The test-cell was placed at a permanent position taking advantage of the variations of the direct radiation level. Constant internal daylight mode and current control were selected, while both the implemented approaches for the estimation of the transmittance are also presented in Fig. 15. It is worth noting that, at the beginning of the experiment the first approach for the transmittance sensing could not estimate the actual transmittance to due unequal radiation levels on the light sensors.

The inertia of the system was evaluated from the preliminary experimental results. Thus, it was concluded that only in 10.6% of the total time a coloration or bleaching process was performed, while for the 48.45% of the time the system was forced into idle mode. Therefore, the remaining 40.95% of the experimental time the system was in standby mode, since there was no need to change the transmittance of the window. From the latter percentage, it is verified that the desired inertia of the system was achieved, since a new event was not occurred immediately after the end of the forced idle period. Consequently, the protective functions, e.g. the idle periods, the transmittance tolerance, and the average radiation, combined with the constant current

technique may contribute to an extended lifespan of the EC window. However, additional experimental results are required to evaluate both the inertia of the system and the cycling durability of the EC window in real functioning conditions under the proposed control scheme.

5. Conclusions

In this work, a prototype for controlling the transmittance of an EC device in window applications was presented. Even though the proposed controller could be combined with EC devices regardless of their scale or fabrication process, the design of both the window and the controller were analyzed with adequate detail.

Through the user interface, three different operating modes (constant internal daylight, constant transmittance, manual) could be selected and two control techniques (constant voltage or current) could be performed, counting six different modes in total. The automatic modes of the system (constant internal daylight and constant transmittance) were achieved by utilizing the photodiodes as light sensors to determine both the incident solar radiation and the transmittance of the window. Moreover, the system was able to operate at a wide range of incident radiation due to the combination of the photodiodes with programmable gain transimpedance amplifiers. Two different approaches were utilized to measure the transmittance of the window, one dependent on the solar radiation and an independent one. The latter was verified as more suitable, reliable, and robust, since it was not affected by the fluctuation of the solar radiation or shading issues.

The proposed prototype system was evaluated under real time outdoor conditions and the robustness of the system was verified. The fluctuation of the incident radiation and the partial shading of the light sensors were counteracted by the software implementation of the average irradiance during a time interval of one minute. The one minute relaxation period, after achieving the desired transmittance, and the transmittance tolerance ensured the desired inertia of the system. From the extended experiment under different sky distributions, it was concluded that the system was in standby mode for the 41% of the total time. Thus, the desired inertia of the system was achieved. In addition, an ongoing process of the controller changing the EC window coloration state amounted for only about 11% of the time. Consequently, the proposed control scheme is expected to enhance the long-term cycling durability of the EC window.

The different control techniques (constant voltage or current) were evaluated by observing the experimental results and it was concluded that the constant voltage technique outperformed the constant current one in terms of speed, since the former could give the same change in transmittance three times faster than the latter. Nevertheless, the current spikes observed at the beginning of a new process, whenever a change from coloration to bleaching (and vice-versa) was effected, was the main drawback of the implemented voltage control technique. Therefore, current control is considered to be less stressful to the window and could also be used for the regeneration of the EC device during night hours.

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