 doi:10.20944/preprints202107.0012.v1

Article

An Efficient HVAC Network Control for Safety Enhancement of a Typical UPS Battery Storage Room

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Abstract: Lead-acid batteries utilised in electrical substations release hydrogen and oxygen when these are charged. These gases could be dangerous and cause a risk of fire if they are not properly ventilated. Therefore, this research seeks to design and implement a network control panel for heating, ventilation, and air conditioning system (HVACS). This is done by using a specific range of controllers, which have more than thirty loops of proportional, integral and derivative (PID) control to achieve a cost-effective design. It performs the required function of extracting hydrogen, oxygen, and maintaining the desired temperature of the battery storage room within recommended limits (i.e. 25°C ±1°C tolerance) without compromising quality as set out in the user requirement specification in Appendix-A. The system control panel allows the user to access control parameters such as changing temperature set-points, fan-speed, sensor database etc. The hardware is configured to detect extreme hydrogen and oxygen gas content in the battery room and ensure that the HVACS extract the gas content to the outside environment. The results of the system show that the network control panel operates effectively as per the recommended system requirements. Therefore, the effective operation of the HVACS ensures sufficient gas ventilation, thus mitigating the risk of fire in a typical battery storage room. Furthermore, this also enhances battery lifespan because of regulated operating temperature, which is conducive to minimise the effect of sulfation in Lead Acid Batteries (LAB).

Keywords: Air Handling Unit, Battery Room, HVACS, Network Control Panel, and Intrinsic Safe Barrier Module.

Abbreviations

AGM	*Absorbed Glass Matt*
Ah	*Ampere hour.*
AHU	*Air Handling Unit.*
DRL	*Deep Reinforcement Learning.*
ENN	*Elman Network Neural*
FIS	*Fuzzy Inference System*
HDTT	*Humidity Duct Temperature Transmitter.*
HVACS	*Heating Ventilation Air Conditioning System.*
IEEE	*Institute for Electronic and Electrical Engineers.*
IS	*Intrinsic Safety*
LAB	*Lead Acid Batteries.*
LEL	*Lower Explosive Limit*
LFL	*Lower Flammability Level.*
LSTM	*Long-Short-Term-Memory.*
MPC	*Microprocessor-based programmable controller.*
NCP	*Network Control Panel.*
PI	*Proportional-integral*
PID	*Proportional-Integration-Derivative.*
PPD	*Predicted Percentage of Discomfort.*
RL	*Reinforcement Learning.*

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SDRE	*State-Dependent-Riccati-Equation.*
SUT	*Scaled Unscented Transformation.*
TDNN	*Time-Delay-Neural Network.*
UKF	*Unscented Kalman Filter.*
UPS	*Uninterruptible Power Supply.*
VAV	*Variable Air Volume.*
VRLA	*Valve Regulated Lead-Acid.*

1. Introduction

This research is an extension of paper [1] published at the *International Energy Conference, 2020*. Electrical substation designs can be classified as stationary, offshore and modular. The offshore substations comprise upper construction, which has battery room on the third layer. In this study, the battery room is separate from other rooms in the electrical substation. Battery rooms are included for power switchgear control or for the uninterrupted power system to ensure that a reliable power supply source is available in case of standby or emergency [2]. The global market of consumer batteries has increased significantly since the year 2017 with Europe and China being the leading consumers. This global capacity reached 103 GW-h in 2017 and expected to reach 278 GW-h by end of 2021 [3]. The substation rooms consist of lead-acid batteries, which are commonly used because of their low maintenance structure [4]. These batteries release hydrogen and oxygen during charge, which is ignitable if it accumulates beyond limits. Because of these reasons, battery rooms are considered hazardous areas. Furthermore, at very high temperatures, these batteries can cause fire [5]. Subsequently, battery lifespan and performance reduce significantly at very low temperatures [6]. Hence, heating ventilation and air conditioning (HVAC) systems are necessary for these rooms to ensure low gas concentration and appropriate temperature levels. The installation of HVAC systems has grown significantly year-on-year in the last 20 years [7]. HVACs can be classified as air handling units (AHUs). Their purpose is to provide quality fresh air, cooling, heating, intake air filtration, humidification, and de-humidification, respectively. With proper control of AHUs, the de-humidification could assist the battery room environment to sustain its conditions [8]. The HVACs are usually integrated with overpressure systems, chemical filtration and they connect to the fire and gas system to adhere to safety regulations [9]. These units also operate in circulation unless gas detection in battery rooms reaches greater levels (10% of LFL and 15 ppm of H_2S). HVACs could be monitored and controlled through the panel, thus it is important to define a sequence of operation early in the design phase [10], [11]. In the case of fire-fighting functions, the air inlet and outlet ports in each room where the fire is detected, and in a carbon dioxide protection zone compartment, the HVAC control panel has to provide the electric damper with a command to automatically close and switch off before the fire extinguishing agent radiates. This is to ensure an appropriate carbon dioxide concentration within the room [12]. In contrast, HVACSs have emerged as major energy consumers [13]. However, the conventional forced-air systems that currently operate in buildings are not fully established, and AHUs are constantly fixed to a particular set-point despite dynamic changes of operating conditions [14]. The applied controls are not optimised because they use rule-based control methods. These control methods are static and differ only by pre-set schedules and seasonal changes. On the one hand, human capacity is required to continuously monitor HVACS behaviour and adjust it dynamically during operation [15]. Consequently, identifying and developing complete equations for designing the control system using conventional methods is difficult and almost unachievable [8].

In [15] a framework of achieving optimal control using long-short-term memory for AHUs is proposed to estimate the practical HVAC action and to build deep reinforcement learning algorithms training for the environment. The study uses two years of building automation system data as an evaluation testbed. The results show a 0.0015 mean square error when using the 1st year data across 16 normalised AHU parameters. Deep reinforcement learning results show 27-30% saving of energy compared to the energy consumption of the conventional system and sustained 10% of the predicted percentage of discomfort (PPD). Liu *et al*. [16] evaluate 5 layouts to reduce power consumption in AHUs. The results show that the air-to-air heat exchangers affect the power consumption of the coils. Time-averaged ventilation control is proposed in [17] by Kaam *et al*. to reduce extreme use of energy, and decrease the risk of overcooling the areas that have HVACs. The results show that the mean zone airflow fraction is reduced from 0.44 to 0.27 during the intervention period. Also, the average heating, cooling, and fan power are reduced to 41%, 23%, and 15%, correspondingly.

Li *et al*. [18] models and applies a prediction method for indoor temperature lag response using time-delay neural network (TDNN) and Elman network neural (ENN). This is because of the difficulty in building accurate models caused by lag response characterisation in regulating indoor temperature. The study uses a variable air volume (VAV) air conditioning system as a study base. The results show that ENN can be used as a better model for indoor temperature predictions because of its simpler network structure. Many studies discuss different types of air conditioning system for buildings such as in [19]. Liu *et al*. [20] emphasises that modern control methods for HVAC systems are emerging, such as reinforcement learning (RL) and should be utilised in the future control of these systems. Perng *et al*. in [12] use a multi-objective particle swarm optimisation to simultaneously enhance the ventilation performance while considering inlet size and outlet opening. The study uses a simulation tool ANSYS to simulate the air velocity and temperature distribution within the building. The results show that the rooms could be cooled down by 2.9 °C and 1.7 °C, respectively. Han *et al*. [21] studies the SF_6 gas dispersion characteristics using experimental and numerical methods in a substation building. The gas leakage angles are analysed and different ventilation design parameters adopted (i.e. air outlet layout, size and air change rate) to evaluate air ventilation performance. The results show that the gas leakage angle could influence the concentration level in the room, thus requiring proper position and installation of the ventilation system. The study further emphasises that there is severe worry in confined spaces such as battery rooms. Thinning ventilation is recognised as an active method to control and alleviate dangerous gas content in a crisis of unplanned escape. However, for most ventilation systems in industrial buildings, there is a lack of detailed design and optimal performance criterion. Brzezińska in [22] and [23] elaborates different tests that shows conditions which could occur in a battery room if ventilation fails. The study conducts experiments on a full scale hydrogen emission to evaluate the emission time and flammable cloud formation based on the assumed emission velocity. The results show that different ventilation systems provide the battery with attenuating efficiencies of hydrogen removal. Moreover, natural ventilation is effective as compared to mechanical systems.

The conventional proportional and integration (PI) control has inefficiencies which include the inability to deal with nonlinear systems, the gains are tuned for setting operating conditions of the HVAC system, and the control architecture is decentralised [24], [25], [26]. Consequently, proportional-integrate-derivative (PID) controllers focus on controlling the fan speed, fuel usage, and provide weak rapid response to varying conditions [27]. Also, Perekrest *et al*. [28] argue that to effectively manage the heat supplied to rooms, it is important to determine the amount of heat energy needed for the room to maintain proper temperature conditions during varying times.

In [29], Qiang *et al*. design and develop an online monitoring and remote network technology, which provide online temperature and humidity monitoring, and an indoor environment control system for high power distribution room in real-time. This is done to improve the operating environment in the switch cabinets by condensing the humid air into water and discharge it outdoor. However, no results of the system performance are presented.

Therefore, based on the literature review, HVAC system network control panel design has not been extensively studied and has received little attention as is clear from the existing body of literature. Therefore, this research study fills this gap by designing an HVAC network control panel for a typical UPS battery storage room comprising lead-acid batteries (particularly, valve-regulated lead-acid (VRLA) batteries). This design provides air at a suitable temperature for the batteries. Due to the presence of hydrogen, oxygen and electrical connections in the room, the room is at a higher risk of an explosion or fire, which needs to be taken into the highest consideration during the initial design phase. Also, it ensures that the air is supplied to the room at a suitable rate and temperature such that gases are extracted into the atmosphere.

The paper is herby organised as follows; Section 2 discusses the material and methods used for the study, Section 3 elaborates the results and discussions, and Section 4 concludes the findings on the design and implementation of the HVACS controller with the recommendations for future work.

2. Materials and Methods

The HVAC network control panel is installed to control the AHU, thus ensuring that the temperature in the battery storage room is kept constant at 25-degree celsius with ± 1 °C tolerance. Air used for ventilating battery rooms should not exceed 26 °C. However, according to the specification used by the electric utility supply Eskom, the battery room HVAC system has to be separate from the rest of the building's HVAC system. An airflow sensor located across every fan is needed to monitor individual fans. Airflow sensors should have a minimum of Ex rated or be part of the Intrinsic Safety (I.S) loop [30]. Consequently, the IEEE standard *1634-2018/ASHRAE E-Guideline 21-2018* stipulates that the I.S barrier module is an intrinsic safety barrier used to protect the device mounted in a hazardous location. It isolates the device mounted in a hazardous area and keeps it safe. All the components (exhaust temperature sensor, exhaust fan airflow switch and limit switch of fire damper) that are installed on the exhaust side of the battery room should be part of the I.S loop because the battery room is considered a hazardous area. As the battery room is considered a hazardous area and therefore, the actuator damper has to be approved before use, as it needs to be ATEX Exd Rated. If the flow switch is Exd rated from the factory, then it can be used as an option, but if it is not Exd rated then an I.S barrier module can be added. The extracting fan should always run to minimise the content of gases in the room. Also, this study does not consider natural ventilation systems because of their inefficiencies during uncertain weather conditions. Therefore, forced ventilation is adopted [31].

In [32], a state-dependent optimal control based on pseudo linearisation and state-dependent Riccati equation (SDRE) is presented to accommodate the complex dynamic model. This is because of the nonlinear and complex nature of integrating AHU variables. An unscented Kalman filter (UKF) based on scaled unscented transformation (SUT) is proposed to provide a state estimation of AHU that is controlled through a linear quadratic regulator. The UKF achieves higher accuracy by utilising a scaled unscented transformation (UT). It makes use of sigma points and does not employ linearisation to produce less error, thereby preserving the nonlinear characteristics of the system [33]. In [34], a novel switched adaptive control method is introduced that results in less computational complexity and solves the challenges of nonlinear inputs. It achieves stability and good performance by linearising the nonlinear dynamics concerning discrete working modes. An adaptive law with anti-windup compensator and a switching law established on dwell time are implemented to deal with uncertainties of the switched system. An experiment to test

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the performance of a modulating function technique is used in [35], which provided positive results. The modulating function technique creates a system of linear equations by multiplying the nonlinear inputs signals by a known variable. Other techniques such as using long-short-term-memory (LSTM) networks and deep reinforcement learning (DRL) were presented in [15]. This paper adopts a range of controllers, which have a thirty loop PID control because the system operator selects the operational requirements based on the engineering experience of the facility managers and the facility manager's familiarity with the product.

To ensure proper ventilation control, the hydrogen concentration in a battery room should be below 4% as its lower explosive level (LEL). The ventilation consists of both mechanical and natural systems [22], [23]. Electric energy is commonly used to transmit the measurement of a change in a controlled condition from a controller to other parts of a system and to translate the change into work at the final control element. The signals received from sensing elements can be used to produce one or a combination of electro-mechanical outputs. For example, several actuators are controlled by one controller. Single controller-actuator combinations are possible without the need for a main-air source like in pneumatic control.

The HVAC system should accommodate the various battery operating modes, which includes accelerated charge or recharge, discharge, bulk charge, float charge, accelerated/boost/equalise charge, respectively. The hydrogen generation and heat generated are determined by assuming that valve-regulated lead-acid batteries (VRLABs) with low antimony absorbed glass mat (AGM) are used for the application and equation (1) through to (10) are used as stated in [31]:

$$H_{2-rat} = n_c \times C_8 \times 2.69 \times 10^{-11} \quad (1)$$

Where n_c is the number of cells in the room and C_8 is the 8-hour ampere rating of a lead-acid cell to 1.75V at 25°C.

$$q_w = 0.34 \times I \times n_c \quad (2)$$

Where q_w is the total heat generated in watts and I is the current through each string in amperes.

Therefore, for the accelerated charge operating mode, equation (3) and (4) are used to determine the hydrogen and heat generation:

$$H_{2-rate} = n_c \times C_8 \times 5.36 \times 10^{-11} \quad (3)$$

$$q_w = 0.449 \times I \times n_c \times t \quad (4)$$

Where $I = C_8 \times 0.0130$

During discharge mode, batteries deliver power to the load and it can last for hours. Thus, during this mode, particularly for the UPS, a high rate discharge pattern takes place. Therefore, only heat generation is associated with this mode and is determined as in equation (5):

$$q_{wh} = (I \times t \times n_c) \times ((0.727 \times (s.g.)) + 0.0718 - \frac{V_{c-end}}{2}) \quad (5)$$

Where $I = \frac{I_L}{N_s}$, N_s is the number of parallel strings supplying the load, I_L is the load current, $s.g.$ is the nominal specific gravity of the fully charged cell, and V_{c-en} is the average expected end-of-discharge voltage per cell in the battery room.

It is worth noting that during the bulk re-charge mode, there are no gases and only heat is generated. Equation (6) represents the heat generated during the re-charge mode. This is because the re-charge is highly controlled by the battery charge set limits. However, during the initial and refreshing charge mode, this mode occurs once during battery lifespan, and ventilation design is not necessary for this mode of battery operation.

$$q_{wh} = C_{r-s} \times n_c \times 0.138 \quad (6)$$

Where C_{r-s} is the ampere-hour (Ah) removed from the battery string during the discharge period

The failure mode is one condition that can occur during battery operation, which can include thermal runaway, shorted cells, cell reversal, and charger runaway, respectively. During thermal runaway, high currents are drawn through the battery in float or equalise mode, thus increasing gassing. This phenomenon can be detected by battery temperatures that are higher than ambient. Therefore, the generated heat and hydrogen during thermal runaway can be determined as in equation (7) and (8):

$$q_{wh} = 0.455 \times I \times n_c \quad (7)$$

$$H_{2-rate} = n_c \times C_8 \times 6.28 \times 10^{-10} \quad (8)$$

Where $I = C_8 \times 0.0257$

Although cell reversal is an extremely rare case to occur in battery rooms, theoretically one or two cells could undergo reversal during discharge. Hence, it is important to determine the heat and hydrogen rate that can be emitted during this condition using equation (9) and (10). Also, toxic hydrogen sulfide gas is possible.

$$q_w = 3.28 \times I \times n_c \quad (9)$$

$$H_{2-rate} = 1.27 \times 10^{-7} \times I \times n_c \quad (10)$$

Where $I = \frac{I_{ct-spar}}{N_s}$, $I_{ct-spare} = (\sum_{c=1}^{n} I_c) - I_L$, $I_{ct-spare}$ is the maximum spare charging capacity available to charge the battery, I_c is the capacity (ampere) of the individual charger, and I_L is the average parallel load current over a given period.

The network control panel (NCP) consists of two parts as shown in Figure 1 namely;

1. One part being the control of normal operations for all units that are local to the battery room or area where the NCP is located via the software.
2. Critical control (hard-wired), which include manual start, stop and fire signal; the second one being the critical control, which controls all normal run and fire conditions, and they are all hard-wired in the panel.

They follow a sequence of events set out by the cause and effect matrix, as shown in Table 1. The NCP form part of the building management system but are situated locally to plant rooms or areas where the units are being controlled. Some of these electric controls consist of valve/damper actuators, temperature/pressure/humidity controllers, relays, motor starters and contactors. They are powered by low voltage, which depends on the circuit

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requirements. Controllers can be wired to perform either primary or limit functions (high or low limit). Electric actuators can also be either spring return or non-spring return. Here, in this case, the controllers are hard-wired to perform primary functions and electric actuators are spring return.

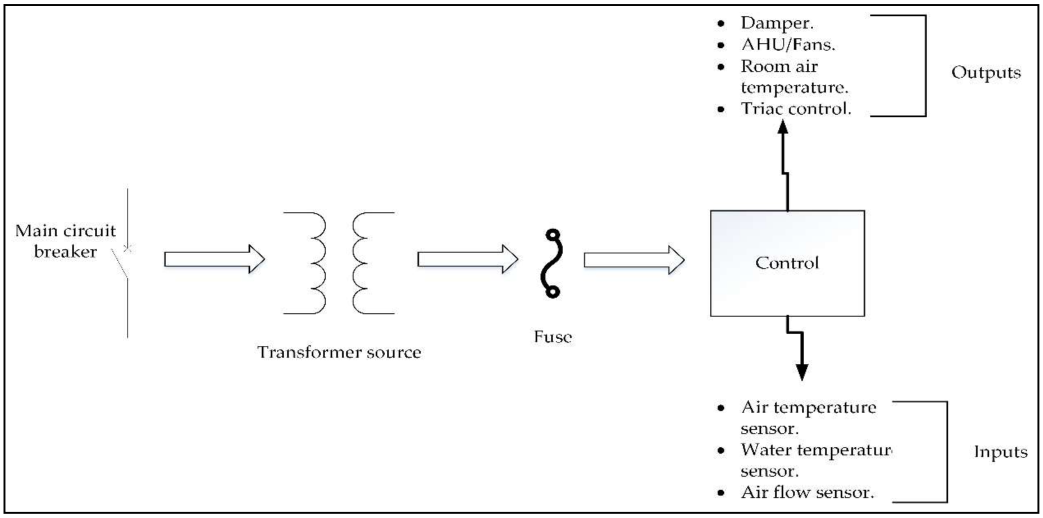

Figure 1. Proposed network control panel.

2.1 Control Panel equipment

These specific range of controllers are microprocessor-based HVAC programmable controllers that are designed to control various building automation applications such as air handling units, chillers, boilers, pumps, cooling towers etc. This range, which is one type of these controllers, is a compact and embedded controller/server platform. It pulls the integrated points together for instance control, supervision, data logging, alarming, scheduling and network management functions with internet connectivity, and web serving capabilities in a small, compact platform. I.S barrier module is used to protect the devices mounted in hazardous locations. It isolates the devices mounted in these areas. Thus, all the components (exhaust temperature sensor, exhaust fan airflow switch and limit switch of fire damper) that are installed on the exhaust side of the battery room should be part of the I.S loop. This makes the control panel for the battery room simple and easy to implement and install. In normal buildings, the I.S barrier module is not used because the areas are not referred to as hazardous. If the components are left out of the I.S loop, they could damage these devices and the entire control panel.

2.2 Field control equipment

Air differential pressure switches; these differential pressure switches are suitable for low differential pressure switching applications in air conditioning systems for indicating fan status or ´a dirty filter. Duct humidity and temperature transmitter; the duct humidity and temperature transmitter (HDTT) measures the relative humidity and temperature of the air duct temperature sensor. The duct temperature sensor (TDSH) is used for sensing the air temperature in heating, ventilation and air conditioning systems (e.g. it supplies air, extract it outdoor). In terms of immersion temperature sensors; these sensors TISB/TIS are used for acquiring the temperature of liquid or gaseous media (e.g. heating water) in heating, ventilation and air conditioning systems. Room humidity and temperature transmitter measure the relative humidity and temperature of the air. The spring-return actuator, various actuators are used for adjusting dampers with safety functions on all fire dampers and dampers on the air handling units. The

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fire damper for this design is different because the damper is located inside the battery storage room, thus the damper has to be I.S rated from factory rotary actuator. Various rotary actuators have seen wide applications in butterfly valves and on the piping installation for control of the shut-off valves. The modulating valve actuator is used for 3-way valves on the piping installations, they vary from 0-100 %. The triac control heat module controller receives a signal of 0-10Vdc from the controller and output power to heater elements. It comes in different heating capacities (kW). Proper control of pressure and temperature can ensure improved comfort, energy, and monetary savings. Mixing loops could be used to meet the required different pressure and thermal power amongst consumers to enhance performance and energy efficiency [25].

2.3 Normal operation of an AHU with internal heating system and external air supply through the damper

For all AHU dampers, as well as fire dampers, there is a weekly test that is conducted to tests the dampers for faults with the actuator or the dampers themselves. When the weekly test is activated all AHUs where the dampers are located will come to a halt, and they will return to normal operating conditions once the weekly test is de-activated. In the event of a fire, a signal from the battery management system activates the section within the critical control, which handles a fire condition. When a fire signal is activated, the critical control, which is hard-wired, will stop all normal operations on all AHUs and fans that are supplying the area within the zone. Also, it will stop all operations where the fire is situated and close all AHU dampers, and fire dampers to suffocate the fire within that zone. Once the fire marshal has cleared the fire and needs the smoke to be extracted from the zone where the fire was detected, all AHU heater will be switched on. It needs to reach a certain heat (±25°C ±1°C) in a room, because the system may fail to reach the required heat/temperature when the water is stopped to flow. This is to avoid having the heater turned on and chilled water circulating simultaneously. Even if the heater is supposed to start up and there is no airflow, it will not switch on because the heat will accumulate greatly inside the unit and damage some devices. The considered AHU design is based on equation (11) as described in [27].

$$\frac{du}{dt} = Q_{loss} + Q_{gain} \tag{11}$$

Where Q_{loss} is the heat transfer from room to the outside, Q_{gain} is the heat transfer from the heater to the room, du is the internal heat, and dt is the change in time, respectively.

These range of controller applies fuzzy inference system (FIS) algorithm to switch the heater on/off at a set temperature requirements as stated in [31], which state that the temperature should be 25°C with a ±1°C tolerance.

2.4 Design of the main controller

Although existing literature report intelligent control methods, which include model predictive control (MPC), gain scheduling, optimal control, robust control, nonlinear adaptive control, fuzzy logic, genetic algorithm, etc. As compared with PIDs as proposed in this study via mixing loops, they are robust and energy-efficient. However, they have drawbacks, which include the requirement of centralised operation with a heavy burden for sensing, communication, computation, thus leading to higher implementation cost as compared to on/off PID control [36]. Figure 2 show the room temperature regulation algorithm that is programmed on this range of the controllers. The local level PID controller mixing loops are implemented to regulate the battery room temperature set-point [37].

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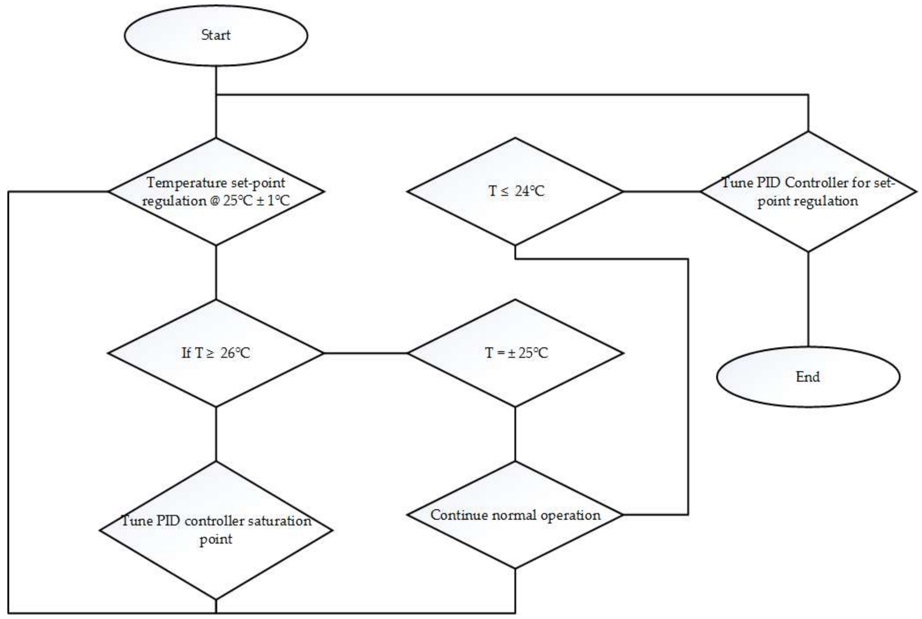

Figure 2. Set-point temperature control algorithm for a battery room.

2.5 Hardware and Software design

The system can be custom programmed using EC-*gfx*Program through either EC-Net^{AX}™ Pro, which is powered by the Niagara^{AX} Framework® or through any LNS®-based software such as Distech Controls' Lonwatcher 3. This creates an easy interface to quickly create an individual control sequence that can meet many specifications for AHUs. The control display allows the operator to have immediate access to internal controller data. The typical system comprises with wall unit profile, hardwired gas detection profile, hardwired fire alarm profile, hardwired full ventilation profile, hardwired full recirculation profile, hardwired safety instrumented system, ten universal inputs, and eight universal outputs, respectively. These inputs and outputs control a wide range of HVAC equipment. The controllers embedded in this system can operate with a range of sensors, especially those in the Allure™ EC-Smart-Vue series of communicating room sensors. These sensors are used for indoor temperature measurements, set-point adjustments, fan speed selection, and state override. Moreover, this controller is Open-to-Wireless ready. Hence, Figure 3 shows the hardware connection of the system.

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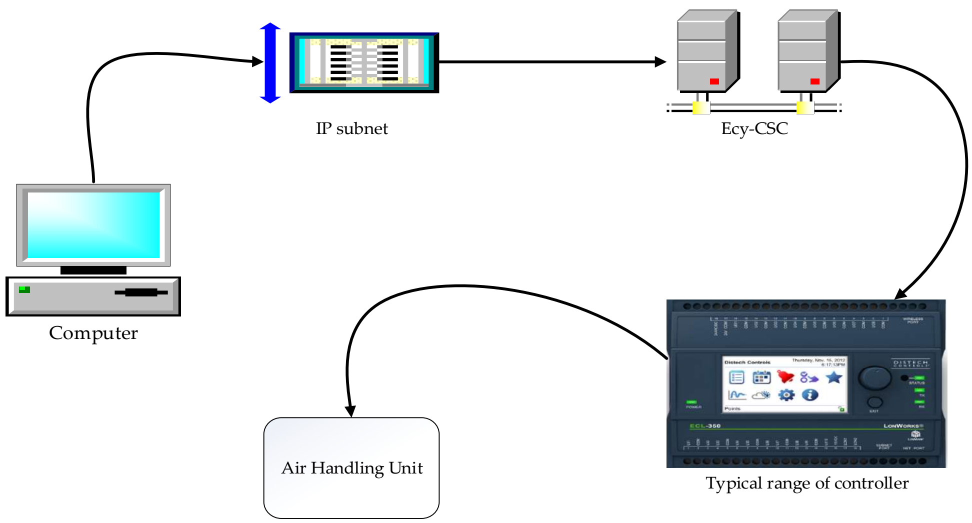

Figure 3. System demonstration during programming for AHU.

In terms of the software, the operational sequence adopts the following steps:

- The controller sends an output signal to open the AHU dampers.
- The controller receives an input signal that is relevant to the AHU dampers and allows the dampers to open.
- Also, the controller receives an input signal that is relevant to the AHU fire dampers and allows the dampers to open.
- Then the controller sends an output signal to startup the fan.
- After 120 seconds, and after the fan or AHU is commanded to startup, the controller receives airflow feedback, and the fan status is set to “run mode”.
- Heating and cooling are controlled by a single PID loop. This is to avoid simultaneous heating and cooling operation from the AHU.
- Thus, a weekly damper test is conducted two hours before the AHU/fan lead/lag (ie. Run/standby operation) changeover is done using a scheduler.

In terms of general and critical alarm functions; firstly, the general alarm when it is active, there is no changeover operation of the AHU.fan, however, it needs to be attended to, to ensure effective operation. Second, the AHU/fan undergoes general alarm settings if the following conditions are not met, which include damper failing a weekly test and if the AHU/fan commanded to stop (OUTPUT OFF), and the airflow status reflects “flow” and an alarm is generated. The fan has to be stopped manually.

The critical alarm when it is active/ ring, forces change in the operation of AHU/fan to a standby AHU/fan. Once the critical alarm is cleared, the operation will be reverted to before the alarm occurred (original lead unit resumes operation). The fan/AHU should undergo critical alarm if the following conditions are met, which include (i) If the AHU/fan motor overload is tripped, (ii) If the fan start command is active and no airflow is detected or the fan motor running status is not received after 120 Seconds. The AND logic gate is used to achieve this goal, (iii) Heating safeties will generate an alarm and disable heating automatic reset overheat status, (iv) Manual reset overheat status (Trips the isolator/circuit breaker), and (v) Triac alarm.

3. Results

This section discusses the results of the tested product. The panel is tested at the workshop using fans and damper logic cause and effect matrix as shown in Table 1. Fans and damper cause and effect matrix is a procedure describing how fans and dampers should operate in the event of normal and fire event. Due to field components not connected when the panel is tested at the workshop, the study uses a 24Vac pilot light to simulate the damper and fan. If the light is OFF that means that the fan is OFF and if the light is ON it means the fan is running/ON. All the dampers are spring return, supply and exhaust air damper is spring open, hence they need a 24Vac to be driven to close. The fire damper is spring closed, thus it needs 24Vac to be driven open. Point to point test/checks are conducted using a multi-meter to ensure continuity and correct wire marker. The protective components such as fuses and circuit breakers are tested for correct functionality. A bridge piece is used as a fire signal.

3.1 Testing procedure

The below steps are followed to test the control panel:

- The drawing used to design is approved or all red lines have been addressed.
- The panel should be switched off before testing.
- All the equipment used has been approved.
- The colour coding of the wires is checked to confirm that they are correct. The panel is as per the drawing: The layout matches the drawing, fuse and breaker sizes are as per the drawing.
- Wire markers and other components labels are as per the drawing. Check for no loose connections. Check if the gland plate, door and transformer are earthed.
- Switch the panel on. Test for correct functionality using the cause and effect matrix.

3.2 Tested product results

Table 1 shows the results obtained when the panel is tested under normal conditions. Some fans are run and on standby; only one fan can run at a time and the damper of the running fan is open while the damper of the OFF fan is closed. These fans are installed in parallel because if the other one is running, the other one must be OFF, thus the damper closes to avoid the air from returning. Fire damper (FD1) is open to allow the air to flow to the battery room. In case of fire, power is interrupted on both supply fans even if one fan was running just to avoid spreading the fire. Their dampers do not matter if they are closed or open since FD1 will always be closed. The exhaust fans will continue to run to extract the gases.

Table 1. Tested control panel.

Results of the tested control panel		
Under normal conditions		
Description	**Label**	**Effect**
Supply fan A	AHU1A	Run/Standby
Supply fan B	AHU1B	Run/Standby
Supply damper for AHU1A	SAD1A	Open/Close
Supply damper for AHU1B	SAD1B	Open/Close
Fire damper 1	FD1	Open
Exhaust damper A	EAD5A	Open/Close

Exhaust damper B	EAD5B	Open/Close
Exhaust fan A	FC1A	Run/Standby
Exhaust fan B	FC1B	Run/Standby
In the fire event		
Supply fan A	AHU1A	Off
Supply fan B	AHU1B	Off
Supply damper for AHU1A	SAD1A	Open/Close
Supply damper for AHU1B	SAD1B	Open/Close
Fire damper 1	FD1	Closed
Exhaust damper A	EAD5A	Open/Close
Exhaust damper B	EAD5B	Open/Close
Exhaust fan A	FC1A	Run/Standby
Exhaust fan B	FC1B	Run/Standby

These are the result obtained when the panel is tested under normal condition. Some fans operate to run and be on standby, and the only one fan can run at a time. The one that is running its damper will be open and the one that is off its damper will be closed. The results of the tested control panel and HVAC system is compared to the specification/ requirements as shown in Table 2. The panel has been completed successfully. All the requirements have been met. All the changes to the original design were made and it is recommended that field components be purchased upfront.

Table 2. Comparison of the tested product results against the requirements.

Under normal conditions				
Results of the tested product			**According to requirements**	
Description	**Label**	**Effect**	**Similar/Different**	**Status**
Supply fan A	AHU1A	Run/Standby	similar	Correct
Supply fan B	AHU1B	Run/Standby	similar	Correct
Supply damper for AHU1A	SAD1A	Open/Close	similar	Correct
Supply damper for AHU1B	SAD1B	Open/Close	similar	Correct
Fire damper 1	FD1	Open	similar	Correct
Exhaust damper A	EAD5A	Open/Close	similar	Correct
Exhaust damper B	EAD5B	Open/Close	similar	Correct
Exhaust fan A	FC1A	Run/Standby	similar	Correct
Exhaust fan B	FC1B	Run/Standby	similar	Correct
In the event of a fire				
Supply fan A	AHU1A	Off	similar	Correct
Supply fan B	AHU1B	Off	similar	Correct
Supply damper for AHU1A	SAD1A	Open/Close	similar	Correct

Supply damper for AHU1B	SAD1B	Open/Close	similar	Correct
Fire damper 1	FD1	Closed	similar	Correct
Exhaust damper A	EAD5A	Open/Close	similar	Correct
Exhaust damper B	EAD5B	Open/Close	similar	Correct
Exhaust fan A	FC1A	Run/Standby	similar	Correct
Exhaust fan B	FC1B	Run/Standby	similar	Correct

Therefore, Figure 4 below shows the visual illustration of the above-tabulated results. It shows that the air from the battery room is extracted to the outside environment as indicated by the orange line. The two dampers located in the battery room (FAD1A and FAD1B) are not part of the control. Therefore, they are manually adjusted to provide 100% of fresh air to the battery room. The extracted air from the battery room is represented by the orange line, It extracts the air to the outside environment through a damper. However, the damper is in an open state all the time because it is not required to operate.

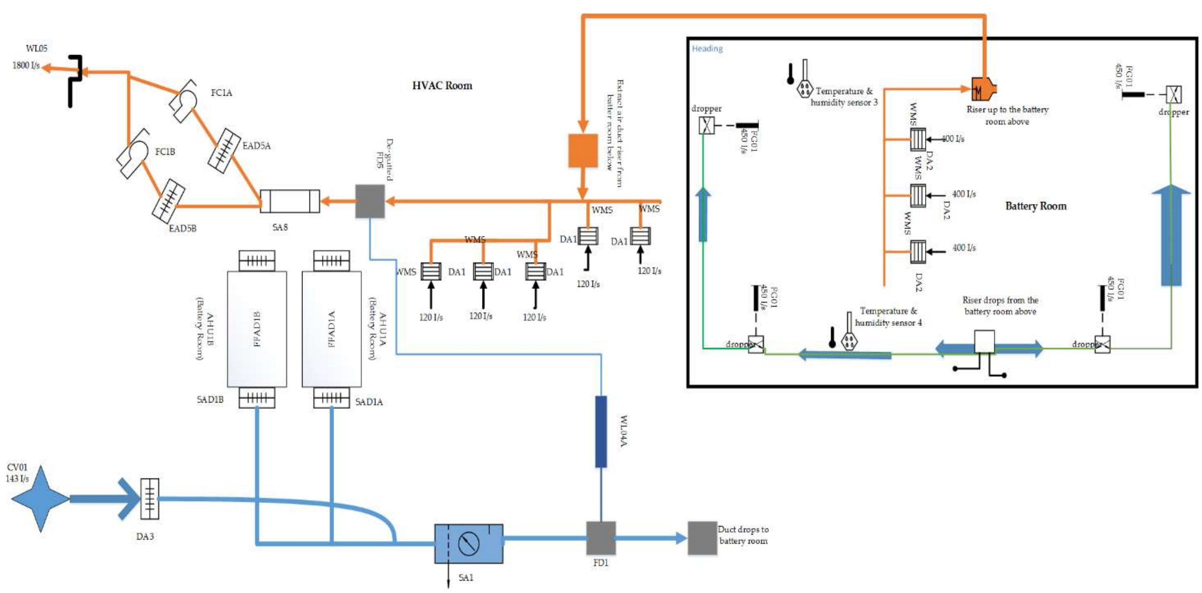

Figure 4. Results visual demonstration

5. Conclusions and Recommendations

Here in the study an HVAC network control panel is designed and implemented for the safety enhancement of the UPS battery storage housing room. The HVAC control panel ensures that there is no return of air inside the battery room to the AHU. The two fans on the exhaust side of the battery room extract the gases from the battery room. The exhaust fans of the battery room run all the time interchangeably leading to no interruptions of fans operation. All battery room critical alarms are sent to the control desk. These critical alarms include parameters for sensing extreme hydrogen and oxygen gases in the room as well as parameters of temperature deviations from the set temperature value of 25°C with a tolerance of ±1°C. All safety alarms and indicators of this controller are fail-safes, thus even when detecting failed equipment, the alarm will be triggered by namely; no airflow, very high or low temperature, and smoke detection. The designed network control panel operates successfully as required according to the specification. Therefore, the study contributes to the body of knowledge in controlling extreme hydrogen and oxygen gases in UPS battery chambers, as well as controlling the acceptable temperature limits for safe operation. This also enhances the performance as well as the lifespan of batteries. The system control panel allows the user to access control parameters such as changing temperature set-points, fan speed, sensor database etc. The hardware is configured to detect and extract extreme hydrogen and oxygen gas content in the battery room to the outside environment through HVACS. Besides, the software of the controller ensures that the AHU dampers and the function for cooling and heating are controlled effectively.

It is recommended that the research is furthered for enhancing the performance of these HVACS. In future, the authors will further this research to evaluate the gas emission dispersion and its influence on the battery room. It will further enhance the performance of the HVACS since the gas dispersion emission angle may influence the operation of safety devices within the battery housing room.

Author Contributions: For research articles with several authors, a short paragraph specifying their contributions must be provided. The following statements should be used "Conceptualisation, M.J.L, S.P.D.C, and S.M.; Methodology, M.J.L, S.P.D.C, and S.M; Validation, M.J.L, S.P.D.C, LN, S.M. and M.S.; formal analysis, M.J.L, S.P.D.C, and S.M; investigation, M.J.L, S.P.D.C, and S.M.; resources, M.J.L, S.M.; data curation, M.J.L, S.P.D.C, and S.M; writing—original draft preparation, M.J.L, S.P.D.C.; writing—review and editing, M.J.L, S.P.D.C, S.M., M.S and LN; visualisation, M.J.L, S.P.D.C, S.M, and LN.

Funding: This research received no external funding.

Acknowledgements: The authors would like to thankfully appreciate the Tshwane University of Technology, Pretoria, South Africa, Enviroware Construction, South Africa, and Eskom for providing the necessary infrastructure and support to conduct this research study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Approved user requirement specification

i. Functional specification

The HVAC control panel shall be installed to control the Air Handling Unit (AHU) to ensure that the suitable temperature in the battery room is served shall be kept constant 25˚C ± 1 ˚C. Air used for ventilating battery room shall not exceed 26 ˚C. The panel will ensure that there is no return air from the battery room to the AHU. There are two exhaust air fans (run and standby). The exhaust fans of the battery room should run all the time – changing each other. When there is no air flowing the motor must stop and the heater must go off for safety sake. All battery room critical alarms shall be sent to the Control desk. All safety alarming and indication shall be fail-safe, thus even when the detecting equipment fails then the alarm will be triggered such as no airflow, very high or low temperature and smoke detection.

ii. Non-functional requirements

The panel is a top entry and top exit for the cable, the panel must be installed under a roof. The degree of protection for the panel is (IP rating of 3X) which means it is 50% protected against the dust and no protection against water, hence the place of installation must be clean and no drops of water. The sheet metal must be 2 mm thick in case it falls and the components inside do not get damaged.

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