Centralized Smart Air Purifier System for Industrial Applications

Aditya Asabe, Deepak Tiwari, Manu Dubey, Vedant Joshi, Shardul Shrikhande, and R. Mohan

Abstract Small-to-medium scale enterprises (SMEs) in India involve many manufacturing operations which involves emission of air pollutants, gases with foul odor, etc. inside the workplace which results in an unhealthy environment. This in turn affects the workers' health on the long term. There are certain industry grade air purifiers out there in the market. But, they are not economical and not smart enough to meet day-to-day operational requirements. So this article aims to present the concept, design and analysis of the prototype of a smart centralized air purifier system. The simulations are carried out in Ansys Fluent software to substantiate our model and empirical data. The proposed centralized air purifier is able to eliminate air pollutants of 10 microns and above from the polluted air in the industrial environments and it operates on the concepts of connected devices. Thus an economical, smart and healthy air purifier is developed to suit industrial applications.

Keywords Connected devices · Industrial air purifier · IoT · Smart devices · Air pollution

1 Introduction

World Health Organization estimated worldwide about 8 billion premature deaths every year due to cardiovascular and respiratory diseases as a result of exposure to particulate matter which are 2.5 μm or less in contaminated ambient air [1]. The indoor air pollutants are more dangerous and cause diseases in affected places [2]. This adequate filtration is essential to maintain good indoor air quality to avoid eye irritation and headache [3]. Air purification based on principles of filtration and catalytic oxidation types are being used to prevent the harmful contaminants [4, 5]. The filtration type air purifiers remove air pollutants efficiently, whereas fouled filters increases energy consumption by resisting the air passing through it, thereby increase in operating cost [6]. So, manual intervention is inevitable to restore the

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filtering efficiency. In general, operating costs contributes 81% of filter's total life cycle cost [7]. So, there is a need for an economical and efficient indoor air purifier with minimal human interference for instance, to set them up, gives them instructions or accesses the data.

In this research work, an attempt was made to design efficient filtration-based air purifier with IoT based automation for better serving its purpose in an industrial environment as well as Covid-19 quarantine centers during pandemic, where no physical contact will be made between user and air purifier control unit. Air purifier prototype design iterations were carried out using DS SolidWorks. A sample control volume of 1000 mm × 700 mm × 400 mm was generated corresponding to the dimensions of the prototype. CFD analysis and simulations were carried out in ANSYS Fluent to analyze the nature of flow of air within the duct and a HEPA filter. To illustrate that the system holds its place in the industry, an industrial schematic simulated operating conditions using automation studio is presented.

2 Design and Analysis of Air Purifier Prototype

2.1 Design of Air Purifier

In order to design the purifier, the whole system was divided into three parts, first intake of air, purification system and lastly the outlet of the purified air. For the air inlet, an outer casing with open top was designed where the fan can be assembled. The fan is an induced draft type which can suck in air. This way air gets inside the purifier. For the purification system of air just after the fan, filters are placed such that the air particles flow through the filters. There are two beds of filters designed; first being the normal filter which will filter out the coarser particles from the air and the second filter bed is HEPA filter which then filters the finer particles up to 10 μm in size and several harmful gases [8]. After air passes through the filters, a duct is provided to channel air further which is optimized based on the results of CFD analysis of the system. The air from duct passes through water which increases the moisture content of the air. Humidity of air can be manipulated by passing it through silica filter installed above the water level. For killing the germs and microbes, two UV emitters are also provided [9]. Lastly for the outlet of purified air, some openings were provided in the form of cuts in outer casing. Table 1 shows the dimensions of all components arrived based on air flow, and Fig. 1 represents the model of air purifier.

The blower fan designed in DS Solidworks 2018 was imported to Ansys Design Modeler and then an enclosure was inserted around the blower fan to set a flow restriction which resembled and replicated the optimized air duct. The cushion radius, positive and negative cushion direction were taken to be 1, 1.1 and 0.1 mm according to the prototype design. A conical duct toward the outlet was designed in order to accelerate the particles through the outlet, using continuity equation. Two planes were created 10 mm away from each other to divide the cylindrical part of the duct in

Table 1 Specifications of air purifier

Items	Specifications
Fan	170 mm × 170 mm × 50 mm (along with the fan casing)
Outer casing	Height: 420 mm; inner diameter: 195 mm; wall thickness: 3 mm
Duct	Height: 200 mm; diameter: 195 mm; draft angle: 71.35°; thick: 2 mm
Filters	Normal filter: thickness: 10 mm & HEPA filter: thickness: 15 mm

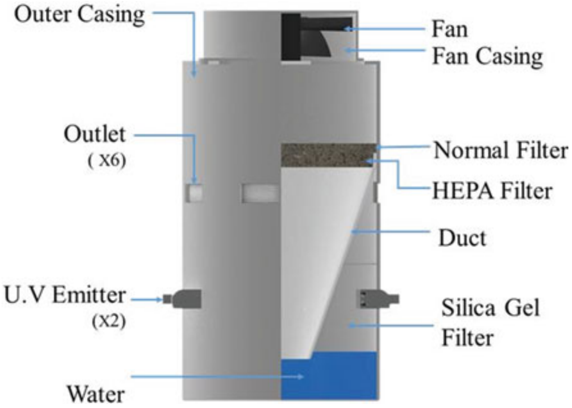

Fig. 1 Model of air purifier

to a smaller cylindrical region which was considered as a porous region resembling a HEPA filter. The slice command was used to split the duct in to separate entities giving a separate body for the porous region.

2.2 CFD Analysis of Air Purifier System

Computational fluid dynamics (CFD) has undoubtedly been of utmost importance, while dealing with fluid flow problems. After the model was designed, it was split into small finite elements to analyze each and every portion of the model. Different size mesh was applied to different regions based on its importance and criticality.

The wall of the frustum was given a face mesh with a patch conforming method to optimize the mesh for most accurate and precise details. A tetrahedral mesh shows more diffusive character in contrast to a hexahedral mesh and hence it was taken into account. The porous region is main focus and the flow of air particles through the outlet invariably depended on the flow characteristics of the same air particles through a HEPA filter. Hence, the size of the tetrahedral mesh on the curved surface of the porous region was drastically reduced to allow increased precision. Moreover, 3 times refinement was given on the 2 edges of the region dividing the porous region and the wall which is illustrated in Fig. 2. This was carried out to accurately observe

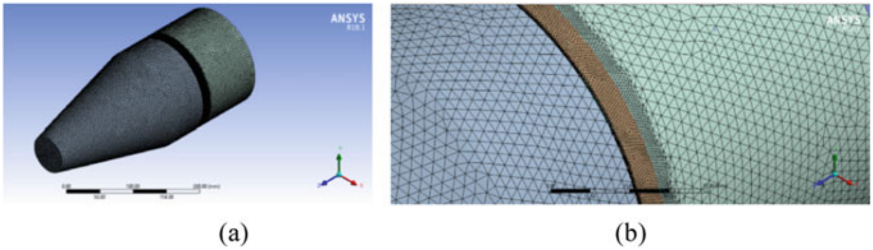

Fig. 2 **a** Meshing of the model and **b** mesh refinement at the region of interest

the transition of the characteristics of air particles from the filter zone to the normal zone.

To analyze the air flow through a HEPA filter and duct, a viscous model was taken into account. The energy model was not taken into consideration as the problem had not dealt with any temperature changes from the inlet and outlet. Further, a k-epsilon model and realizable were chosen as it was deemed to be the most putative pertaining to the required analysis. The realizable model satisfies general mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows, which cannot be carried out using the standard or RNG model. Moreover, Enhanced Wall Treatment was deployed as the simulation involved a detailed study of air flow and accumulation along the walls of the duct. Alternate models like multiphase, discrete phase, radiation, heat exchanger were impertinent and hence not taken into consideration. Air was the primary flowing fluid in the following simulation. Hence, the values of density and viscosity of air were inserted from the fluent database. As the whole model comprised of 4 parts, i.e., the inlet and outlet side of the casing, the porous region, and the blower fan, distinct cell zone conditions were applied to each region. The inlet and outlet part of the casing were standard fluid regions with zero frame motions. The blower fan was taken as a solid zone with a certain rotational frame motion. The fan which was chosen had a rotational velocity of 2600 rpm which is equivalent to 272 rad/s. The porous media model is used to define a cell zone and the pressure loss in the flow is determined. The porous jump model is applied to a face zone, not to a cell zone for robust and yields better convergence. To insert accurate coefficients for the porous region, a pressure drop versus face velocity graph of a HEPA filter was used. For a porous cylinder, values 0, 0, 1 were entered as the axis vector, and 0, 0, 0 were entered for the cone axis since the frustum has its axis parallel to the z axis. The cone angle of the cylinder was taken as 0° as it was a perfect cylinder. Furthermore, directions 1, 2 and 3 were entered accordingly. For the Conical option Direction 1 is tangential, i.e., along its length, direction 2 is normal to the cone surface and direction 3 is circumferential. A pressure inlet and a pressure outlet were taken into account for the simulation. The fan was the only solid zone in the CFD model, whereas all other sections were considered to be fluid zones along with the porous zone of the HEPA filter. The duct wall was construed as adiabatic involving no heat or mass transfer between the control volume and the surrounding.

Solution methods, residuals, initialization and running calculations: Simple scheme method was chosen for the analysis. Least-squares cell-based gradient was incorporated as it proved to be the most efficient, while dealing with similar fluid flow problems. Second-order upwind was taken into consideration for the turbulent kinetic energy and turbulent dissipation rate as well as the pressure and momentum. Residual with a precision of 0.0001 was considered to provide highly accurate and converged results. Hybrid Initialization was performed for a total of 10 iterations, and the comprehensive simulations was done for a total of 150 iterations to provide maximum accuracy and precision. The velocity vector and stream line of the HEPA filter is shown in Figs. 3 and 4, respectively. The velocity streamline of model is compared with three different speed of exhaust fan. At 200 rad/s the fan is not effective in developing uniform flow across the purifier as the speed is low for this model, we increased this speed to 320 rad/s and there is turbulence created across purifier this resulted in increasing kinetic energy of the air molecules resulting in the loss.

Now, from the theoretical calculations we got 272 rad/s as boundary condition when plotting streamlines there is no overlapping of airflow as a result, we uniformity is maintained throughout the purifier and no turbulence is created. This shows that the losses are less and no rise in temperature inside the purifier.

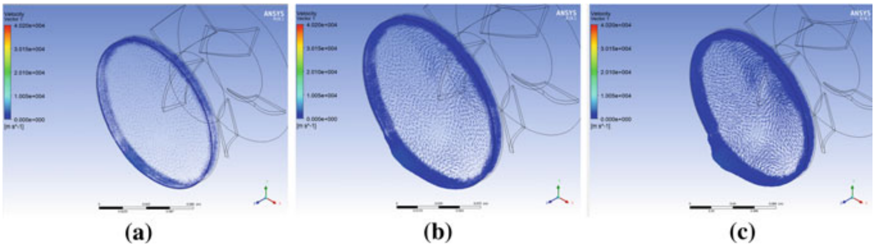

Fig. 3 HEPA filter velocity vector **a** 200 rad/s, **b** 272 rad/s, **c** 320 rad/s

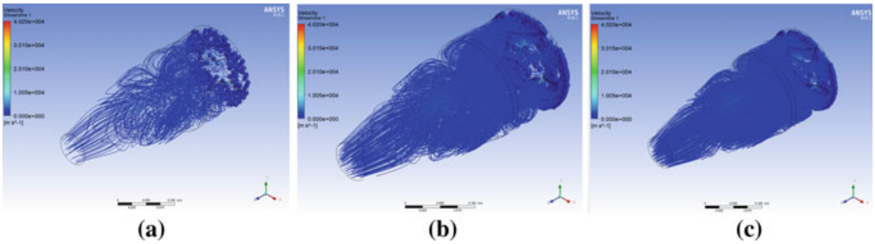

Fig. 4 HEPA filter velocity streamlines **a** 200 rad/s, **b** 320 rad/s, **c** 272 rad/s

3 IoT Based Air Purifier Prototype

IoT is an interrelated system consists of network-enabled smart devices that use embedded systems, such as processors, sensors and mechanical systems, to receive, transfer and act on data they acquire from the environments. IoT enabled devices share the sensor data they collect by connecting to a network where data is either sent to the cloud to be analyzed or analyzed locally [10]. IoT based automation of air purifier prototype requires various components including Arduino UNO, Inlet Fan, UVC Light, DHT11, Humidity Sensor, Bluetooth Module, 9v Battery which are represented in Fig. 5. After the circuit is assembled, Arduino coding for giving instructions to microcontroller to control the connected components in a specific manner is done. Provisions are made in the design to perform both purifier and humidifier functions simultaneously or individually as per need. A Bluetooth module in the system is designed to receive specific input from user's smartphone or any other smart devices to operate the prototype. Interface shown in Fig. 6 for the operation of device is designed using MIT App Inventor. It has various options to operate manually as well as automatically as per user requirements.

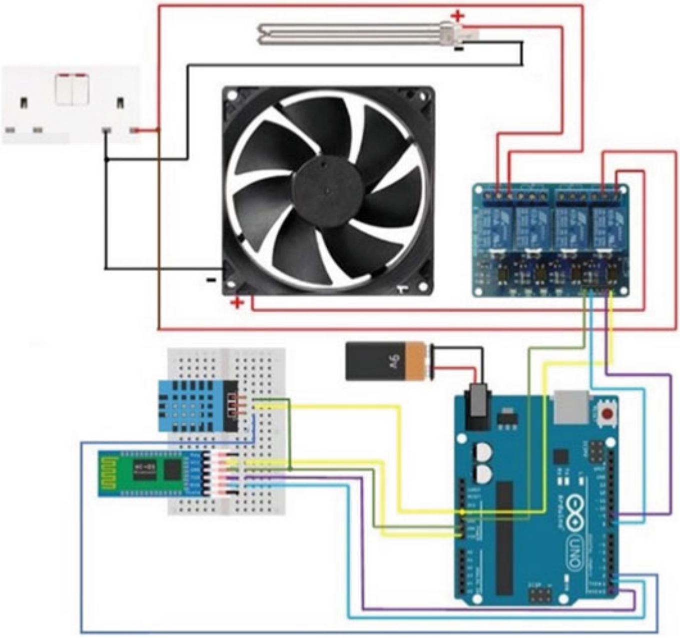

Fig. 5 Components of IoT based automatic system

Fig. 6 Operational interface

Smart Air Purifier

40

Desired Relative Humidity

4 PLC Based Simulation of Industrial Air Purifier

The concept for industrial air purifier can serve as a centralized system in many industries like manufacturing, medical, office, shopping complex and theaters. The schematic representation of industrial air purifier is shown in Fig. 7. It operates as purifier with self-cleaning capabilities and controlled by any internet enabled smart devices. In purifying mode, fan act sucks air due to negative pressure created inside the intake manifold. Then, the air passing through three layers of filters (including Activated Carbon filter to remove both NO_2 and HONO gases) before it is accelerated

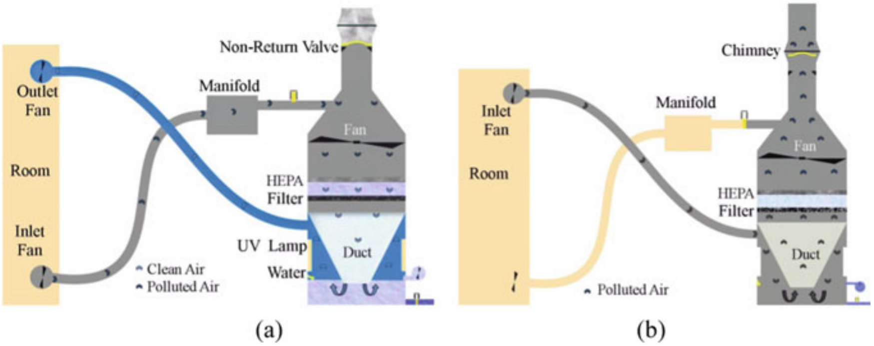

Fig. 7 Schematic representation of **a** purifying mode and **b** cleaning mode

in a duct to pass through the water bank and humidified [11]. Finally, filtered, odorless air suitable for the occupants is delivered to workplace. The cleaning mode is provided as a maintenance measure to clean the filter using reverse flow of the air. At the beginning of this process, an electronically actuated normally open valve is closed to prevent the polluted air from entering the workplace. Then, the fan sucks the air from the outlet part which is below the Filter bed. So, the sucked in Air passes through the filter and brings the particles along with its path. A gate hinged at the exhaust port opens up due to the air pressure. This is how the air will leave the purifier taking the filtered particles and hence cleaning it.

A programmable logic controller (PLC) is a ruggedized computer used for industrial automation. These controllers are capable to automate a specific process, machine functions or even entire production lines [12]. The automation studio software provides an excellent platform to design circuits and is used to do Ladder Logic Programming for PLC in this research work. Toggle switches are used as Human Machine Interface (HMI), while designing the circuits for PLCs.

Design of electrical circuits with components and the associated ladder logic program are shown in Figs. 8 and 9, respectively. The same is verified in the software itself using simulation function to ensure that all functional requirements are fulfilled. Table 2 highlights the labels and its functions used in PLC programs for simulation.

Simulation of the PLC automation for purification and cleaning process: When the purification toggle switch is activated, switch s_1 gets closed and current flows through OUT0, OUT1 and OUT4 which are corresponding to inlet fan located at inside the room, UVC lights as well as outlet fans inside the room and the main inlet fan inside the purifying unit. Thus, the purification process continues till the s_1 switch is opened by toggle switch. During operation, level switch s_2 keep monitoring water level in the humidifying chamber; get closed if below the specified level by passing current to OUT2. OUT2 is connected to a water pump to fill the water inside the

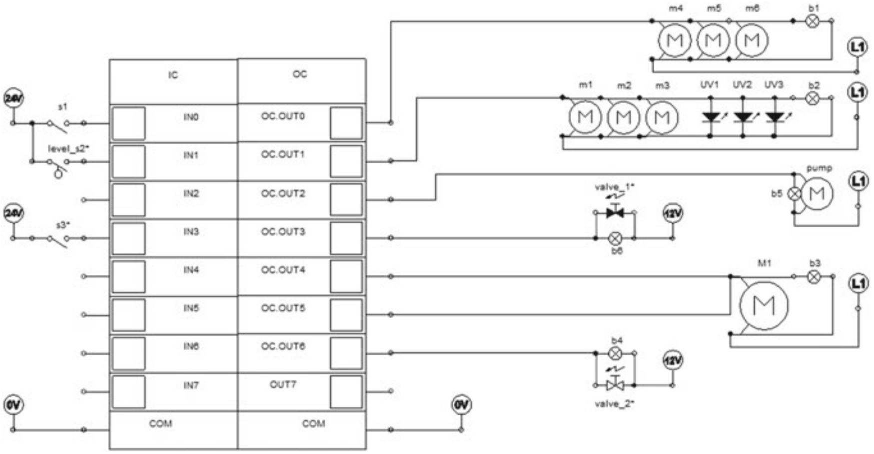

Fig. 8 PLC circuit diagram

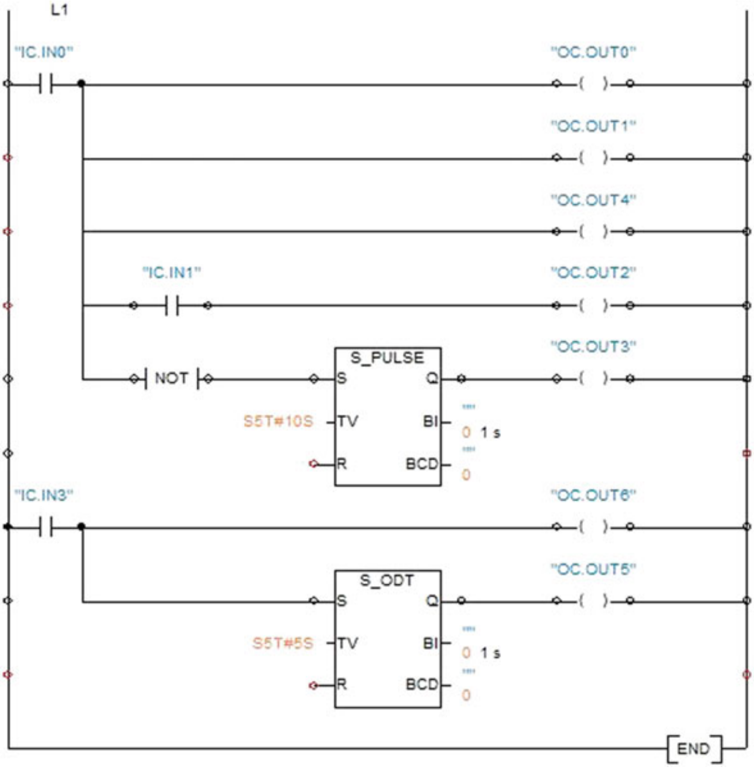

Fig. 9 Ladder diagram of PLC coding

Table 2 Defining the labels in PLC circuit

Labels	Components
m_1, m_2, m_3	Intake fan inside the room
m_4, m_5, m_6	Outlet fan inside room
UV1, UV2, UV3	UVC lights inside purifying unit
M1	Main inlet fan inside purifying unit
Pump	Pump to fill water inside purifying unit as humidifier
valve_1	Normally closed electronic valve
Valve_2	Normally open electronic valve
s_1	Initiate purifying
s_2	Level switch
s_3	Initiate cleaning

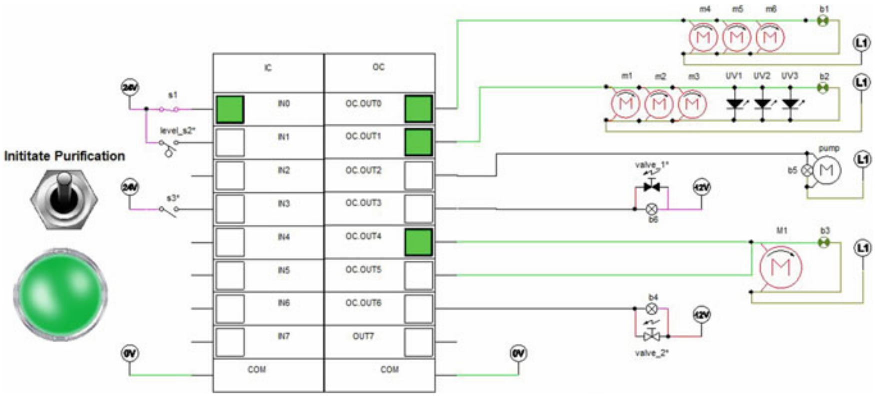

Fig. 10 Simulation of initiate purification command

humidifying chamber to allowable level so that level switch s_2 can again get open. When the users again toggle OFF the switch s_1, S_PULSE counter will get activated which will provide current to OUT3 for 10 s before completely opening the circuit. OUT3 is connected to electrically actuate normally closed valve which gets open to drain the existing water inside the chamber. The cleaning process is incorporated to facilitate cleaning of filters periodically per maintenance practice of the industry. To initiate this process, inlet valve located at inside the room is closed and main inlet fan inside the purifying unit starts rotate in opposite direction to force the pollutants from the filters to escape into atmosphere through chimney. When users activate toggle switch s_3, provides current to OUT6 and OUT5. OUT6 is connected to electrically actuated normally open valve will get closed which block the only inlet path to the room. OUT5 is connected to main inlet fan inside the purification unit, before switching on the fan in opposite direction S_ODT counter give 5 s to properly close the inlet valve. After, 5 s the fan will rotate in opposite direction to successfully force all pollutant away from filter. Figures 10 and 11 show the simulation results carried out using automation studio.

5 Conclusions

In this article, the concept, design and analysis of the prototype of a smart centralized air purifier system are presented. The simulation carried out in Ansys Fluent software ensures optimal design of air purifier for its intended use. IoT based operation of the purifier provide safe and efficient operation environment, Simulated operating conditions using Automation Studio facilitates industrial applications of centralized air purifier that eliminates air pollutants of 10 μm and above from the polluted air in the industrial environments. Thus an economical, smart and healthy air purifier is developed to suit industrial applications. The model is scalable and the effective

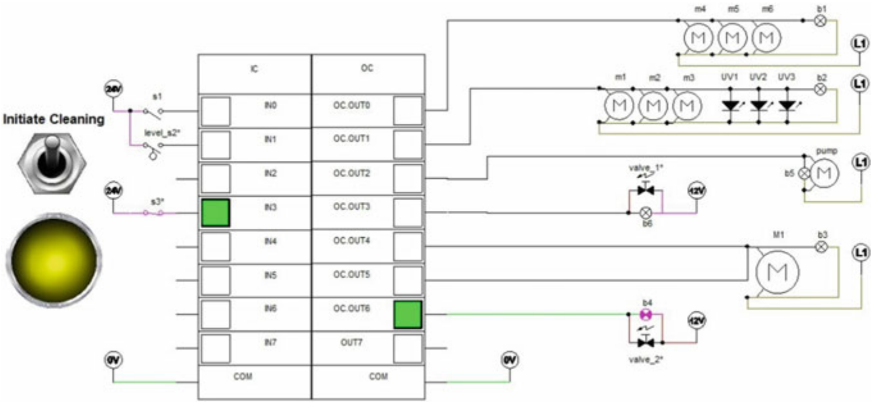

Fig. 11 Simulation of initiate cleaning command

area of the purifier can be altered with respect to specific industrial or large area air purifying requirements.

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