Type - 1 Fuzzy Based Cascaded Intelligent Multistage Ventilator Model: A Proposed Concept

Eshan Samanta, Samarjit Kar, Sagarika Pal, Partha Sarathee Bhowmik

***Abstract*—Resisting the coronavirus pandemic has now become a global objective for every human being. Though it is showing some outstanding mutation rates and seems it is difficult to fight without technological up gradation. The numerous genotypes of SARS-CoV-2 are acting as a rheostat in developing antidotes for any specific cure. The sustainability of SARS-CoV-2 might lead to an increase in the number of patients suffering from respiratory syndrome indeed. In this paper, we have discussed coronavirus and presented all the possible ways out from it with justified pros and cons as well. The resolution discussed for all the agendas entitled in this paper is basically a proposed idea of type - 1 fuzzy based algorithm for an intelligent ventilator to assist a maximum of up to 4 patients with weaker lung compliance. The entire model of cascaded concept is carried out using MATLAB environment and validated the same by introducing rule viewer and respective scope analysis indeed. In this present work it is verified that around more than 50% of risk factor eradicated in terms of lung collapse scenario or other relatable serious issues.**

***Index Terms*—Ventilator, Fuzzy Logic Controller (FLC), Acute Respiratory Distress Syndrome (ARDS), Functional residual capacity (FRC), Lung Compliance**

I. Introduction

Controlling the effects of the SARS-CoV-2 pandemic is exceedingly challenging in the current situation. Despite the fact that history has demonstrated that the effects of pandemic disease are Spanish Flu, a pandemic influenza outbreak, was extremely hazardous and occurred in 1918. The discovery that Tyrrell and Bynoe could spread a virus known as B814 marked the beginning of the history of human coronaviruses in 1965 [1]. At about the same time, Hamre and Procknow invented 229E, named coronavirus [2]. The prior OC viruses discovered by McIntosh et al. and the 229E agent discovered by Hamre and Procknow shared a similar morphology. Tyrrell oversaw a team of virologists who worked with human strains and other animal viruses in the late 1960s. They included the transmissible gastroenteritis virus of swine, mouse hepatitis virus, and infectious bronchitis virus, all of which had been shown to be morphologically identical as observed through electron microscopy. The coronavirus term, which refers to the surface projections' crown-like appearance, was given to this novel group of viruses before it was formally recognised as a new virus genus.

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The severe effects of the coronavirus first appeared in 2002–2003 as the SARS–CoV, which originated in southern China and spread with measurable speed throughout the entire world. Although the virus's origins are not entirely understood, it is thought that it may have originated in bats and was later transmitted to Himalayan civets based on the research of several virus genomes. But in 2012, a new lethal pandemic disease called Middle East Respiratory Syndrome Coronavirus (MERS-CoV) emerged, killing a significant portion of the population [3]. Again, it is thought that it might have started in bats and spread to camels in the distant past. The coronavirus is making a dangerous comeback in 2019 along with some truly new characteristics. The host mutant is believed to be this time pangolin with 99% genetically confirmed. It has been first predicted in china by December 29, 2019 [4]. The first place it is registered is in Wuhan. The rate of mutation for this new coronavirus is exceptional. Based on factors like the climate and other factors, it can adjust to the circumstance. Due to the extremely rapid rate of mutation, it has instead evolved several different genotypes. The coronavirus in question is genetically identical to SARS-CoV, which is why it has been given the moniker SARS-CoV-2.

Owing to the new characteristics of SARS-CoV-2, it is difficult to create antidotes as quickly as is needed worldwide due to the significant loss of human life and to rescue humanity as well. Only close contact between humans can result in the transmission of coronaviruses. It basically attacks the pulmonary system and kills people randomly with weaker lung compliance. Humans die due to Acute Respiratory Distress Syndrome (ARDS) [5]. The only method to stop this transmission is to keep a specified amount of social distance for a set amount of time. But in the case of densely populated country, this idea of social distance will not work at all. Thus it requires a sustainable medical care system. And it is also important to take care of the doctors and nurses by considering their safety measures indeed. The rest of the paper presents the same by framing the sections with related works, the effect of SARS COV 2, background mathematics, proposed method, results and discussions, future research direction and subsections framed with fuzzy system rules, fuzzy logic controller, membership function. Finally, the main conclusion and contributions have been discussed in the section X.

II. Related Works

Madekuroza et al. discussed a cheap ventilator in terms of classical traditional ICU ventilator [6]. In [6], a new concept based ventilator has been discussed with limited features. The purpose of the concerned ventilator is to meet the demand and supply ratio during the pandemic. Rather in the conclusion part, the authors have claimed that the motivation of their research is to design a cheap ventilator for middle income countries. The shortage of ventilators is not very new agenda at all. This was first recognized in [7]. The most important point is that the issue of this respiratory disease is now a kind of global incident [8], [9]. But the same problem usually initiated around 10 years ago from now. Raymond et al. [10], [11] have discussed high class, low cost emergency ventilator. They proposed a novel approach to design one mechanical ventilator compared to traditional mechanical ventilators employed for a few decades. Many papers have discussed related ventilators, specifically mechanical ventilators like [6], [10], [12]. Whereas incorporation of Artificial Intelligence (AI) was introduced in the year 2021 by Jayant Giri et al [13]. In [13] the authors have proposed a new concept by introducing cost effective intelligent mechanical ventilator using MATLAB software simulation and validated. The authors have validated by developing an optimal model using PEEP,PIP and other parameters to ensure that for a single patient a very cost effective AI based mechanical ventilator is possible. In [14], the authors have discussed regarding a ventilator by implementing fuzzy and neural network analyzer as well. The main objective of [14] is to identify the non linear respiratory system and to investigated the same. The authors have incorporated both Gaussian and triangular membership functions to design the concerned FLC. These articles are basically prepared by considering a single patient. The motto of these systems is to introduce a portable or cost effective ventilator for low income or medium income based countries.

The issue of developing a vast supply management system for large populations somehow like China and India, then the previous researches are not that easy to inculpate for any reliable medicare services at all. To eradicate the problem of convenient demand and supply management ratio multiple objective oriented smart ventilator is very much effective under this critical scenario. Nowadays in India, adenovirus is also taking charge over corona to take another control over mankind, thus a sustainable technology is required to be established for a reliable and peaceful future indeed.

This paper has three main contributions : 1) First time a cascaded concept introduced using type 1 fuzzy logic in controlling ventilation system for multiple patients. 2) Proposed an idea of developing intelligent ventilators by reducing overall cost of investment in buying expensive ICU ventilators. 3) Proposed an idea of eliminating Bag Valve mask (BVM) type of mechanical low cost ventilator which is far dangerous to collapse the lung compliance due to excess pressure if delivered. Table I represents the novelty of the proposed concept as compared to the previous work carried out after incorporating fuzzy algorithm.

III. Impact of SARS-COV 2 in human body

In electron micrographs of negatively stained preparations, coronaviruses, which are medium-sized RNA viruses, have a very distinctive appearance. The nucleic acid is single stranded, positive in nature, 30 km long, and polyadenylated. The largest known viral RNA is called RNA, and it codes for a substantial polyprotein. Viral-encoded proteases cleave this polyprotein to produce the following: OC43 and several other group II coronaviruses contain a surface hemagglutinin-esterase protein, an RNA-dependent RNA polymerase, and an ATPase helicase [17]; the membrane glycoprotein (M protein), the big surface glycoprotein (S protein), which creates the petal-shaped surface projections, the tiny envelope protein (E protein), and the nucleocapsid protein (N protein), which interacts with the RNA to form a complex [18]. Several more ORFs' coding purposes are unclear. A nested collection of messenger RNAs with shared polyadenylated 3-ends is used by coronaviruses as part of their replication mechanism. The translation just includes the 5-end's distinctive part. In nature, mutations are frequently seen. Additionally, if two coronaviruses infect the same cell at the same time, the viruses can recombine genetically.

IV. The ventilators - Best Resolution

The era of viruses are now typically considering respiratory tract as common section to attack and set infections. Most of the cases are found related to respiratory issues since last couple of years. In that case it is obvious that coronavirus including adenovirus as well and somehow might some other viruses or something else might occur or evolve, might encounter with certain respiratory tract and thus excellent improved and advance form of ventilators are very much required for excellent medicare facilities throughout the world.

1) In view of the foregoing disadvantages in terms of demand supply management after considering the conventional ventilators during this serious pandemic scenario.
2) It is therefore an object of the present work to provide the solution of existing problems associated with the cost effectiveness of the ventilators due to one to one arrangement.
3) The present research work also aimed to provide a solution for developing an intelligent ventilator to feed four patients together.
4) The present smart invention also provides a solution to protect patients' lungs from getting collapsed due to excess use of ventilator by providing one safety piston too.
5) The object of the present research is to protect doctors and nurses from the infections by automating the monitoring system and reducing the frequency of visits to the patient.
6) Yet another object of the present invention is to provide sustainable solutions for any respiratory disease inculpated patients.
7) Another objective is to provide a cost effective setup using ventilators with an autonomous features using the intelligent algorithm that could save up to few millions.

V. Cascaded concept - An Overview

The concept of cascaded FIS was first introduced for intelligent relaying purposes in the year 2020. The concept is

TABLE I: Taxonomy based novelty analysis

Sl. No.	Publications	Contribution based on single ventilator design			
		Cost effective	Multiple Patient	Safety to Medical Experts	Trachea Pressure
1	H.Zhu et al. [14]	Yes	No	No	Yes
2	H. Kwok et al. [15]	Yes	No	No	No
3	J. Giri et al. [13]	Yes	No	Yes	Yes
4	H. Guler et al. [16]	No	No	No	Yes
5	Proposed Cacaded Method	Yes	Yes	Yes	Yes

proposed by Samonto et al. [19]. The cascaded FIS concept for intelligent ventilator is shown in Fig. 1. From Fig. 1 it is clear that multiple back to back FIS connected to execute any rule based learning mechanism is generally termed as cascaded FIS. Now in this work the number of stages considered is three only. This ventilator will collect information based on trachea pressure and volume of the lungs to decide lung compliance in the first stage. Then in the second stage, both lung compliance and flow of oxygen to the lungs will be considered as variable functions and based on these, two solenoid valves connected to the oxygen cylinder will operate. Finally, while entering stage three, each valve is considered as input this time and a special piston are controlled to provide the exact amount of oxygen to the specific patient.

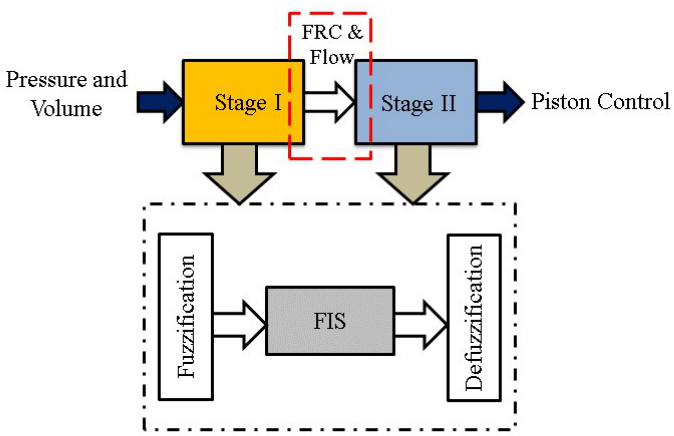

Fig. 1: schematic block diagram of cascaded concept showing internal operation of Stage I and Stage II with a dotted border

VI. Background Mathematics

The physical characteristics of a material, such as whether it is solid, viscous (fluid), or viscoelastic, determine the relationship between stress and strain. Young's modulus (Y), a proportionality constant, governs how stress and strain are related in elastic materials [20],

$$Stress = Y strain \tag{1}$$

In the context of pulmonary mechanics, stress is PL and strain is the ratio of tidal volume (VT) and functional residual capacity (FRC), [21]

$$P_L = K\frac{VT}{FRC} \tag{2}$$

Where K is a PL equivalent measure of specific lung elastance, which increases lung volume to an amount equal to the FRC. Clinical investigations have estimated the specific lung elastane (K) in humans to be around to 13.5 cmH2O [22]. It remains normal in baby lung in ARDS, supporting the concept that baby lung is not stiff, but small healthy lung [23].

Now, from equation 1, it is very clear that as the ventilators induce external pressure to the lungs so in that case it is somehow very much risky in terms of optimum pressure to be maintained within the respiratory tract. If in case this is not considered seriously then patient might die due to excessive pressure injection. Again, in equation 2 it is clearly shown that FRC is inversely proportional to the pulmonary stress. This resembles that FRC has to be a controllable parameter to design any intelligent ventilator or might be conventional mechanical ventilator as well.

VII. Proposed Method

It is difficult to produce long-lasting antidotes as quickly as it is necessary in the entire world owing to the enormous loss of humanity and to rescue humanity as well, due to the innovative qualities of SARS-CoV-2. In that circumstance, only close contact between humans can result in the transmission of any of these corona viruses. Basically, it affects the respiratory system and randomly kills persons who have less lung compliance. Acute Respiratory Distress Syndrome (ARDS) caused the individual to pass away. The only method to stop this transmission is to keep a specified amount of social distance for a set amount of time. But in the case of the densely populated country, this idea of social distance will not work at all. Thus it requires a sustainable medical care system. And it is also important to take care of the doctors and nurses by considering their safety measures indeed. More particularly, the main objective of this ventilator model is to provide service during huge demand and its automated monitoring system ensures relaxation to the entire medical team for not reaching the infected p[patient frequently and simultaneously, they could be saved. In terms of cost effectiveness it will also save many millions if evaluated by considering conventional ventilators of this generation indeed. Here in Fig. 2, it is clearly shown that the intelligent ventilator is designed using a fuzzy logic controller. A new concept by cascading multiple fuzzy inference system is introduced to develop this ventilator algorithm. In Fig. 3, a complete proposed setup is shown on how exactly the ventilator will work to feed four patients together. An ODD EVEN pattern is followed to provide an interlock valve mechanism system by introducing a solenoid valve. This will provide more safe oxygen to each and every patient without infecting each other. And this will reduce the complexities among the doctors and nurses as well.

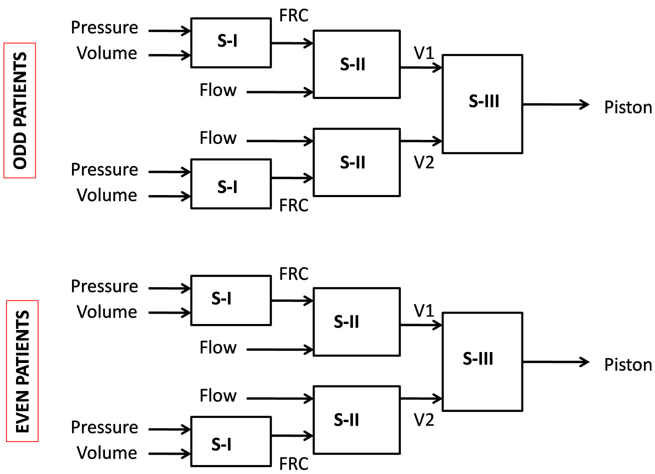

Fig. 2: Block diagram of intelligent ventilator

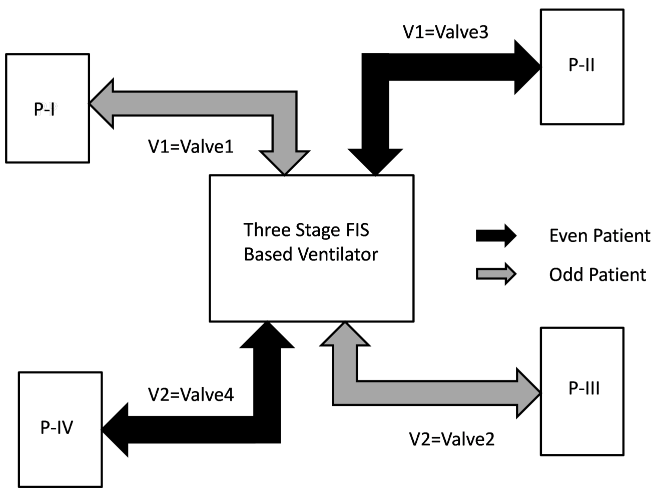

Fig. 3: ODD EVEN concept schematic

A. Surface View

The rules declared for cascaded intelligent ventilators are now thoroughly viewed by justifying the concerned surface view of the FIS developed under MATLAB environment. In Figs. 4,5,6 an extended figure of the surface view has been explained in terms of Figs. 7,8,9 for the proper validation. The surface view is a GUI tool that let us examine the output surface of a particular FIS stored in a file, for any one or two inputs. In this work all the membership functions are considered by taking three separate status of the input parameters. The most commonly incorporated terminologies are Low, Moderate and High. In the surface view section in Figs. 4,5,6 three different colors are visible. Yellow color represents the high MFs, whereas blue and indigo indicate moderate and low respectively. In Fig. 4, from the yellow colored section, it clearly shows that as per learning rules, if the pressure is low Functional Residual Capacity (FRC) is high. Likewise blue color indicates that the FRC is moderate and the indigo ensures the low value of FRC. In Fig. 5, again yellow colored portion ensures that in case if FRC is high then the valve has to activate open fast MF. Here, a green colored surface indicates open slow MF which is actually imposed for low FRC and maximum flow condition. The deep blue surface indicates the close slow MF and the indigo portion ensures the close fast MF as designed for valve section while developing MFs. In Fig. 6, it is clearly showing that the status obtained from stage II ensures the position of the piston. Pmax indicates the maximum position of the piston in case if all the valves are open. The yellow surface ensures the same in Fig. 6. The indigo here reflects the status of piston position in case one valve remains activated depending on flow, FRC and volume as declared in stage I and stage II previously.

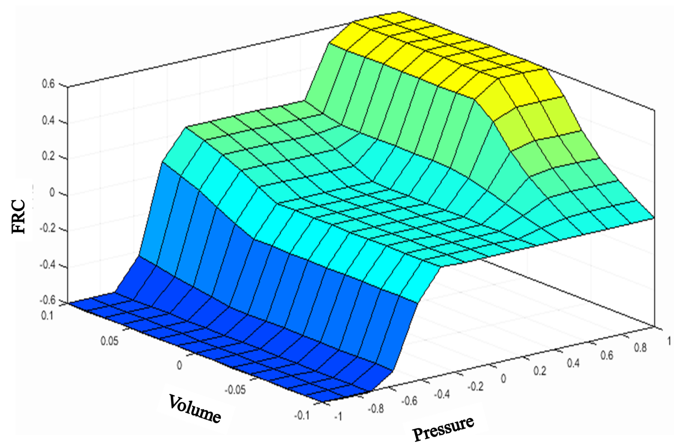

Fig. 4: Surface View of First FIS

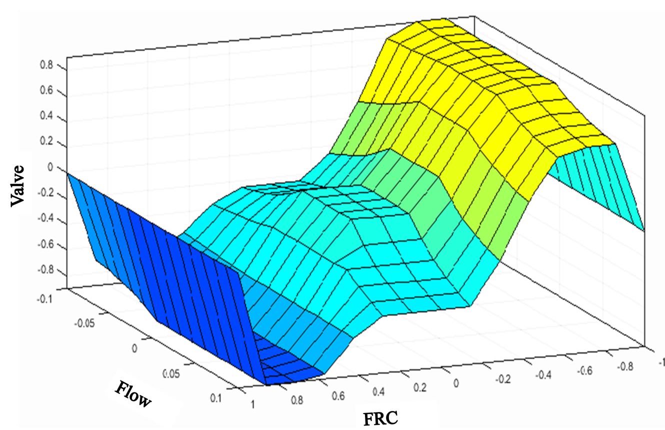

Fig. 5: Surface View of Second FIS

B. Membership Function

In this work, the triangular membership function is considered. The main motivation behind this decision is very clear. As in this case as the sequences of the overall work-flow are very instantaneous so, in that case, it is hereby considered to inculpate the triplets for designing the entire rules of this cascaded FIS based intelligent ventilator. In this section, a detailed analysis of the membership functions is carried out for all three stages of cascaded intelligent ventilator using triplets membership function (MF) only. Fig. 7 indicates that

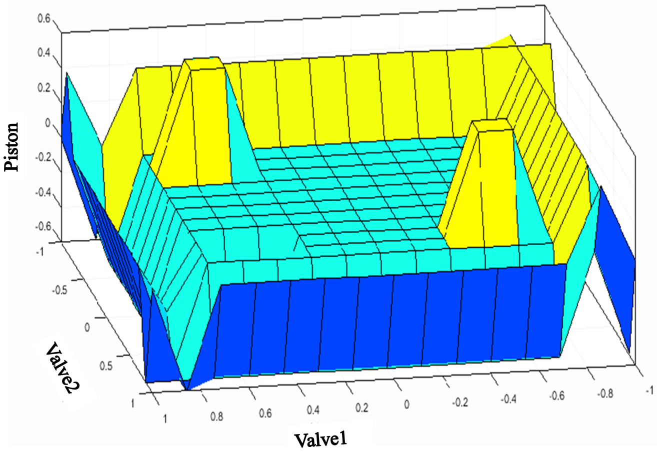

Fig. 6: Surface View of Third FIS

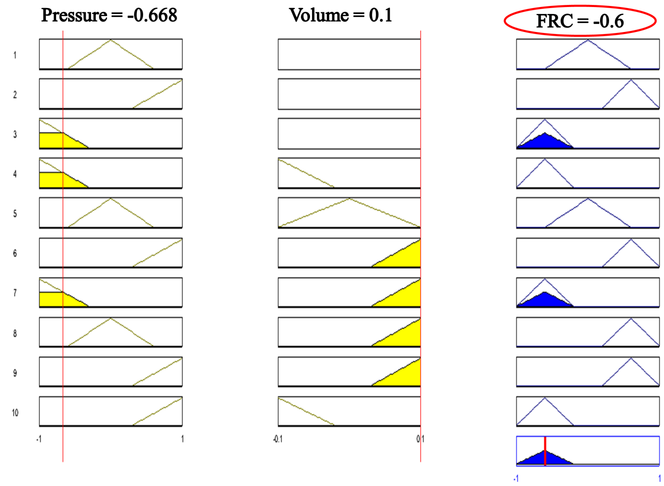

Fig. 7: FLC Rule Viewer for stage I

if trachea pressure is high and lung volume is high, then lung compliance is low. As per the theory of medical science [24]–[26], this is absolutely perfect and thus authenticated using a simulation model. In Fig. 8, it is clearly showing that the red circled FRC is low, as Fig. 7 and the flow of oxygen is high. As per the learning rules the solenoid valve must open in a very moderate way which is neither slow but tends to fast indeed in this case. This picture is very clear in Fig. 8 with a green colored circle. From Fig. 9 it is very prominent how two valves are together providing the concerned FIS for optimum piston pressure to safely assist the patient to inhale oxygen from this proposed smart ventilator. So, from the above explanation, it is clear that this ventilator will collect information based on trachea pressure and volume of the lungs to decide lungs compliance in the first stage. Then in the second stage, both lung compliance and flow of oxygen to the lungs will be considered as variable functions and based on these two solenoid valves connected to the oxygen cylinder will operate. Finally, while entering stage three, each valve is considered as input this time and a special piston is controlled to provide the exact amount of oxygen to the specific patient. The concept of ODD EVEN configuration is to provide an interlocking valve mechanism to provide oxygen to all four patients without mixing the exhale among all four patients indeed.

C. *Fuzzy System Rules*

The fuzzy algorithm has been incorporated as an intelligent ventilator to feed the signal to the valve for controlling the lung compliance. Overall, three sets of rules have been introduced considering each stage. Among these rules, some rules are taken by accessing pressure, volume, and FRC in case of designing stage I black box as shown in Fig. 7. In Fig. 8, that is stage II, the entire rules have been presented by considering FRC and the flow of oxygen as input to the black box and the final manipulated output is taken as a valve. Now after the execution of valve it is also important to check which valve must be operated based on the ODD EVEN concept. Fig. 9 ensures the third stage of the entire proposed technique of intelligent ventilator. Here, two sets of valve system is

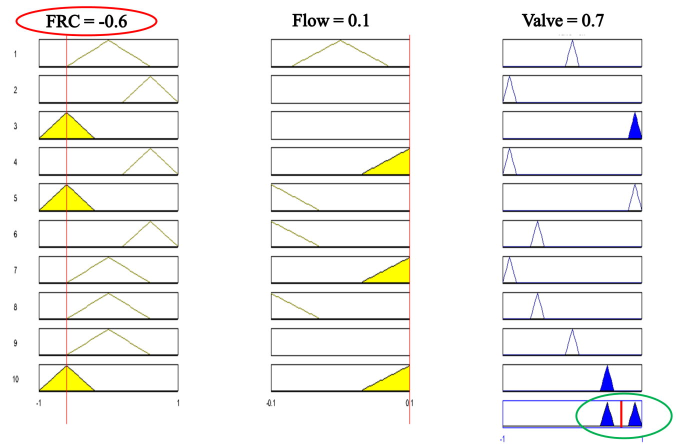

Fig. 8: FLC Rule Viewer for stage II

considered for each set of the patient in terms of the ODD EVEN concept. The status of the valve actually controls the position of the piston to maintain the oxygen flow to the patient. Overall 30 rules have been designed for developing a learning system for the smart ventilator. Each stage comprises of 10 rules only. Stage I ensures the status of FRC, stage II ensures the status of the valve and stage III controls the piston for inhaling and exhaling.

VIII. Results and Discussions

In this section, a detailed analysis of the simulation results is presented. In Figs. 10,11,12 it is explained how the three stages of an intelligent ventilator work under three different modes of operation. Fig. 10 demonstrates properly about this proposed smart ventilator which is validated using a simulation model. In Fig. 10 output performance of the piston is clearly shown. Here, Pmin is considered as the minimum pressure required by the piston to provide optimum oxygen to the concerned patient indeed. That is why along the positive scale of the universe of discourse, Pmin is not actually 100% low but still required to provide minimum oxygen to the patients is needed. But the picks are shown along the positive discourse as well as negative discourse too due to ambiguous learning

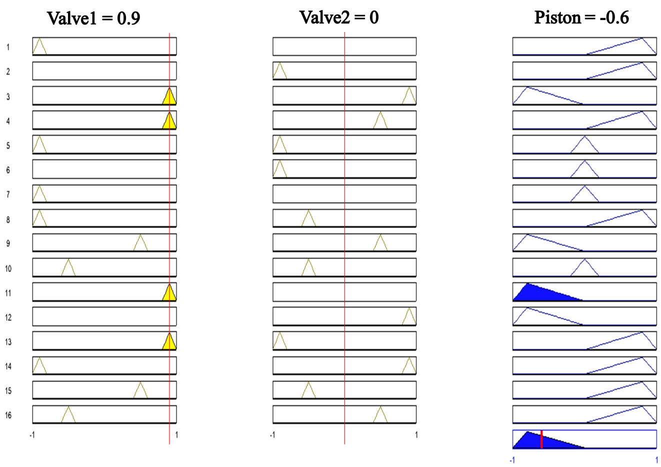

Fig. 9: FLC Rule Viewer for stage III

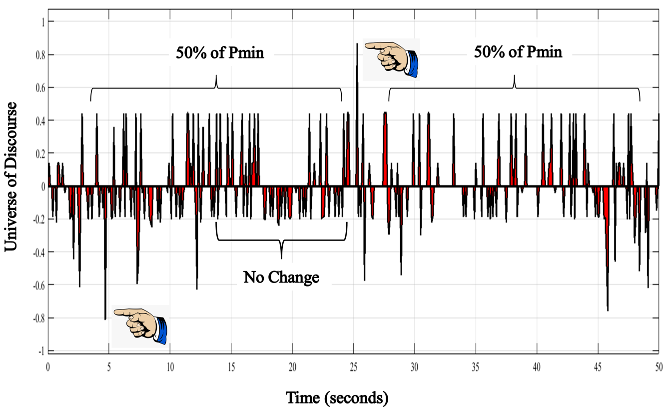

Fig. 10: Output during Normal Lung Compliance

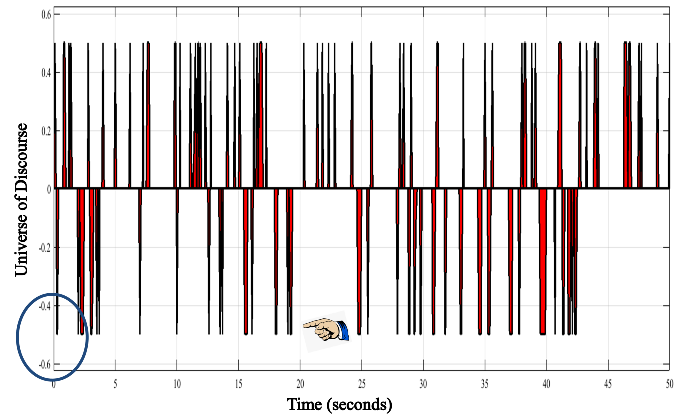

Fig. 11: Output during Moderate Lung Compliance

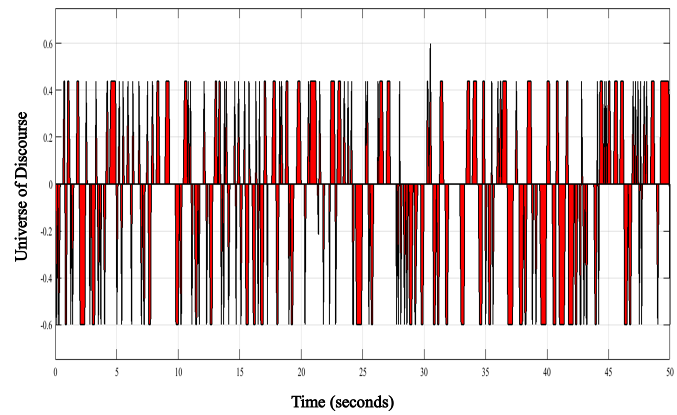

Fig. 12: Output during Critical Lung Compliance

based on rules. Fig. 11, ensures the valve is operating under moderate situation and thus along the positive axis with respect to universe of discourse it is clearly showing that the required valve is found closed as compared to open. In Fig. 11, the blue coloured mark indicates that the valve itself is giving optimum output as alternate spikes are authentic. And the maximum pick is registered based on the designed membership function. Fig. 12 tells a lot about the critical scenario in case if patients require urgently during an emergency then how will the intelligent proposed ventilator work. The spikes are so frequent and the rise level is high enough to indicate and confirms that the piston position is following a sustained to and fro motion due to critical lung compliance of any concerned patient. This work also eliminates the need of bag valve mask which is implemented for providing rescue ventilation to patients with apnea or severe ventilatory failure. Since the second stage itself is controlling the flow as well and so it will automatically detect the volume of oxygen and limit the same instantly. Whereas, in case of BVM this facility is almost next to impossible and thus rise a high concern for lungs collapse or failure indeed.

In the present scenario densely populated country utilizing mechanical ventilators in the hospital especially in the ICU section. This ventilators costing around 7.5 Lakhs INR and is only capable of providing support to only one patient as of now. The proposed ventilator is intelligent enough to provide support to more than one patient at a time with the same costing but reducing the number of ventilators spaces within the hospital arena. Whereas, for one patient as per conventional model entire costing is around 7.5 Lakhs INR. Now considering four ventilators for separate four patient it will cost around 30 Lakhs INR. But in case of proposed method based developed prototype the costing will reduce to around 10 Lakhs INR and this drop ensures a saving of around 20 Lakhs INR for every four ventilators. The conventional ventilators are risky enough to induce the susceptibility in case of serious concern to the medical team as well. Whereas the intelligent algorithm is smart enough to monitor the patients automatically but preventing medical team to approach frequently to the risky patient as well and maintain a controlled ambience within the system.

Before concluding this work let us first take a look for what reason four patients have been considered in this proposed design of ventilator. In general normal adult breath approximately 15 times per minute [27]. So clearly each cycle comprises of 15 times breathing rate only. In that case it is possible to accommodate overall four cycles in a minute and that is why the design is confined to maximum four patients only. As 15 times breathing rate for four patients total coverage is 60 which is very much rational and reliable to include within a minutes which comprises of actually 60 seconds.

IX. Future Research Direction

The proposed concept is very much effective until the solution of most challenging part resolved. The four patients together in case if inhale and exhale then there will be a problem of backflow. Earlier this problem was solved using air duct damper but for backflow odor and for single patient only [28]. Along with air damper a customized intelligent valve has to be developed and already we are working on it and soon it will submitted to intellectual property rights office. Application of neural network along with fuzzy controller will also enhance the working ability of this concerned intelligent ventilator. Apart from this since typical Mamdani FIS ensures multiple solutions, so, in that case incorporation of Fractional FIS [29], [30] is more valuable to this significant research content for better medical facility.

X. Conclusion

In this paper, an intelligent advanced ventilation system is discussed by introducing cascaded FIS technology. The impact of introducing such an advanced ventilator is to improve the medical service throughout the country during the pandemic or might be other emergencies.

1) A cost effective authentication under a simulation model using MATLAB environment. This will feed four patients together by saving four separate ventilators that could have been incorporated earlier.
2) The overall setup will balance the demand and supply management curve in terms of patients and the number of ventilators required.
3) The cost effective ventilator, wherein a new technique has been introduced to organize the functionality of intelligent ventilator by introducing ODD EVEN concept for a smooth flow of oxygen to the patient by incorporating the one way valve in the system for protecting each of them from getting infected due to individuals exhale.
4) The SMART ventilator ensures the autonomous monitoring of pressure and volume of the trachea, lung compliance, inhale rate and oxygen flow as well.
5) The proposed intelligent ventilator of claim 1 to 5, wherein will bring the evolution in the history of medical science.
6) The proposed ventilator allows a user to operate smoothly because of its simple algorithm.

The motto of improving emergency service with higher cost effectiveness including the life safety of various medical teams is also considered as the most important objective and motivations of this concerned research work.

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