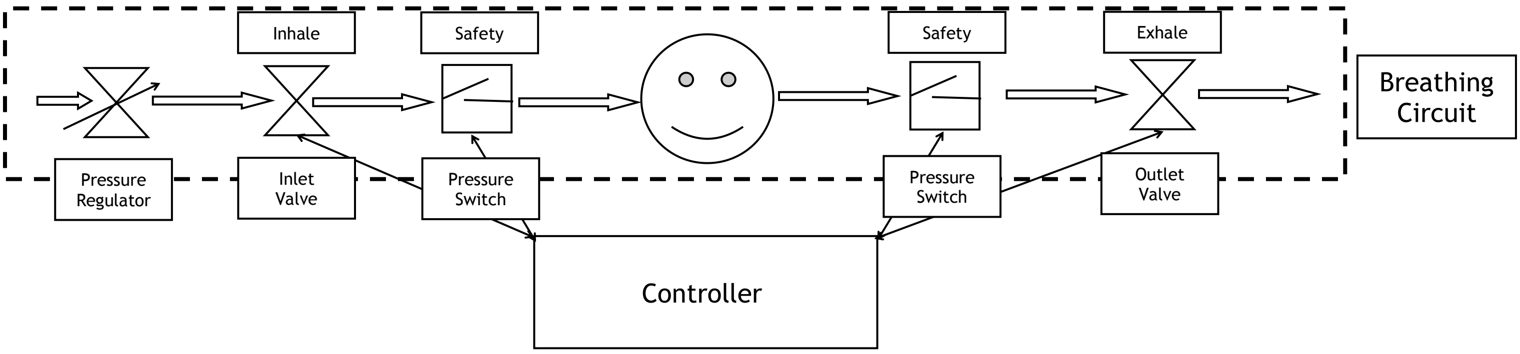
VentAid: A Low Cost Ventilation Aid for COVID-19 Patients using Off-the-Shelf Component
A Proposal

Goal:

√ Low Cost
√ Easy to Manufacture/Assemble (very short Turn Around Time)
√ Very Basic in Nature (but with Provision of Future Expansion using Modules)
√ Manual Mechanical Inlet Air Pressure Control
√ Flow Control (Inhalation/Exhalation Timing Control)
√ Repetition Rate (Breathing Rate) Control
√ Safe (built-in Alarm System)

Limitation:

- Not Ready for Intensive Care Use
- Patient Flow Pattern can't be Programmed
- No Backup Power (but System Failure Alarm using Battery Power can be added.)
- Uses Pressurized Air/O2 Supply available in Most of the Modern Hospitals, thus does not have own Air/O2 Source (can be used with any other Pressurized Air Source including Air Compressor though.)



System Block Diagram

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Introduction:

VentAid is not designed to replace any Proper Medical Ventilator, instead it's aim is to 'Aid' in Ventilation for Patients who are in dire need during COVID-19 Outbreak; by using Infrastructure already available (Compressed Air/O2 Supply) in Hospitals. Another Goal is to use/modify Modules/Kits already Cheaply Available in Bulk with 'Jelly Bean' Components to Integrate the Whole System (to Reduce Overall Cost & Delay in Assembly; as Stated with Other Goals in the Beginning.). If need arises (GOD Forbid, it should never arise!), Assembly/Integration of the Complete System should be 'Doable' with Minimal Training & Effort which will help in Rapid Deployment.

VentAid does not Conform to any of the Medical Equipment Standards at Present but can be Modified to do so if necessary for it's Use. This Responsibility Relies on the Entity intends to use this Design (not on me) & should follow the Necessary Medical Standard Applicable for it's Territory. I've released the Design under GPL2.0 (It's Applicable Primarily for Distributing Source Code but it's the Closest I could get.), so; all it's Conditions apply to VentAid. It's Primary Focus during Development was to Help the Contingency Pandemic Situation.

E-Vent by M.I.T. Team is One of the Best Open Source 'Proper' Ventilators available at Present (I've learnt a lot from them.) & should be the Preferable Option if Need arises. It Conforms the Medical Standards too. However the Device Presented here tries to solve the Problem from Different Angle with Minimum Sustainable Functionality & not Directly Comparable with E-Vent or any such Efforts.

Theory of Operation:

VenAid Consists of 2 sub-systems; Mechanical (the Breathing Circuit) & Electrical (the Controller). Breathing circuit is primarily responsible for delivering the compressed air supply to the patient but it's under the supervision of the controller for timing & monitoring purpose. VentAid is pressure (Positive Pressure) controlled mechanical ventilator (P.C.V.) in nature.

Inlet (Inspiration Part) of the Breathing Circuit has to be connected to the In-House Pressurized Air/O2 Supply using a Manual Mechanical Pressure Regulator (with a Pressure Gauge) (often this Pressure Regulator with a Humidifier is part of the Existing Air/O2 Delivery System & each Air/O2 Outlet has one with it.). Maximum Safe Pressure required to deliver Right Amount (Volume) of Air/O2 to the Patient has to be set by adjusting this Regulator by Doctor/Respiratory Therapist. Inspiration Valve allows the Air/O2 to reach the Patient. Pressure Switch acts as a Safety Measure & triggers the Alarm if Pressure is too low in the Breathing Circuit. Expiration Valve allows the Expired Gas (consisting of Dead Space Gas and Alveolar Gas) to Vent (Exhale). Controller supervises the Timing of Inspiration & Expiration Valves, Breathing Rate (Breaths per Minute) & Inhalation to Exhalation Ratio can be adjusted by it. Alarm Unit notifies (Auditory/Visual) reg. the Fault Conditions; namely Controller Failure & Air/O2 Supply Failure.

Alarm Unit can be omitted if necessary as Operation of the Controller does not depend on it. End Delivery Method/System (Endotracheal Tube, Face or Nasal Masks etc.) can be chosen as per Patient's Condition & according to Doctor's Advice. Only Requirement from VentAid is, it needs two different paths for Inhalation & Exhalation (a 2 Limbs System). Though modification of the Breathing Circuit & the Controller is possible to accommodate Single Limb System. Oxygen Saturation Level in Blood is to be monitored by a Pulse-Oximeter as VentAid does not have any provision to do it on it's own.

VentAid is Portable as it can be Powered by a Single 9V Battery & can be connected to Medical Oxygen Tank for Air/O2 Supply, under Proper Administration for Obvious Reasons.

Controller:

Description/Assumption:

The Controller is built around Very Popular & Cheap 555 Series I.C. It's Primary Responsibility is to Control the Timing & Repetition Rate of Breathing (Inhalation/Exhalation Ratio & Breathing Rate) by Operating (Opening/Closing) the 2 Solenoid Valves (Part of Breathing Circuit) connected to it. Both Breathing Rate & Inhalation/Exhalation Ratio can be adjusted within Predefined Minimum & Maximum Limits. Another 555 I.C. takes care of the Alarm for Fault Conditions. The Design is Completely Analog in Nature & does not depend on too tight Component Tolerance Specification to Operate. Off the Shelf Components can be used to Construct the Controller Unit, even readily available 555 P.W.M. Controller & 555 Timer Modules (these are Very Cheap & Available World Wide through different Suppliers.) can be modified (according to the Design) with Off the Shelf 'Jelly Bean' Components to produce the Controller & Alarm Unit respectively.

I've not gone for Micro-Controller based (they're great & I'm aware of that many Excellent Arduino based Open Source Ventilator Designs are available.) Design on Purpose for keeping the Design Simple, Cheap & Easy to Produce & without any need for Programming to make it Ticking.

Specification:

√ Breaths per Minute (B.P.M.): Min. ~5 to Max. ~15 (Continuously Variable)

√ Inhalation to Exhalation Ratio (I:E): Min. ~1:1 Max.

√ Fault Indication Detection:
- Controller O/P Stuck at 'High' (Inhalation Cycle)
- Required Air Pressure not available in Breathing Circuit

√ Alarm: Visual Indication via L.E.D. but a Small Piezo Buzzer can be used in Place of L.E.D. for Auditory Indication

√ No. of User Control I/P: 2 (B.P.M. & I:E)

√ Power Supply: 9V (can be Battery Powered)

Operation:

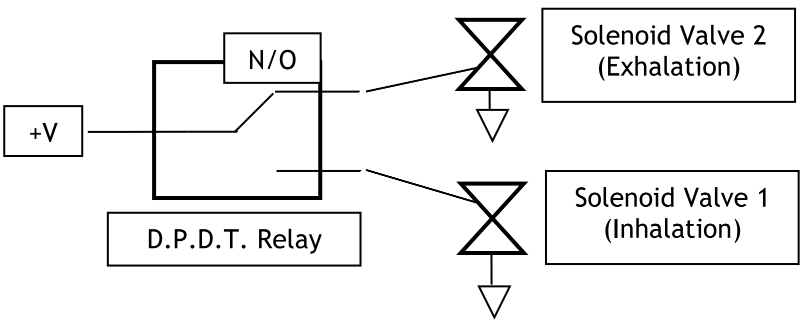
The 555 is configured as A-Stable Multi-Vibrator in Controller Part with Provision to adjust the Duty Cycle (P.W.M.) & Frequency which in turn controls B.P.M. & I:E. There're different ways to achieve the same Goal, only Special Consideration here is for Dual Diode Resistor Divider Network & the Values of 'R's & 'C'. R3 & R5 (as LTSpice does not have any Potentiometer Model!) in Schematic has to be replaced with a ~288K (nearest available value will do just fine.) Linear Potentiometer. Rider of the Pot. has to be connected to the D1D2* Node, One End should connect to R8 & Other End should go to R2. This Part controls the Duty Cycle. R4 too should be replaced with a ~576K (again, nearest available value will do just fine.) Linear Potentiometer, Rider should be connected to C2; while one of the Ends should connect to R8D1* Node. O/P Pin of 555 I.C. is connected to a Regular N.P.N. Transistor which drives the D.P.D.T. Relay (again LTSpice does not have any Relay Model! I've placed a Regular Coil with Random Value for Simulation, you can notice the Small Spike due to Inductive Kickback in Simulation Results. D3 is Freewheeling Diode & should be present in D.P.D.T. Relay Connection.). Solenoid Valves (2 in Total) are to be connected to the D.P.D.T. Relay according to the Wiring Diagram. Pressure Switch (Type: Normally Open, Closed at Desired Pressure) is to be connected in series with the Alarm I/P Line (Ref. Wiring Diagram). This Switch can be omitted if desired (it may be difficult to procure.) but it's highly recommended to put it in place as this is the only way to detect the Air/O2 in Breathing Circuit (in Current Configuration) or Absence of the Same (Alternate Configuration, will be updated in Next Release.).

Alarm Circuit is designed using another 555 I.C. Basically, it's wired as a Classic Missing Pulse Detector (ref. Application Notes in TI 555 Datasheet.). It's Time Constant is set at ~20s (slowest Time Period of the Controller is ~12s.). If the Controller O/P got stuck at 'High' for more than 20s, Alarm goes off. Same is the Case for Pressure Switch too (if it's not Closed (not enough Pressure in Breathing Circuit) for more than ~20s, Alarm will go off.). Alarm Circuit resets itself if Controller recovers (or Pressure Switch Closes)(before or after 20s), it can be modified to 'Latching Type' (won't Self-Reset) if necessary (will be included in Next Release, may be.). L.E.D. is used for Visual Indication of the Failure in Present Configuration, a small Piezo Buzzer can be added in place of the L.E.D. if Auditory Indication is preferable. Current Limiting Resistor R9 may not be required in this case.

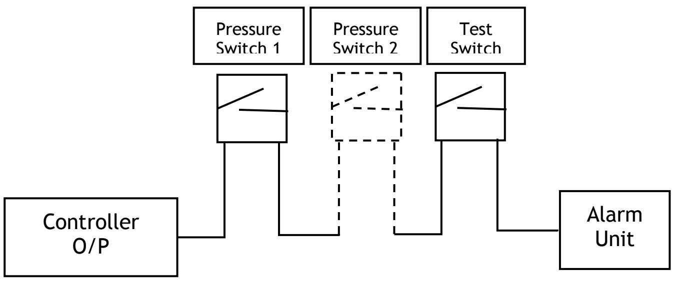
It should be noted here that Alarm Unit can only detect ‘Stuck High’ Failure Mode of Controller (Relay Activates the Solenoid Valve responsible for Inhalation when Controller O/P is High.) or ‘Open Pressure Switch’ (Not Enough Air Pressure in Breathing Circuit) Condition in Present Configuration. If the Controller O/P is stuck at Low (during Exhalation Cycle), current Alarm Configuration won’t be able to detect it. An Edge Triggered Alarm Design would have been more suitable & would have taken care of both ‘Stuck High’ & ‘Stuck Low’ Conditions but I’ve left it for the time being as I wanted to repurpose readily available Modules for keeping the System Simple & Easy to Assemble.

As LTSpice does not have Potentiometer Model available (as I’ve mentioned earlier.), I had to manually change the values of the Resistors (R3, R4 & R5) during different steps of Simulation to ‘Simulate’ different position of a Potentiometer’s Rider.

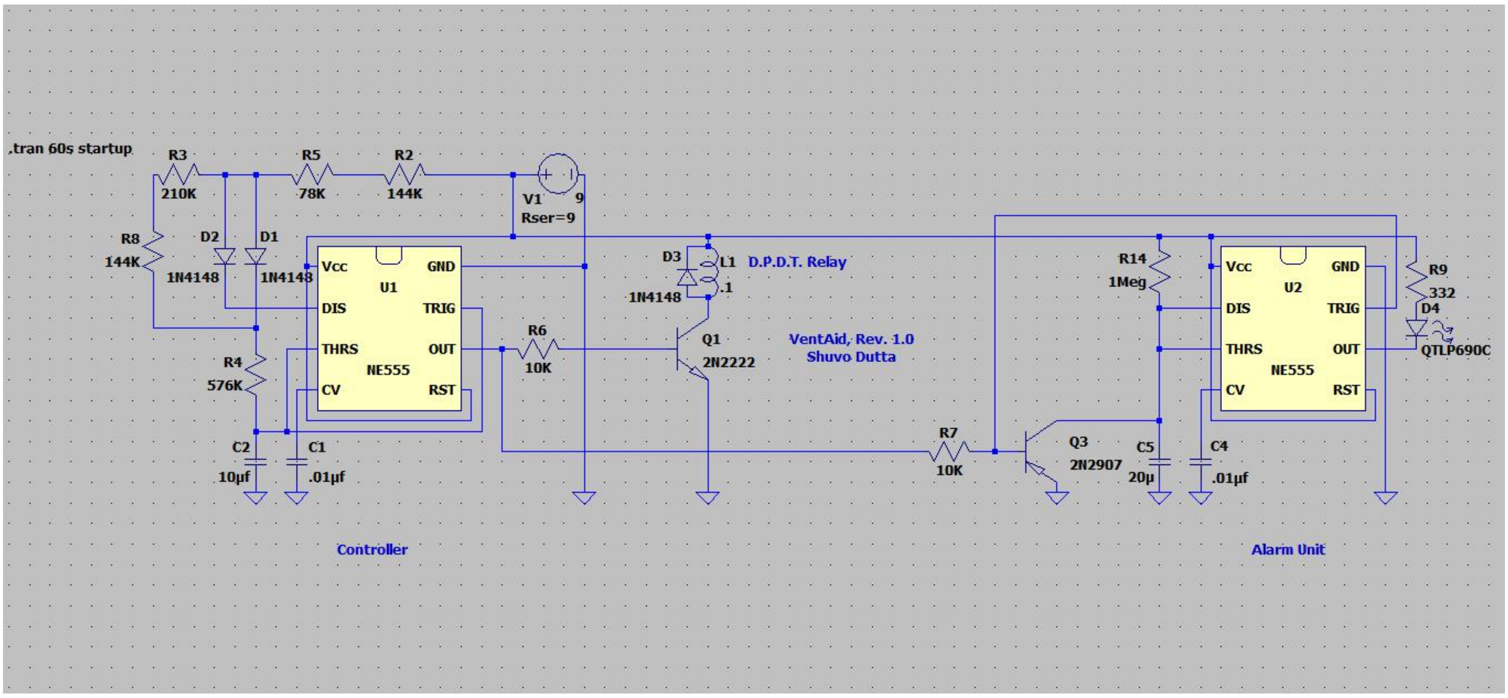
They’re not actual SPICE Nodes, I’ve used the Naming Convention according to Schematic for easier Understanding.



Wiring Diagram a), 1 Set of Contacts is used in D.P.D.T. Relay



Wiring Diagram b)



Schematic, VentAid Controller. Refer Description for R3, R4 & R5

B.O.M.: (*generated from LTSpice, the same is available in github Repository under ltspice Directory.*)

Ref.	Mfg.	Part No.	Description
C1	--	--	capacitor, 10nF
C2	--	--	capacitor, 10μF
C4	--	--	capacitor, 10nF
C5	Murata	GRMJN7R61C206ME05	capacitor, 20μF, 16V
D1	OnSemi	1N4148	diode
D2	OnSemi	1N4148	diode
D3	OnSemi	1N4148	diode
D4	Fairchild	QTLP690C	diode
L1	--	--	inductor, 100mH, 1A pk
Q1	NXP	2N2222	bipolar transistor
Q3	NXP	2N2907	bipolar transistor
R2	--	--	resistor, 144K
R3	--	--	resistor, 210K
R4	--	--	resistor, 2M, 1%, 0.1W
R5	--	--	resistor, 78K
R6	--	--	resistor, 10K
R7	--	--	resistor, 10K
R8	--	--	resistor, 144K
R9	--	--	resistor, 332, 1%, 0.1W
R14	--	--	resistor, 1M, 1%, 0.1W
U1	(unknown)	NE555	(unknown 3rd party model)
U2	(unknown)	NE555	(unknown 3rd party model)

Linear Potentiometers (~288KOhm & ~576KOhm) D.P.D.T. Relay, Pressure Switch & Piezo Buzzer has to be added to this List.

If readily available 555 P.W.M. Modules are being used (Preferably which use Diodes in Duty Cycle adjustment part), only D1, D2, R2, Linear Potentiometers, R6, C2 & Q1 will be necessary for modifying the Module. R7, R14, C5 & Q3 will be required to assemble the Alarm Unit if Off the Shelf 555 Timer Module is being used for it.

A Regular 9V D.C. Plug Pack (with around 500mA Current Capacity) should be sufficient to power this System. Controller & Alarm Units don't consume much power on it's own (measured value), D.P.D.T. Relay & Solenoid Valves will consume most of the energy while operating (though they're not continuously on.). As the Solenoid Valves are driven by the Relay, they can have their own Power Rails if required. (The Pair I've for Prototyping, runs on 24V D.C.)

A Suitable Enclosure may be 3D Printed (I don't own any 3D Printer at Present & never used one before, so can't comment much on this approach.) or a Generic Plastic/Metal Project Enclosure can be used with necessary modification for mounting various Parts (P.C.B.s, Switches, Controls, Valves etc.).

Fabrication/Assembly:

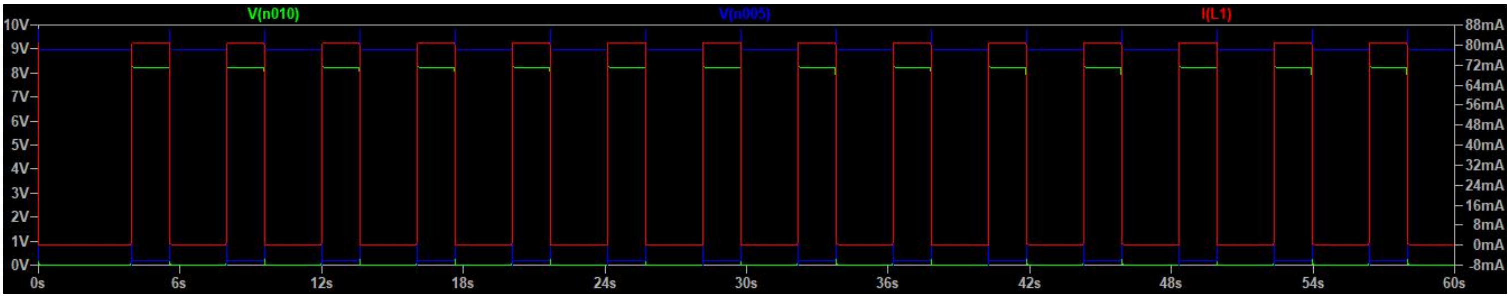
Fabrication/Assembly should be easy as the Electronics does not contain any Special Components (All Through Hole Components) & does not need any Special Care/Handling. All the Components are safe to handle. General Purpose Vero-Board/Strip-Board can be used or a Single Sided P.C.B. can be made (Netlist File is available in github Repository under ltspice Directory.) for the Build. If readily available 555 Modules are being used for the Build, make the Modification according to the Schematic and mount the extra Components on a small piece of Vero-Board/Strip-Board if possible. An Alarm Test Switch (Normally Closed) can be added in Series to the Pressure Switch Connection (ref. Wiring Diagram.), Alarm should go off if this Switch is Pressed (kept open) for more than 20s. Relay can be P.C.B./Chassis Mounted. Good Quality wire (Preferably Shielded) to be used for Internal Wiring. Relay & Solenoid Valves will be Operating in Continuous Fashion during the Lifetime of the Device, they should be reliable enough to handle this (Datasheet consultation is necessary before finalizing these Components.).

Possible Improvements:

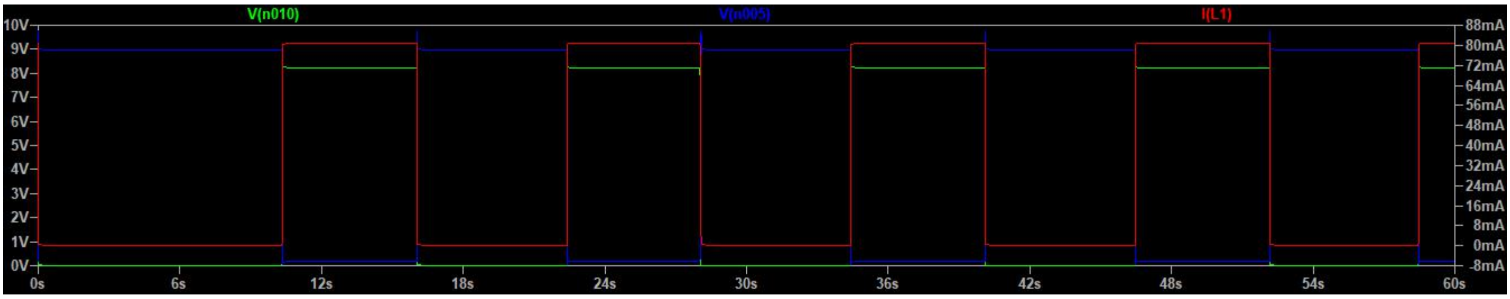
- √ Edge Triggered Alarm (for detecting both 'Stuck High' & 'Stuck Low' O/P Condition of the Controller)
- √ Self Latching Alarm (Alarm won't Reset itself once Triggered)
- √ Duty Cycle Control using Pin 5 (CONT) of 555
- √ Delivery of Certain Volume of Air/O2 by Pulse Width Modulated control of the Solenoid Valves (within it's Mechanical Operating Bandwidth) with the help of a 'Flow Sensor' in Breathing Circuit (& Comparator & other Necessary Electronics).

(*All or Few of these may or may not be implemented in Subsequent Releases.*)

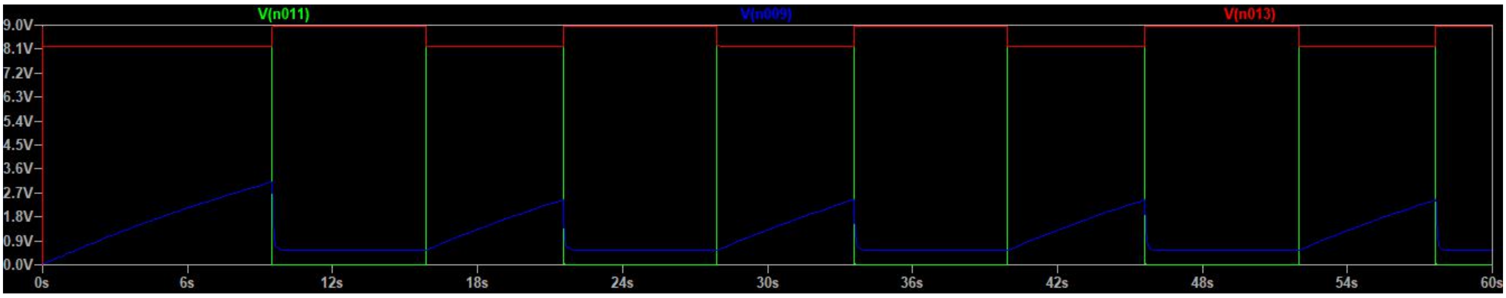
LTSpice Simulation Results:



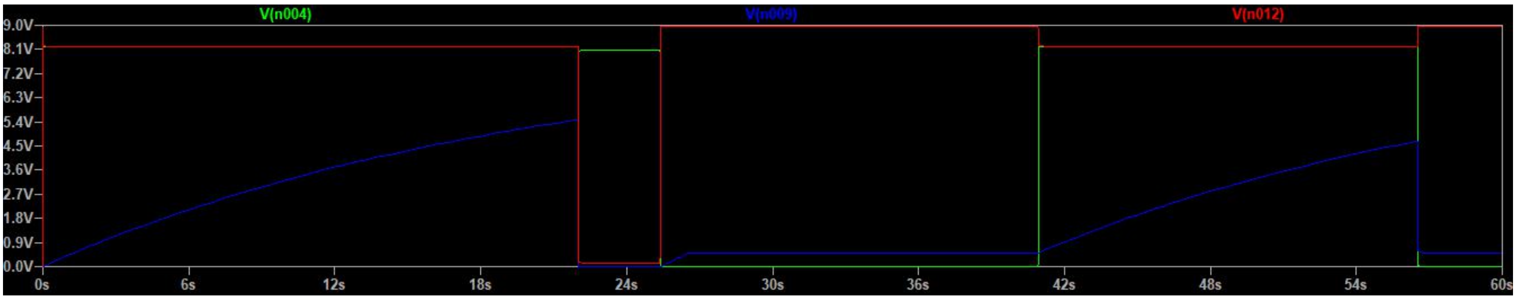
Simulation 01, Breathing Rate set at ~15B.P.M., I:E: ~1:1.2, V(n010):Green: Voltage O/P of the Controller, V(n005):Blue: Voltage at Coil End L1, I(L1):Red: Current through Coil L1



Simulation 02, Breathing Rate set at ~5B.P.M., I:E: ~1:1.2, V(n010):Green: Voltage O/P of the Controller, V(n005):Blue: Voltage at Coil End L1, I(L1):Red: Current through Coil L1



Simulation 03, Breathing Rate set at ~5B.P.M., I:E: ~1:1.2, V(n010):Green: Voltage O/P of the Controller, V(n009):Blue: Voltage at Cap. C5 of Alarm Circuit, V(n013):Red: Voltage O/P of the Alarm Circuit, Alarm Resets Periodically; Normal Condition



Simulation 04, V(n010):Green: Voltage O/P of the Controller, V(n009):Blue: Voltage at Cap. C5 of Alarm Circuit, V(n013):Red: Voltage O/P of the Alarm Circuit, Alarm Triggered as O/P of the Controller was Stuck High for more than 20s

Duty Cycle Variation Plots are to be added, Values of R3, R4, R5 has to be mentioned with each Plots.

Breathing Circuit:

Description/Assumption:

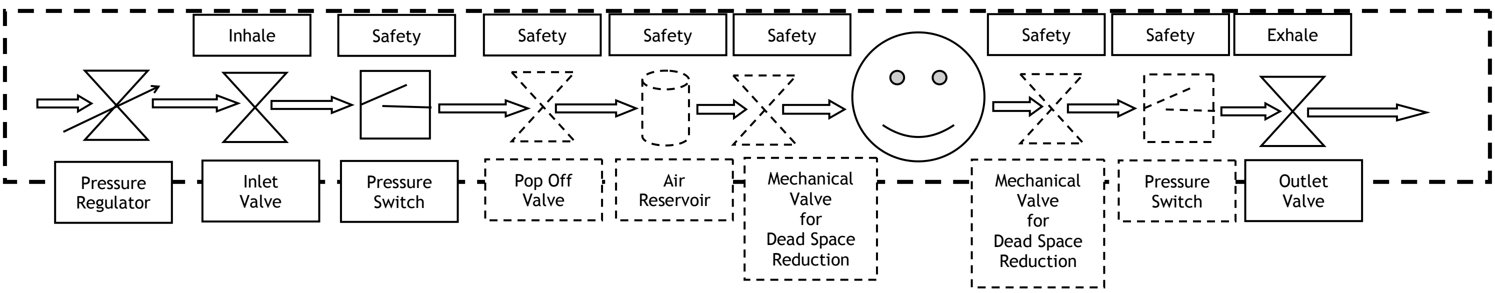
This part is Mechanical (Controlled & Monitored by the Controller) & delivers the Air/O2 to the Patient under treatment as stated in the Simplified System Block Diagram in the First Page. It consists of,

- √ Air/O2 Supply (not part of VentAid)
- √ Mechanical Pressure Regulator
- √ Solenoid Valves (2)
- √ Pressure Switch (1 or 2, according to the Configuration)
- √ Plumb-Lines
- √ End Delivery System (Endotracheal Tube, Face or Nasal Masks etc., should be chosen according to Doctor's Advice & should be Administered by Him/Her.)
- √ Various Mechanical Couplers/Adapters to attach Various Components if necessary
- √ Pop Off Valve (not Part of the Simplified Block Diagram, to neutralize accidental high pressure in Breathing Circuit)
- √ Mechanical Valves on Plumb-Lines (Inhalation & Exhalation); closer to Patient for reducing Dead Space Volume (not Part of the Simplified Block Diagram)
- √ Air-Reservoir/Air-Bag (not Part of the Simplified Block Diagram, near the end of Inhalation Circuit; as Buffer)

Dotted Parts in the Diagram are not Present in the System Block Diagram & a Bare Bone Functioning System can be built without them but it's Highly Recommended to put them in Place as almost all of them adds Safety to the Breathing Circuit. A Pressure Switch can be put in place of Pop Off Valve & can be connected to the Alarm I/P in Series with Existing Pressure Switch Connection in an Electrically Complementary Fashion to detect Excess Pressure in Breathing Circuit. If Pop Off Valve opens, it too will trigger the Alarm (after ~20s of the Event) as Air Pressure will Drop inside Breathing Circuit due to this Event.

This Design is no where near Ideal/Optimal (& I'm not Mech. Engg. Major.) but should be able to do the Basic Job of A Mechanical Ventilator when needed. As I've stated before, VentAid is meant to assist the Patients who are in need of such attention where Proper Medical Ventilators are busy in Supporting Patients with more Critical Condition & will be available later but not immediately. VentAid desires to act as a 'Stop Gap' Arrangement made with Readily Available Modules/Components. That's it's Sole Purpose. It's not & won't ever be the Replacement of a A Proper Medical Ventilator.

E-Vent (by M.I.T. Team) Resources has been an Excellent Source of Critical Information in General & reg. Dead Space in Particular while & after I was figuring out the Breathing Circuit. These input were Truly Invaluable as I'm not from Medical Instrument Design Background.



Breathing Circuit

Fabrication/Assembly:

Certain Mechanical Parameters (i.e. Diameter of the Valves, Plumb-Line etc.) are Standardized for Medical Equipment as far as I understand. All the Components in Breathing Circuit should be selected keeping this in mind, it'll help in an Easy Integration (without using too many Converters/Couplers) & a Leakage Free Breathing Circuit. If a Breathing Circuit is Readily Available, that can be adapted too (Controller should be able to Operate the Existing Control Valves & Pressure Switches/Sensors if available.). Pressure Switch (Normally Open) may be more difficult to procure than other components. Some D.I.Y. Pressure Switch Designs are available but Milage may vary.

Once the Breathing Circuit is assembled then it should be thoroughly tested before putting into use. There should be no Leakage, Solenoid Valves should operate Freely, Pressure Regulator & Gauge should Indicate the Right Air Pressure (better to verify with another Pressure Gauge.), Pressure Switch should Trigger at the Right Pressure & Pop Off Valve too should open in Excess Pressure.

Controller should be assembled before Breathing Circuit, otherwise Testing the Breathing Circuit may Prove Difficult.

The System should be put under Test Continuously for at least 24Hrs. before start using.

Possible Improvements:

A Flow Sensor can be put in Breathing Circuit with necessary Modification in the Controller. That's the only possible improvement I can think of at Present. Anyone with Industrial Design/Medical Equipment Design/Mech. Engg. Background (or Anyone who has better understanding of such Systems) can Provide their Valuable Suggestion for Improvement, I'll be Happy to provide any Input they need.

Ref.:

E-Vent by M.I.T. Team: https://www.e-vent.mit.edu/

This is One of the Best Open Source Ventilator Designs available, Excellent Work done by M.I.T. Team. Resources they've provided should be Must Read for Anyone Interested in Exploring this Avenue. Discussion Threads are also too Good. I can't Thank them enough for their Hard Work, they've released everything for Free of Cost too including the Results of their Experimental Study & the Input provided by Medical Practitioners.

AvE Channel on Youtube: https://www.youtube.com/watch?v=oqRgISFuE0k&t=459s

Another Excellent Source of Information. He takes a more Formal Approach reg. Specification of a Ventilator & shows a Prototype in a Practical Manner in this Video, One of my Inspirations for developing VentAid.

NA/NE/SA/SE 555 Datasheet from TI (Invaluable Source of Information on 555)

https://accessmedicine.mhmedical.com/content.aspx?bookid=520&sectionid=41692239%20
https://f1000research.com/articles/9-218
https://www.hackster.io/news/open-source-ventilator-openlung-projects-aim-to-address-the-covid-19-ventilator-shortfall-c7a5ee2f8e58

Few Concluding Words:

First of All, VentAid is an Independent Effort, I've not Collaborated with Anyone while developing VentAid till now. That does not mean I won't do it in Future. Anyone Interested in VentAid or have Suggestion, is welcome to reach me via my email Address mentioned in the Footer of this Document. If this Design has something Good in it; you're Free to use it as it is or may use it in your own Design, if there's something Horribly Wrong, Probably that's due to me & you're Free to make the Necessary Correction (& let me know if Possible.).

This Document may have Unintentional Errors Present. Please notify me if you've noticed such Errors. I'll try to Correct them in Next Release.

I've highlighted few things in Yellow in this Document. Those Parts need to be updated with Data & it'll be done in Next Release. Few Other Parameters (like Suggested/Min./Max. Inlet Pressure for Breathing Circuit, Pressure Threshold of the Pressure Switch, Pressure Threshold of the Pop Off Valve etc.) are not mentioned on Purpose as they need Experimentation with the System before Finalizing their Values & will be done in Future. I'm looking for Preferable Values for these Parameters at Present to Begin With.

Prototype System Building is under Progress as of May, 2020 but it's getting Delayed due to Delay from Component Suppliers as my Country (India) is going through Nation Wide Lockdown due to COVID-19 Outbreak (& I'm away from my Lab. & in a Red/Containment Zone at Present.). I'll update the Document with Photographs, Preferable Component List, Build Notes & Test Results once the System is Ready.

The Name 'VentAid' is coined by me as this Device 'Aids' in Ventilation. I'm not currently aware of any Product with the Same Name for the Same Purpose. If there's any, which I've missed, that's entirely Coincidence.

At the End, I wish VentAid should never be Required by Anyone across the World. That's the Best I can Hope for.

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