Surge Avoidance Using Speed and Valve Methodologies Controlled by PID, Fuzzy and Neural Networks Approaches

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Abstract — **Surge is a global nonlinear instability that affects compression systems. It limits the operating range and degrades the system performance. This paper introduces two common surge avoidance techniques to extend the operation range of the compressor. These two methods are controlling the compressor flow and controlling the compressor speed. Air bleeding is utilized by two bleeding valves one of them with high gain and the second with low gain. Fuzzy logic, PID, and neural networks were used to control such two methods. A comparison between the three control techniques is performed to demonstrate the most effective of them using simulations based on SIMULINK. The results show that the two bleeding valves produce more stable behavior than using one bleeding valve. Furthermore, neural network controller shows quick arrival for the different set points and also is more stable than other techniques in avoiding the surge.**

Index Terms — **controllers, compressor, surge, valve, bleeding.**

Nomenclature

Symbols	***Description***
a_s	The speed of sound
A_c	The flow area in the compressor
B	Gretizer Parameter
H	compressor map semi height
l_c	Equivalent length of the compressor and its ducts
R	rotor mean radius
T	Time
V_P	Plenum volume
U	mean rotor velocity
W	compressor map semi width
ε	The nondimensional time variable
ρ	ambient air density
γ_T	Throttle gain
Ψ	plenum pressure
$\dot{\psi}$	The derivative of ψ with respect to ε
ψ_{c0}	compressor map shut-off value
Φ	The annulus averaged mass flow coefficient
$\dot{\Phi}$	The derivative of ϕ with respect to ε
$\Phi_{CV}(\psi)$	Control valve characteristic
$\Phi_T(\psi)$	Throttle characteristic

Subscript	***Description***
CV	Control (bleeding) valve
CVT	Tuning control valve
0	Initial operating point
SP	Setpoint (desired operating point)
T	Throttle valve

I. Introduction

Centrifugal compressors have wide applications. These compressors are relatively dependable, trouble-free, come in different sizes and almost any gas could be compressed by them. However, the performance of all aerodynamic compressors (including centrifugal) is generally limited by an instability known as surge. Surge is a phenomenon that occurs at low compressor flow rates causing the compression system to operate on the positively sloped region of the compressor characteristics [1], [2]. The surge region is characterized by periodic pressure and flow oscillations throughout the compression system. The flow fluctuates in magnitude and sometimes it even reverses its direction [3] which may lead to a lot of process disruptions. This instability limits the range of operation of the compressor and jeopardizes its stability.

Over the years, many measures have been introduced to overcome the problem of surge in compressors. Traditionally, the problem has been tackled by using surge avoidance techniques [4]. However, these well established methods limit the operational range of the compressor and reduce its efficiency [5], [6]. As a result, active surge control was introduced as an alternative approach to deal directly with the surge instability rather than avoiding it.

Active surge control has been a subject of active research for almost two decades. The method was first introduced by Epstein [7]. The approach has the advantage of allowing stable compressor operation in previously unstable, high-performance areas and also has the advantage of relatively low-energy consumption, since it operates on small amplitude disturbances when it tries to stabilize surge in its earliest stages [7]. The literature reports the use of many actuators for active control. Many examples are presented in [6]. In many of the cases, proportional feedback was used as a control law and has proved to be successful [8], [9].

This paper introduces a new methodology for controlling the surge problem through bleeding valve with varying compressor speed controlled by different techniques, PID, fuzzy and neural networks. The controllers use two bleeding valves; one of them is a main valve with high gain and the second is a fine tuning valve with low gain. The controllers also change the compressor speed to obtain the desired flow set point at optimal speed. This combination of valves is arranged to make the compressor to be more stable during the surge avoidance. A comparison between the three control techniques is performed to demonstrate the most effective of the three controllers where assessment has been made on the basis of how far the operative initial point from setting point.

II. COMPRESSOR MODEL

The researchers studied and developed different models for the turbo machines instabilities. One of the first models was developed by Emmons [10]. However, the model proposed by Moore and Greitzer [11] that has gotten wide acceptance for Centrifugal and axial compressors. The compression system modeled by Moore and Greitzer consists of a compressor, plenum, throttle valve, control (bleeding) valve and connecting ducts (Fig.1). Where, all symbols and subscripts are defined in nomenclature.

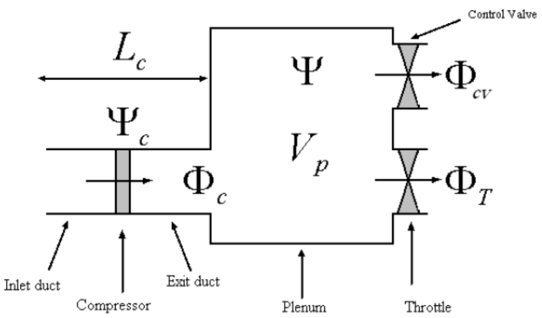

Fig.1 The Moore-Greitzer model with bleeding valve

The model was modified in [12], [13] to account for the effects of a control valve (bleeding valve) as shown in Fig.1 and resulted in the following set of nondimensional equations:

$$\dot{\Phi} = \frac{1}{l_c}(\Psi_c(\Phi) - \Psi) \qquad (1)$$

$$\dot{\Psi} = \frac{1}{4B^2 l_c}\left(\Phi - \Phi_T(\Psi) - \Phi_{cv}(\Psi)\right) \qquad (2)$$

A. The proposed compressor model

In this research, it's proposed a modified compressor model which includes two control valves (Fig.2). The first control valve (CV) has a high gain that could be used to operate with fast response. The second control valve (CVT) has slow response because of its small gain and it is used for fine tuning. According to this modification, the equation number (2) above will be changed to the following:

$$\dot{\Psi} = \frac{1}{4B^2 l_c}\left(\Phi - \Phi_T(\Psi) - \Phi_{CV}(\Psi) - \Phi_{CVT}(\Psi)\right) \qquad (3)$$

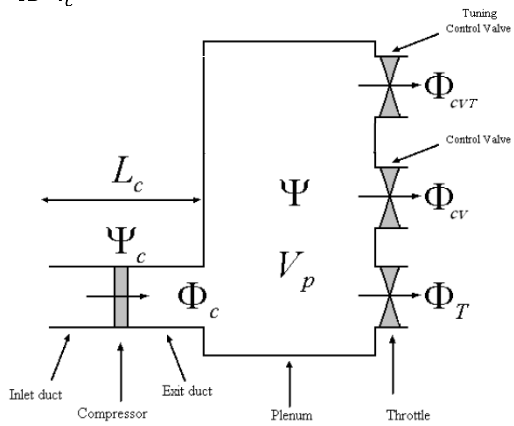

Fig.2 The proposed compressor model with two bleeding valves

The behavior of the compressor, also known as the compressor characteristic, is usually described by the following cubic equation:

$$\Psi_c(\phi) = \psi_{c0} + H\left(1 + \frac{3}{2}\left(\frac{\Phi}{W} - 1\right) - \frac{1}{2}\left(\frac{\Phi}{W} - 1\right)^3\right) \qquad (4)$$

Where, the parameters $\boldsymbol{\Psi_{c0}}$, $\boldsymbol{H}$ and $\boldsymbol{W}$ are determined from the steady-state measurements of the compressor characteristic [14]. On the other hand, the characteristics of the throttle and control valves are described as following:

$$\Phi_T = c_T u_T \sqrt{\Psi} \qquad (5)$$

$$\Phi_{CV} = c_{CV} u_{CV} \sqrt{\Psi} \qquad (6)$$

$$\Phi_{CVT} = c_{CVT} u_{CVT} \sqrt{\Psi} \qquad (7)$$

Where $\boldsymbol{U_T}$, $\boldsymbol{U_{CV}}$ and $\boldsymbol{U_{CVT}}$ describe, respectively, the fractional openings of the throttle valve, control valve and tuning control valve and their values could only be between 0 (fully closed) and 1 (fully opened). On the other hand, $\boldsymbol{C_T}$, $\boldsymbol{C_{CV}}$ and $\boldsymbol{C_{CVT}}$ are measures for the capacity of the fully open valves.

B. The simulation of the proposed compressor model

To control the surge phenomenon, the flow rate signal is used as a feedback signal to the controller. The control valve is closed in the desired equilibrium point and can only open when the mass flow deviates from the equilibrium point. Fig.3 shows how the proposed compressor model is implemented using MATLAB/SIMULINK.

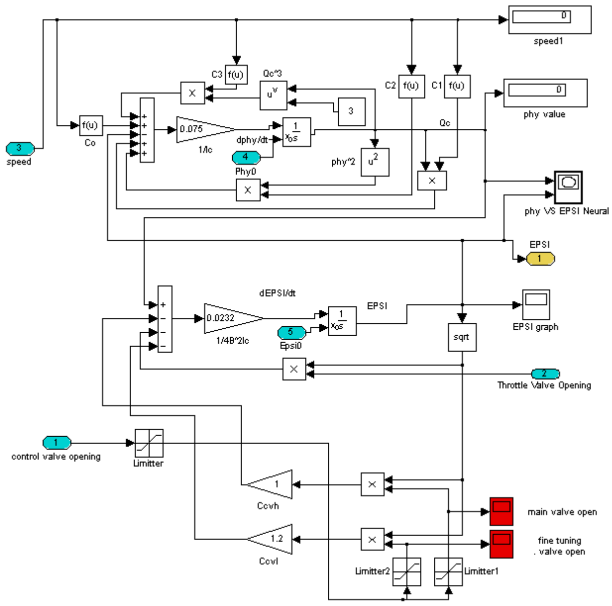

Fig.3 The simulation of the proposed compressor model in MATLAB/SIMULINK

III. CONTROLLERS

In this study, the compressor flow rate is controlled by both the compressor speed and the bleeding valve(s). The main goal of the control of the compressor is to keep the compressor in the safe area or in the stable operation region. Also, the control strategy makes the compressor to follow the set point or desired operation point for achieving optimal operation conditions. The control strategy also keeps the compressor to be stable during the surge avoidance. The control techniques are evaluated and compared using three control techniques: PID controller [15], Fuzzy logic controller [16] and neural network controller. The comparison would be achieved by the ability of the controllers' behavior in saving the compressor from the surge and in achieving optimal operation conditions.

A PID controller is implemented for controlling the bleeding valves (Fig.4) and another PID controller is used for controlling the speed of the compressor. The tuning of the PID is made by trial and error technique.

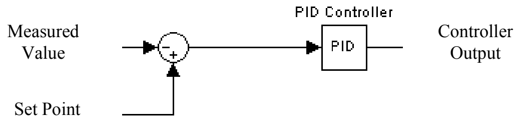

Fig.4 The PID controller model using MATLAB/SIMULINK

The fuzzy logic controller which was implemented in this study has two input membership functions, flow region and flow change, as shown at Fig.5. It has also two output membership functions, one for the bleeding valve opening and the other for the speed. It handles the logic by 15 rules. Also, the Fuzzy rules were experimentally developed in MATLAB/SIMULINK.

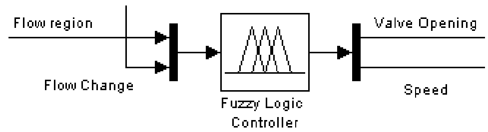

Fig.5 The Fuzzy controller modeling in MATLAB/SIMULINK

Two layers feed forward neural network controller is developed (Fig.6). The neural network is designed to control both the control valves (two bleeding valves) and the compressor speed. The proposed controller has three inputs; the compressor mass flow, the mass flow error and the discharge pressure. Also the controller has four outputs; the compressor speed, control valve opening, control valve safe open at 80% and control valve safe open at 100%. The neural network is trained up to accuracy of 0.01. Therefore the controller is accurate enough to achieve its mission. The main principle of this structure is to minimize the mass flow error and to avoid the instability problems in optimum way.

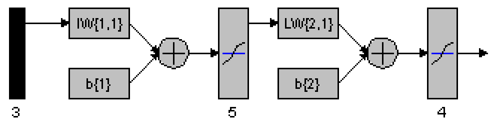

Fig.6 The neural network structure

Each of the three controllers is designed to achieve the desired mass flow set point during stable operating area and also designed to avoid the surge if the compressor falls in the unstable area through adjusting the speed, if it fails to success then it adjusts the control valve(s) opening.

IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations are carried out in the MATLAB/SIMULINK using parameter values listed in Table 1. Three case samples that express the compression system under possible operating conditions have been assigned, as listed in Table 2. Each controller state is divided into two valve(s) combinations: (A) Controlling one bleeding valve and the compressor speed. (B) Controlling two bleeding valves and the compressor speed.

Each state is examined by PID, Fuzzy logic and neural network controllers. These cases depend on the locations of the initial and the desired operating points with respect to the surge line, i.e. in the stable or unstable region. The controller performance is evaluated based on quick arrival to the set point with stable behavior. Also, the evaluation of the controllers is depending on surge avoiding without disturbances. The sequence of the evaluation is performed through two steps. The first step is by giving the controllers certain flow set point and then watching their behavior during the first zone (T<1000) (see Fig.7 and Fig.8). The second step is by closing the throttle valve to simulate the surge and then watching the surge avoiding behavior of the controller during the second zone (T>1000) (see Fig.7 and Fig.8).

Table I
Parameter values used in the model

Parameter	Value	Parameter	Value
Φ	[ ]	ρ	1.15 [Kg/m3]
Ψ	[ ]	ψ_{c0}	0.3 [ ]
$\Phi_T(\Psi)$	[ ]	W	0.25 [ ]
$\Phi_{CV}(\Psi)$	[ ]	H	0.18 [ ]
U	173 [m/s]	R	0.1 [m]
a_s	340 m/s	T	[ ]
V_P	1.5 [m3]	ε	$\varepsilon = Ut/R$
A_c	0.01 [m2]	$\dot{\Phi}$	$\dot{\Phi} = \Phi/\varepsilon$
B	1.8 [ ]	$\dot{\Psi}$	$\dot{\Psi} = \Psi/\varepsilon$
l_c	13.33 [ ]	γ_T	[ ]

Table II
Operating conditions used in simulation

Case	Φ_0	ψ_0	u_T	Φ_{SP}
1	0.8	0.1	1→0	0.65
2	1.05	1.0154	1→0	0.95
3	1.15	2.177	1→0	1.2

A. Controlling one bleeding valve and the compressor speed

Fig.7. a, b, and c demonstrate the different behaviors for the three controllers using one bleeding valve. Also, Fig.7 shows that in each state the neural network controller produces stability in the machine operation and provides quick arrival to these set points. From Fig.7.a it can be seen that the PID controller makes simple overshoot in achieving the set point but it comes back to the steady state and it is successful in the surge avoidance, the fuzzy and neural controllers are stable with no overshooting through two zones. Fig.7. b shows that the fuzzy controller becomes unstable, the PID and neural controllers succeed in making the machine behaves more stable in achieving the set point and in the surge avoidance. From Fig.8.c it's observed that the same results occurred in case 2. During the three cases the neural network controller is better than the PID because it succeeds in optimizing the valve opening. Fig.7.d, e and f show the compressor performance curve during the different operating ranges. The compressor performance plots give the same results but, these introduce the results with another view. This view gives a global illustration for the simulations results where it introduces the relation between the compressor flow rate, compressor pressure ratio and the compressor speed.

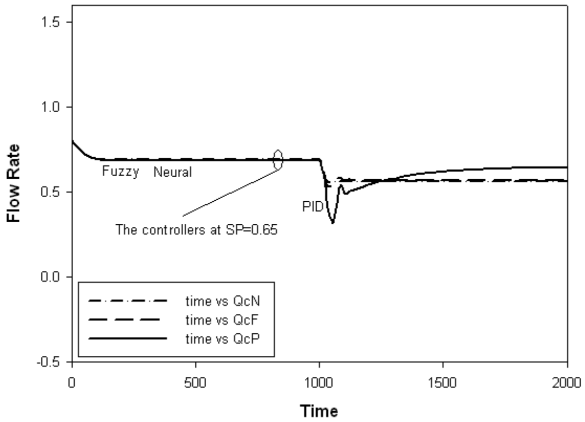

Fig.7.a The compressor flow rate with the three controllers using speed and one bleeding valve at: Φ_0=0.8, ψ_0=0.1 and Φ_{SP}=0.65

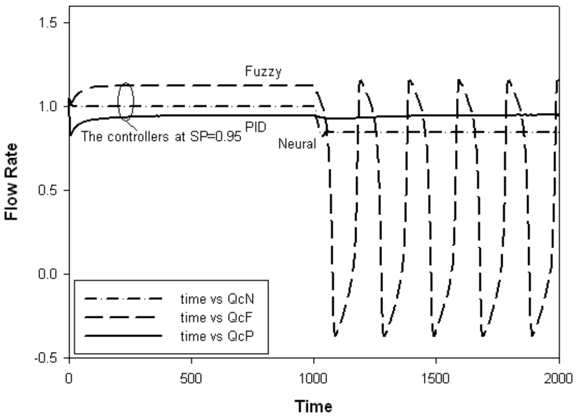

Fig.7.b The compressor flow rate with the three controllers using speed and one bleeding valve at: Φ_0=1.05, ψ_0=1.0154 and Φ_{SP}=0.95

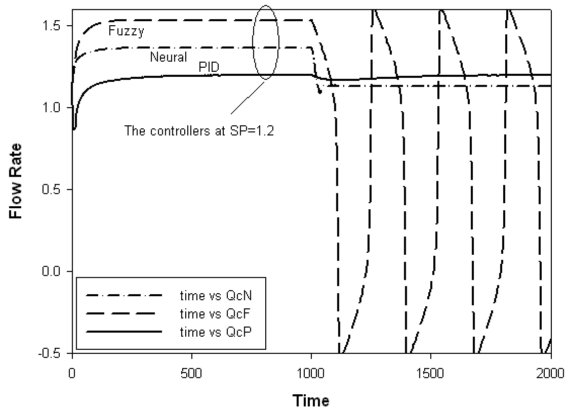

Fig.7.c The compressor flow rate with the three controllers using speed and one bleeding valve at: Φ_0=1.15, ψ_0=2.177 and Φ_{SP}=1.2

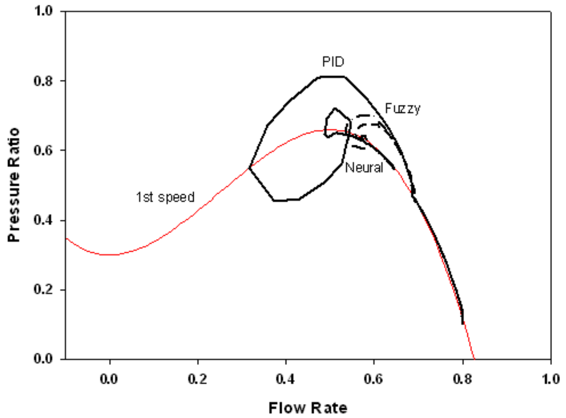

Fig.7.d The compressor characteristics curve with the three controllers using speed and one bleeding valve at: Φ_0=0.8, ψ_0=0.1 and Φ_{SP}=0.65

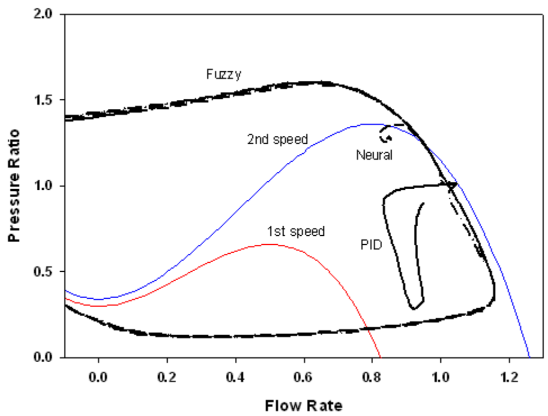

Fig.7.e The compressor characteristics curve with the three controllers using speed and one bleeding valve at: Φ_0=1.05, ψ_0=1.0154 and Φ_{SP}=0.95

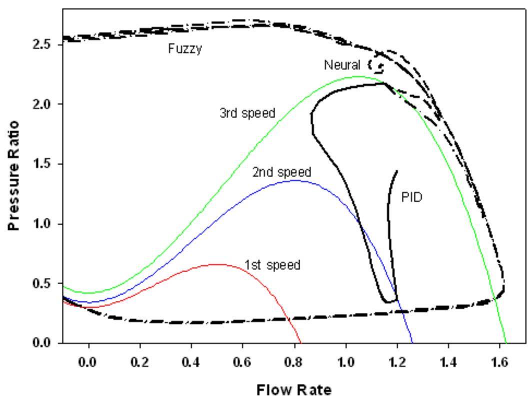

Fig.7.f The compressor characteristics curve with the three controllers using speed and one bleeding valve at: Φ_0=1.15, ψ_0=2.177 and Φ_{SP}=1.2

B. Controlling two bleeding valves and the compressor speed

Fig.8.a demonstrates that the three controllers are stable during two zones. However, the PID makes some overshooting in achieving the set point. From Fig.8.b and c, the three controllers give stable behavior. Comparing Fig.8.a, b and c with Fig.7.a, b and c, one can see that the behavior of the neural network controller is the same. On the other hand, the fuzzy controller is stable in the three cases and has set point quick arrival. The use of two valves combination makes the PID and the fuzzy controllers have stable behavior. Therefore this combination is better than one valve combination in case of using the PID and Fuzzy controllers. Note also that the fuzzy controller has better behavior than PID. Fig.8.d, e and f show the compressor performance curve during the different operating ranges.

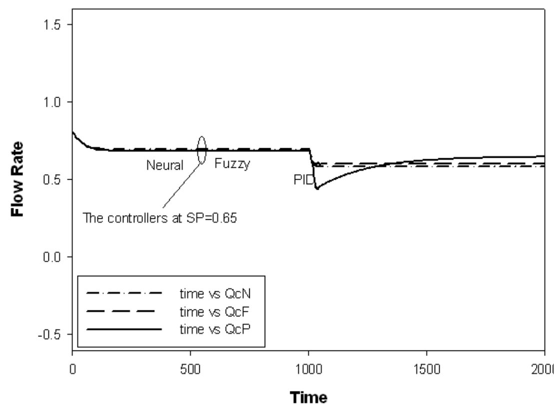

Fig.8.a The compressor flow rate with the three controllers using speed and two bleeding valves at: Φ_0=0.8, ψ_0=0.1 and Φ_{SP}=0.65

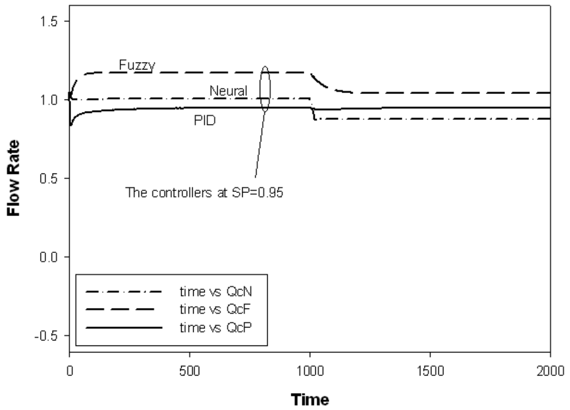

Fig.8.b The compressor flow rate with the three controllers using speed and two bleeding valves at: Φ_0=1.05, ψ_0=1.0154 and Φ_{SP}=0.95

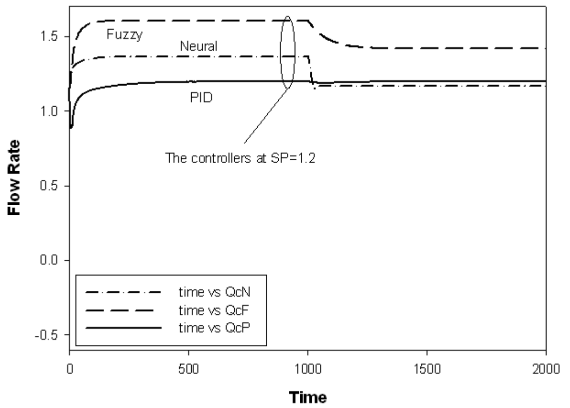

Fig.8.c The compressor flow rate with the three controllers using speed and two bleeding valves at: Φ_0=1.15, ψ_0=2.177 and Φ_{SP}=1.2

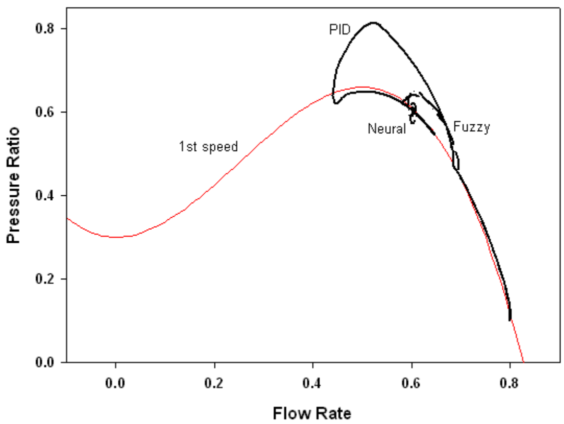

Fig.8.d The compressor characteristics curve with the three controllers using speed and two bleeding valves at: Φ_0=0.8, ψ_0=0.1 and Φ_{SP}=0.65

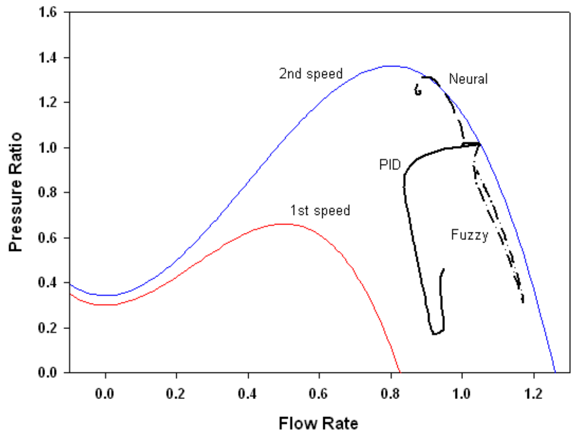

Fig.8.e The compressor characteristics curve with the three controllers using speed and two bleeding valves at: Φ_0=1.05, ψ_0=1.0154 and Φ_{SP}=0.95

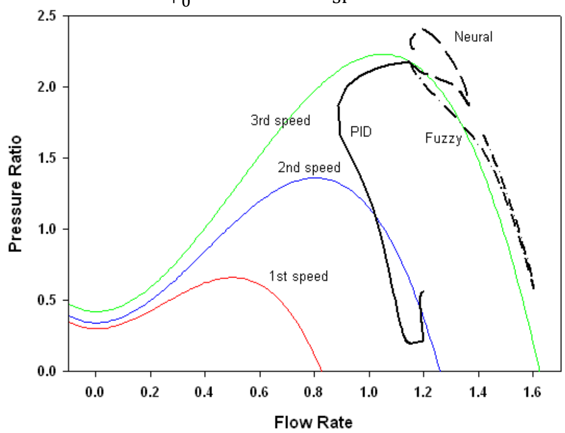

Fig.8.f The compressor characteristics curve with the three controllers using speed and two bleeding valves at: Φ_0=1.15, ψ_0=2.177 and Φ_{SP}=1.2

V. CONCLUSION

In this paper, the surge avoidance is presented using bleeding valve(s) and varying compressor speed. The control valves and the compressor's speed were controlled by using different techniques such as PID, Fuzzy and Neural networks controllers. The motive behind this study is to build an intelligent controller to control the surge problem giving promising results. The neural network controller is designed to have two hidden layers with three inputs and four outputs. A neural network approach produces a new and optimized solution for avoiding and controlling the surge problem in variable speed compressor. The controller also varies the compressor speed to obtain the desired flow set point through optimum way. The simulation results show that The PID and fuzzy controllers produce less stability in the system compared to the case of using the neural network controller. The neural network controller is able to stabilize the system over a wide range of operating points. On the other hand it's observed that the two bleeding valves make the system more stable under all operating ranges and we got better stability for the three controllers. Finally by using two valves and neural networks the optimum stability at optimal compressor speed is given for the compression system.

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