PID Controller Tuning Using Neuro Fuzzy Controller and Anti Windup Method for Improving the Boost Converter Performance

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Abstract: DC-DC converter is used to stabilize or control the DC voltage of a battery. In addition to other applications, DC converters feed electric vehicles and domestic inverters. Several control methods are used to control boost converters. In this PID controllers are used to optimize the boost converter performance. In order to obtain the best coefficients of the controllers, Neuro fuzzy (ANFIS) and Anti windup methods are applied. The design of its loop control is quite complex due to the non-linearity of its behavior, the commutation of a switch makes its equivalent circuit to change continuously in the time. In this work, the coefficients and poles of the closed loop transfer function for the average model (approximated linear model) of the boost converter are selected using ANFIS and Anti windup techniques, with the purpose of improving the dynamic performance of the voltage regulator. The result of simulation shows the capability of the ANFIS and Anti windup method in designing an optimized PID controller which improves the performance of the boost converter.
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1. Introduction

Considering the wide use of electronics equipment's and utilization of renewable energy sources, DC-DC converters have found significant attention in the recent decades. The main purpose of a DC-DC converter is to supply a regulated DC output voltage to a variable-load resistance from an unstable DC input voltage. The converters are widely used for the control of motor voltage in electric cars, ceiling elevators, mine excavation etc. Their specific features are the precise control of acceleration with high efficiency and fast dynamic response. The problem of regulating the output voltage of these converters has been a subject of great interest for many years, due to the switching property included in their structure, DC-DC converters have a non-linear behavior and consequently their controlling design is accompanied by complexities. In addition, due to the non minimum phase nature of the boost converter, much effort has been directed at the control of this configuration.

Transfer function of the DC-DC converter is obtained from the State Space model which is derived by using the SSA (State Space Averaging) technique. This work extends the use of the state-space averaging method for determining switching converter for steady-state condition.

Some control methods have stated the issue of control through pole placement .Another method is the use of state feedback in the control of DC-DC converters. In modeling area of DC-DC converters, a variety of models are presented which comprise desirable responses by administration of control methods. Most of the articles have concentrated on design of PI and PID controllers. The tuning of PID controller is performed mostly using the conventional techniques Ziegler-Nichols method, GA etc.., Tuning a controller means adjusting the controller gains to satisfy the performance specifications like margin of stability, transient response and bandwidth. The objective of the paper is to use the ANFIS and Anti Windup methods in order to obtain optimal PID controller settings for performance of a boost converter. Although trial and error can be used, analytical approach is used to compute the gain of PID that can minimize the performance index which is represented as a function of error. The commonly employed performance indices are:

- Integral Absolute Error (IAE)
- Integral Squared Error (ISE)
- Integral of time multiplied by absolute value of error (ITAE)
- Integral of time multiplied by squared error (ITSE)

2. State Space Averaging Technique

A significant advantage results from the capability of the SSA steady-state method to achieve a steady-state in a fast, accurate and reliable manner. This allows the SSA steady-state method to be efficiently used in cases when computation has to be repeated for many different operating points within defined operating space without essential time loss and fear of potential convergence failure while the algorithm is executing. The operating point of a converter can be defined as a vector p whose elements are values of variables such as input voltage, output load current, and device parameters, all ranging between predefined minimum and maximum limits. At each operating point, the simulation and inspection of converter circuit nodal steady-state voltages and currents can be carried out, and a vector of variable of interest v can be found. The vector of variable of interest v can include, for instance, peaks, ripples, average and rms values of converter nodal voltages or currents. The output from such algorithms can be waveforms of converter selected circuit variables, curves, surfaces or multidimensional matrices of values of peaks or ripples of nodal voltages or currents, device power losses, converter overall efficiency or parametric sensitivities. Thus, the SSA steady-state method allows for the development of efficient algorithms for thorough circuit analysis and complex characterization of switching converter steady-state response.

2.1 State Space Averaging Technique for Boost Converter

Consider the DC-DC boost converter circuit shown in Figure 1. During the interval when switch Q1 is off, diode D1 conducts the current i_L of inductor L towards the capacitor C_0 and the load R_0. During the interval when switch Q1 is on, diode D1 is open and the capacitor C_0 discharges through the load R. The converter transfers the energy between input and output by using the inductor.

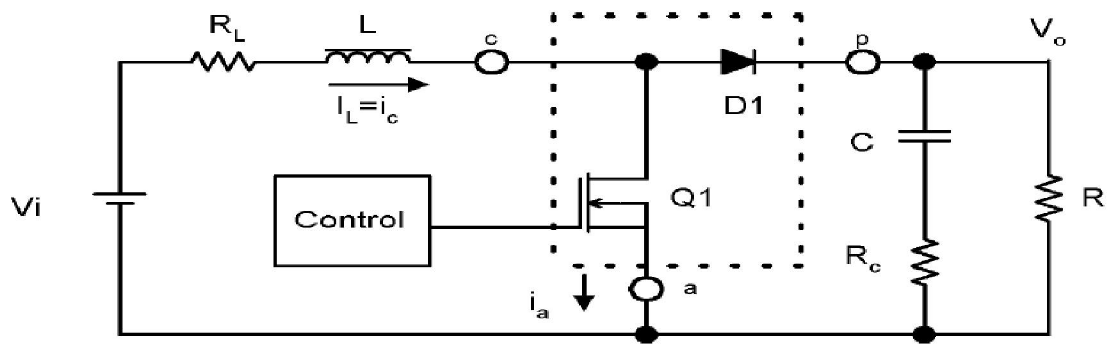

Figure 1 Circuit Diagram of Boost Converter

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}\frac{R_C R(d-1)-Rl(R+R_C)}{L(R+R_C)} & \frac{R(d-1)}{L(R+R_C)}\\ \frac{R(1-d)}{C(R+R_C)} & \frac{-1}{C(R+R_C)}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_{in} \quad (1)$$

$$Y(t)=\begin{bmatrix}1 & 1\end{bmatrix}\begin{bmatrix}\frac{i_L(t)}{v_0(t)}\end{bmatrix} \quad (2)$$

3. PID Controller

The PID controller is well known and widely used to improve the dynamic response as well as to reduce or eliminate the steady state error. The derivative controller adds a finite zero to the open loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin, thus increasing type of the system by one and reducing the steady state error due to a step function to zero. A common strategy that is used for controlling a system with PID controller is shown in Figure 2.

The transfer function of the PID controller looks like the following:

$$k_p+\frac{k_i}{s}+k_d s=\frac{k_d s^2+k_p s+k_i}{s} \quad (3)$$

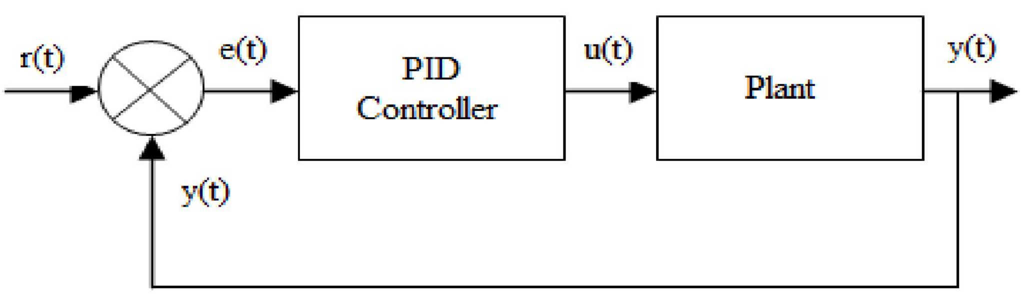

Figure 2. Schematic PID controller

The PID controller works in a closed-loop system using the schematic shown in Figure 2. The variable (e) represents the tracking error, the difference between the desired input value (r) and the actual output (y). This error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is now equal to the proportional gain (K_p) times the magnitude of the error plus the integral gain (K_i) times the integral of the error plus the derivative gain (K_i) times the derivative of the error.

$$u = k_p e + k_i \int e dt + k_d \frac{de}{dt} \quad (4)$$

This signal (u) will be sent to the plant, and the new output (y) will be obtained. This new output (y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral gain.

4. Design Procedure of Neuro Fuzzy Controller of boost converter

Neuro-Fuzzy controller is designed based on an average state space model of the boost DC-DC converters. The design of Neuro Fuzzy controller needs a good knowledge of the system operation (figure 4). The various steps involved in the design of Neuro Fuzzy controller for power converter are stated below. A universal Sugeno type Neuro Fuzzy controller has been simulated for the boost converter. In order to train the parameters of the PID controller, two inputs and one output the adaptive neural based fuzzy inference systems is used.

4.1. Identification of inputs and outputs

This step in the design identifies the key inputs that affect the system performance. The goal of the designer is to ensure that the output voltage matches the reference voltage. The inputs of the Neuro Fuzzy controller are i. The voltage error ii. The change of voltage error. The voltage error input is sampled once in every cycle.The output of the controller is the duty ratio.

4.2. Fuzzifying the inputs and outputs

The universe of discourse of the inputs is divided into five fuzzy sets of triangular shapes outputs are also mapped into several fuzzy regions of several singletons. The variables are voltage error and change in voltage error and the output is the duty cycle.

4.3. Development of rule base

The rules connecting the inputs and the output singletons are based on the understanding of the system. Normally the fuzzy rules have if…then… structure. The inputs are combined by AND operator. The rule-base contains the fuzzy IF-THEN rules of sugeno's first order type. The number of rules used is twenty five.

4.4. Defuzzification

The output space with the 'fired 'singletons is'defuzzified' to get a final crisp value of the incremental control, in which the output of each rule is a linear combination of input variables plus a constant term.

Layer 1:Each node in this layer performs a Triangular membership function.O1, i= max (min (x-a/b-a, c-x/c-b), 0), i=1,…,5. (3) Where the parameters a and c locate the "feet" of the triangle and the parameter b locates the peak of the fuzzy set, xi is the input to the node i.

Layer 2:Every node in this layer represents the firings strength of the rule.O2, i = w_i =min (uA_i(x),uB_i(y)), i=1,…,5. (4)Eventually the nodes of this layer perform fuzzy AND operation.

Layer 3:The nodes of this layer calculate the normalized firing strength of each rule.O3, i = w_i = w_i / &w_i , i=1,…,5. (5)wi –firing strength of a rule.

Layer 4:The nodes in this layer output the weighted consequentpart of the rule table.O4, i =wi f_i=wi(p_ix+q_iy+r_i), i=1,…,5. (6)Where {pi,qi,ri } is the parameter set of this node.

Layer 5:The single node in this layer computes the overall outputs the summation of all the incoming signals.O5, i =E$w_i f_i$/Ewi , i=1,…,5. (7)Where O 5, i denote the output of the 'i'th node in layer 5.

The Adaptive Neuro-Fuzzy Inference System (ANFIS) training is done assuming that no expert available and the initial values of the membership functions parameters are equally distributed along the universe of discourse and all consequent parts of the rule table set to zero. The ANFIS starts from zero output and during training it gradually learns the rules and functions as close to the desired controller. Thus during training the network structure update membership functions and rule base parameters according to the gradient descent update procedure.

4.5. Simulation and Results

With regard to boost converter, parameter which is shown below is for Figure 3.

$L = 161.95 \times 10^{-6}$ H	$V_g = 24V$
$R_L = 80 \times 10^{-3}\ \Omega$	$R = 10\ \Omega$
$C = 220 \times 10^{-6}F$	$V_O = 48V$
$R_C = 5 \times 10^{-3}\ \Omega$	$D = 0.53$

Then by substituting the values in equation 3 and 4 we will get the state space model boost converter as

$$A = \begin{bmatrix} -510 & -2900 \\ 2100 & -450 \end{bmatrix}, B = \begin{bmatrix} 150000 \\ 0 \end{bmatrix},$$
$$C = [0 \quad 1], D = [0] \quad (4)$$

Open loop Simulink model and open loop response is depicted in Figure 3 and Figure 4. In order to optimize V_o, PID control method with ANFIS is used.

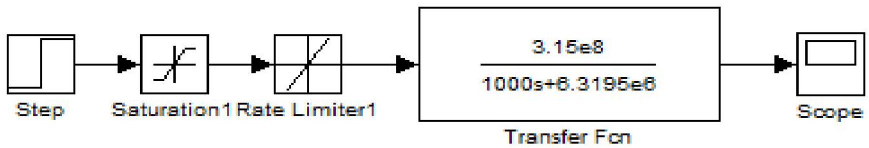

Figure 3 Open loop Simulink Model of Boost Converter

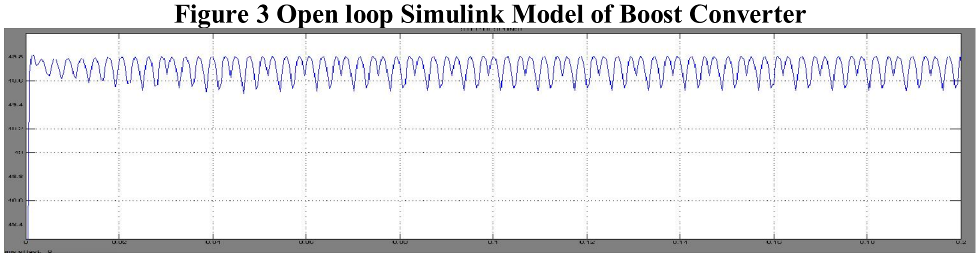

Figure 4 Open Loop Response of Boost Converter

4.6. The Proposed Model for PID Tuning With ANFIS

SIMULINK Model boost converter with PID control using ANFIS which is shown in Figure 5.

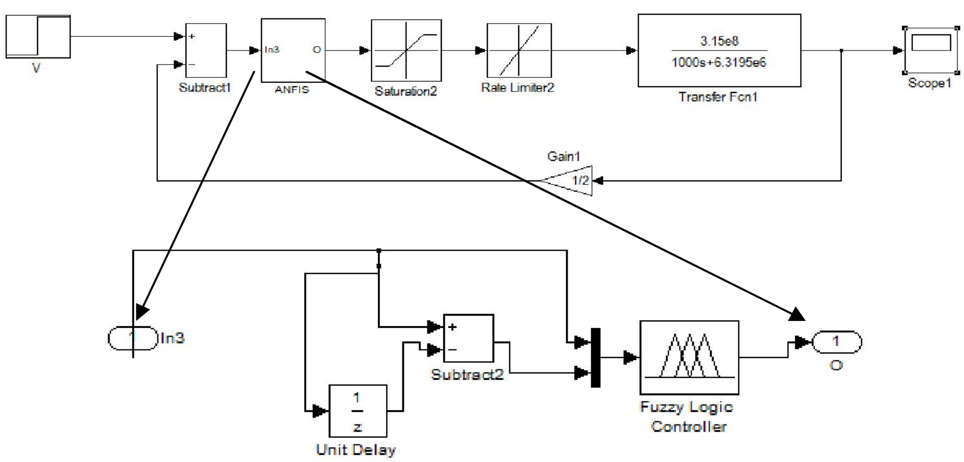

Figure 5 Simulink Model of Boost Converter Using ANFIS-PID Control

The result for boost converter response using PID-ANFIS is shown in Figure 6.

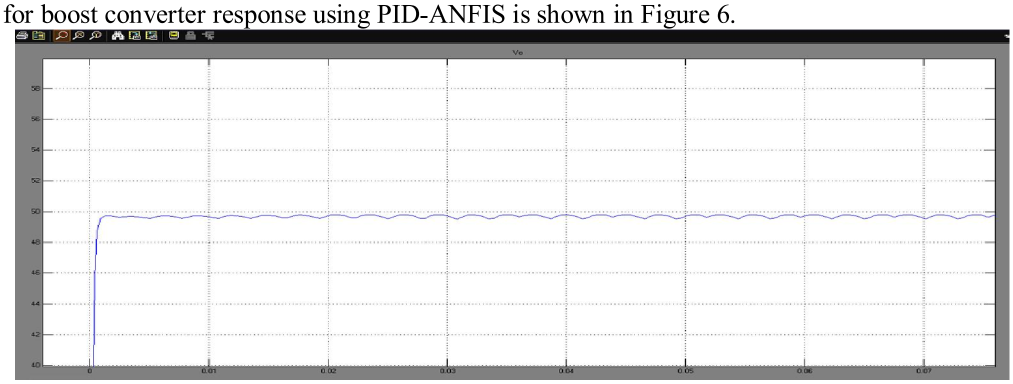

Figure 6. Simulation result of ANFIS

5. Anti-Windup

All actuators have physical limitations, a control valve cannot be more than fully open or fully closed, a motor has limited velocity, etc. This has severe consequences for control. Integral action in a PID controller is an unstable mode. This does not cause any difficulties when the loop is closed. The feedback loop will, however, be broken when the actuator saturates because the output of the saturating element is then not influenced by its input. The unstable mode in the controller may then drift to very large values. When the actuator desiderates it may then take a long time for the system to recover. It may also happen that the actuator bounces several times between high and low values before the system recovers.

5.1 Integrator Windup

Integrator windup is illustrated in the Figure 7,8,9 below, which shows simulation of a system where the process dynamics is saturation at a level of ±0.1 followed by a linear system with the transfer function:

$$G_{(s)} = \frac{1}{s(s+1)} X \qquad (5)$$

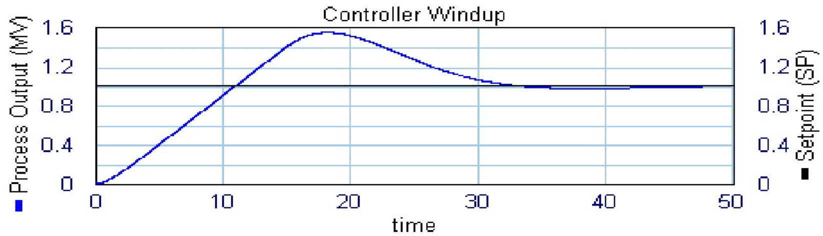

Figure 7 Controller Windup

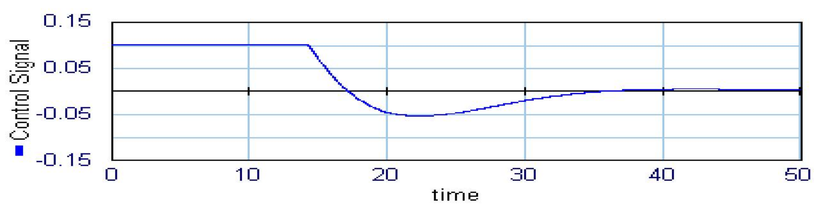

Figure 8 Control Signal

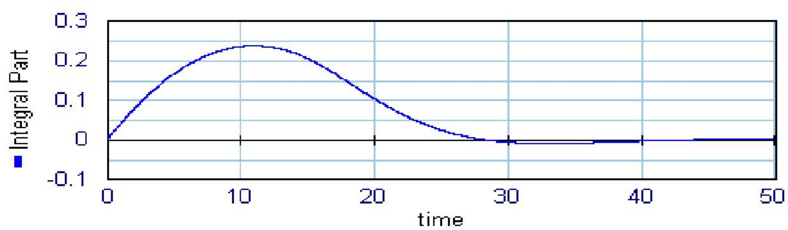

Figure 9 Integral Part

Because of the saturation in the actuator, the control signal saturates immediately when the step is applied. The control signal then remains in saturation level and the feedback is broken. The integral part continues to increase because the error (SP - PV) is positive. The integral part starts to decrease when the process output (PV) has become larger than the set point (SP), but the process output remains saturated because of the large integral part. Slowly the process output decreases towards the set point. The net effect is that there is a large overshoot. This phenomenon is called "integrator windup". A good insight in windup is found when looking at the proportional band.

5.2 Proportional Band and Windup

The values of the process output that correspond to the minimum and maximum output are denoted as y_{max} and y_{min}. The controller operates linearly only if the process output is in the range (y_{max}, y_{min}). The controller output saturates when the process output is outside this band. A good insight into the windup problem is obtained by investigating the range (y_{max} , y_{min}). All 20-sim controller models in parallel form with anti-windup scheme have the extra variables P B _high and PB _low which are equal to y_{max} and y_{min}.

An illustration of the proportional band and controller output is given below Figure10 and 11. The same linear system is used with the same controller. As can be seen, the actuator is saturated from t = 0 until t = 14. At t = 14 the process output enters the range (PB _high, PB _low) and controller feedback is regained.

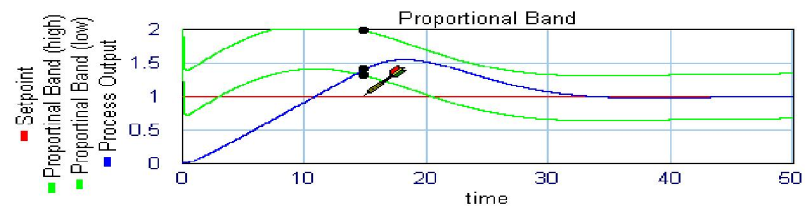

Figure 10 Proportional Band

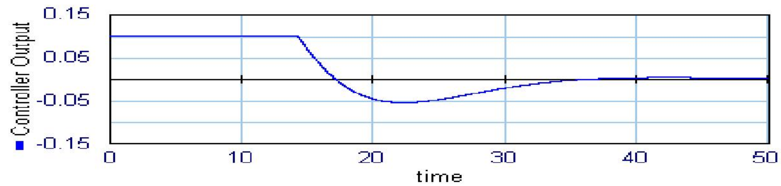

Figure 11 Controller Output

5.3. Anti-Windup

Integrator windup can be avoided, by making sure that the integral is kept to a proper value when the actuator saturates, so that the controller is ready to resume action, as soon as the control error changes. This anti-windup scheme is known as tracking or back calculation.

5.4 Tracking Time Constant

To prevent the integrator from saturating, the tracking time constant must be chosen small. Too small values however decrease the controller performance.

5.5 External Tracking

As long as the actuator output is equal to the controller output, anti-windup scheme will not be activated and the controller is in normal operation (*control mode*). When the actuator saturates, the anti-windup scheme will be activated and prevent the controller output from wandering away. In effect the anti-windup scheme matches the controller output and actuator output. This is why the actuator output is also known as the tracking signal (TR) shown in Figure 12.

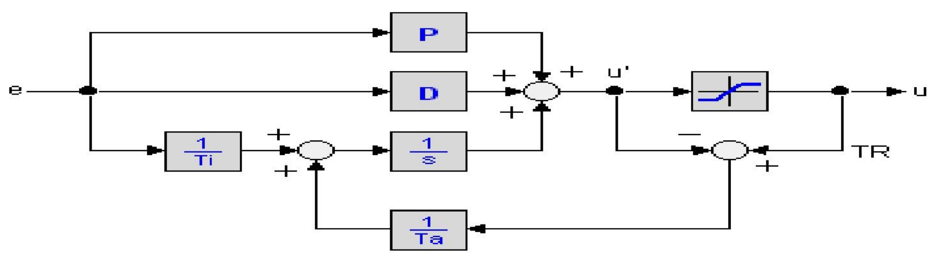

Figure 12. External Tracing

When an external actuator signal is used (external tracking signal) is important to compensate for the actuator gain. Otherwise the tracking signal is not equal to the controller output, during normal operation and the anti-windup scheme is activated.

5.6 Actuator Model

Anti-windup schemes are based on the difference between actuator input (controller output) and actuator output. These signals are not always available. Therefore an actuator model can be used inside the controller to yield this difference. In the library models, a signal limiter is used the actuator model shown in Figure 13.

output = minimum; (input < minimum)

output = input; (minimum <= input <= maximum)

output = maximum (input > maximum)

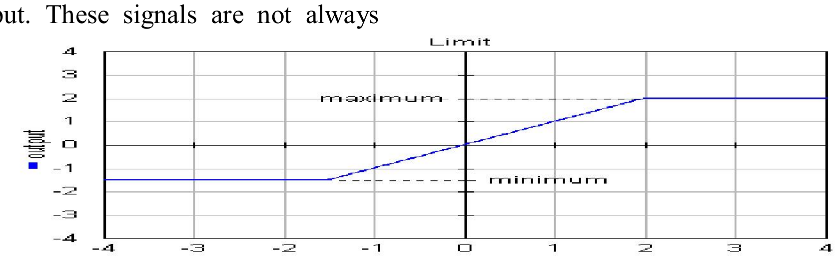

Figure 13 Actuator Output

5.7. Simulation and Results of Anti Windup

With regard to boost converter, parameters which is mentioned above for Figure 14.Then by substituting the values in equation 3 and 4 we will get the state space model boost converter as mentioned above for Figure 14,16.

Open loop Simulink model and open loop response is depicted in Figure 14 and Figure 15. In order to optimize V_o, PID control method with Anti Windup is used.

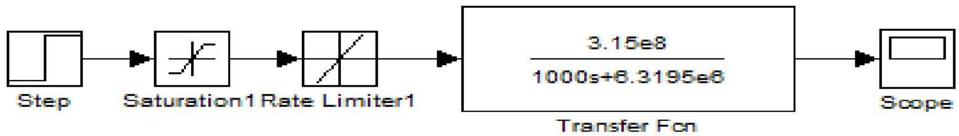

Figure 14. Open loop Simulink Model of Boost Converter

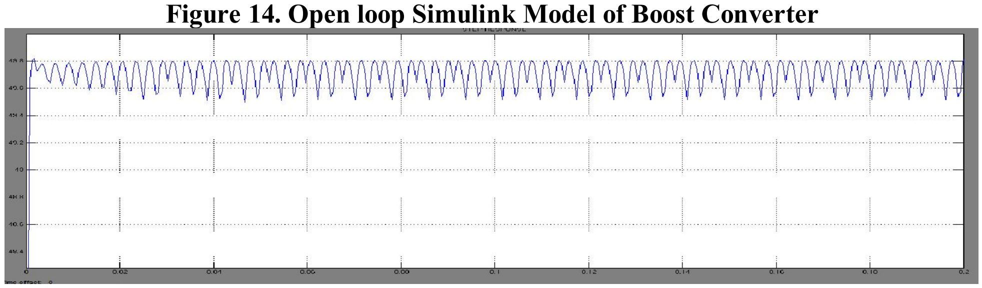

Figure 15. Open Loop Response of Boost Converter

5.8 The Proposed Model for PID Tuning With Anti Windup

SIMULINK Model boost converter with PID control using anti windup which is shown in Figure 16.

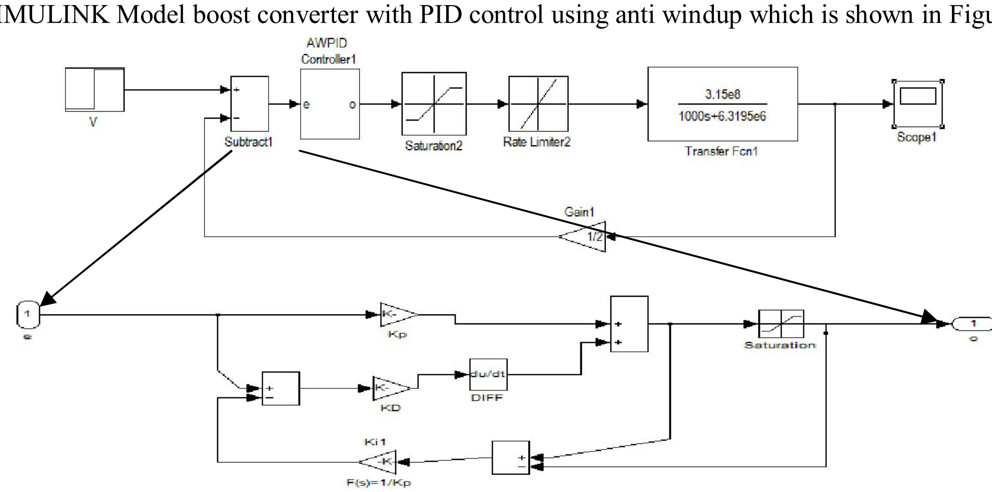

Figure16. Simulink Model of Boost Converter Using Anti Windup-PID Control

The result for boost converter response using PID-Anti Windup is shown in Figure 17.

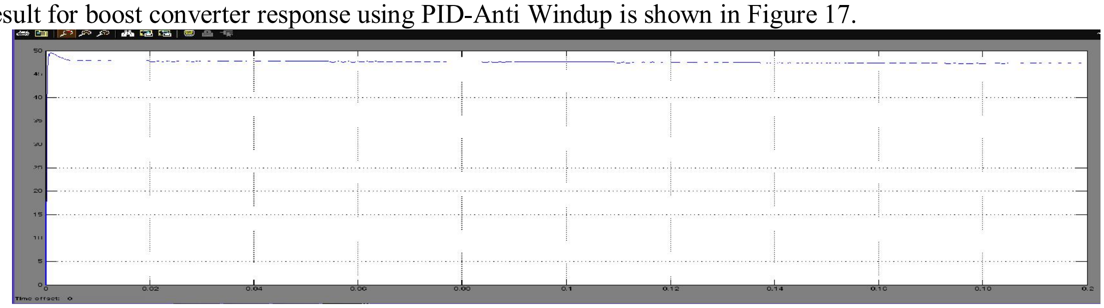

Figure 17. Boost Converter Response with PID-Anti Windup Controller

6. Comparition of Anfis and Anti windup

Table 1: Comparison between ANFIS and Anti-Windup Parameters

S.No	Technique	Peak Overshoot	Steady State Error	Settling Time	Rise Time	Distortion
1	Anti-Windup	3.1%	1.04%	0.008	$3.4*10^{-4}$	Average
2	Anfis	0%	-3.12%	0.001	$3.5*10^{-3}$	Average

By using ANFIS the linearity achieves by reducing the overshoot by zero with slight distortion in the output. In Figure 19 the output which is achieved using Anti Windup the overshoot is very high and the settling of output voltage and peak overshoot is worst compare to the ANFIS. It is found very clearly that ANFIS based controller drastically reduces the distortion as compared to the Anti-Windup method.

7. Conclusion

The optimum design method for PID controller is able to control the dynamic behaviour of the converter efficiently using Neuro fuzzy for the calculation of optimum coefficients of PID controllers can bring about optimum dynamic response. The optimal PID controller parameters are dependent on selection of the weighting factors. So the main challenger was to choose these specific weighting factors. The weighting factors as dynamic optimizing parameters within the Neuro fuzzy technique were considered as an optimization and global selection of all PID controller and weighting parameters. The results of PID controller tuned with ANFIS method are more satisfactory than the PID controller with Anti-Windup method.

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