GTO Based PowerBridge Inverter to Control Nonlinear Behavior of Power Electronic Circuits using MATLAB Simulation

Sadaf Qasim[1], Sony Verma[2] ,Rashmi Pant[3] and Shalini singh[4]

[1,2,3,4] *Department of Electrical and Electronics Engineering*
Shri Ram Murti Smarak College of Engineering and Technology, Bareilly, India

sadaf.riya@gmail.com[1], sonysrms@rediffmail.com[2], rashmi.pant20@gmail.com[3], shalinisinghaec@gmail.com[4]

Abstract: This paper proposes a novel, power electronics system, a high power DC to AC converter, capable of converting power. This paper describes efficient method to avoid instability in power inverter. MATLAB/SIMULINK as a teaching tool is used for modeling and simulation of line commutated dc to ac converter (inverter). A GTO based Three Phase Bridge Inverter has been taken and nonlinear phenomena is investigated using a software package MATLAB/SIMULINK. It is observe that the inverter moves from stable operation to unstable operation as the input voltage to the converter is decreased. This information plays a vital role for designing practical circuits in power electronic circuits.

Keywords: Power Bridge Inverter, Nonlinearities, Instabilities, Controller for compensation.

1. INTRODUCTION

Any power electronics converters may be termed as nonlinear time-varying dynamical systems because they exhibit a wealth of nonlinear phenomena, including various kinds of chaos. The principal source of non-linearity is the inherent switching action and presence of nonlinear components (e.g. the diodes) and control methods (e.g. pulse-width modulation). These nonlinearities are a potential source of engineering malfunction. In order to avoid these phenomena it is very important to predict and analyze the nonlinearities of a converter.

The devices which can convert electrical energy of DC form into AC form are known as power inverters. They come in all sizes and shapes, from a high power rating to a very low power rating, from low power functions like powering a car radio to that of backing up a building in case of power outage. Inverters can come in many different varieties, differing in power, efficiency, price and purpose.

The fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristors. This method is known as phase control and converters are also called "phase controlled converters".

Some of the important industrialapplications of inverter are:

- Variable speed a.c. motor drives
- Induction heating
- Aircrafts power supplies
- Uninterruptible power supplies(UPS)
- High voltage d.c. transmission lines
- Regulated voltage and frequency power supplies etc.

2. BACKGROUND AND LITERATURE REVIEW

Devices that convert dc power to ac power are called inverters. The purpose of an inverter is to change a dc input voltage to ac output voltage which will be symmetric and will have desired magnitude and frequency. The output voltage can be varied by varying the input dc voltage and keeping constant inverter gain, however, if the input dc voltage is fixed and cannot be controlled, the gain of the inverter has to be varied to obtain variable output voltage.

Varying the gain of the inverter is mainly done by a scheme which is known as Pulse Width Modulation (PWM). The inverter gain is basically the ratio of ac output voltage to the dc input voltage. The occurrence of distortion and chaos in power electronics was first reported in the literature by Hamill [3] in 1988. Experimental observations regarding bounded, scattering and instabilities were also made by Krein and Bass [4] back in 1990. Although these early reports did not contain any rigorous analysis, where they provided solid evidence of the importance of studying the complex behaviour of power electronics and its possible benefits for practical purpose. The occurrence of period doublings, sub harmonics and chaos in a simple converter was demonstrated by Hamill [5] using numerical analysis, MATLAB simulation. The derivation of a closed-form iterative map for the boost converter under a current-mode control scheme was presented later by the same group of researchers [6, 9].

3. BASIC PRINCIPLE

Switch pair in each leg, i.e. S_1, S_2, S_3, S_4, S_5, S_6 are turned-on with a time interval of 180^o. It means that switches S_1 conduct for 180^o and switch S_4 for the next 180o of a cycle. Switches in the upper group i.e. S_1, S_3, and S_5 conduct at an interval of 120^o. It means that if S_1 is fired at 0^o, than S_3 must be triggered at 120^o and S_5 at 240^o. Same is true for lower group of switches.

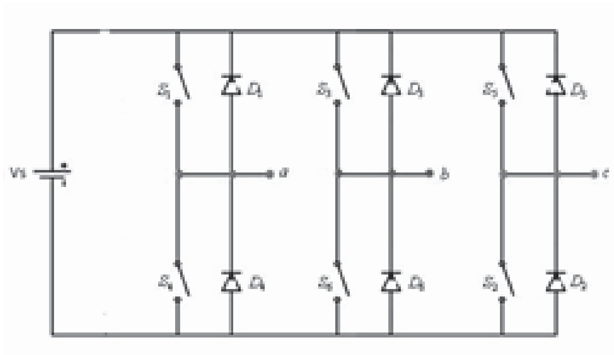


Fig. 1: Basic Circuit of Three Phase Bridge Inverter

Table 1: Summary Operation:

S.No.	Firing Interval	Turn-on devices	Conducting devices
1	0^o-60^o	S_1	S_5 S_6 S_1
2	60^o-120^o	S_2	S_6S_1 S_2
3	120^o-180^o	S_3	S_1 S_2 S_3
4	180^o-240^o	S_4	S_2 S_3 S_4
5	240^o-300^o	S_5	S_3 S_4 S_5
6	300^o-360^o	S_6	S_4S_5 S_6

Under the assumption that the inductor current is essentially piecewise linear, the dynamics of the controlled current is described by the following map:

$I_{n+1} = I_n + m_1T$ if $I_n \leq I_{ref} - m_1T$ (1) $I_{n+1} = I_{ref} - m_2t_n$ if $In > I_{ref} - m_1T$ (2)

Where $I_n = I_L(nT)$ is the value of the inductor current at the clock instant nT; m_1 and m_2 are respectively the magnitudes of the slopes on the increasing and decreasing segment of I_L and $t_n$is the duration of the OFF cycle in the clock in the cycle between nT and nT + T. Under steady state operation in periodic or chaotic mode, with a constantinput voltageV_{in}andallowrippleoutputvoltageofconstantaveragevalue V_{out}, the constants m_1, m_2 and α can be expressed as:

$$m_1 = \frac{V_{in} - V_{out}}{L} \quad \text{and} \quad m_2 = \frac{V_{out}}{L} \tag{3}$$

$$\alpha = \frac{m_2}{m_1} = \frac{V_{out}}{V_{in} - V_{out}} \tag{4}$$

Here α istheratioofslopesmagnitude. If α >1, then stateof operation ofconverter is unstable. Fig. 2 shows a typicalregion of the inductor current, I_L, of a dc-dc converter under currentmodecontrolinthe unstable region.

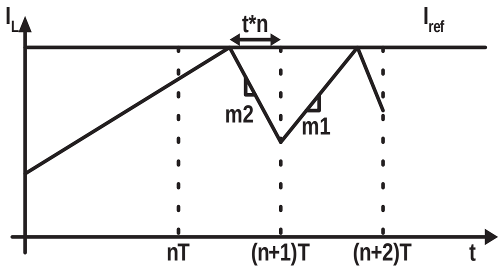


Fig. 2: Inductor Current for abnormal behaviour

4. METHODOLOGY

Designing a three phase inverter for required purpose or UPS (Uninterruptible Power Supply), the basic things we have to design are:

- LC Filter
- PID controller

a) LC Filter Design

While designing L-C filter, the cut-off frequency is chosen such that most of the low order harmonics is eliminated. To operate as an ideal voltage source, that means no additional voltage distortion even though under the load variation or a nonlinear load, the output impedance of the inverter must be kept zero.

Each value of L and C component is determined to minimize the reactive power in these components because the reactive power of L and C will decide the cost of LC filter and it is selected to minimize the cost, then it is common that the filter components are determined at the set of a small capacitance and a large inductance and consequently the output impedance of the inverter is so high. With these design values, the voltage waveform of the inverter output can be sinusoidal under the linear load or steady state condition because the output impedance is zero..

Using the closed relation between the filter capacitor value and the system time constant, the capacitor value can be calculated. The effect of the load current to the voltage distortion can be calculated from the closed form. It is also possible to analyse how much the voltage waveform is distorted in the system in case of a nonlinear load.

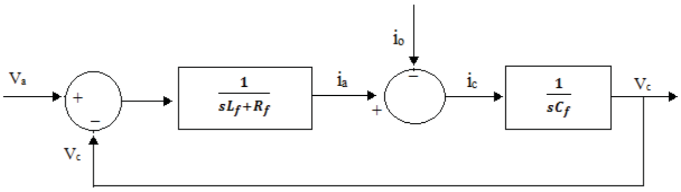


Fig. 3: Design of LC Filter

Figure3 shows the system block diagram of the Design of LC filterand the Input and Output Transfer Function

$$V_c(s) = \frac{1}{L_f C_f s^2 + j R_{f C_f}} V_A(s) - \frac{L_{f s R_f}}{L_f C_f s^2 + j R_{f C_f} + 1} I_o(s)$$

(5)

The frequency transfer function can be expressed as:

$$V_c(j\omega) = \frac{1}{1 - L_f C_f \omega^2 + j R_f C_f \omega} V(j\omega) - \frac{j\omega L_f + R_f}{1 - L_f C_f \omega^2 + j R_f C_f \omega} I_o(j\omega)$$

(6)

To determine the transfer function:

$V_a(s) - s L_f I_a(s) - R_f I_a(s) - V_C(s) = 0$(7)

$$\frac{V_a(s)}{V_C(s)} = 1 + \frac{I_a(s)(sL_f - R_f)sC_f}{I_c(s)}$$

(8)

As, $i_a = i_c + i_o$ $\quad I_a(s) = I_c(s) + \frac{V_c(s)}{Z_L}$ (9)

$$\frac{V_a(s)}{V_c(s)} = 1 + \left(1 + \frac{1}{s C_f z_L}\right)(s L_f + R_f) s C_f \quad (10)$$

$$\frac{V_C(s)}{V_a(s)} = \frac{Z_L}{s^2 L_f C_f + s L_f + s C_f R_f Z_L + R_f + Z_L}$$

(11)

Now, through transfer function we can find the step response. The above equation can be simplified by neglecting the imaginary part in both the terms as equivalent series resistance of inductor is very small that means

$$|1 - L_f C_f \omega^2| >> |R_f C_f \omega| \quad (12)$$

So,

$$V_c(j\omega) = \frac{1}{1 - L_f C_f \omega^2} V(j\omega) \quad (13)$$

This filter design procedure can be well applied to the linear load. But in case of nonlinear load or transient load change, the output current term cannot be neglected due to the increase of load current harmonics. Therefore, for the analysis of voltage harmonics under the nonlinear load, it should be considered. In order to be independent of the load current, the inductor value should be minimized and on the contrary maximized the capacitor value at the same cut-off frequency. Then it satisfies the zero output impedance and works as an ideal voltage source.

At Cut-off frequency,

$$\frac{V_c(j\omega)}{V_a(j\omega)} = \frac{1}{1 - L_f C_f \omega^2} \quad (14)$$

The filter output to input voltage harmonics must be less than 3%.

So,

$$\frac{V_c(j\omega)}{V_a(j\omega)} = 3\% \quad (15)$$

$$\frac{1}{1 - L_f C_f \omega^2} = 0.03 \quad (16)$$

$$\left| \frac{1}{f^2 \frac{X_L}{X_c} - 1} \right| \leq 0.03$$

(17)

$$\frac{X_L}{X_c} \geq 34.\frac{32}{f^2} \quad (18)$$

Where, f = corner or cutoff frequency.

So from this we can find out the L and C for the filter.

b) PID Controller for system:

The combination of proportional, integral, derivative control action is called PID control action.

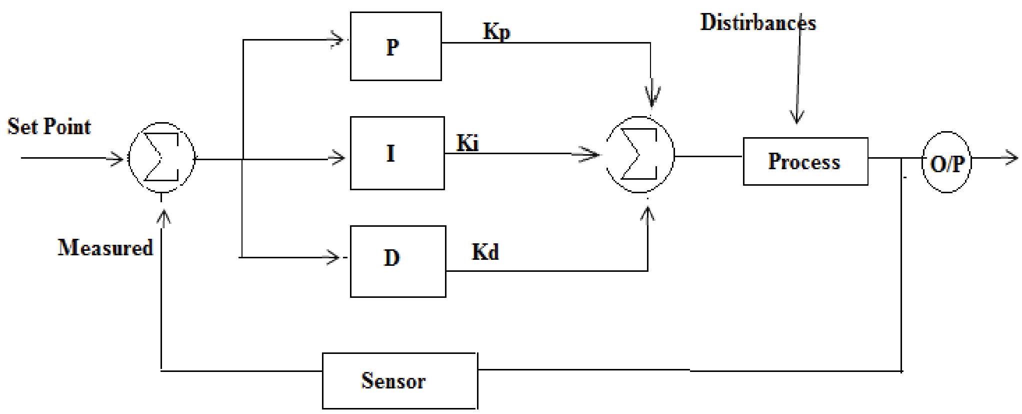


Fig. 4: Combination of three controllers

Mathematically, $y(t)=K_p e(t) + K_p \frac{1}{T_i}\int_0^t e(t)dt + K_p T_d \frac{d}{dx} e(t)$ (19)

Where, $y(t)$ = output K_p= proportional gain T_d= derivative time T_i = integral time

$e(t)$= error signal. Laplace Transform $Y(s) = K_p E(s) + \frac{K_p}{sT_i} E(s) + K_p T_d \frac{d}{dx} e(t)$ (20)

$$\frac{Y(s)}{E(s)} = K_p\left[1 + \frac{1}{sT_i} + sT_d\right] \quad (21)$$

KVL for closed switch in basic circuit of inverter can be written as,

$$R_i + L\frac{di}{dt} + \frac{1}{C}\int i\,dt = V_s \quad (22)$$

Laplace Transform

$$I(s) = \frac{V_s}{L}\frac{1}{\left(s^2 + \frac{sR}{L} + \frac{1}{LC}\right)}$$

(23)

The roots of $s^2 + \frac{sR}{L} + \frac{1}{LC}=0$ are $s = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$ (24)

For under damped circuit, $\left(\frac{R}{2L}\right)^2 - \frac{1}{LC} < 0$ or $\left(\frac{R}{2L}\right)^2 < \frac{1}{LC}$ (25)

$s = -\frac{R}{2L} \pm j\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$ $s = -\xi \pm j\,\omega_r$

(26)

Where, $\xi = \frac{R}{2L}$ and $\omega_r = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$ If $\omega_o = \frac{1}{\sqrt{LC}}$, then $\omega_r = \sqrt{\omega_o^2 - \xi^2}$

Or $\omega_o = \sqrt{\omega_r^2 + \xi^2}$ (27)

Therefore, $I(s) = \frac{V_s}{L}\frac{1}{\omega_r}\left[\frac{\omega_r}{(s+\xi)^2 + \omega^2}\right]$

(28)

Its Inverse Laplace will be $i(t) = \frac{V_s}{\omega_r L} e^{-\xi t} \sin \omega_r t$ (29)

Then, $\xi = \frac{R}{2L}$ (damping factor) (30)

In PID control the actuating signal consists of proportional error signal added with derivative and integral of error signal. A PID controller has thus three adjustable parameters:

- K_i= controller gain and calibrated as proportional band (PB), conversion relation thus given as,

$$K_i = \frac{100}{PB}$$

- T_i
- T_d

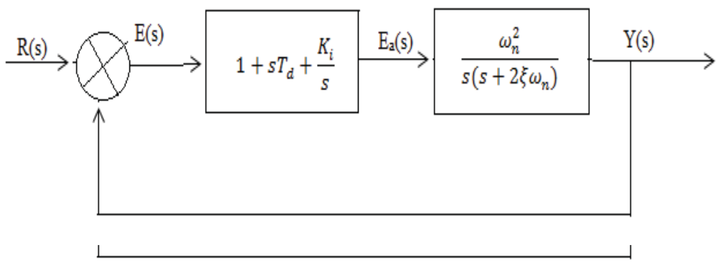


Fig. 5: Block Diagram of PID Control

$$E_a(s) = E(s) + sT_d\,E(s) + \frac{K_i}{s}E(s) \tag{30}$$

$$= E(s)\,1 + sT_d + \frac{K_i}{s} \tag{31}$$

For e.g.: for transfer function,

$$\frac{Y(s)}{R(s)} = \frac{2}{4s^2 + 2s + 1} \tag{32}$$

Table 2: System Parameters and Performances

Control Parameters	Tuned	Performance	Tuned
P	1.0686	Rise Time(sec)	2.09
		Settling Time (sec)	10.8
I	0.3293	Overshoot (%)	4.91
		Peak Time	1.08
D	0.8522	Gain Margin	inf
		Phase margin	0.797
N	91.0441	Closed loop Status	stable

The characteristics of PID control action are:

- No oscillations
- High Accuracy
- High Stability
- Improves the transient response
- Improves the steady state response

5. MATLAB SIMULINK MODEL

Simulink (Simulation and Link) is an extension of MATLAB by Mathworks Inc. It works with MATLAB to offer modeling, simulating, and analyzing of dynamical systems under a graphical user interface (GUI) environment. The Simulink model in MATLAB provides a graphical user interface, users can call the standard library module from where the necessary blocks and components are selected and are properly connected to form the dynamic system model.

Scopes are used to get the output waveform of voltages and current and workspace is also used for the same.

a) Simulink Model :

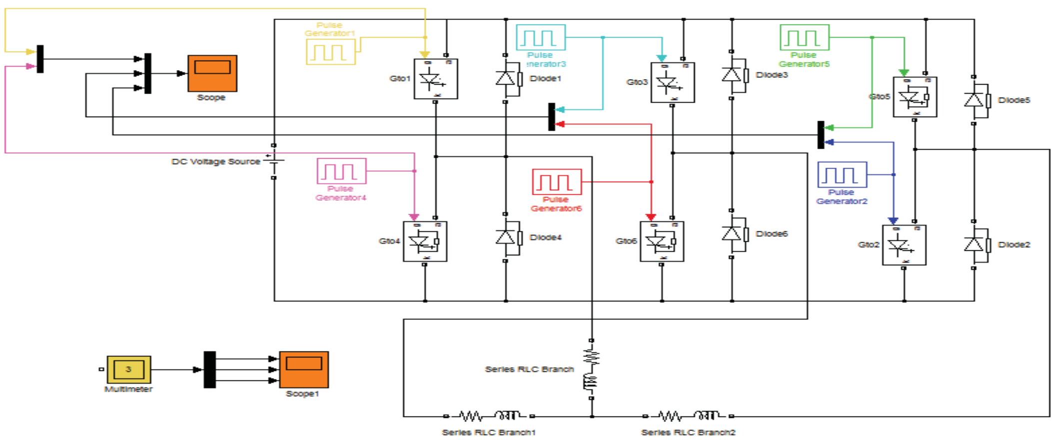
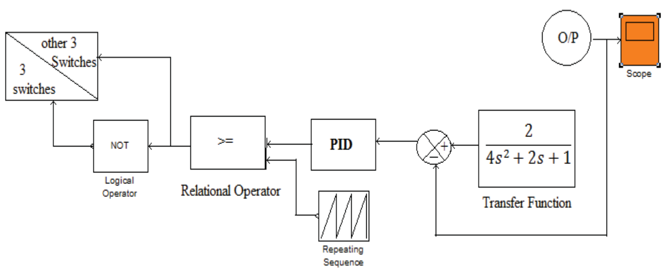


Fig. 6: Simulink Model of Power BridgeInverter

b) Simulink Design of PID Controller:



c) Simulation Result:

i. At R=10Ω,L=30 mH,V_{dc}=48V

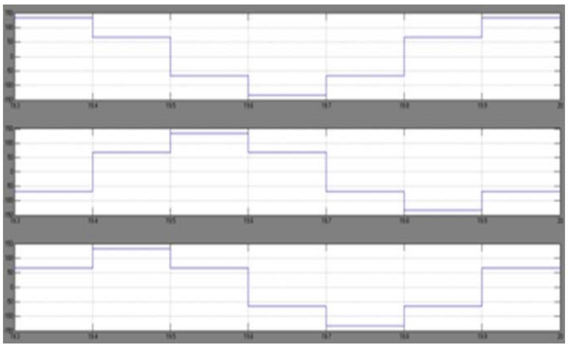


Fig. 7: Output Voltage Waveform of Power Bridge Inverter

ii. At R=100Ω, L=1000 mH,V_{dc}= 48V

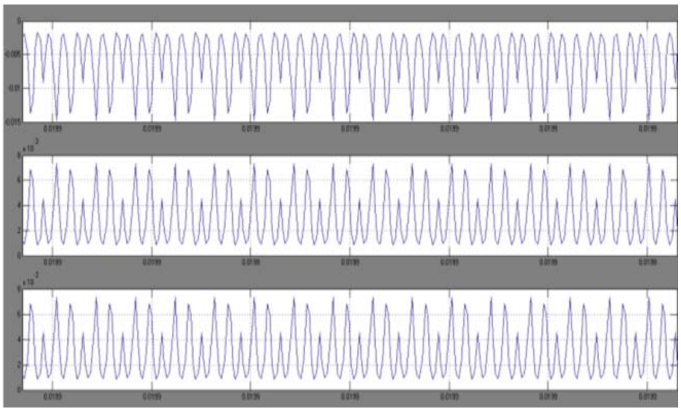


Fig. 8: Distorted Output Voltage after variation in Load

iii.

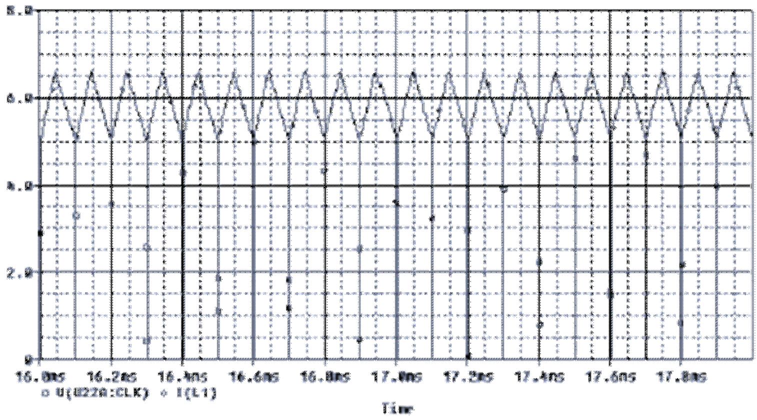


Fig. 9: Waveform of Inductor Current in stablecondition of inverter

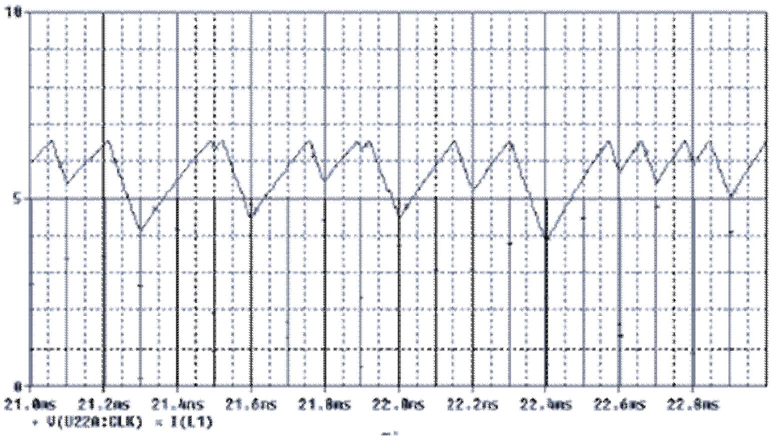


Fig. 10: Waveform of Inductor Current in unstable condition of inverter

iii. PID Controller Response:

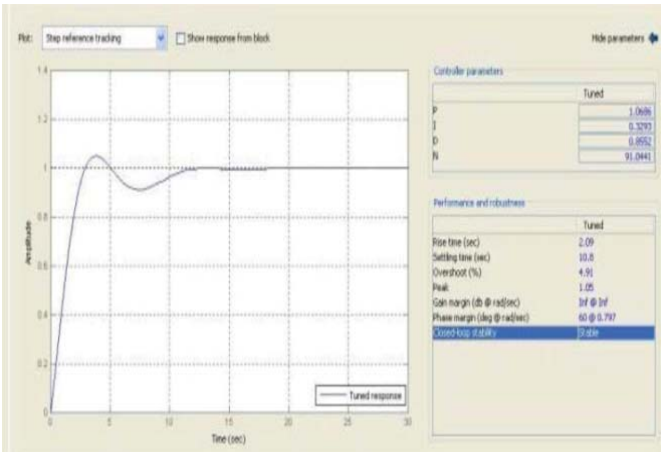


Fig. 11: Response of Controller

6. CONCLUSION

This paper presents an approach to avoid Nonlinearities and instabilities by accommodating controller with power converter. Power quality disturbances can be caused by various reasons and in order to overcome this, it is needed to be analyzed output response on the existing system to get the actual reason for its occurrence. This paper has focused on nonlinear phenomena of Three Phase Inverter. Current and Voltage waveform are obtained at different input parameters which show that inverter operates in period one, period two, higher period and chaotic mode i.e. converter moves from stable region to unstable region. These nonlinearities are a potential source of engineering malfunctions and failures. In order to avoid these phenomena it is very important to predict and analyze these nonlinear phenomena of an inverter before practical implementation.

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