Analysis Of Non-Linear Robust Control Strategies Of Switch Mode Dc To Ac Inverter With Reactive Load

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Abstract- Control strategies are having necessity to remain the output voltage stable for large disturbances at input as well as at output . A dc-to-ac inverter, which gives the nearer sinusoidal output by using nonlinear robust control based on the dc-to-dc converter topology. Computer simulation results show the robustness and fast dynamical response of the control system. Then the nonlinear control law has been extended to a bidirectional inverter to overcome some of the drawbacks. The stability analysis of the control system is presented. The closed loop control system under P control, Pl control, PD control and PID control of the voltage loop for different types of loads are investigated. The results show that the PD control is the best choice. All the work is carried out in MATLAB simulation environment and the results are presented.

I. INTRODUCTION

Nowadays switch–mode dc-to-ac inverters are used in various types of applications, such as uninterruptible power supplies, communication ring generators, aerospace power systems, and variable-speed ac machine drives where the objective is to produce a sinusoidal ac output whose magnitude and frequency can be controlled. The loads in the aforementioned applications are either critical or sensitive. A good steady state and dynamic performance of the switch-mode dc-to-ac inverter is desirable for these applications.

Usually a bridge configuration is employed for the switch-mode dc-to-ac inverters. If the input to switch-mode inverters is a dc voltage source then they are referred to as voltage source inverters (VSI). The other types of inverters which are used for high power ac motor drives are current source inverters (CSI), where the dc input to the inverter is a dc current source.

Recently, switch-mode dc-to-ac inverters using a dc-to-dc converter topology have been developed. Using the dc-dc converter, controlled dc output in the form of a fully rectified sinusoidal wave is generated which becomes the input for the controlled bridge which then outputs a pure sine voltage waveform.

Compared to the bridge-type inverter, the inverter using a dc-to-dc converter configuration has several advantages. Only one switch operates at high frequency and, as a result, switching losses will be significantly less. The conduction loss will be slightly higher because of one extra switch to the bridge configuration. The overall losses will be less, thereby increasing efficiency. In addition, the output filtering capacitors in the dc-to-dc converters can be a dc-type capacitor.

II. PRINCIPLE OF OPERATION

The principle of operation of this type of inverter is illustrated in fig 1, where the dc-to-dc converter is of buck configuration. The average output voltage of this buck converter, Vo, is the product of duty ratio and the input voltage i.e., if the input voltage is constant and the duty ratio is varied slowly, relative to the switching frequency, in the form of a fully rectified sinusoidal wave, the output will naturally be a fully rectified sine wave. Through a bridge circuit, which is synchronized with the fully rectified sine waveform of the duty ratio of the dc-dc converter, the output is "unfolded" into a sinusoidal waveform as shown in fig 2. In which both the magnitude and frequency of the output are controlled by the dc-dc converter, based on the magnitude and frequency of the reference signal.

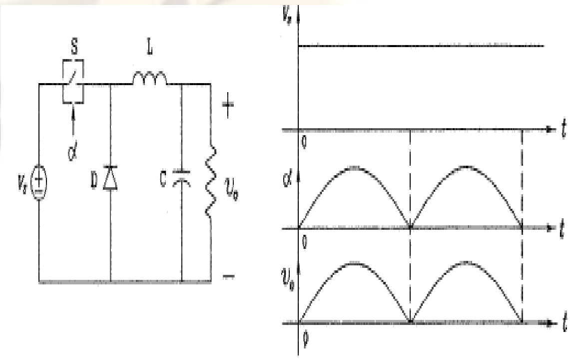

Fig. 1 Buck converter with duty ratio varying in theform of a fully rectified sine wave.

A switch-mode dc-to-dc converter is generally composed of two basic parts. One is the power stage, or the switching converter, the other is the control circuit, as shown in fig 3.where V_r is the reference voltage, y denotes the combination of the feedbacks, and α is the duty ratio.

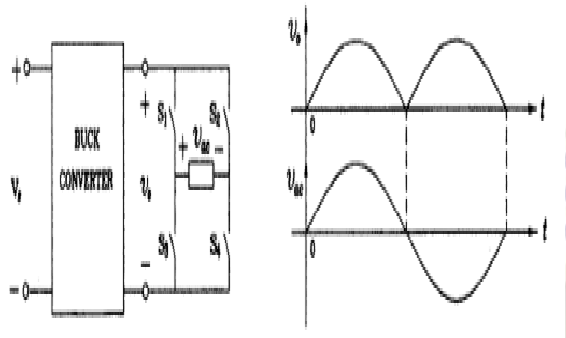

Fig.2 A bridge synchronizer following the buck converter .

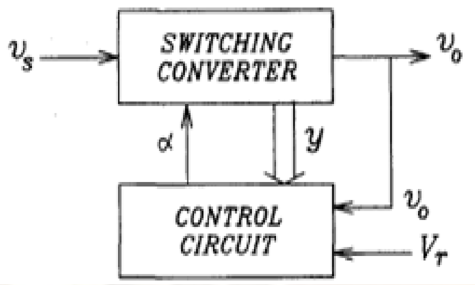

Fig. 3 General Block diagram of switching converter

The power stage controls the power absorbed from the unregulated supply voltage and provides a regulated constant output voltage at the load. The main purpose of the control circuit is to generate a proper duty ratio according to the conditions of the circuit so that the variation of the output voltage is reduced as much as possible when the supply voltage or load current changes. For different control laws, the effect of such disturbance is different.

In order to achieve robust control of the output voltage, i.e., to eliminate the effect of the supply voltage or load current disturbance, the control strategy should be particularly constructed and feedbacks should be properly selected so that the control circuit can provide the exact duty ratio required by the power stage. This implies that the closed loop output voltage should be independent of either the supply voltage or the load current and should be determined only by the reference voltage.

A nonlinear control strategy can be applied to the buck-type dc-to-dc converter to realize the above objective. The low-frequency averaged equivalent model of a buck converter is shown in fig 4.This model is valid only for continuous conduction mode operation.

In this averaged-circuit model, the active switch is modeled by a controlled current source with its value equal to the average current flowing through it over one switching cycle, i.e., $\mathbf{i_s = \alpha i_L}$ for the buck converter, where "i_L" is the averaged inductor current and α is the duty ratio. The average output voltage

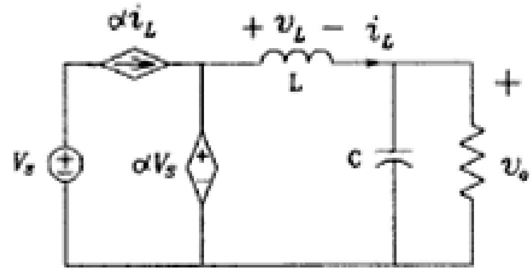

Fig. 4. Averaged model of the buck converter.

across the diode over one switching cycle is modeled as a controlled voltage source with its value equal to $\mathbf{V_d = \alpha V_s}$ for the buck converter.

From fig 5, the output voltage can be expressed as

$$\mathbf{V_o = \alpha_p Vs - V_L} \qquad \textbf{(1)}$$

Where V_L is the averaged value of the indicator voltage and $\boldsymbol{\alpha_p}$ is the duty ratio required for the switching converter. This $\boldsymbol{\alpha_p}$ can be expressed as

$$\mathbf{\alpha_p = (V_o + V_L)/V_s} \qquad \textbf{(2)}$$

equation(2) defines the duty ratio required by the buck converter at a specific operating point of V_o, V_L and V_s.

The control circuit can now be constructed to generate the duty ratio. Let the input and output relation of the control circuit be formulated as

$$\mathbf{\alpha_c = [K(V_r - V_o) + V_L]/V_s} \qquad \textbf{(3)}$$

Where V_r is the reference voltage, K is the gain of the proportional error amplifier, and α_c denotes the duty ratio generated by the control circuit. The implementation is shown in fig 5(a).

The proposed dc-to-ac inverter using nonlinear robust control system.

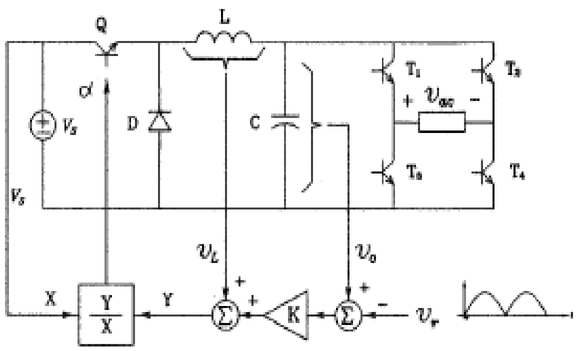

Fig. 5(a).The diagram of the proposed inverter.

Practically the output of the control circuit is connected to the gate of the active switch in the power stage, making $\alpha_p = \alpha_c$. Therefore, the closed-loop characteristic can be obtained as

$$(V_o+V_L)/V_s = [K(V_r-V_o) + V_L]/V_s \qquad (4)$$

From the output voltage can be found as

$$V_o = [K/(K+1)]V_r \qquad (5)$$

It is to be noted that the output voltage V_o at the left side is rms value, Vr is also rms value and K is gain of the proportional error amplifier.

$$V_o = [K/(K+1)]V_r|\sin\omega_o t| \qquad \mathbf{(6)}$$

and represents a fully rectified sinusoidal waveform having the same frequency as the references signal V_r.

The bridge-type synchronizer composed of T_1 – T_4, as shown in fig .6 is used to generate a sinusoidal ac voltage waveform for which input is the buck converter output V_o given by above equation. In this synchronizer, the switching cycle of the diagonal pair of switches, (T_1, T_4) or (T_2, T_3) is synchronized with that of the reference signal V_r. For example, T1 and T4 are turned on at 0, T, 2T etc., and T_2 and T_3 are turned on at (T/2), (3T/2) etc., as shown in fig 3.4 Therefore, the fully rectified sinusoidal voltage V_o can be unfolded into a sinusoidal output voltage V_{ac}. This sinusoidal output voltage V_{ac} is immune to disturbances in the input voltage or output current. The proposed closed-loop control system of the switch-mode dc-to-ac inverter using the buck converter topology is illustrated in fig 5(b).

The output equation shows that by the control law (3), the closed loop averaged output voltage is forced to be proportional to a reference voltage.

This result means that the closed loop output voltage is independent of supply voltage and the load current. In other words, the averaged output voltage remains unchanged even when there is disturbance from either the supply voltage or load current. Zero voltage regulation or robust control of output voltage is, therefore, achieved.

Various waveforms of the proposed dc-to-ac inverter.

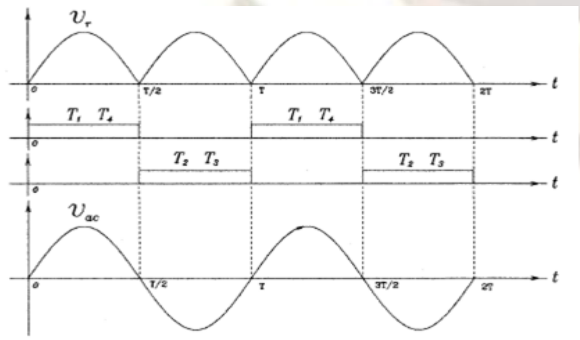

Fig.5(b).The sinusoidal output voltage is obtained by the bridge-type synchronizer.

The control law (3) is nonlinear. The duty ratio is proportional to the sum of the averaged inductor voltage and the output of the error amplifier and is inversely proportional to the supply voltage. Nonlinear control law combined with the inherent nonlinear buck converter has resulted, in this case, in a linear closed loop system. The averaged closed loop output voltage is proportional to the reference voltage.

When the supply voltage changes, the duty ratio will react immediately and change accordingly to such an extent that it can cancel the effect of the supply voltage disturbance. Thus the output voltage keeps unchanged.

The feedback of the averaged inductor voltage is used to correct the disturbance of the load current. The inductor voltage is proportional to the rate of change of inductor current, which is the sum of the load current and the capacitor current as shown in fig 5. i.e., $\mathbf{V_L = L\ di/dt}$ and $\mathbf{I = ic + io}$. As soon as there is a tendency for the load current to change, i.e., even before the load current has actually changed, the correction action of the control circuit begins. The generated duty ratio is accurate enough so that the low frequency averaged output voltage does not change.

The block diagram of the Function Controlled Buck converter is shown in fig 7. The low frequency component of the inductor voltage is retrieved and is added with the output of the controller to formulate the numerator of the control law (3). The controller specified here can be of P, PI, PD, etc. type. Finally the duty ratio is generated by
dividing V_n by V_s as defined in fig 6.

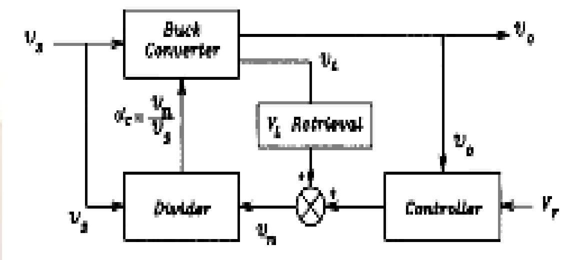

Fig. 6. Block Diagram of function control.

The major drawback of the proposed circuit is that it can only work for resistive load but will not work efficiently for reactive load. In the switch-mode dc-to-ac inverter, the load can be resistive, inductive, or capacitive. Therefore the energy flows bidirectionally. As a remedy to this a bidirectional power stage of the Buck converter is considered, as shown in fig 7.

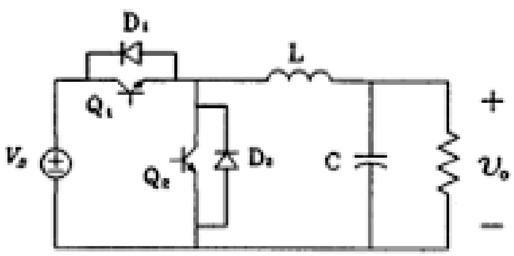

Fig. 7 Bidirectional buck converter.

In this bidirectional power stage, the switches Q1 and Q2 are triggered complementarily.

When energy flows from input to output, Q1 and D2 are active. The power stage functions like a Buck Converter. When energy flows from output to input, Q2 and D1 are active. The power stage functions like a Boost converter. As a result, the inductor current is always continuous, even at a no load condition. The low-frequency averaged circuit model for the bidirectional converter is shown in fig 8, which is a combination of a Buck Converter and a Boost converter.

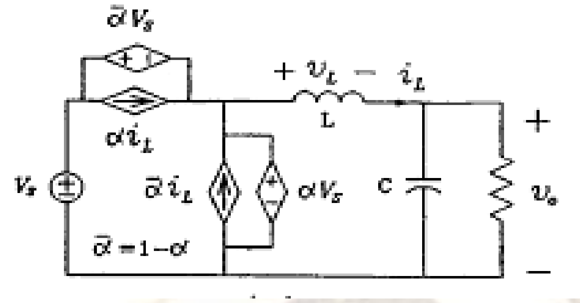

Fig. 8 Averaged model of the bidirectional buck converter

According to Kirchhoff's current and voltage law, the circuit model shown in fig 8, can be simplified to a simpler model, shown in fig 9. Obviously this circuit model is the same as that shown in fig. 4. This paves a way to extend the aforementioned nonlinear robust control to the switch-mode dc-to-ac inverter.

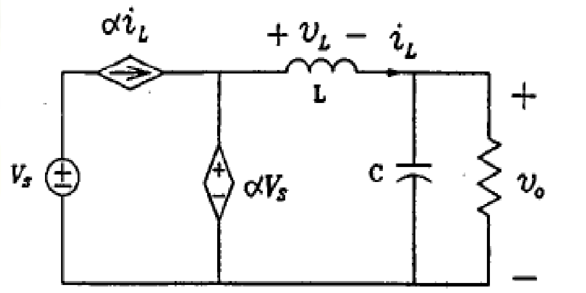

Fig. 9 Simplified averaged model of the bidirectional buck converter.

III. STABILITY ANALYSIS

In order to ensure that the dc-to-ac inverter using the nonlinear robust control will generate the desirable output voltage, irrespective of disturbances such as variations in the input voltage and perturbations in the load current, the closed control system needs to be carefully studied.

The low-frequency averaged circuit equivalent circuit model shown in fig 4 is used to perform the stability analysis. As the winding resistance of the inductor, RL, and equivalent series resistance (ESR) of the filtering capacitor RC, should be included, the equivalent circuit is redrawn and shown in fig 10.

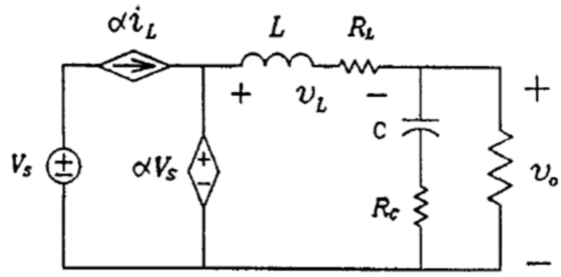

Fig. 10 Low-Frequency average circuit model for stability analysis.

The average voltage of the inductor is indispensable in the construction of the control circuit. However, the actual inductor voltage is a high-frequency rectangular wave. It consists of a low-frequency component and a series of high-frequency components, which are multiples of the switching frequency. A switching average low-pass filter discussed in the last section is used to retrieve the useful low-frequency component and suppress greatly the high-frequency components. Approximately the low-frequency component of the inductor voltage at the output of the filter delays the actual one by one switching period.

First, the resistive load is considered for the stability analysis. The parameters of the power stage are: fs = 10 KHz, L = 5mH, C = 10e–6F, R = 30 Ohm and RL = 0.05 Ohm; RC = 0.01 Ohm.

A) PROPORTIONAL CONTROL

The dynamic response of the closed-loop system to the disturbances in line and load are investigated and the results are presented as follows.

Fig 11 shows the root locus of the closed control system when the proportional gain of the error amplifier of feedback loop K_p varies from $K_p = 1$ to $K_p = 100$. The control system is unstable for the given parameters because two roots are in the right half s-plane.

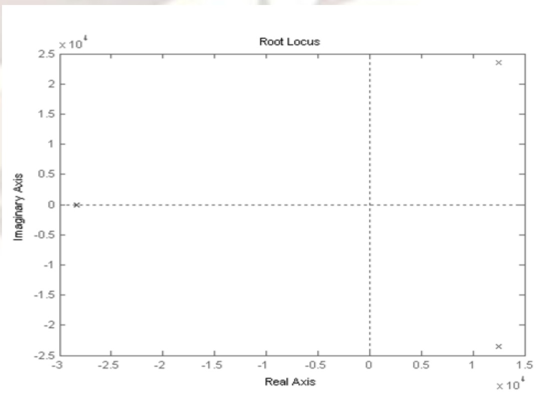

Fig. 11 Root locus plot of the control system with P control (K_p 1 to 100)

B) PROPORTIONAL-PLUS-INTEGRAL CONTROL

The root loci of the closed-loop system where the feedback loop of output voltage is under

PI control are shown in fig 12(a), (b) and (c). The diagrams shown in fig 13(a) and (b) describe the root loci when the proportional gain varies from K_p = 1 to

K_p = 100 under the condition that the integral gain K_I is fixed at K_I = 1 and K_I = 20, respectively. It can be seen that two categories segments of the roots lie in the right half s-plane in both diagrams. Fig 4.3(c) shows two roots in the right half s-plane when K_I changes from K_I = 0.1 to K_I = 50 and K_p = 1 is kept. Obviously, the closed-loop control system using PI control is unstable for the given parameters.

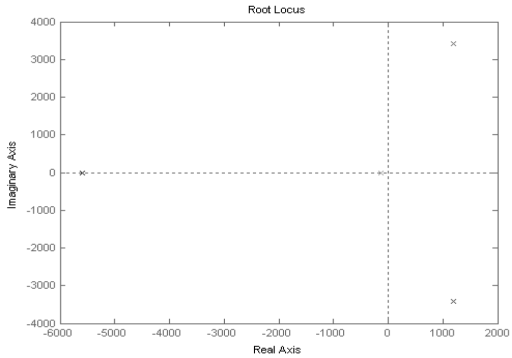

Fig. 12(a). Root locus plot of the control system with PI control (K_p 1 – 100 ,K_I=1)

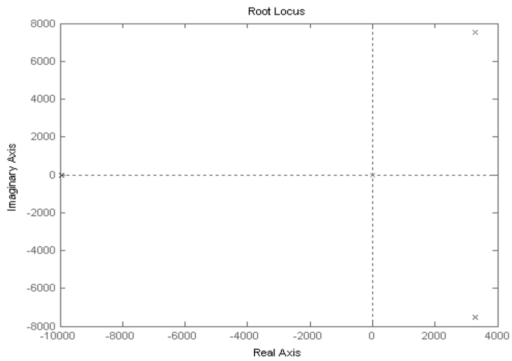

Fig. 12(b). Root locus plot of the control system with PI control (K_p 1 – 100 ,K_I=20)

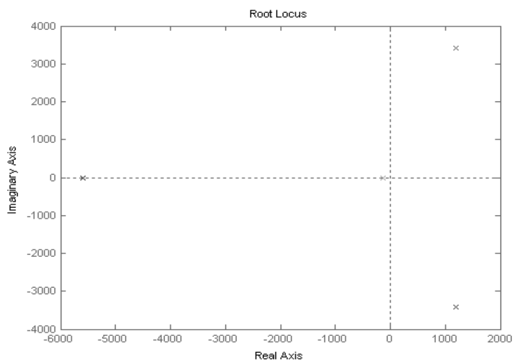

Fig. 12(c). Root locus plot of the control system with PI control (K_p 1,K_I=0.1-50)

C) PROPORTIONAL-PLUS-DERIVATIVE CONTROL

Root locus analysis is performed for the closed-loop control system with PD control. Fig 13(a) and (b) gives the root loci of the closed-loop control system.

The derivative gain K_d is fixed at K_d = 0.01 and K_d = 0.1, respectively while the proportional gain K_p is being varied from 1 to 100. All the roots are in the left half of s plane. For each value of K_d there are three segments. One segment is on the real axis and becomes the dominant root and the other two segments are conjugate and lie far away left from the real root. Fig 13(c) gives the root loci of the PD control for K_p = 10 while the K_d is varied from 0 to 0.01. It can be seen that as the K_d value is increased,

the two conjugate roots move into the left half of s-plane. Thus, from the analysis it is seen that for the given parameters, the system can be stabilized when the gain K_d is proper.

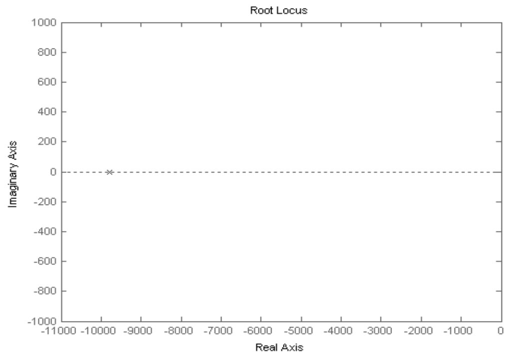

Fig. 13(a). Root locus plot of the control system with PD control (K_p 1-100 ,K_d=0.03)

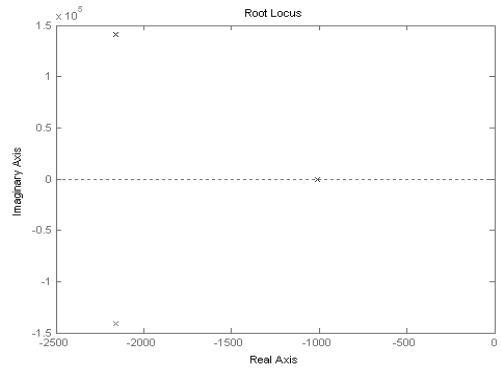

Fig. 13(b). Root locus plot of the control system with PD control (K_p 1-100 ,K_d=0.1)

D) PROPORTIONAL-PLUS-INTEGRAL-PLUS-DERIVATIVE CONTROL

PID control for the output voltage feedback loop is also analyzed. The effect of the gains, K_p, K_I and K_d on the stability of the system is investigated. From the analysis we can say that if the gains are selected properly, the system can be stable. However, if the gains are not properly selected, the system cannot be stable.

Comparing with PD control, in both cases where $K_d = 0.01$ is kept, PID control adds one real root between the root of PD control and the origin. It is this root that is dominant. As a result, PID control has slower dynamic response or is more oscillating that PD control. The reason is that the PD control can be made stable and Pl control is not stable. The integral part in the PID control moves the roots of the PD control system toward the right half s-plane. Therefore, the performance of the system with PID control is worse that PD control.

The closed-loop control systems for inductive load with P control, PI control, PD control and PID control for the output voltage feedback loop

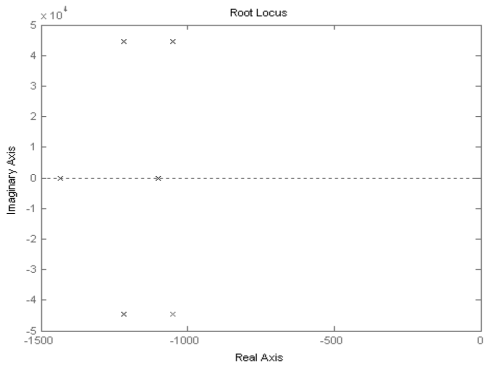

Fig. 13(c). Root locus plot of the control system with PD control (K_p 10 ,K_d=0-0.01).

have been investigated. The root loci are similar to those for resistive load, except for an additional small segment on real axis around (-314, 0). This additional root is caused by the $sL_o + R_o$. Because this root is on the negative real axis and is confined within a tiny range around (-314, 0), it will not affect the stability.

As a result of the stability analysis, PD control is selected for the output voltage feedback loop.

IV. COMPUTER SIMULATION RESULTS

A) RESISTIVE LOAD

The switch-mode dc-to-ac inverter using a dc-dc converter topology with the nonlinear robust control strategy with resistive load as shown in fig 5 is simulated using MATLAB. The simulation details are enclosed in the appendix.

The parameters of the inverter are as follows.
Input voltage 200 V dc
Buck filtering inductor 5mH.
Buck filtering capacitor 10e-6F.

Reference voltage = 25* sin(2*pi*50*t) Volts (pp).
Switching frequency = 10 KHz,
PD control is used in the voltage loop

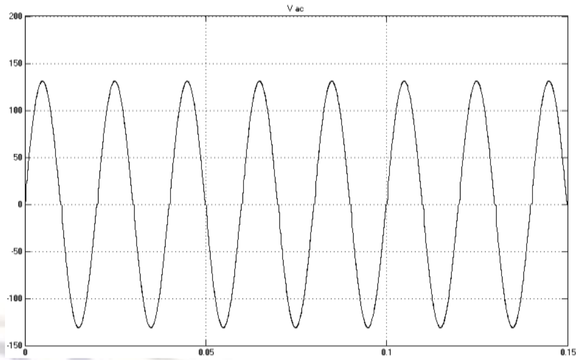

Fig. 14 output voltage (in volts) of the switch-mode inverter for R load.

B) EFFECT OF SUPPLY VOLTAGE DISTURBANCE

The simulated result is shown in fig 15. This result shows that, when the supply voltage variations are in the between 150 and 250 V, the output voltage of the inverter does not change.

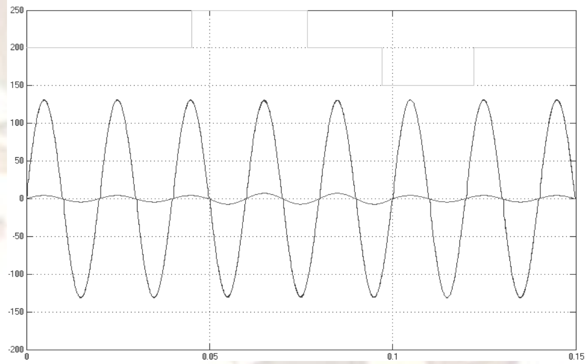

Fig:15 Effect of the input voltage step changes on the output voltage.

C) EFFECT OF THE OUTPUT LOAD STEP CHANGES ON THE OUTPUT VOLTAGE

The response of the control system to a large disturbance in the load is also studied by simulation. The result is illustrated in fig 16. The output current is plotted along with the voltage. The output current suddenly changes from 5 to 7.5 amps (peak – peak) in magnitude in response to a load disturbance. To get a clear idea of the load disturbance scaled output current along with voltage is plotted in fig 17. The simulation result reveals that the output voltage of the inverter under the proposed control technique is not affected by the deviations in the load.

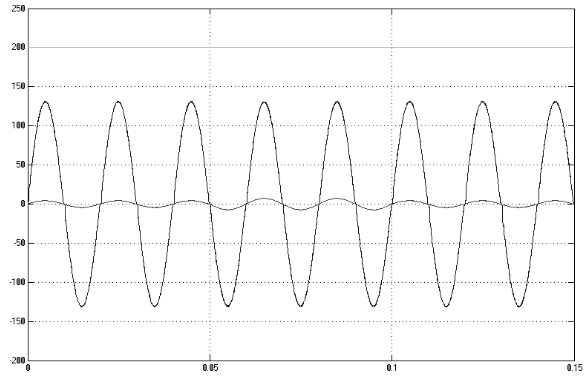

Fig.16 Effect of the load disturbance on the output voltage.

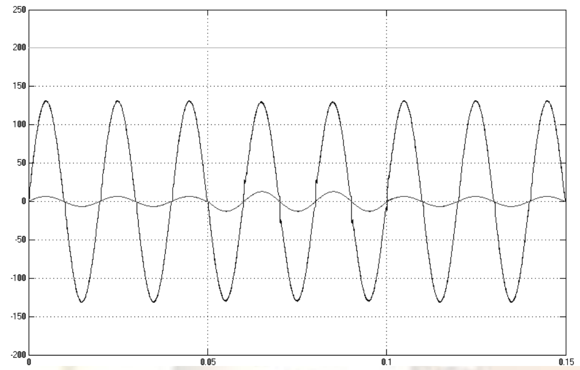

Fig. 17 Effect of the load disturbance on the output voltage with scaled current.

D) RESPONSE TO A STEP CHANGE OF THE REFERENCE SIGNAL

Finally, the response of the control system to a step change in the reference signal is simulated. The result shown in fig 18 demonstrates that this control system has fast dynamic response. The response is plotted for a step change in reference signal from 20 to 30 V in magnitude.

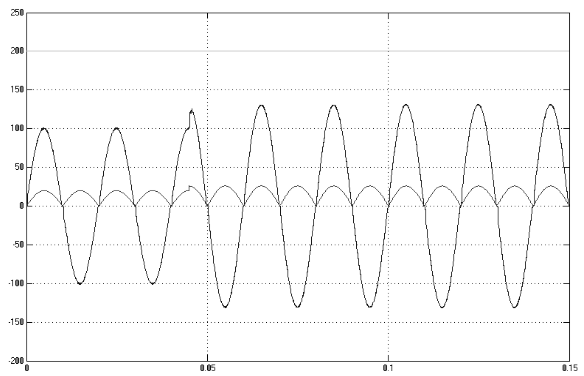

Fig.18 Response for step change in reference signal.

E) REACTIVE LOAD

Almost similar results as shown above are obtained with inductive load also. The output voltage as obtained from the simulation for reactive load is plotted as shown in fig 19 and fig 20 shows the effect of inductive load disturbance. The output current suddenly changes from 5 to 7 amps (peak-peak) in magnitude in response to a load disturbance. Output voltage along with scaled output current is plotted. This result confirms that the proposed model works well for both resistive and reactive loads.

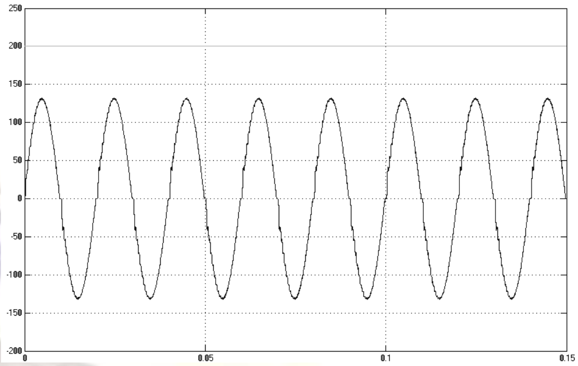

Fig.19 Inverter output voltage for inductive load.

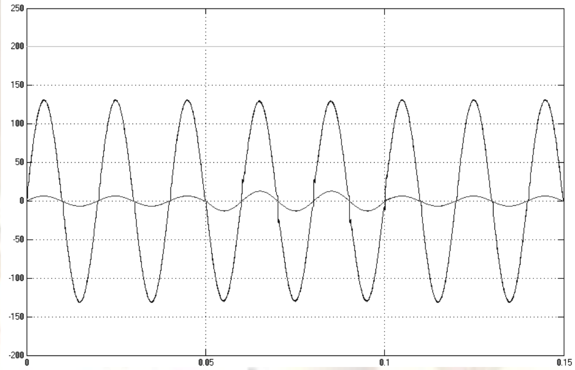

Fig.20 Effect of the load disturbance on the output voltage with scaled current.

V. CONCLUSIONS

The bidirectional inverter with dc-dc converter topology has been simulated using MATLAB. The simulation results confirm that the nonlinear robust control, which has been employed, provides dynamical stabilization of the output voltage of the inverter thus achieving zero voltage regulation. Also with dc-dc converter topology for the inverter pure sinusoidal output has been generated. Also the inverter has high efficiency. By the extension of this novel nonlinear control strategy the bidirectional inverter has also been simulated which works both for resistive and reactive loads. Stability analysis of the control system under P control, PI control, PD control and PID control of the output voltage feedback loop is carried out. The root loci reveal that PD control is the best among the four control schemes.

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