CHAPTER EIGHT

NOVEL CONCEPT OF ELECTRONIC TRANSFORMER

8.1 INTRODUCTION

As seen in previous chapter, Power Quality is important aspect for the efficient operations of load. While the impact of load in terms of reactive power compensation demand can be addressed by different novel means as illustrated in the previous chapters, the quality of power fed by the source still remains a challenge. Especially for the process sensitive applications like pharmaceutical, hospital, process industries source voltage profile assumes very important dimension. To address this aspect, novel concept solution, of Electronic Transformer (ET) for Low Voltage (LV) distribution system application is introduced in this chapter. This chapter initially highlights the need for such a requirement. It then introduces a novel concept of power electronics based voltage transformation- Electronic Transformer (ET). Further, the chapter gives details on concept and simulation results.

8.2 NEED FOR ELECTRONIC TRANSFORMER

The Special Economic Zones(SEZs) and the state utilities have been looking for improving the LV distribution network. The improvement must bring tangible benefits to the utility as well as to the consumers. There is hence stress on quality of supply delivery, unity power factor operation of Distribution Transformers (DT), and reduced losses in the system with relevant improvements. Presently the 11/22 kV substations deliver power to number of DT's connected to it. The supply quality is poor. Network has considerable losses, which then increase transmission losses. Some effort is being put in by the utilities to incorporate Thyristor Switched Capacitor banks for reactive power compensation. However, there is no other conscious effort to improve the power quality and a large reduction in losses. The concept suggested is an offshoot to provide economical but effective solution while mitigating above needs.

8.3 CONCEPT OF ELECTRONIC TRANSFORMER

In this concept, electronic transformation of supply voltage through Electronic Transformer (ET), for typically an 11/22 kV substation power fed locations, where normally DT's would have been installed is proposed. It is presumed that the Electronic Transformer (ET) is substituted at every of these locations, instead of a normally used Distribution Transformer (DT) supplying the power to the concerned location. The ET consists of an Low Voltage DC (LVDC) link consisting of rectifier and buck converter converting the higher DC voltage to about 850 Vdc voltages, along with a suitable capacity IGBT based three-phase half bridge inverter.

The ET offers good output voltage and frequency regulation and less voltage distortion. Thus, the consumer is benefited due to quality power supply. The ET draws near unity power from the substation supply and hence the losses in Transmission and Distribution (T&D) are also expected to be reduced, once the ET's are installed in large numbers. Two different schemes, are suggested which provide good quality power, retaining the galvanic isolation provided by the DT.

In the first scheme as shown in fig. 8.1, a three-phase diode rectifier and single active switch (say an IGBT) based boost converter is used [239] at the output of a DT. This is a non-regenerative single quadrant converter. It produces the required 700 to 850 V dc bus (as decided by the designer) from which a three–phase 415 V, 50 Hz quality output supply can be produced for the consumers. The boost converter acts as a Low Voltage DC link and separates the incoming ac and the outgoing ac voltages. The boost converter draws discontinuous currents with sinusoidal envelopes from the DT. The input side filter filters out the switching frequency component and allows near sinusoidal currents to be drawn from the DT at unity power factor. This is the main advantage of this scheme.

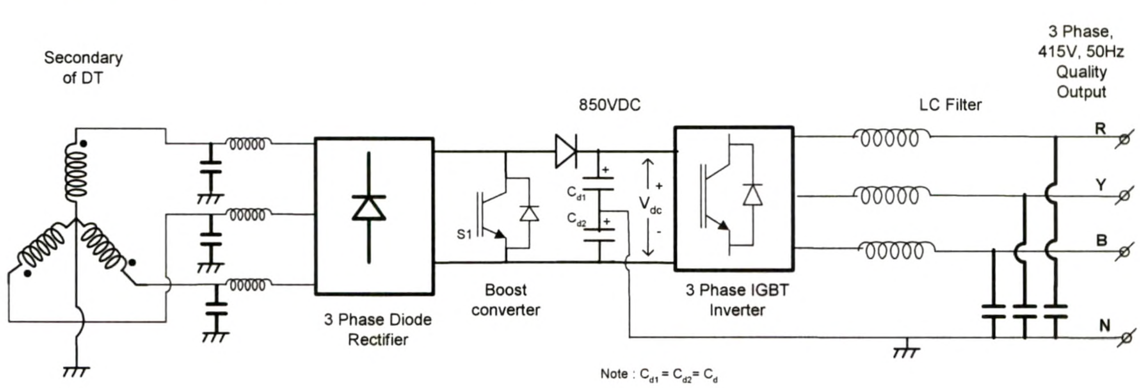

Fig. 8.1 Electronic transformer galvanically isolated for 11/22kV distribution system – Scheme 1

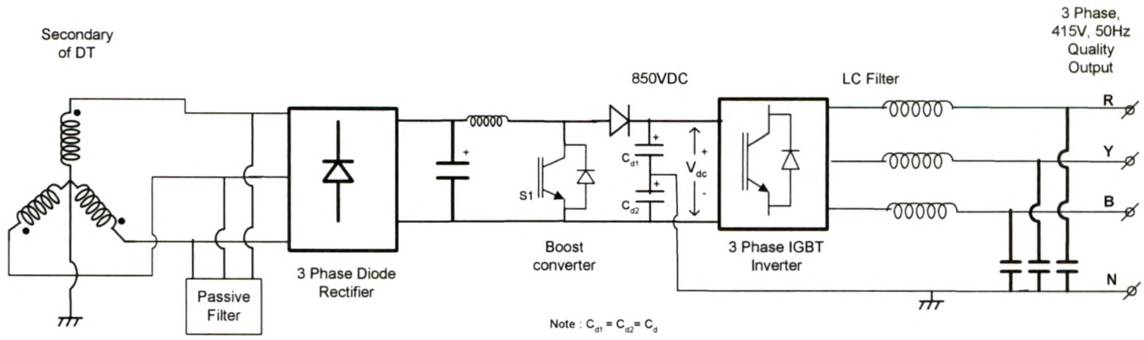

Fig. 8.2 Electronic transformer galvanically isolated for 11/22kV distribution system – Scheme 2

In this case the central point of this tapped portion of the capacitor bank (Cd1 and Cd2) can be grounded and also can act as neutral for the output side.

It is also possible to see that the boost converter of a larger capacity is installed in a substation and the DC bus of 700 to 850 V (2 wires) runs to different local stations (where the three-phase inverters can be installed feeding the local distribution loads of DT's). This could be more economical.

A second scheme as shown in fig. 8.2 has a rectifier output given to a normal boost converter with the shunt connected IGBT switch. The diode rectifier draws peak currents and the line currents will have positive current peaks at 60 and 150 deg. & negative peaks at 240 and 300 degs. The fundamental power factor is unity. However, the current distortion is high and the overall Power factor could be 1 * 0.7 = 0.7, where 0.7 is the current distortion factor. The harmonic content will be 5, 7, 11, 13, etc. (6K +/- 1 harmonics). Thus, a passive filter is required. The passive filter can be designed to improve the current distortion from 0.7 to 0.9 or a little above based on economics or its cost.

For both of the suggested schemes, the output of the inverter will be a quality output with good supply voltage as well as frequency regulation. If necessary a closed loop for the inverter output voltage control can also be introduced without much of an additional cost.

The potential for such a quality supply is considerable with private utilities as well as with High Tension (HT) consumers who have there own internal distribution based on HT voltage supply (220/132/66 kV supply). The immediate application areas can be considered as substitution of the DT's (mainly in urban areas where consumers are ready to pay for quality supply) and also includes substations in a large factory (where the HT supply is taken to number of substations).

8.4 MODELING AND SIMULATION

The Proposed system can be seen to have three sub-systems as its critical functional blocks. As depicted in fig 8.3

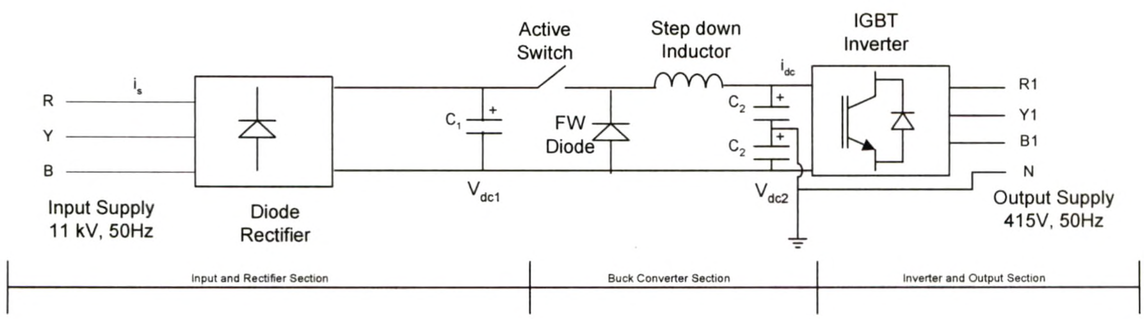

Fig 8.3 Electronic Transformer Conceptual diagram

The three sections are :

1. Input Line side of 3Ø 11KV 50Hz ac with rectifier and filter capacitor

2. Buck Converter

3. Inverter for generating 3Ø 415V 50Hz ac with filter

8.4.1 INPUT LINE SIDE RECTIFIER STAGE

The technology for the input line side rectifier can be very easily achieved using conventional High Voltage (HV) diode rectifier with filter capacitor making use of series connected diode and capacitor for achieving desired operating ratings/ margins. As the distribution load is normally not regenerative, diode based rectification is adequate for rectification of incoming 11/22kV supply. Even if some regeneration is there, it can be taken care by the output side dc capacitor The diode rectifier typically will be three phase type (6 diodes) with each diode having a Peak Inverse Voltage (PIV) of 36 kV and current rating @ 10A Iav at 60 deg.C is desired. The diodes can be can be connected in series for voltage and paralleled for current to get the desired rating for example for this application Semikron HV diode HSKE5000/2200-0.5 having PIV=12 kV, Iav=0.6 can be used with 3 in series for obtaining 36kV and 17 in parallel for obtaining 10A, implying effectively 3 x17 = 51 such diodes for front rectifier section. The rectifier dc voltage is to be filtered by using dc capacitor. The current drawn by rectifier will be half wave symmetrical 4 pulses in one power cycle. More details are covered in report [240].

8.4.2 OUTPUT INVERTER

Similarly, the inverter for delivering the 415 three-phase, as output can also be designed on similar lines as described in the design for STATCON with 850VDC as the operating dc link voltage and described in the earlier chapter. This inverter very easily can be realized using IGBT for delivering @500kW as in case of DTs.

8.4.3 BUCK CONVERTER SECTION

Buck converter is the key stage which steps down the input rectifier dc voltage Vdc1 to Vdc 2, which is adequate for generating 415V from a Pulse Width Modulated (PWM) inverter at the output. The buck converter section as shown consists of active switch (S1), dc inductor (Ld), free wheeling diode (FWD1) and the dc capacitor bank (C2). The switch S1 operates for 6 times in one power cycle allowing the energy to be transferred from input rectifier stage capacitor C1 to the capacitor C2. This energy has to be equal to the energy delivered to the load in one power cycle. When the device S1 closes, the current idc will flow through input capacitor (C1), S1, Ld and C2. When the S1 opens, the current freewheels through FWD1, Ld and C2. At the end of each cycle dc capacitor bank C2, has to reach the same voltage level, if the output delivery remains the same. It has been established that the "on" time of the switch is proportional to square root of the output direct current. Details of the basic relationship for the output dc current Idc and the "on" time of active device S1 has been covered in ref. [240]. However, For holding the voltage across the capacitor for varying load (0 to 100%), a closed loop system has to be implemented. The important block hence to be investigated is the buck converter control design to step down the input rectified voltage to the inverter DC link operating voltage levels. Hence, simulations for the viz. open loop, closed loop Proportional and Integral (PI) & Proportional , Integral and Differential (PID) involving current feedback, closed loop PI (& PID) involving voltage feedback have been done and the results with control optimizations are provided in next sections.

8.4.4 BUCK CONVERTER SIMULATIONS

The simulation of the buck section for the concept of electronic transformer is preformed using MATLAB/Simulink.

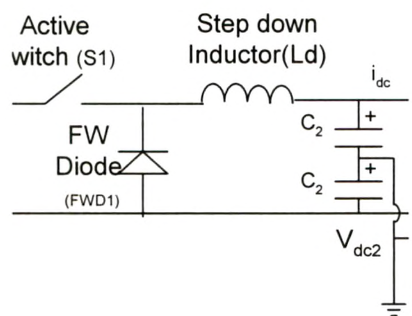

Fig. 8.4 Buck Section

Basic parameters used for Simulation / computation are listed in Table 8.1 below.

Table 8.1 Simulation parameters

Simulation Parameter	Value
Load (Only Resistive)	100 kW
I/P Voltage	15556 V
Inductor (L)	2 mH
O/P Capacitor	0.01 F
Switching Frequency	300 Hz

Basic computations (formulas) used in the simulations are illustrated in table 8.2 which has been extracted from excel file.

Table 8.2 Electronic Transformer formulae

Supply voltage	V_{L-L}	user	11000
Rectifier Capacitor Voltage	V_{DC1}	$V_{DC1}=\sqrt{(2)} * V_{L-L}$	15556.34919
Buck O/P Voltage (Capacitor)	V_{DC2}	$V_{DC2}= 2*\sqrt{2}*V_{Ph(rms)} / MI$	754.2472333
Buck O/P Voltage (Capacitor) **3rd harmonic injection**	V_{DC2}	$V_{DC2}= 2*\sqrt{2}*V_{Ph(rms)} / MI /1.155$	653.0279076
O/P (Inverter) Phase rms voltage	$V_{Ph(rms)}$	user	240
Modulation Index (**Inverter**)	MI	$MI = V_{sig} / V_{trig}$	0.9
Amplitude of Fundamental Signal	V_{sig}	user	0.9
Amplitude of Triangular Signal	V_{trig}	user	1
Power Delivered to Load (VA)	Po	user	16000
Power Factor	P.F.	user	0.85
Current drawn by load at above pf	I_{load}	$I_{load}=Po/(\sqrt{3}*415*P.F.)$	26.18739704
Current delivered from DC link (Buck O/P Capacitor)	I_{DC}	$I_{DC}= Po / V_{DC2}$	24.50124997
Turn on time of switch (**Buck**)	Ton	$Ton= K* \sqrt{I_{DC}}$	5.59748E-05
Constant	K	$K= \sqrt{((2*L_D *V_{DC2}*T) / (V_{DC1}*(V_{DC1}-V_{DC2})))}$	1.13083E-05
Switching Time Period	T	T=1/Fs	0.003333333
Switching Frequency	Fs	user	300
Buck Inductor	L_D	user / formula	0.00681
Buck Capacitor	C_D	user / formula	

8.4.5 OPEN LOOP CONTROL FOR BUCK CONVERTERS

This simulation is done with the purpose of understanding the buck converter and to test initial calculations done in excel file. While the basic simulation block is shown in fig. 8.5, The resultant waveform of o/p voltage and current are depicted in the Fig. 8.6.

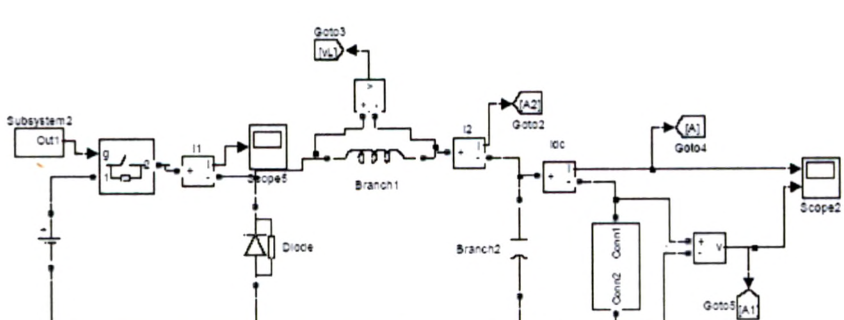

Fig. 8.5 (a) Simulink Block set for Open Loop Simulation of Buck Converter

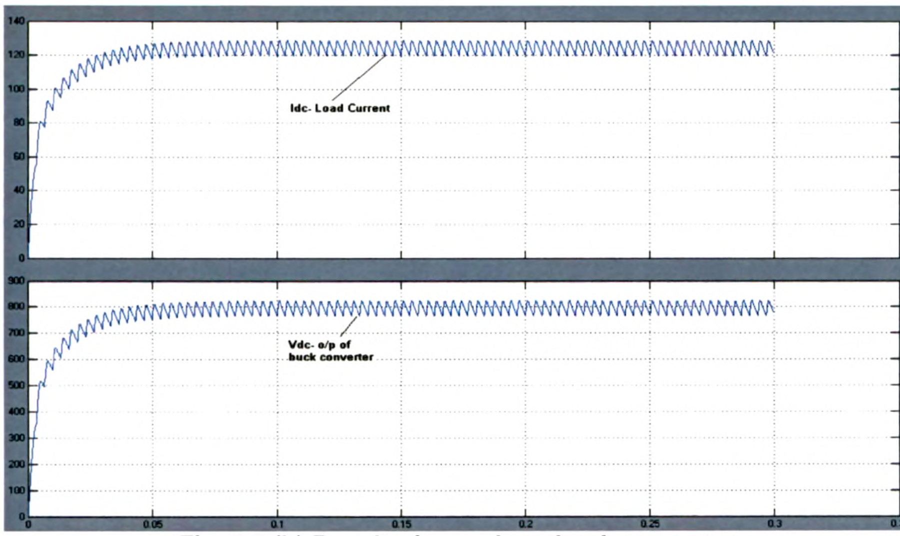

Fig. 8.5 (b) Result of open loop buck converter

8.4.6 CLOSED LOOP CONTROL – CURRENT FEEDBACK FOR BUCK CONVERTER.

The switch ON time is calculated using equation $T_{ON} = k\sqrt{I_{dc}}$

The value of k can be calculated using equation $k = \sqrt{\dfrac{2 \times L_d \times V_{dc2} \times T}{V_{dc1} \times (V_{dc1} - V_{dc2})}}$

Simulation parameters are listed in the Table 8.1 Simulation parameters

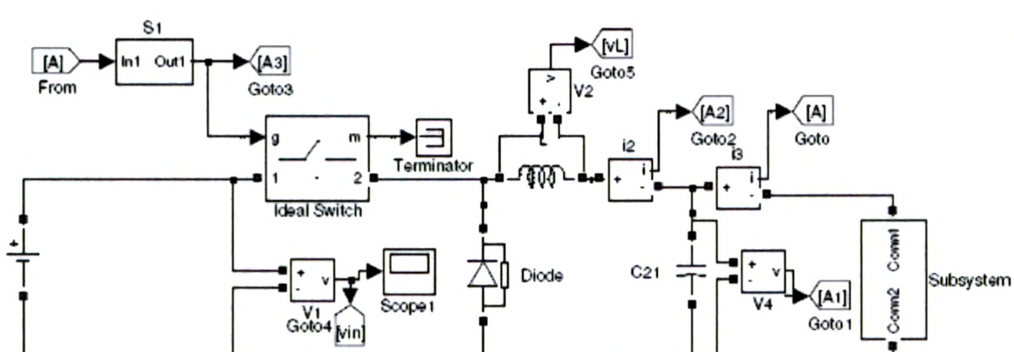

Fig. 8.6 Closed loop control of Buck Converter with current feedback

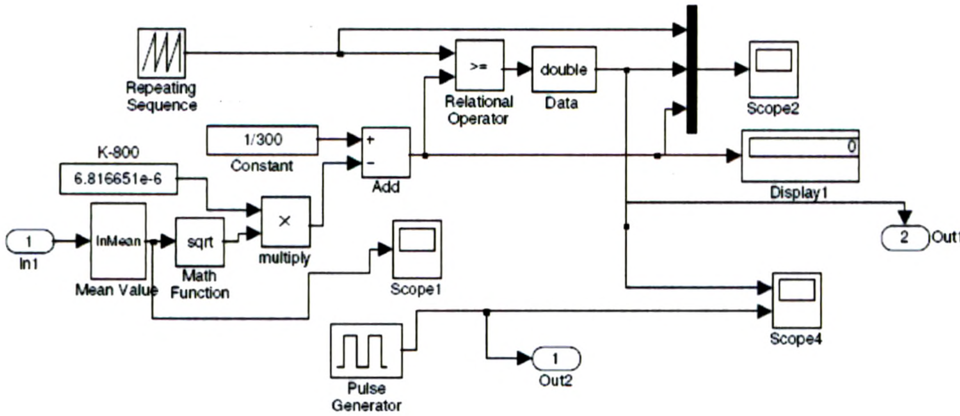

Fig. 8.7 Controller Subsystem (S1)

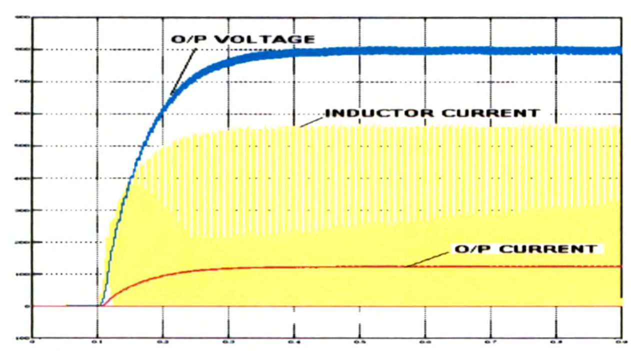

Fig. 8.8 Voltage & Current Waveform

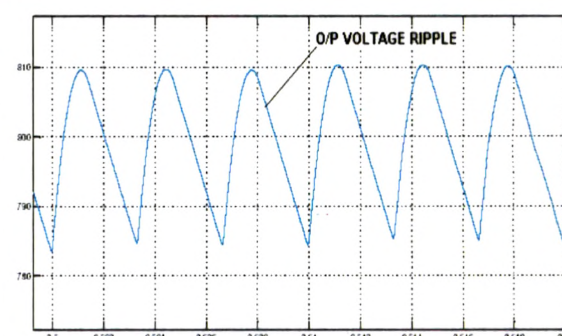

Fig. 8.9 O/P Voltage Ripple Waveform

8.4.7 CLOSED LOOP CONTROL -VOLTAGE FEEDBACK FOR BUCK CONVERTER

Simulation parameters are listed in the Table 8.1 Simulation parameters

PI control parameters (Kp =0.5, Ki=0.4, sample time = 5e-6 sec.)

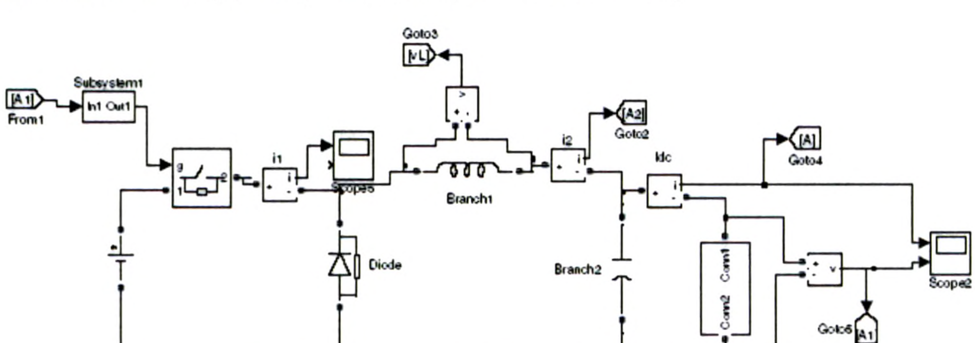

Fig. 8.10 Close Loop Control of Buck converter with Voltage Feedback

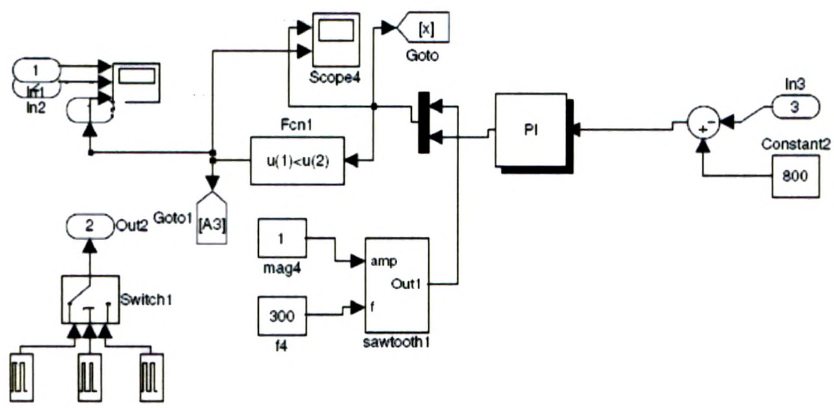

Fig. 8.11 Controller subsystem

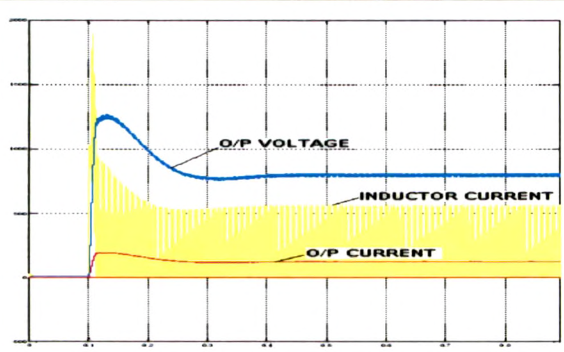

Fig. 8.12 Voltage & Current Waveform

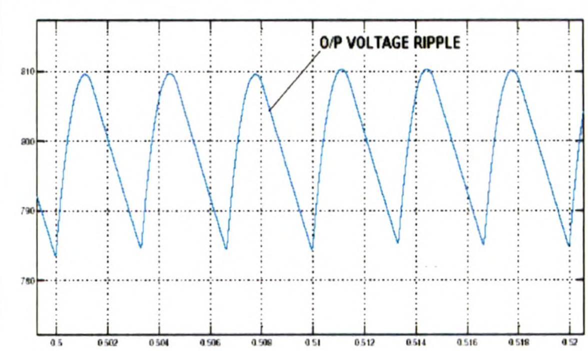

Fig. 8.13 O/P Voltage Ripple

8.4.8 CLOSED LOOP CONTROL FOR BUCK CONVERTER WITH VOLTAGE FEEDBACK AND PI CONTROLLER WITH RECTIFIER AND FILTER CAPACITOR USED AT INPUT SIDE

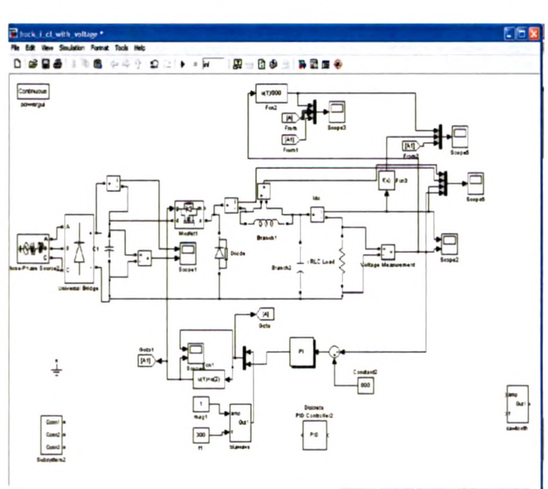

Fig. 8.14 Close Loop Control of Buck converter with Voltage Feedback PI Controller

Parameters, considered are :c1=c2=5000e-6f; L=0.001h;R=6.4 with PI controller parameter (Kp= 0.8, Ki=0.9, sample time = 50e-6)

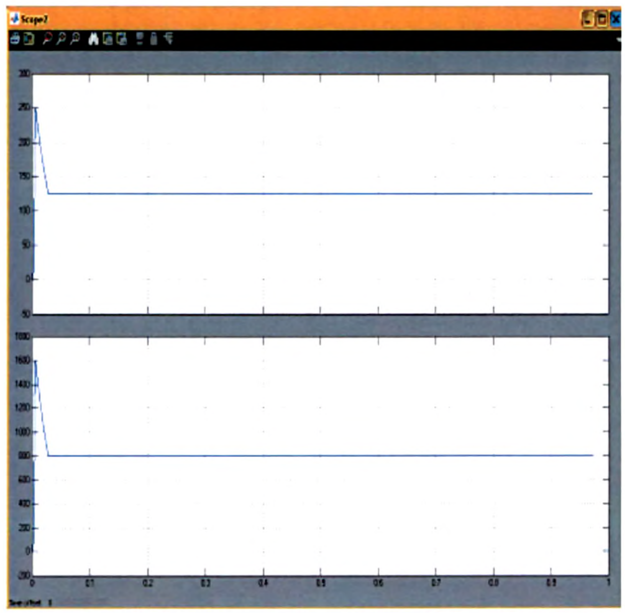

Fig. 8.15 Output current & voltage: with PI controller parameter (Kp= 0.8, Ki=0.9, sample time = 50e-6)

8.4.9 DIFFERENT CASE FOR CLOSED LOOP CONTROL FOR BUCK CONVERTER WITH VOLTAGE FEEDBACK AND PID CONTROLLER

L=1e-3 ; c=5000e-6 ; vdc=15556.349 v;

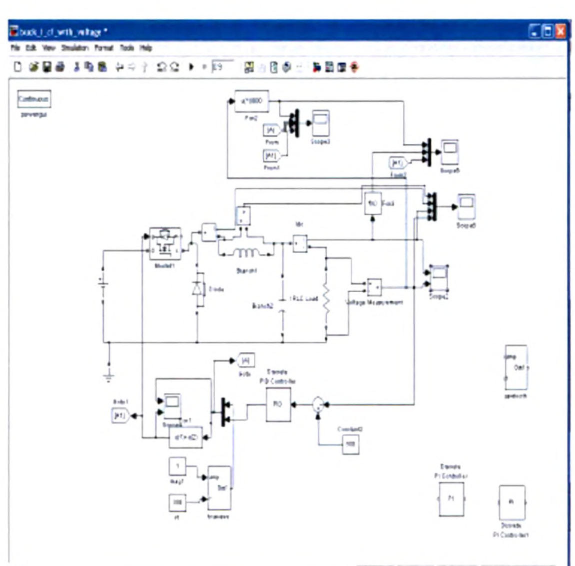

Fig. 8.16 Close Loop Control of Buck converter with Voltage Feedback PID Controller

Case 1: Voltage and current waveforms for PID control with Parameters (Kp=0.6, Ki=0.4, Kd=0.002 , td=0.5e-5 , sample time = 50e-6)

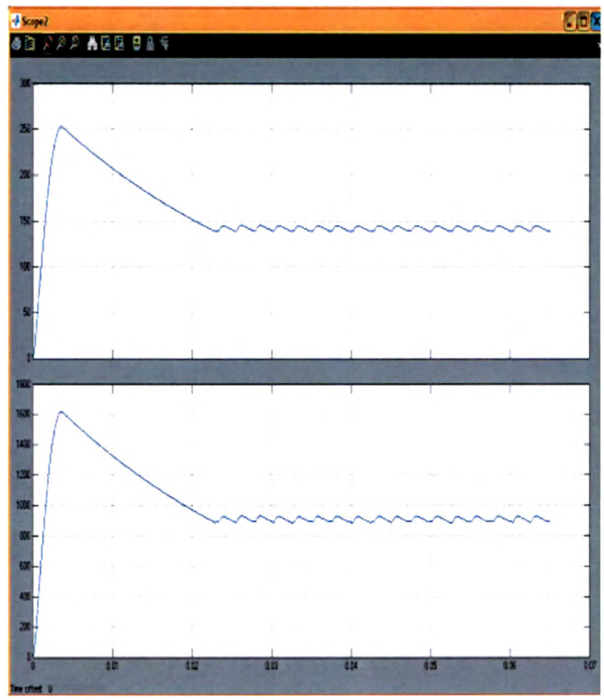

Fig. 8.17 Voltage and Current waveforms with PID Control- Case 1

Case 2 : Voltage and current waveforms for PID control with Parameters For Kp=0.6, Ki=0.9, Kd=0.002 , td=0.5e-4, sample time = 5e-6;

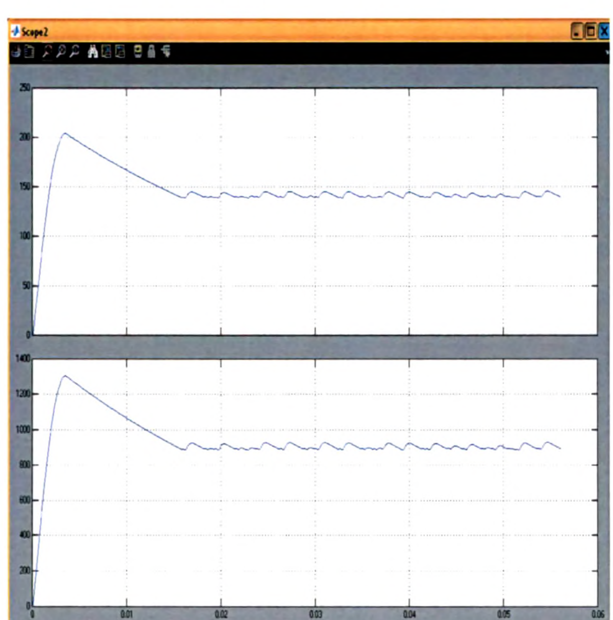

Fig. 8.18 Voltage and Current waveforms with PID Control- Case 2

In steady state:

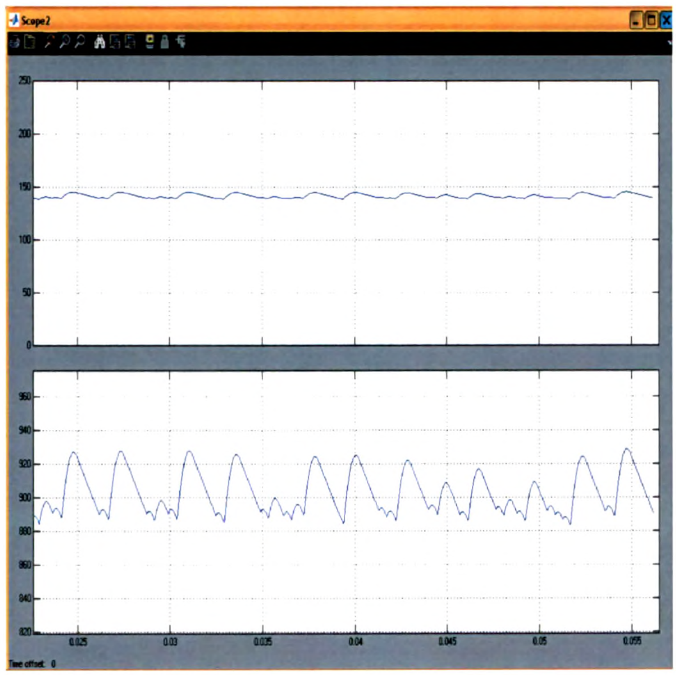

Fig. 8.19 Voltage and Current waveforms with PID Control- Case 2 in steady state

Case 3 : Voltage and current waveforms for PID control with Parameters (For kp=0.6 , kd=0.9 , kd=0.002 , td=0.5e-5 , sample time = 50e-6)

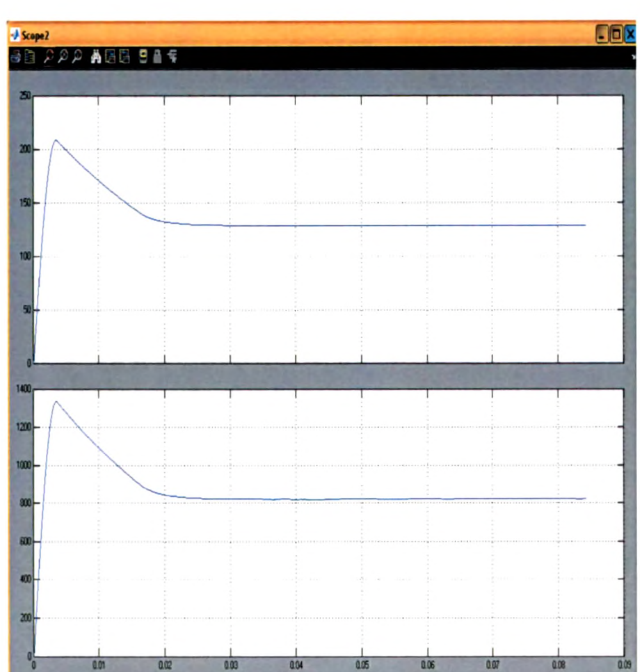

Fig. 8.20 Voltage and Current waveforms with PID Control- Case 3

UNDER STEADY STATE:

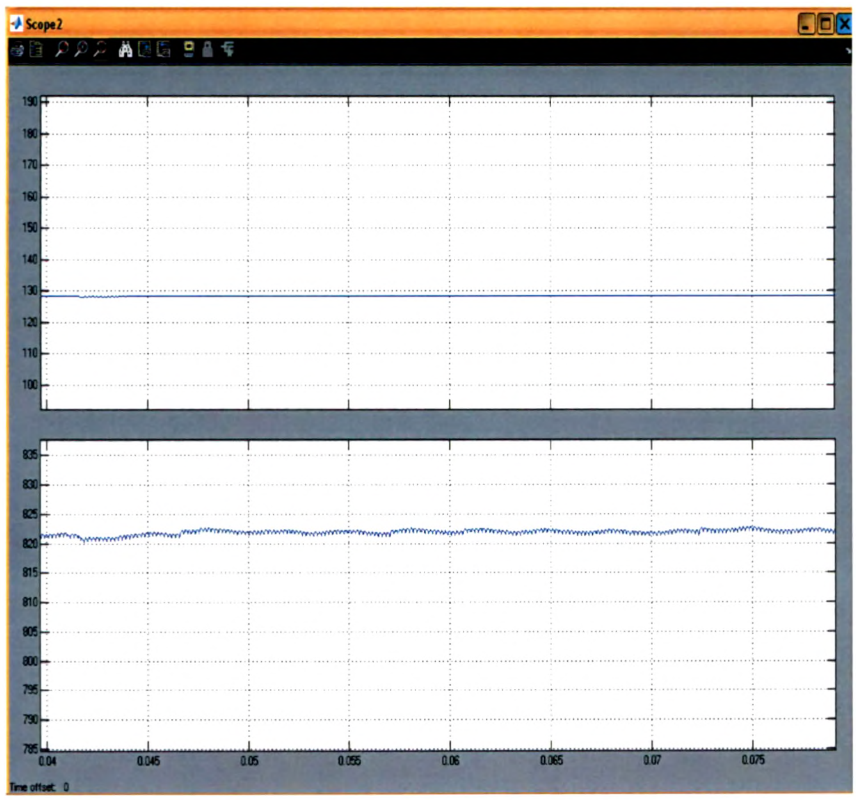

Fig. 8.21 Voltage and Current waveforms with PID Control- Case 3 in steady State

Case 4 : Voltage and current waveforms for PID control with Parameters (For kp=0.6 , kd=0.9 , kd=0.005 , td=0.5e-5 , sample time = 5e-6)

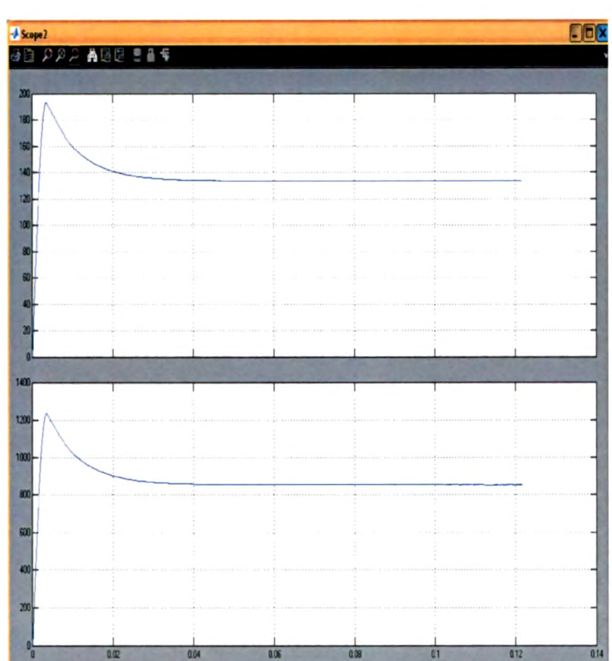

Fig. 8.22 Voltage and Current waveforms with PID Control- Case 4

UNDER STEADY STATE:

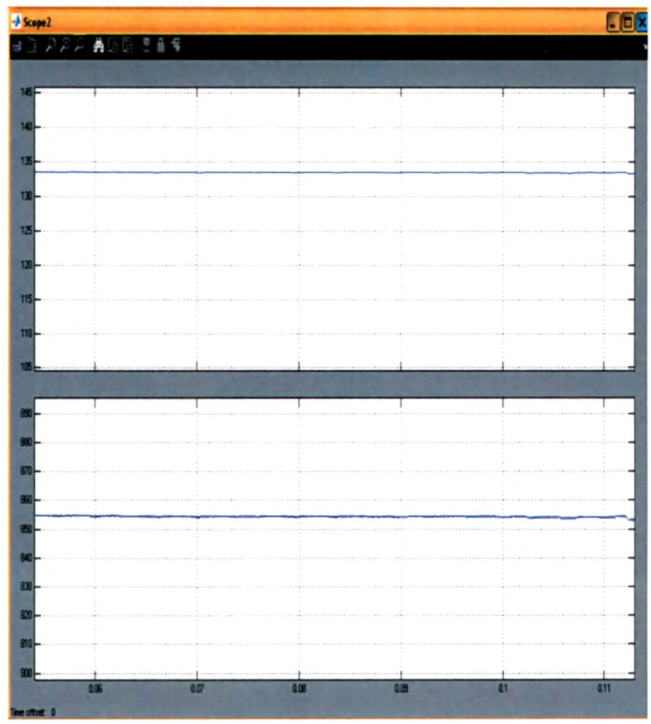

Fig. 8.23 Voltage and Current waveforms with PID Control- Case 4 in steady State

8.4.10 CLOSED LOOP CONTROL FOR BUCK CONVERTER WITH VOLTAGE FEEDBACK AND PID CONTROLLER WITH RECTIFIER AND FILTER CAPACITOR AT INPUT SIDE

PID controller parameters are Kp=0.6, Ki= 0.9, Kd=0.005, Sample Time = 5e-6

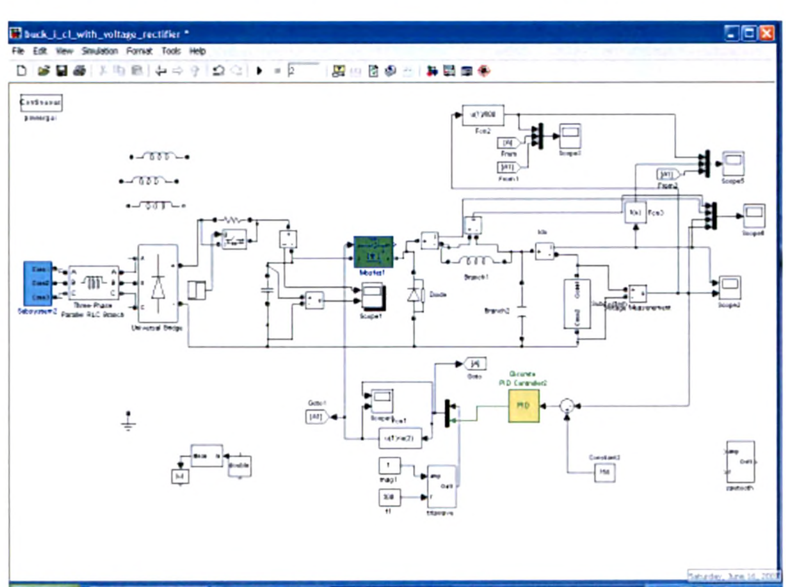

Fig. 8.24 Close Loop Control of Buck converter with Voltage Feedback PID Controller with rectifier and Capacitor on input side

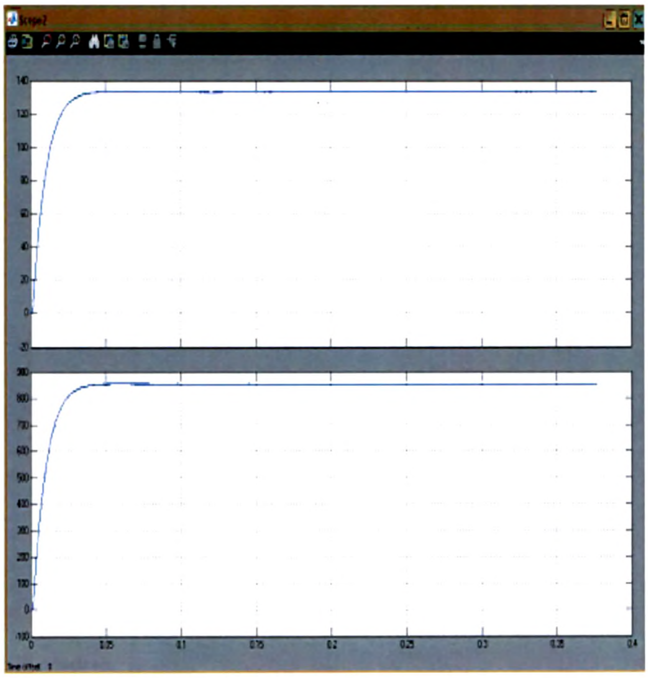

Fig. 8.25 Voltage and Current waveforms with PID Control with rectifier and capacitor on input side

8.4.11 CLOSED LOOP CONTROL FOR BUCK CONVERTER WITH VOLTAGE & CURRENT FEEDBACK (ADVANCED CURRENT CONTROL)

In the current controller T_{on} is obtain from the load current feedback. The advanced current controller has the voltage feedback, which improves the system response with load variation.

Deviation in O/P Voltage $$\Delta V_{dc} = V_{set} - V_{dc}$$

Estimated value of load is $$R_{est} = \frac{V_{dc}}{I_{dc}}$$

Deviation in O/P Current $$\Delta I_{dc} = \frac{\Delta V_{dc}}{R_{est}}$$

$$\therefore \Delta I_{dc} = \frac{(V_{set} - V_{dc})}{V_{dc}} I_{dc}$$

The Turn-on time $$Ton = K\sqrt{(I_{dc} + \Delta I_{dc})}$$

Simulation parameters are listed in the Table 8.1 Simulation parameters

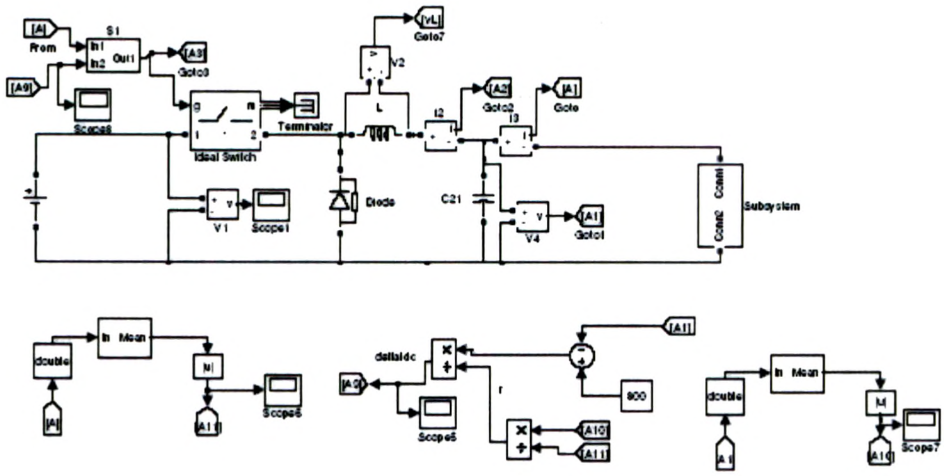

Fig. 8.26 Advanced Current Control using voltage & current feedback

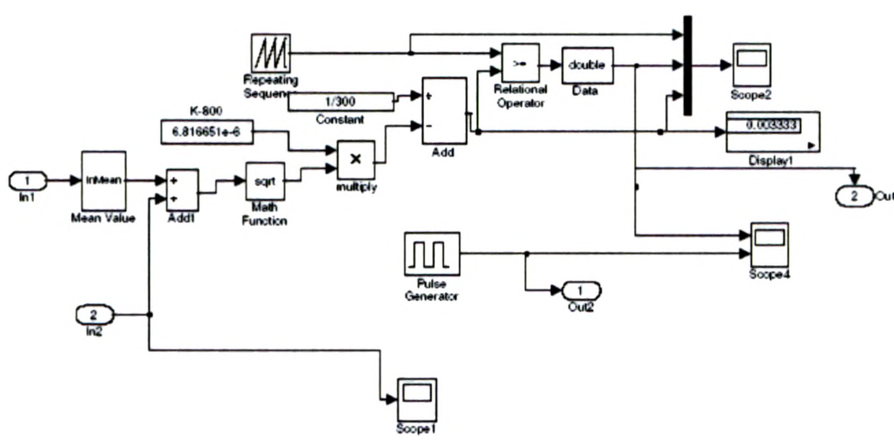

Fig. 8.27 Controller Subsystem

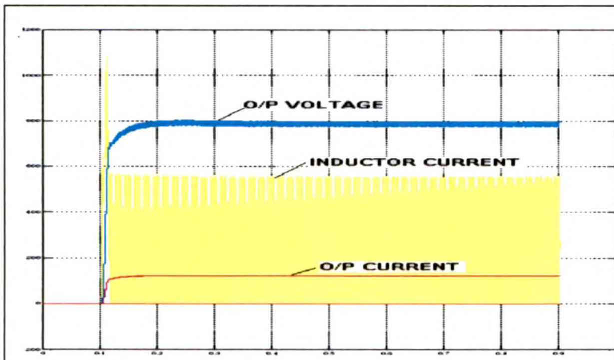

Fig. 8.28 Voltage & Current Waveform

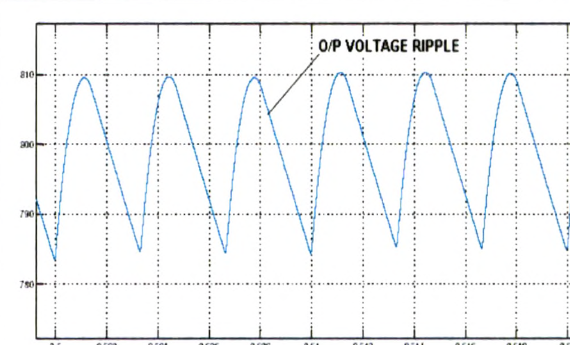

Fig. 8.29 O/P Voltage Ripple

8.5 SUMMARY

The proposed concept for the electronic transformer thus has been simulated. It can be seen from the above simulations that very smooth dc voltage buildup without significant overshoot and controlled ripple even with full load dynamic conditions, can be achieved by proper tuning of PID controller. Thus, with mature technology based power devices and control deployment and simulation results establishing the concept, Electronic Transformer (ET) solution can be constructed and deployed for given distribution system improvement. While the cost of such solution on first look may appear to be higher, economical suitability also has been checked for practical feasibility of this solution [241]. Especially usage of same for Low Voltage (LV) distribution transformer applications can help overcome the costs associated with periodic maintenance needs which is required for conventional transformers, apart from benefits coming in the form of improved kVA utilization, reduction of the feeder losses and high quality power (with improved voltage profile, stable frequency and better voltage regulation) facilitating premium rates from the end customer. When these benefits are considered, calculations do establish cost effective realization of such a concept.

8.6 CONCLUSION

A novel concept to improve the LV distribution performance thus has been presented. The concept can facilitate the 11/22Kv substation to work as close to unity power factor. The lower order harmonics generated due to rectifier stage can always be filtered using harmonic filters located at substations. Such a concept can be economically very lucrative as it mitigates major power quality problems by converting all loads close to sinusoidal and unity power factor operation, apart from providing stable/ regulated power supply including voltage and frequency, towards the distribution grid side. This, thus helps in increasing the efficiency of the entire distribution grid, completely mitigates impact of secondary faults and can facilitate very low no load losses. Even the concept can be used for low power asynchronous link as in case of HVDC links and thereby one can deploy two dc power supply cables instead of using three wire transmissions. Further, this design helps substitute for the conventional oil filled distribution transformer –prone to high failure rate and thus becomes environmentally friendly. While the present cost of such solution on direct replacement basis is on higher side, the rapid advancement happening in the semiconductor domain do indicate that the cost for such solution will be coming down as against rising cost of materials getting used in the conventional distribution transformer constructs.