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Comparative Study of AC Voltage Controllers

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Abstract**—** This paper describes a single phase AC to AC Power Electronic Converter that converts fluctuating electrical power from incoming AC mains supply into controlled value of true RMS AC voltage for the load, within the predestinated tolerance limits of line disturbances. These power electronic converters are periodic variable structure systems due to built in static semi-conductor switched operation with magnetic or electrostatics isolation interface. The present topology, Solid State AC Voltage Controller hereinafter abbreviated as SSVC, has unique power circuit design without any energy storing device like dc link capacitor. It is compact in size because main auto transformer has to handle only variable portion of the rated output power without cutting off the supply load current. It has magnetic flux control by using power electronically controlled dedicated auto-transformer that can be operated in either in buck mode or in boost mode performing the dual control action required for correction of input voltage sags or swells. It has very high correction speed and conversion efficiency with pure sinusoidal output waveform. The magnitude of true RMS of output voltage regulation has been improved to high degree of precision by using an advanced RMS to DC converter technology. The tolerance limits of controlled output voltage value, input voltage sag or swells, load or power factor and total harmonic distortion is predestinated by hardware design. The controller is operated in a negative feedback closed loop consisting of PWM phase control through semiconductor device. Higher frequency model consists of IGBT with AC chopper controller where as main frequency model consists of SCRs with PWM phase angle controllers. Naturally commutated SCRs designs being simple and reliable, widely accepted for higher power rating up to 1000 KVA, suitable for practical R-L load and power factor. A prototype model rated for single phase 1 KVA was tested at mains frequency in laboratory for critical technical parameters of quality to tabulate experimental results. Three-phase operation of SSVC is configured by connecting three identically rated models in star or delta connection. This was further investigated by software simulation in Labview Multisim as well as Matlab Simulink. Experimental results of prototype are critically compared with results of test runs on software simulation design of SSVC.

Keywords**—** ***AC-AC Converters, PWM Phase Angle Control, Semi-conductor switching, AC Choppers.***

I. INTRODUCTION

Operation of sensitive equipments depends upon continuous supply of power at mains frequency and voltage. Discontinuous supply condition hereinafter referred to as supply event, such as extended under/over voltage, transient sag / swell, harmonic distortion etc. are the parameters of quality. It has become critically important to control the voltage not only in utilization area but also in generation, transmission, distribution area of an electrical power. Generically AC-AC conversion is achieved by DC link or matrix either direct or indirect manner. The AC-AC conversion technology [10] with controllers has been advancing very rapidly [1]. These systems rely on power semiconductors as an interface that supply,

(1) Isolates the controller from the electrical power network, to which they connect, (2) Limit both peak voltage and edge-speed (frequency) of electrical transients, (3) Control the electrical environment without introducing undesirable side effects, and (4) Convert noisy safety ground to a noise-free signal sound.

SSVC is revolutionary solution to improve the quality of electric supply. Main components of SSVC circuit are shown in fig. 1 below.

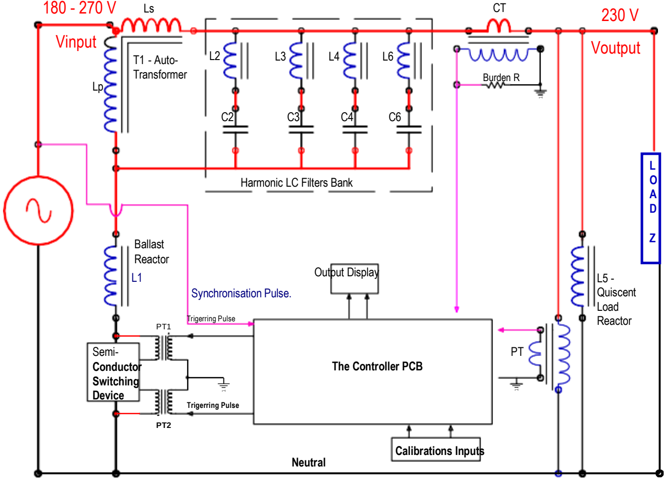

Fig.1. Power Circuit Diagram of SSVC

II. OPERATION

A. *BUCK State of Power Circuit*

MAIN BUCK BOOST AUTOTRANSFORMER (T1) — This can be operated in either in buck mode or in boost mode

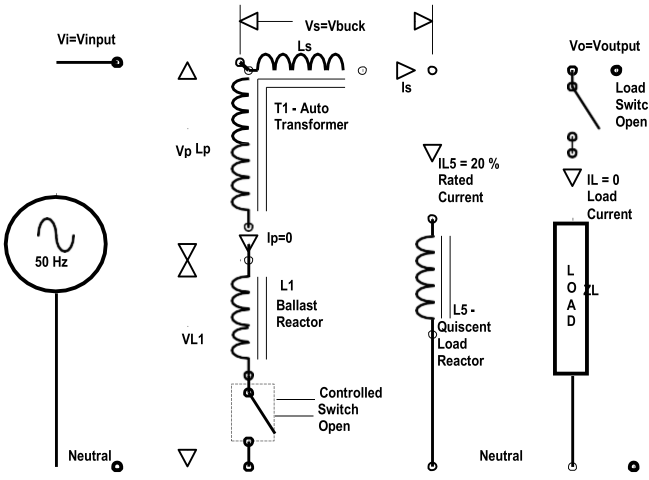

Fig.2. BUCK State of Power Circuit without LC filter

depending on semi-conductor switch is open or closed respectively.

- Auto-Transformer Boost Mode– Output voltage value of is more than the input voltage by step up ratio.
- Coupled Inductor Buck Mode–Output voltage value of is less than input voltage by inductive drop.

Thus the secondary winding flux performs the dual function of correcting voltage sags and swells of input voltage.

L5—QUISCENT CURRENT LOAD REACTOR—Facilitates PWM controller with inductive load under no load condition. Nominally set at 20% of the full load current.

L1—BALLAST REACTOR OR CHOKE—Limits the di/dt in the power semiconductor switching device connected in series between SCR and primary winding [T1p] in shunt path [SCRs + L1 + T1p] and restores the steady current.

HARMONIC LC FILTER BANK—Eliminates the introduced distortion because of power switching, selectively by band pass LC filter and restores the sinusoidal wave shape in the output line, connected across output line and shunt path junction of primary winding [T1p] and ballast reactor [L1] . It consists of LC filters. third (150 Hz), fifth(250 Hz), seventh (350 Hz), ninth (450 Hz) .

CT AND PT– Current and potential Transformers are onnected as shown in fig. I. It samples the mirror of the output load current and voltage for comparator of the power electronic controller by sensing.

POWER SEMICONDUCTOR SWITCH—Controls the triggering phase angle and the conduction period of the shunt branch, the primary circuit of auto transformer. In order to obtain steady magnitude of the output voltage, the error voltage is added or subtracted to the mains line input voltage depending on required corrective action as decided by the controller in closed negative feedback loop. Higher frequency SSVC hardware consists of IGBT with AC chopper controller whereas lower frequency SSVC consists of SCRs the anti-parallel pair of SCR'S with PWM phase controller. Pair of anti-parallel SCRs. The buck to boost (OFF to ON) sequence is followed in order to utilize natural commutation of SCRs with Simplified the controller design.

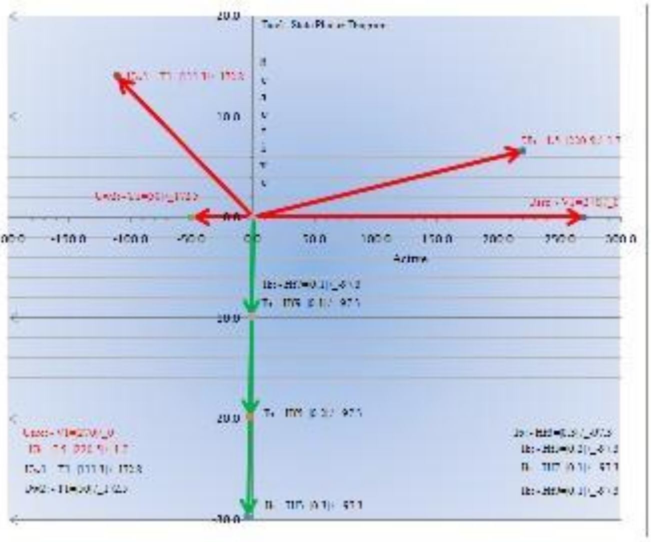

Fig.3. BUCK State of Power Circuit Phasor diagram

The closed loop control system automatically brings boost action in succession to buck action to restore RMS magnitude of the output voltage within predestinated and highly precise levels within 3-4 cycles.

Depending on the position of the SCRs switch is either open or closed SSVC power circuit resumes BUCK OR BOOST STATE respectively. This state is changed from partly buck to partly boost at an angle α [from 0° to 180° during half cycle period] by closing the SCRs switch with Gate triggering pulse. Switch closing instances occur once in its respective half cycle and are 180° apart. By controlling this instant of closing, triggering angle α, SSVC can resume PAC phase angle controlled state. Thus SSVC Power Circuit always remains in BUCK, BOOST or PAC State. This is clearly understood by analyzing states as follows.

BUCK STATE OF POWER CIRCUIT OF SSVC— without LC filter bank, as shown in figure 2 SSVC semiconductor switch is OPEN and the magnitude of output voltage is less than the input voltage by Vbuck volts which is equal to series inductive drop of secondary winding of the T1 Note that Vbuck is minimum at no load condition [quiscent condition].

- I_{L5} - Current flowing through the load reactor L_5 is equal to 20 % of rated magnitude.
- Vinput = Vbuck + Voutput
- Vinput = $j(X_s + X_{L5})\, I_s$ Where I_s - is secondary winding current of T1
- Voutput = $j X_{L5}\, I_s$ Where X_s - is secondary winding reactance of T1
- $\frac{Voutput}{Vinput} = \frac{j\, XL5Is}{jXs\ Is + jX_{L5}Is} = \frac{XL5}{Xs + XL5}$
- V T F = X_{L5} / (Xs + X_{L5}) Where V T F ≡Voltage Transfer function at BUCK State of Power Circuit without LC filter.

B. *BOOST State of Power Circuit*

BOOST STATE OF POWER CIRCUIT WITHOUT LC FILTER—semiconductor switch is closed at full load condtion and the magnitude of output voltage is greater than the input voltage by Vboost volts which is equal to secondary winding of the an auto-transformer, as shown in Fig. 3 given below,

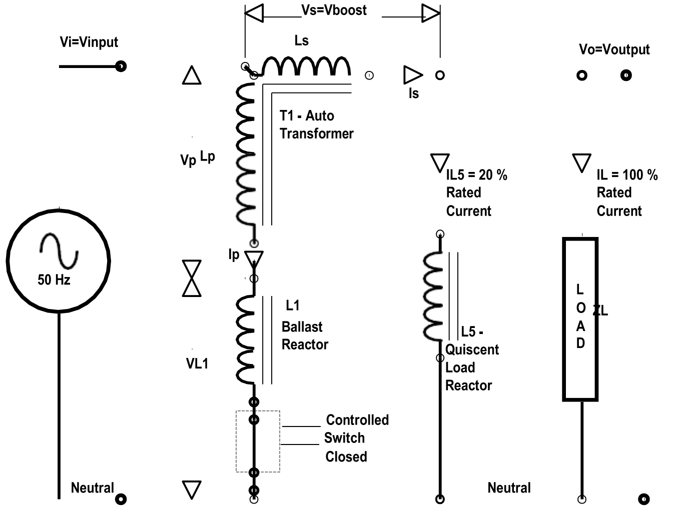

Fig.4. BOOST State of Power Circuit without LC filter

T1— Main autotransformer

- Np & Ns ≡ No of turns of primary & secondary windings
- Vp & Vs ≡ Voltages of primary and secondary winding
- Ip & Is ≡ Currents of primary and seondary windingd
- a ≡ turns ratio of main auto transformer T1.
- $a = \frac{Np}{Ns} = \frac{Vp}{Vs} = \frac{Ip}{Is}$ .... equation (a)
- Total Z $Z_T \equiv jX_{L5} \parallel Z_{L.}$ Where $Z_L = R_L \pm j X_{L.}$
- Vboost $V_s \equiv Vp / a$ and $Is = Vo / Z_T$ ....equation (b)
- Ballast Reactor Voltage $V_{L1} \equiv (jX_{L1})\, Ip$
- $V_{L1} = (jX_{L1})\,(Is / a)$ substituting for Ip from equation (a)
- $V_{L1} = j\, X_{L1}\,(Vo / a\, Z_T)$ substituting for Is from equation (b).
- $Vp = Vi - V_{L1}$ Refer to Fig.3 Boost State Power Circuit.
- $Vp = Vi - j\, X_{L1}\,(Vo / a\, Z_T)$ substituting V_{L1} ≡ Ballast Reactor Voltage.

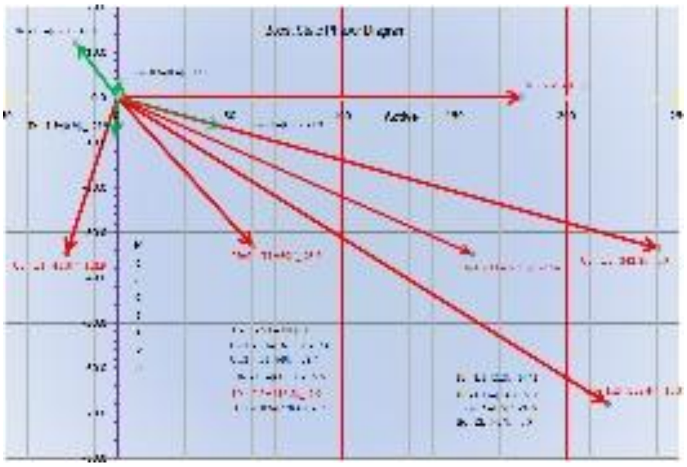

Fig.5. BOOST State of Power Circuit Phasor diagram

- Vo = Vi + Vboost = Vi + Vs = Vi + (Vp / a)
- V T F ≡Voltage Transfer Function = $\frac{Voutput}{Vinput}\ \frac{(a+1)ZT}{a(ZT+jXL1)}$

PHASE ANGLE CONTROLLED STATE— SSVC remains in either buck or boost state. By using phase angle control this state is changed from buck to boost at an angle α known as bi-stable period which is partly buck and partly boost. The magnitude of input and output voltage with α ranging from 0 to 180 is tabulated in Table 1 given below.

TABLE I. POWER CIRCUIT STATES OF SSVC

Buck / Boost / Phase Controlled State	Partial period one AC cycle				
	Buck Period	Boost Period	Bi-stable Period at α°		
SSVC State or Mode			Buck	α°	Boost
Conduction in shunt path [S/w + L1 + T1p]	OFF/ NO	ON/FULL	OFF/ NO	→	ON/FULL
α° ≡ Triggering Angle	[0, α]	[α, 180]	[0, α]	→	[α, 180]
Controller action of Error Voltage in series path T1s	Subtracted from Vinput	Added to Vinput	Subtracted from Vinput	→	Added to Vinput
Voutput	< Vinput	> Vinput	Controlled RMS Value 230 ± 1 Volt		

TRUE RMS→DC CONVERSION OF AN AC SIGNAL— involves squaring the signal, taking the average and obtaining the square root. The averaging time must be sufficiently long to allow filtering at the lowest frequencies of operation desired.
Vm=Maximum Peak or Crest Value of waveform,
Vavg=Mean or Average value
V_{MAD}= MAD (Mean **A**bsolute Deviation Value)
Mathematically

- Vavg = $\bar{v} = \frac{\sum_{i=1}^{N} V_i}{N}$V =Vrms ≡ RMS value;

Where RMS ≡ square Root of Mean of Squared Value RMS or Root Mean Square is a fundamental measurement of the magnitude of an ac signal.

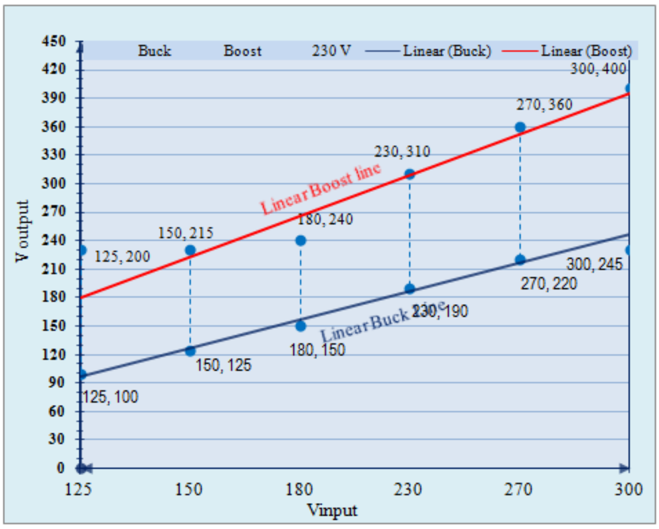

Fig.5. VI Voltage Transfer Characteristics

RMS Value interpreted mathematically and practically
Mathematically,

Vrms = $\sqrt{(V_{av}}$ = $\sqrt{\left[\frac{\sum_{i=1}^{N}}{N}\right]}$ practically; the RMS value assigned to an AC signal is the amount of DC required to produce an equivalent amount of heat in the same load.

III. INDIRECT OR IMPLICIT COMPUTATION METHOD OF AN A.C. SIGNAL MEASUREMENT

A generally better computing scheme uses feedback to perform the square root function implicitly or in directly at the circuit as shown in Fig.6.

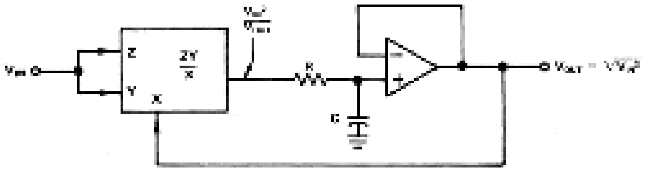

Fig.6. Indirect or Implicit Method of AC Signal Measurement

Divided by the average of the output, the average signal levels now vary linearly (instead of as the square) with the rms level of the input. This considerably increases the dynamic range of the implicit circuit as compared to explicit rms circuits. Ref. fig.V for Block diagram of RMS to DC Converter

Some advantages of implicit rms computation over other methods are fewer components, greater dynamic range, and generally lower cost. A disadvantage of this method is that it generally has less bandwidth than either thermal or explicit computation. An implicit computing scheme may use direct multiplication and division (by multipliers), or it may use any of several log-antilog circuit techniques.

MONOLITHIC RMS→DC CONVERTERS—This uses an implicit method of rms computation employing an absolute value converter, a squarer/divider, low pass filter, precision current mirror and an output buffer refer fig. V: it features 10 volt full scale input range.

The voltage input to the scale RMS to DC Converter is first processed by an absolute vale circuit (a precision rectifier) which has a single polarity output. This output drives a voltage to current converter (an operational amplifier) whose current output, I_{in}, is the rectified input signal.

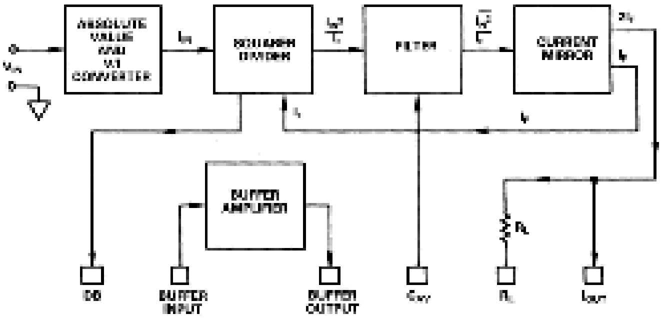

Fig.7. Block Diagram of Monolithic RMS to DC Converter

Current I_{in}, drives a squarer/divider, which performs both the and square rooting functions in one stage by utilizing feedback from the current mirror. The feedback current IF, is divided into the squared input current, using log-antilog circuits. Since dB or decibels are a function of the log of signal, a dB output for the RMS to DC Converter is derived from this squarer/divider stage. The output from this stage / I_F, is averaged by a low pass filter consisting of an internal resistor and an externally connected filter capacitor. This filtered signals drives the current mirror which provides the feedback current, I_F and the output current, $2I_F$.

IV. CONTROLLER CIRCUIT OPERATION OF SSVC

Classical power electronics linear ramp negative feedback pulse width modulated phase angle controller, hereinafter abbrevated referred as is shown in fig. IV as follows.

The Controller Block sensing the output receives Voltage signal by Potential Transformer rated. for 230/5 Volts / 1A, Output is connected to the input of the RMS to DC converter. It monitors the feedback ac voltage from the output it to DC level equivalent averaging RMS magnitude. Ref. fig. IV

This is compared with standby reference voltage obtained by constant voltage reference generator and constant voltage regulator. These both are compared with an integrated error amplifier, The output of the error amplifier is connected to input of the PWM Controller which generates the pulse proportional to magnitude of the error voltage. The instance of positive edge of the pulse is synchronized with zero crossing detector of mains input ac voltage signal. This PWM signal is connected to Gate driver circuit of SCRs

The PWC Circuit consists of synchronous pulse generator, which provides synchronous pulse to the ramp generator circuit. This ramp is compared with variable DC voltage level obtained from error amplifier.

The output signal obtained from the current transformer is rectified. This dc voltage level is then compared with the reference voltage obtained from constant reference voltage generator this is compared by constant current comparator to generate over current limiting error.

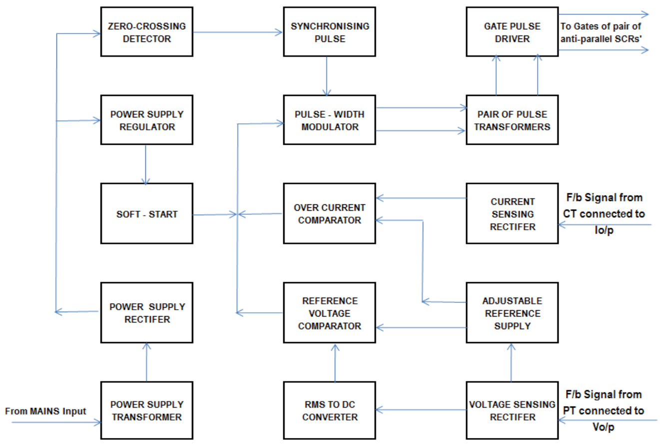

Fig.8. Functional Block Diagram of Control Circuit of SSVC

Whenever the output current rises above the set value the output of CC comparator goes high, which further increases the level of the PWC input circuit. The PWC Circuit modifies the PWC output pulses in such a way that the output voltage is reduced and output current is limited.

A. *Principle of Operation of SSVC*

The operation is clearly understood by correlating the diagrams shown in fig. IV, V, and Table No. I of buck-state boost-state and phase angle controlled states of SSVC.

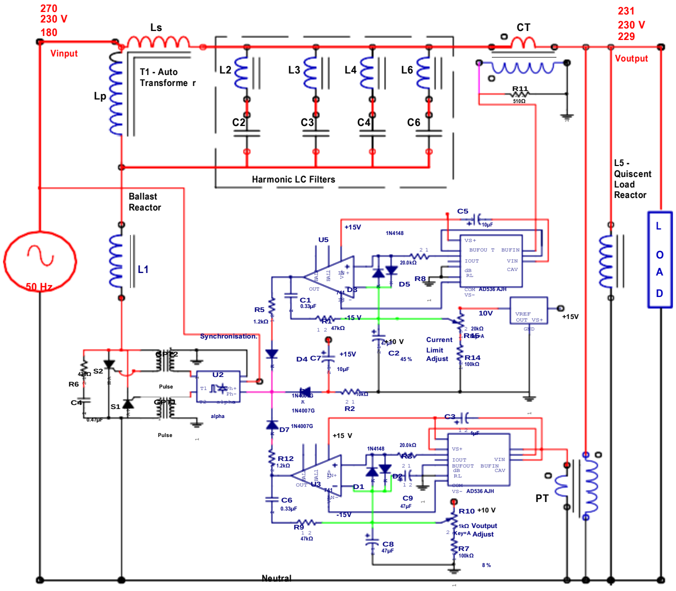

Fig.9. Circuit Digram of SSVC

SSVC continuously monitors and controls the RMS magnitude of output voltage within predestinated level by adding (in boost mode) or subtracting (in buck mode) the secondary(series) winding [Ls] of the autotransformer [T1] to the mains input voltage.This is done by phase angle controlling; the triggering and the duration of conduction period of the anti-parallel pair of SCR'S connected in the primary (shunt) winding of the auto transformer. The closed loop feedback control system automatically brings boost action in succession to buck action to restore RMS magnitude of the output voltage within predestinated level through secondary winding of the dedicated auto-transformer. Obviously closed loop control system involves sensing and measuring the voltage and current value of the load using sensors (PT / CT) then automatically settling on the triggering angle.

B. *Experimental Results*

Prototype Single phase model rated for 1 KVA was tested in laboratory for critical technical parameters of quality. At full resistive load condition the regulation is within 0.5 % .Total Harmonic distortion is less than 4 % load. Output voltage waveform at full resistive load Fig.VII below. The settling time is within 4 cycles (80 m Sec).

C. *Simulation Results*

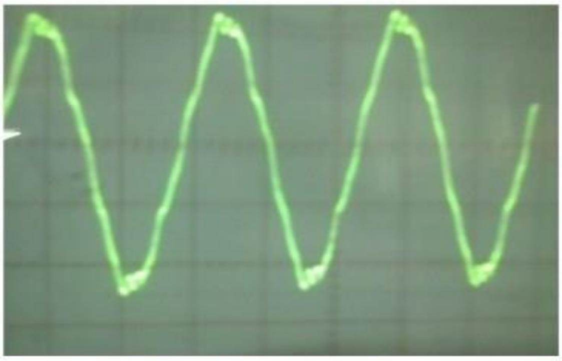

Fig.10. Output voltage waveform at full resistive load

Single phase simulated model rated for 1 KVA in Multisim Lab view environment was tested for critical technical parameters of quality. Line and load regulation the regulation is within 0.3 %. Output Voltage waveform on no load to full load is shown in Fig. XIII. Total Harmonic Distortion is less than 2.5%. Settling time less than 3 cycles. Instant of switching on load is indicated.

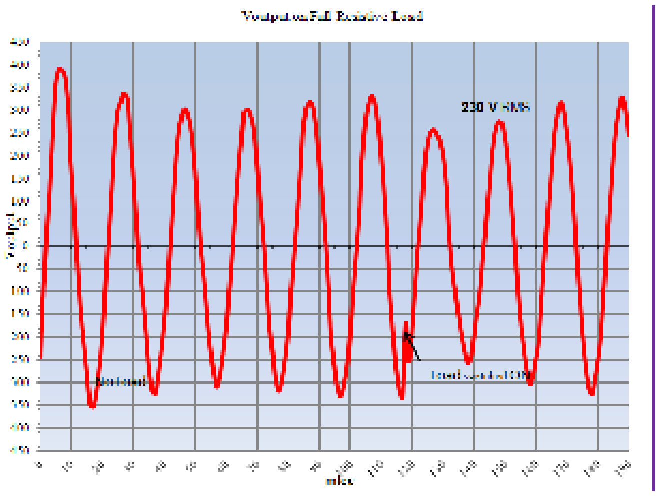

Fig.11. Output Voltage waveform of Simulated Model

True RMS Output Voltage of simulated model at full Resistive load condition Fig.IX. Settling time is Within 3 cycles.

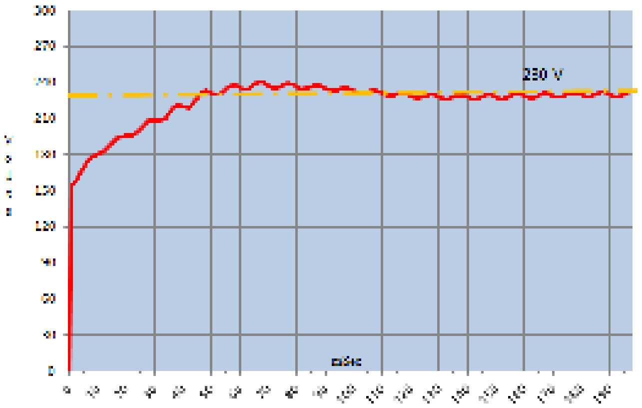

Fig.11. Output Voltage waveform of Simulated Model

V.COMPARATIVE STUDY OF PROTOTYPE AND SIMULATION

Both models rated for single phase 50 Hz, 1 KVA was tested in laboratory for critical technical parameters of quality. SSVC input a current characteristic is plotted against varying input voltage with steps of No load half, load Full, Load with power factor varied from zero to unity. For both Prototype and Simulated model.

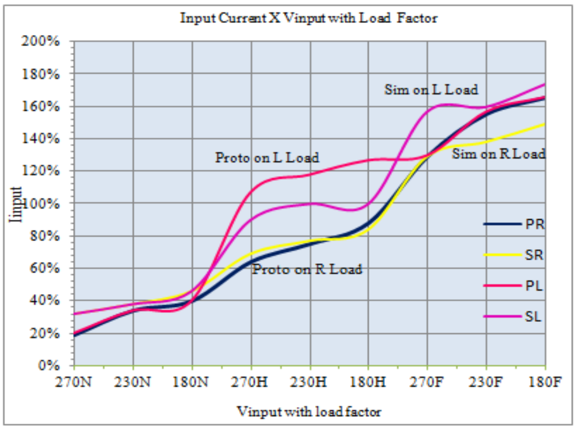

Fig.12. Comparison of Input Current between simulated and Prototype model against Vinput with load and power

Obliviously input current is higher at lower input voltage for same load factor and vice versa. It is higher on inductive load than the resistive load. Input current characteristics of prototype model coincide with characteristics of simulated model on resistive load than that of inductive load. Whereas it is more deviated at 230 Volts input voltage 50% of rated load current

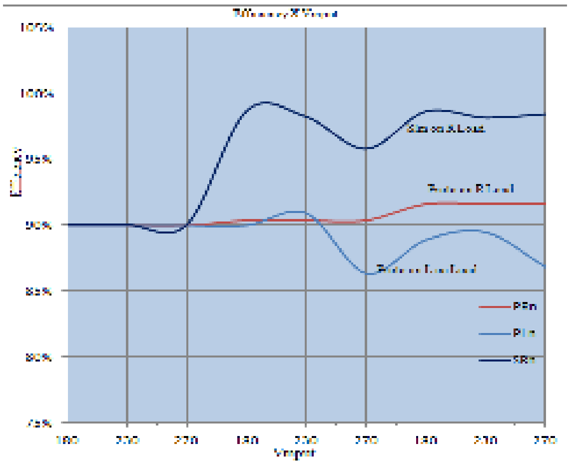

Fig.13. Efficiency curves of simulated and Prototype model against Vinput with load and power factor

Conversion efficiency is higher on inductive load than resistive load as prototype model has more losses on resistive load than inductive load. It is lower at when input voltage is 270 Volts when buck period is maximum.

VI. CONCLUSION

Simulation results are validated by actual experimental Tests to confirm the specifications of the performance. Actual prototype model performance indices are on lower side practical than the simulated design. Harmonics distortions introduced by switching of semiconductor devices is limited by band pass filters and THD is less than 4 %. Settling Time is within 4 cycles. Conversions Efficiency is 92 % +

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