Implementation and Derivation of Working Formula of Three Phase AC Side Switched Active Filter Based Boost Rectifier

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***Abstract*— To get a high performance such as low THD input current and high power factor of both single and three phase rectifiers, the output of the rectifiers is normally switched. But, we can use this switching on input side which will enable us to maintain high power factor as there will be no displacement between the voltage and the current. In this paper, we have implemented such a three phase boost circuit practically and derived working formula of both the single phase and three phase circuit theoretically and numerically.**

Keywords*— *Ac-dc converters,THD,boost rectifier,input current shaping,least square method,newton's polynomial method.

I. INTRODUCTION

The input current shaping of the rectifiers is important for lessening line losses and enhaning the input power factor. Different methods have been proposed in the past to meet these requirements [1-4]. Three phase boost rectification in input or Ac side switching has some advantages like there will be a little or no displacement between the input current and input voltage. Thus there will be high input power factor. As the input current will be switched, there will be some harmonics which will move to higher frequencies. Thus using a little active filter we can eliminate the harmonics. But using this filter and switching will cause lower efficiency. We can use energy recovery snubber for that purpose. Considering all this conditions a three phase ac side switched boost rectifier has been developed [5]. We have implemented the proposed circuit and have confirmed practically that it can deliver the high performance as proposed. It have been found that the input current close to sinusoidal, thus with very low THD, which will really benefit the supply side. We have also checked the output voltage and have found it really close to the simulation result. In this paper, some working formula of both the single and three phase ac side switched boost rectifier has been proposed. These formulas are based on theoretical and numerical methods. Among the numerical methods, polynomial and least square error methods are used. All the simulation and analysis are done using PSIM and MATLAB.

II. CIRCUIT DIAGRAM

A. *Three Phase Ac Side Switched Boost Circuit*

After designing the three phase ac side switched boost circuit, its performance was carefully evaluated. It was found that with a little active filter, we may get great performance acknowledging the input current THD and input side power factor.

The circuit diagram is shown in the fig.1. Here, inductor L1,L2,L3 and capacitor C1,C2,C3 work as active filter. These inductors also work as a boost inductors. While, RL represents the load and CL works as the load capacitor.

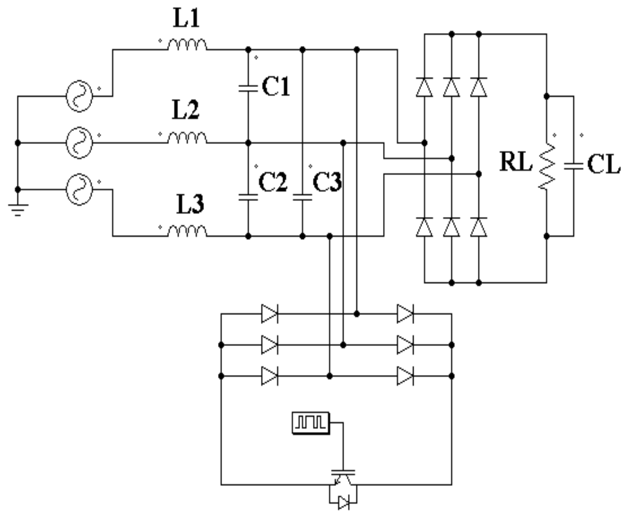

Figure 1: Three phase ac side switched boost circuit with active filter.

B. *Boost Circuit with Snubber*

All the performance of the above circuit can be maintained at a satisfactory level. But, It has been found out that efficiency of that circuit can be as high as 85%. But other performance parameters seem to diminish. For better performance an energy recovery snubber is proposed [5]. That circuit is shown in fig.2. This snubber not only improves the efficiency of the circuit but also decreases the THD of the input current. As a result better performance can be received using this circuit. We will thus implement this circuit. But there are some drawbacks of using this snubber. Most important of those is that boost rectifier with snubber does not act as a boost rectifier for all duty cycle unlike the normal ac side switched boost rectifier. It may function as a boost rectifier for duty cycle reach of 0.1 to 0.7 give or take. While without snubber this rectifier can function in any duty cycle.

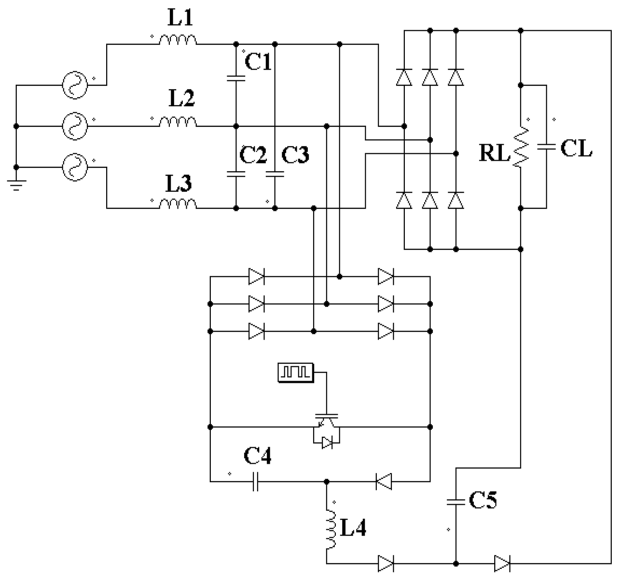

Figure 2: Three phase ac side switched boost circuit with snubber.

III. Practical Implementation

The circuit in fig.2 was practically implemented. Though, we have faced some problems there. Our failure was to provide a balanced load as the inductance and the capacitance of the three-phase was not absolutely equal. As a result, a circulating current was developed. So, it was required to take the data rapidly and afterward turned off the supply. The value of the circuit parameters is given in Table 1.

TABLE I. The Value Of Circuit Parameters

Parameter	Value
L1,L2,L3	10mH
C1,C2,C3	7uF
L5	1m
C4,C5	0.22uF
RL	96 Ω
CL	100uF

The gate pulse of the IGBT switch was supplied by SG3425 chip. The SG3425 is an SMPS power supply controller chip and the chip can also be used for square wave inverter control. The control circuit can be used for the control of choppers as well. The complete control circuit is shown in the fig.3(a). Gate pulse was taken from pin 10.The output voltage shape and input current shape was discovered utilizing the digital oscilloscope. In any case it is unadvised to get the current shape straightforwardly by joining the digital oscilloscope in series with the line as it may hamper our oscilloscope. Three 10Ω resistors were connected in each phase and voltage reading was taken across one resistor. We have used input peak voltage of 30V per phase. The figures of input current (multiplied by input resistance) and output voltage are given in fig. 3(a) and in fig. 3(b) respectively. According to simulation result the peak voltages across the input resistor and the load resistor should be 20V and 34V respectively, which is very close to out practical result. It is clear that there are some harmonics in the current. This is due to two factors. Firstly, inductors and capacitors in the filter were not balanced. And secondly, What's more besides, the data were taken for the first few cycle instead of at steady state so that circulating current can't create to a substantial quality to cause harm to the circuit.

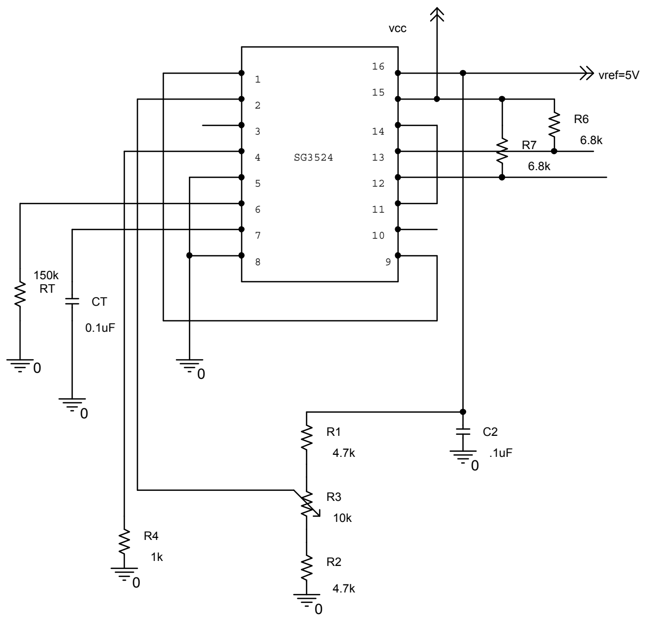

Figure 3(a): Gate pulse generation circuit.

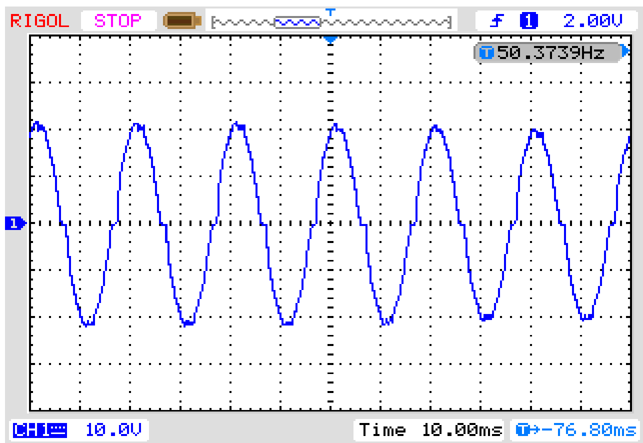

Figure 3(a): Wave shape of voltage across input resistance.

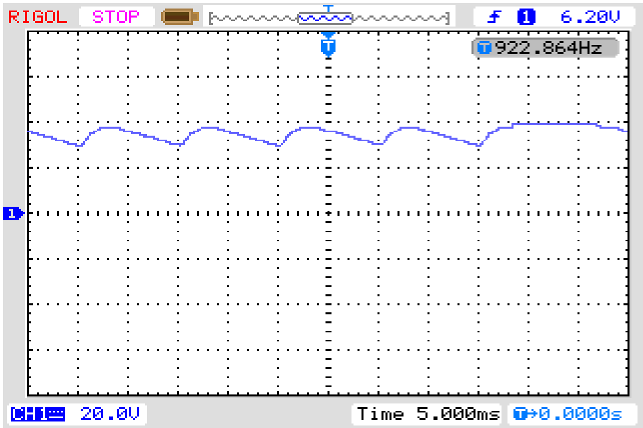

Figure 3(b): Output voltage wave shape.

IV. Theoretical Derivation

A. For Single Phase operation

The single phase ac side switched boost rectifier is demonstrated in fig.4 For simplicity, neither the snubber circuit nor the capacitor for input filter is not considered. Presently we may assume that in a duty cycle the voltage remains constant as the change of voltage in a duty cycle for high switching frequency is quite low. Now for a duty cycle we can consider the voltage to be a constant, V_{st}. Thus, the formula for output voltage for that duty cycle, k can be written as

$V_o= |V_{st}|/(1\text{-}k)$

And $V_{st}=V_m \sin\omega t_1$; where t_1 is a point in time axis within that duty cycle and V_m is the peak value of input voltage. We have used magnitude of V_{st} as the input voltage goes to output through a dc rectifier. Now, for different parts of time axis the input voltage that we have considered for a duty cycle as a constant will vary from one duty cycle to another.

If we consider time then we can write this equation as

$V_o(t)= |V_m \sin\omega t|/(1\text{-}k)$

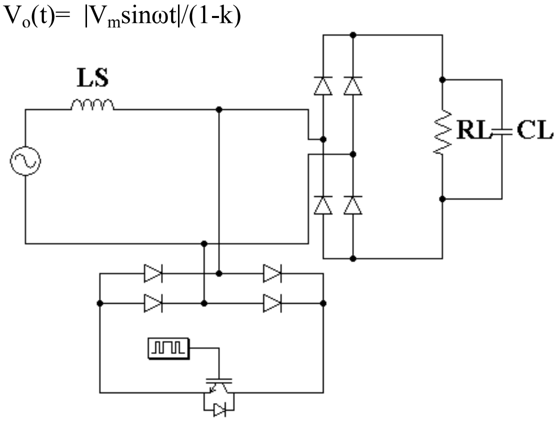

Figure 4: Single phase ac side switched boost rectifier.

Again, this equation is only correct for high switching frequency. For instance, for low value of load capacitance this curve of output voltage is demonstrated in fig.5.

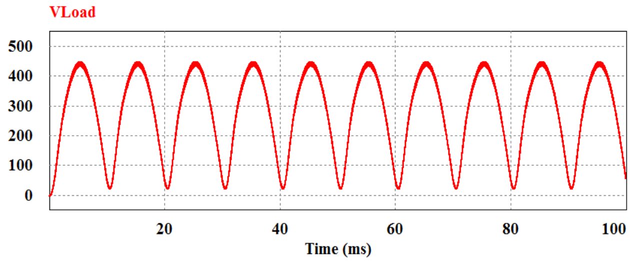

Figure 5: Output voltage curve of simplified single phase ac side switched boost rectifier.

Here, 220V was used as peak value input voltage. 30kHz and 0.5 were taken as switching frequency and duty cycle respectively. So, the output voltage becomes,

$V_o(t)= 440| \sin\omega t|$

If we use a very large capacitor across the output then we will get a constant dc output voltage near 440V.

B. For Three phase operation

In case of three phase operation, after full bridge rectification, the peak value of the rectified voltage becomes $\sqrt{3}\times$phase voltage. Thus, if high switching frequency is applied for boost rectification we can assume the change in voltage is negligible in a duty cycle or we can consider that the voltage as a dc voltage for that duty cycle. So, like the single phase boost this following equation can be written.

Output voltage= rectified voltage/(1-duty cycle)

In fig.6 full bridge rectified voltage curve is shown when 220V phase voltage is used. Peak value of the output voltage is close to 381V. Fig.7(a) represents the simplified ac side switched boost rectifier with a small capacitor. We have switched this circuit at a high frequency with duty cycle of 0.5. As we can see, in fig.7(b), this voltage is doubled compared to rectified voltage.

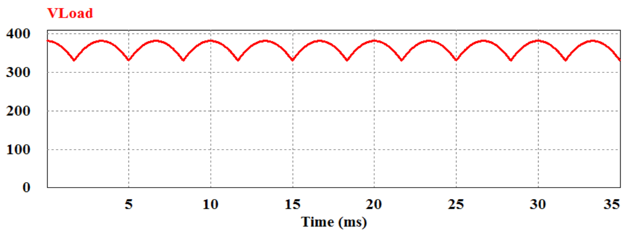

Figure 6: Three phase full bridge rectified voltage.

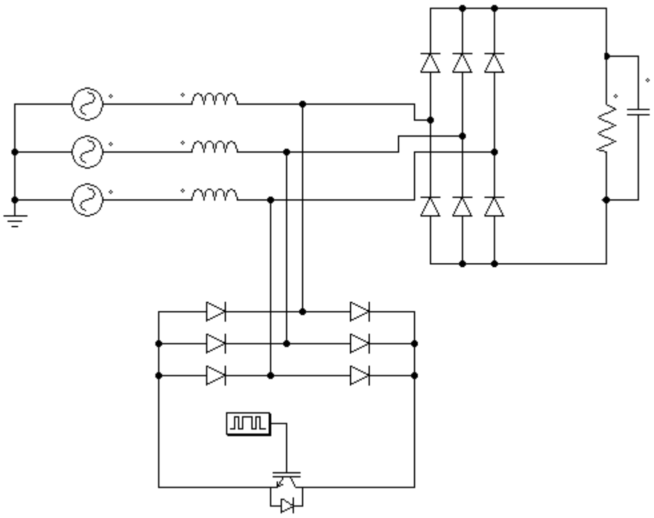

Figure 7(a): Three phase simplified boost rectifier with small load capacitor.

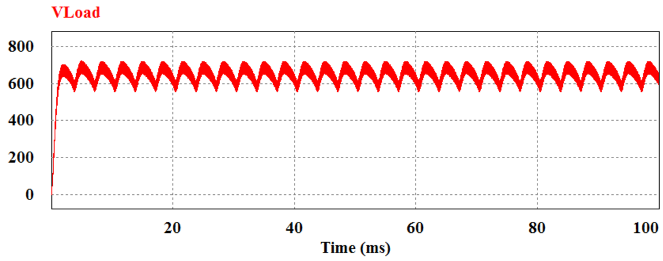

Figure 7(b): Output voltage curve of the circuit in fig.7(a).

I. NUMERICAL DERIVATION

For numerical derivation we have used two methods, the least square method and Newton's polynomial method. In these methods, output voltage is considered to be a variable which depends on duty cycle.

A. *Least Square Method*

For this method, 2nd order equation is considered

$y=ax^2+bx+c$ (1)

Where y is the ratio between output voltage and input voltage and x is the duty cycle. From [6] using this method three equations have been formed to solve for a, b and c. These equations are given below

$a\sum 1 + b\sum x + c\sum x^2 = \sum y$ (2)

$a\sum x + b\sum x^2 + c\sum x^3 = \sum xy$ (3)

$a\sum x^2 + b\sum x^3 + c\sum x^4 = \sum x^2 y$ (4)

Now for L1=L2=L3=10mH, L4=0.7mH, C1=C2=C3=1uF, C4=C5=0.22uF,switching frequency of 5khz and input voltage of 220V, output voltage is simulated under duty cycle variation.

Solving (2),(3) and (4) the value of the constants a,b,c are found to be 1.9845,2.5716 and 0.9716 respectively. These values are implied in (1) to get the output voltage,

$v_o/v_s=1.9845k^2+2.5716k+0.9716$ (5)

Equation(6) is now used to find out for different input voltages under duty cycle variation. These values are then compared with the values found in simulation in table 3.

TABLE II. SIMULATION RESULT FOR 220V INPUT VOLTAGE

Duty Cycle	Output Voltage
0.1	499.52
0.2	553.81
0.3	620.05
0.4	698.49
0.5	783.63
0.6	846.71

TABLE III. COMPARISON BETWEEN SIMULATED VALUES AND VALUES DERIVED FROM EQUATION USING LEAST SQUARE METHOD

Input voltage(peak to peak)	Duty cycle	Output voltage(rms)	Using Least Square Method	Percent of deviation (%)
150V	0.1	340.59	337.71	0.85
	0.2	377.59	380.65	-0.81
	0.3	422.75	426.51	-0.89
	0.4	476.24	475.29	0.2
	0.5	534.3	526.98	1.37
	0.6	577.33	581.58	-0.74
220V	0.1	499.52	495.30	0.84
	0.2	553.81	558.29	-0.81
	0.3	620	625.55	-0.89
	0.4	698.49	697.09	0.20
	0.5	783.63	772.90	1.37
	0.6	846.7	852.99	-0.73
300V	0.1	681.17	681.16	0
	0.2	755.2	755.2	0
	0.3	845.47	845.45	0
	0.4	952.54	951.94	.06
	0.5	1068.52	1068.6	-0.007
	0.6	1154.45	1154.59	-.012

B. *Newton's Polynomial Method*

For six sets of data an equation of sixth order can be derived. Like before, y is a dependent variable and the ratio between output voltage and input voltage and depends on the variable x. which is the duty cycle. From [6],this equation can be used to derive the working formula.The data from table 2 are used to derive the formula from which output voltages for different input voltage under duty cycle variation are found and these values are compared with the simulated values in table 4. The equation derived from this method is written below.

$v_o/v_s = 2.271 + 2.468(k-0.1) + 2.705(k-0.1)(k-0.2)$
$+ 0.303(k-0.1)(k-0.2)(k-0.3)$
$-11.458(k-0.1)(k-0.2)(k-0.3)(k-0.4)$
$- 64.47(k-0.1)(k-0.2)(k-0.3)(k-0.4)(k-0.5)$ (6)

where v_o,v_s and k represent output voltage, input voltage and duty cycle respectively.

TABLE IV. COMPARISON BETWEEN SIMULATED VALUES AND VALUES DERIVED FROM EQUATION USING NEWTON'S POLYNOMIAL METHOD

Input voltage(peak to peak)	**Duty cycle**	**Output voltage(rms)**	**Using Newton's Interpolating polynomial**	**Percent of deviation (%)**
150V	0.1	340.59	340.58	0
	0.2	377.59	377.60	0
	0.3	422.75	422.72	0
	0.4	476.24	475.97	0.06
	0.5	534.3	534.29	0
	0.6	577.33	577.29	.01
220V	0.1	499.52	499.52	0
	0.2	553.81	553.81	0
	0.3	620	620	0
	0.4	698.49	698.09	0.06
	0.5	783.63	783.63	0
	0.6	846.7	846.7	0
300V	0.1	681.17	681.16	0
	0.2	755.2	755.2	0
	0.3	845.47	845.45	0
	0.4	952.54	951.94	.06
	0.5	1068.52	1068.6	-0.007
	0.6	1154.45	1154.59	-.012

CONCLUSION

Three phase ac side switched boost rectifier can be applied in various practical situations. Using the working formula it will be easier to construct the circuit more efficiently. For more accurate results of the output voltage other parameters variation may be considered. It might be utilized to get desired output without going through experiencing an excess of experimentation methodology. Duty cycle required to apply to produce required output for a circuit can be found using these equations (5 & 6). Output additionally differs with the qualities of inductance and capacitance likewise. A mathematical statement relating all these variables as opposed to just duty cycle could be produced. At that point it will be a great deal simpler to design the circuit without much exertion..

REFERENCES

[1] Johann W. Kolar, Hans Ertl and Franz C. Zach; "A Comprehensive Design Approach for a Three-Phase High-Frequency Single Switch Discontinuous-Mode Boost Power factor Corrector Based on Analytically Derived Normalized Converter Component Ratings," *IEEE Transactions on Industry Applications*, Volume: 31 Issue: 3, pp: 569 - 582, May/Jun 1995..

[2] Hengchun Mao, C. Y. Lee, D. Boroyevich, S. Hiti, "Review of high-performance three-phase power-factor correction circuits" , *IEEE Transactions on Industrial Electronics,* Volume: 44 Issue:4, pp: 437 – 446, Aug 1997.

[3] R. Prasad, A.R., P.D. Ziogas, S. Manias,: "An active power factor correction technique for three-phase diode rectifiers," *IEEE Transactions on Power Electronics,* Volume: 6 Issue:1,pp: 83 – 92, Jan 1991

[4] J. W. Kolar, and T. Friedli, "The essence of three-phase PFC rectifier systems", *IEEE 33rd International Telecommunications Energy Conference (INTELEC),* Oct 9-13, 2011, pp. 1 – 27.

[5] Hasan, N. ,Hossain, M.R.T. , Kabir, M.A. , Choudhury, M.A., "Ac side switched active filter based hig performance three phase boost rectification with energy recovery snubber*", Industry Applications Society Annual Meeting (IAS), 2012 IEEE* , 7-11 Oct. 2012, pp.1 – 8.

[6] Steven C.Chapra,Raymond P.Canale,the book "Numerical Methods For Engineers".