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Harmonic Analysis of Front-End Current of Three-Phase Single-Switch Boost Converter

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ABSTRACT
Harmonic analysis of Front End Current (FEC) of three phase single switch boost converter to reduce the total harmonic distortion (THD), active switching & passive filters are incorporated in this work. A constant frequency switching is used for active filtering & pulse width modulation (PWM) technique is used to regulate the output voltage. Power factor improvement is accomplished by using PWM technique and passive LC high frequency harmonics filters. An Electro Magnetic Interference (EMI) filter is used to suppress the high frequency component generated by the active switching. Moreover, a series LC filter resonating with the supply frequency is also used to suppress the low frequency value could be made less than 3%, which is a great improvement over the earlier rectifiers that have only EMI filter. In the earlier types of rectifiers, the THD value was as high as 17%. The efficiency of the module is also studied. As the output voltage has the nonlinear relation with duty cycle, the efficiency is also nonlinear with output voltage variation. But up to certain range of duty cycle it could be made linear in nature with output voltage. The efficiency versus duty cycle and THD versus duty cycle curve for the proposed rectifier circuit is given for a clear understanding of the model.

General Terms
Three Phase Boost Converter, Harmonics Filter.

Keywords
Active Switching, Electro Magnetic Interference, Passive Filter, Power Factor Correction, Total Harmonic Distortion

1. INTRODUCTION
Most electronic equipments are supplied by dc voltage. All these equipments are fed from single phase or three phase ac utility lines. So, ac to dc conversion is very common. Traditionally, ac to dc conversion [1] is achieved using single-phase or three-phase diode bridge rectifier [2-5]. But, a diode bridge rectifier is affected by high THD, large ripple and low power factor. The input current with large harmonics may cause excess heat and unstable operation. Low power factor leads high reactive power requirement and reduces voltage at the load [6-7]. As a result line and equipment losses increase. For stable and reliable operation loads require regulated dc voltage. In this respect switching regulators are available to perform regulation of dc voltage. Recently works have been proposed on switching regulators with single phase or three phase diode bridge rectifier between sources and loads. But non sinusoidal input current, high harmonic distortion, low power factor, large ripple and lower efficiency are the major drawbacks of these regulators [9]. The problem can be solved by adding filter in input and output side of regulators.

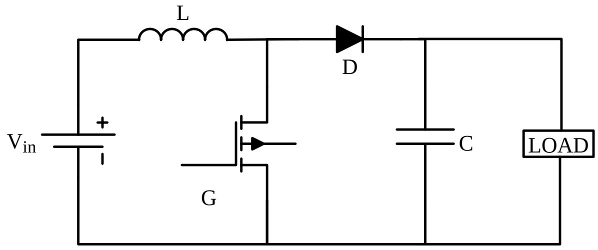

Fig 1: Circuit diagram of a typical Boost regulator

Some regulators have been developed recently with input and output filter which provides power factor near to unity at reduced THD [10-12]. But their sizes are the main advantages. To combats such problems, in this paper a Boost regulator has been analyzed with a three phase diode bridge rectifier. It is possible to improve power factor by this arrangement. Boost also offers large variation of output voltage with small variation of duty cycle. The objective of this work is to improve power factor keeping input current sinusoidal with low THD and improve the performance of the Boost rectifier using additional harmonic filter to maintain input current sinusoidal even with the variation of duty cycle which is necessary for voltage control purposes in variable voltage applications.

2. PRINCIPLE OF OPERATION
In this paper a Boost regulator has been analyzed with a 3-φ diode bridge rectifier for the purpose of power factor correction because at present it is one of the most important research topics in power electronics. The rectifier is best suitable in industrial and commercial application which can provides pure sinusoidal input current with unity power factor. The circuit diagram of a typical Boost regulator is shown in figure 1. It consists of an inductor, a capacitor, a switch (IGBT) and a diode. Inductor is used as an energy storage element which has the tendency to resist the changes in current. When being charged it acts as a load and absorbs energy, when being discharged it acts as an energy source. The voltage it produces during the discharge phase is related to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages. Capacitor C is used for filtering purposes. During high switching pulses switch gets turned on, the power flows from input side to the load side. At this time current through

the inductors start rising linearly and it gets stored. The resulting output voltage is in positive phase of the input voltage. The mathematical expressions in these modes are

$$V_{in} = V_L = L\frac{dI}{t_{on}} \quad (1)$$

$$V_{in}t_{on} = LdI \quad (2)$$

During low state of switching pulse switch gets turned off and inductor released its stored energy to the load through diode and bypass capacitor C. It is a continuous conduction process and power flow bidirectionally. The mathematical expressions in these modes are,

$$V_{in} - V_0 = -L\frac{dI}{t_{off}}$$

$$(V_{in} - V_0)t_{off} = -LdI$$

$$(V_0 - V_{in})t_{off} = LdI \quad (3)$$

From equations (2) and (3),

$$V_{in}t_{on} = (V_0 - V_{in})t_{off} \quad (4)$$

$$V_o t_{off} = V_{in}(t_{on} + t_{off})$$

$$V_o = V_{in}\frac{T}{(T - t_{on})}$$

$$V_o = V_{in}\frac{1}{(1-D)} \quad (5)$$

From equation (5) it is seen that the output voltage is always higher than input voltage. The output voltage is controlled by varying duty cycle (D) with variation of dc reference voltage. The simulated results are shown in table I. From the above analysis it is seen that input current and output voltage are highly distorted. For high frequency switching action output voltage ripple increases with variation of duty cycle which is represented as current harmonics in input size.

3. ANALYSIS

3.1 Boost Rectifier without EMI Filter

At first a single switch Boost regulator with three phase diode bridge rectifier is analyzed without input-side EMI filter. The circuit diagram of the rectifier with PWM control circuit is shown in figure 2. Here a Boost regulator is attached to a 3-φ rectifier with a resistive load. Rectifier is fed from a 3-φ ac utility lines having constant amplitude at constant frequency. The diodes of each phase conducts sequentially through highest positive input phase voltage. The PWM control

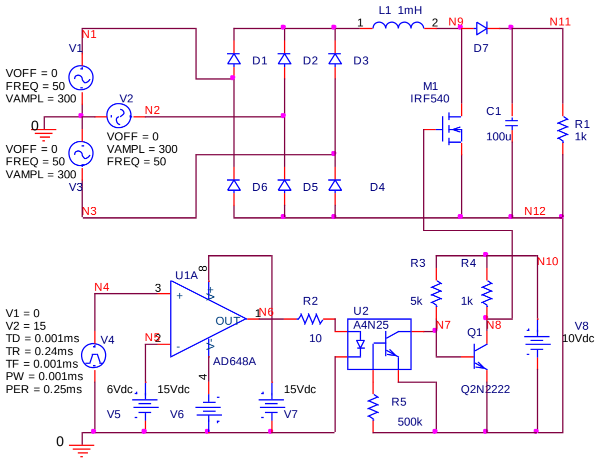

Fig 2: A single switch boost rectifier with PWM circuit

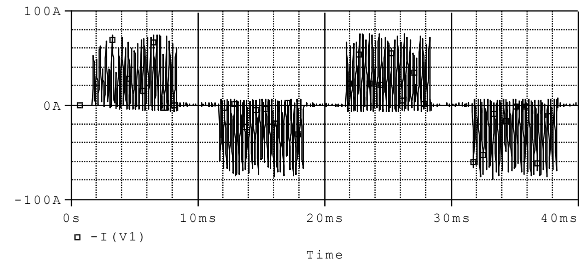

Fig 3: Input side current of the single switch boost rectifier

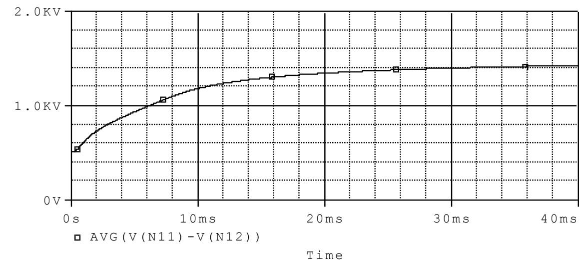

Fig 4: Output voltage of the single switch boost rectifier

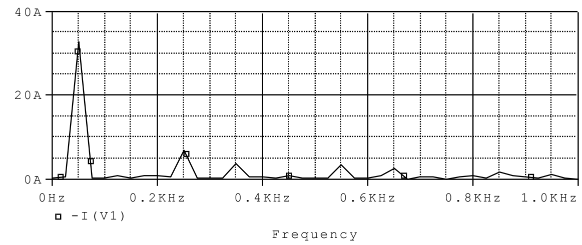

Fig 5: Frequency spectrum of the input side current

circuit generated a switching voltage of limited amplitude which is applied to turn on/off the switching element with low switching stress. The pulse width modulation (PWM) technique has been implemented to generate switching pulses comparing a dc reference voltage with a carrier saw tooth wave. PWM technique is used for its simplicity and low cost. The input current and output voltage wave shapes are shown in figures 3 and 4.

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Table 1. Performance parameter of a three phase boost regulated rectifier [13], [14]

Duty Cycle (D)	THD	PF (cosθ)	V_{out} (dc) volt	I_{in} (peak) amp	Efficiency η (%)
0.2	0.3291	0.545	49.49	800	48.08
0.3	0.3981	0.621	40.21	890	88.53
0.4	0.4903	0.702	37.35	1000	98.54
0.5	0.55	0.767	29.69	900	98.86
0.6	0.5749	0.869	22.62	780	97.23
0.7	0.5903	0.841	17.15	700	99.06
0.8	0.6205	0.903	12.72	600	98.41
0.5	0.6392	0.86	11.45	560	100
0.9	0.5939	0.847	11.17	550	100
0.95	0.7135	0.819	10.46	520	100

The simulated results are shown in table 1. From the above analysis it is seen that input current and output voltage are highly distorted. For high frequency switching action output voltage ripple increases with variation of duty cycle which is represented as current harmonics in input size. The input current is observed highly distorted and non sinusoidal in nature with low power factor. The THD% is calculated with equation (6).

$$THD\% = \frac{\sqrt{\sum_{h=2}^{h=\infty}(I_h)^2}}{I_1} \qquad (6)$$

Where, Ih is the magnitude of current harmonic Component and I1 is the magnitude of the component of current. Putting the values in the equation THD% is found to be 71.35% which is not acceptable. Filtering is required to improve the input current to sinusoidal by reducing the harmonics components and to make the power factor unity.

3.2 Boost Rectifier with EMI Filter

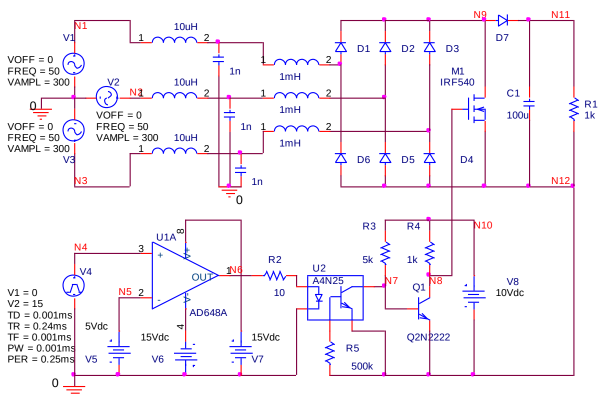

Fig 6: Boost Rectifier with EMI filter and Switching

Passive filter is a common solution to reduce THD from the input-side current of the rectifier. But the size of filter is an important issue to design a filter. Now, the Boost regulated rectifier is analyzed with an input passive filter having parameter L=10uH and C=1nF and with an output filter capacitor C=100uF. The circuit diagram of a Boost regulated three phase rectifier with passive filter is shown in figure 6.

The input side current and output voltages are shown in figure 7 and figure 8 respectively. The simulated results are shown in table 2.

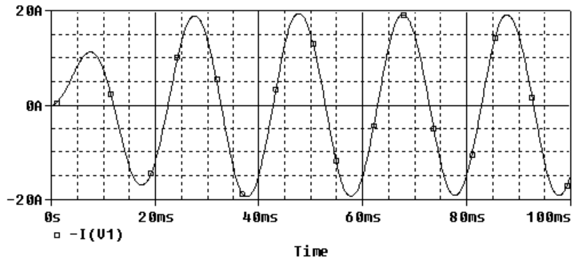

Fig 7: Input current of the boost rectifier with input filters

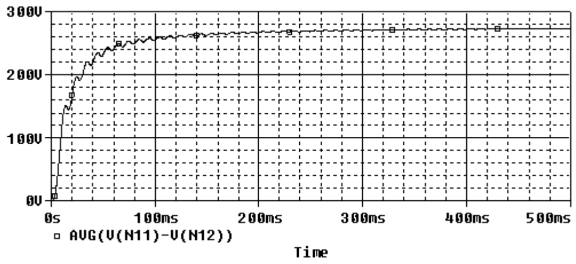

Fig 8: Output voltage of the boost rectifier with input filters

Table 2. THD & Efficiency with duty cycle in single switch boost rectifier without series LC filter

Duty Cycle (D)	THD	PF (cosθ)	V_{out} (dc) volt	I_{in} (peak) amp	Efficiency η (%)
0.80	8.10	0.84	632	32.3	32
0.75	8.32	0.86	795	31.2	52
0.69	7.94	0.89	928	30.0	71
0.63	8.72	0.95	964	25.6	84
0.56	11.78	0.98	896	20.0	90
0.51	14.67	0.99	821	15.0	99
0.43	16.73	0.99	753	12.7	99
0.38	17.86	0.97	695	11.0	99
0.31	22.41	0.95	645	8.0	99
0.25	17.60	0.89	600	9.2	97
0.18	17.52	0.80	555	9.8	86
0.12	16.47	0.70	520	9.0	93

3.3 Boost Rectifier with EMI and series LC Filter

It is seen that the amount of THD% is reduced than the previous condition and the input current is also found almost sinusoidal. But, the power factor has not improved satisfactorily. Another drawback is large harmonics peak is observed at 250Hz. In this perspective a harmonics filter is developed using formula XL= XC. Putting the resonating frequency the product of LC is calculated 4.053*107Changing the various values of L and C it is closely observed that better performance of the filter is found by L=18.83uH & C=0.1mF

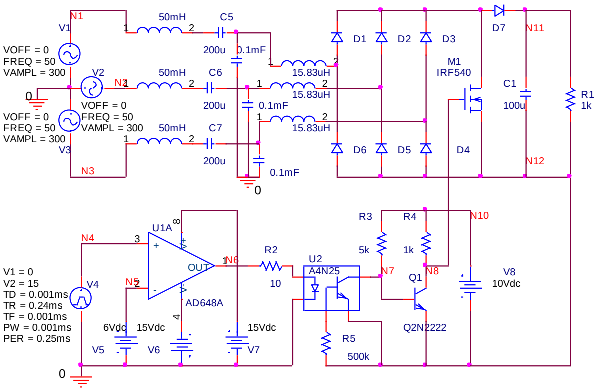

Fig 9: Three phase rectifier with EMI & series LC filter

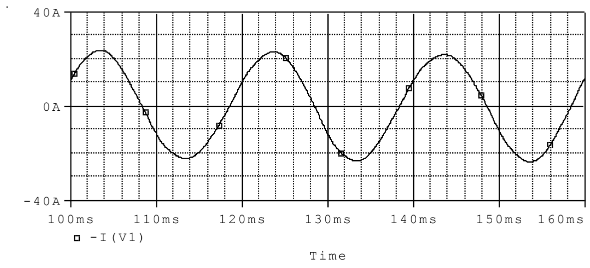

Fig 10: Input current of the boost rectifier with input filters

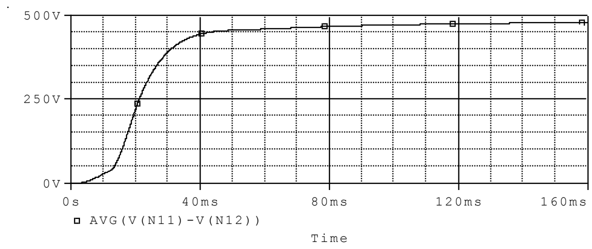

Fig 11: Output voltage of the boost rectifier with input filters

Table 3. THD & Efficiency with duty cycle in single switch boost rectifier with series LC filter

Duty Cycle (D)	THD	PF (cosθ)	V_{out} (dc) volt	I_{in} (peak) amp	Efficiency η (%)
0.96	0.96	0.80	450	33	17
0.88	0.98	0.80	412	32.5	14
0.84	1.03	0.80	640	32	35
0.80	1.04	0.80	800	31	57
0.72	1.14	0.80	930	30	72
0.64	1.33	1.00	900	19.7	91
0.54	1.65	1.00	820	16	93
0.47	2.01	1.00	750	13.5	93
0.31	3.78	0.95	635	11.7	81
0.26	3.85	0.84	590	10.6	87
0.18	3.37	0.72	550	9.9	93
0.12	2.10	0.61	510	9.2	99
0.05	2.04	0.61	483	8.9	99

This harmonics filter permits power quality to improve satisfactorily. Then the simulation results of Boost rectifier is shown in table 3. The proposed model consists of the following parts as follows: (a) a fixed 3-φ ac sources (b) rectifying stage (c) control circuit (d) PFC stage (e) filtering stage and (f) load. The schematic circuit diagram of Boost rectifier with passive high frequency and resonant filter is shown in figure 9. Typical input current and output voltage of this proposed scheme are shown in figures 10 and 11 respectively.

4. RESULTS

The comparison between the two circuits (with and without LC series filter) for THD values, output voltage and efficiency for different values of duty cycle are shown in figures 12, 13 and 14 respectively. Figure 12 shows that, THD is less for the

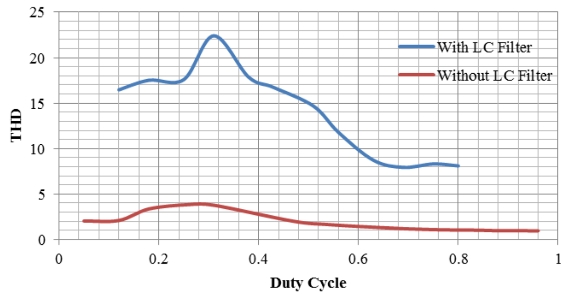

Fig 12: THD vs Duty cycle curves with and without series LC filters

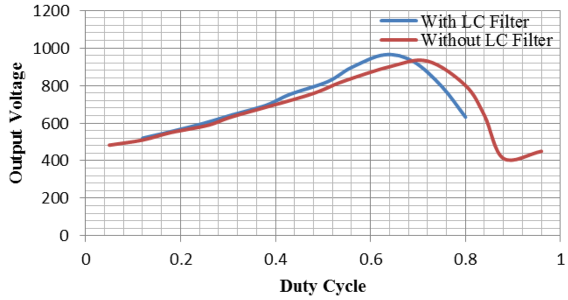

Fig 13: Output voltage vs Duty cycle curves with and without series LC filters

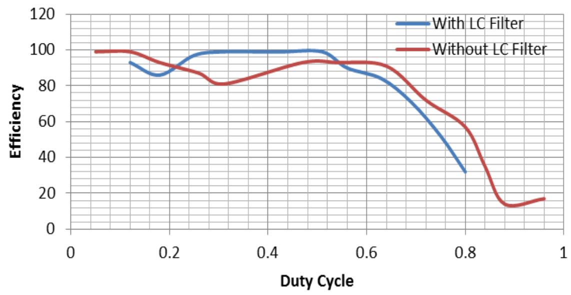

Fig 14: Efficiency vs Duty cycle curves with and without series LC filters

proposed model than the previous model that does not have the LC series filter. Figure 14 shows that output voltage increases for a certain range of duty cycle. It is seen that for a certain range of D the variation of output voltage is linear with efficiency. Wave shapes of efficiency at different duty cycles are shown in figure 14. The variation of power factor with different duty cycle is shown in table 2. It is seen that the power factor remains almost unity with variation of duty cycle. Thus power factor improvement is achieved with proposed model.

5. CONCLUSION

The proposed Boost rectifier is able to improve power factor and overall performance. With the harmonics filter and Boost switching action it is able to draw sinusoidal input current and almost unity power factor with various duty cycle. The efficiency is also improved and it is found above 80% from 0.05 to 0.65 duty cycle. The other advantages of this model are reduction of switching stresses, elimination of resonance problems and use of small input filter. Moreover, it is able to eliminate odd and even harmonics components thus total harmonics distortion is found in the range of maximum 14.7% and minimum 1.33%. Even though power factor is unity and performance is improved, it has some problems such that, the values of input current are higher in the beginning of duty cycle. The output voltage is found always greater than input voltage.

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