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Filter Design for AC to DC Converter

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ABSTRACT: *AC power is available commercially at low cost. DC power is relatively expensive to produce. Therefore a method for changing ac to dc is needed in relatively less expensive way as a source of dc power. The method presented in this paper to convert ac power to dc power is a full-wave bridge rectifier. But the output from the rectifier contains undesirable ripple. In many applications, the ripple has to be under specified limit. To control the ripple, the method suggested in this paper is utilizing a filter circuit. Filter circuits use either capacitor or inductor or both to limit the ripple. Mathematical formula to calculate the value of filter capacitor or filter inductor is available when they are used alone but when both capacitor and inductor are used together, there is no mathematical formula available to calculate their values for controlling the amount of ripple. In this paper, the Alternative Transients Program, ATP model for the case when a filter consists of either only capacitor or only inductor is verified with mathematical formula. After verification of the computer model with mathematical formula, a methodology is presented to design a combined capacitor-inductor filter to control the ripple at specified level.*

Keywords*: AC to DC converter, ATP, Diode, Filter, Rectifier, Ripple Factor*

I. INTRODUCTION

AC power is available commercially at low cost. DC power is more expensive to produce; therefore a method of changing ac to dc is needed as an inexpensive dc source. AC power can be converted to DC power using rectifiers [1]. When ac power is converted to dc power using rectifiers, dc output contains undesirable ac components called ripple. Many rectifier applications require that the ripple do not exceed a specified value. If the ripple exceeds the specified value, different unwanted effects appear in the system. Some of the unwanted effects are stray heating, audible noise etc [2]. Ripple can be mitigated using an output filter [3]. When a capacitor is used alone or an inductor is used alone as a filter, there is mathematical expression available for calculating the values of capacitor or inductor for controlling the ripple under the specified value, but when both capacitor and inductor are used together, there is no mathematical formula available to calculate their values [3]. A computer model is developed and verified in this paper to find out the values of capacitor and inductor when used together for controlling the ripple under specified value.

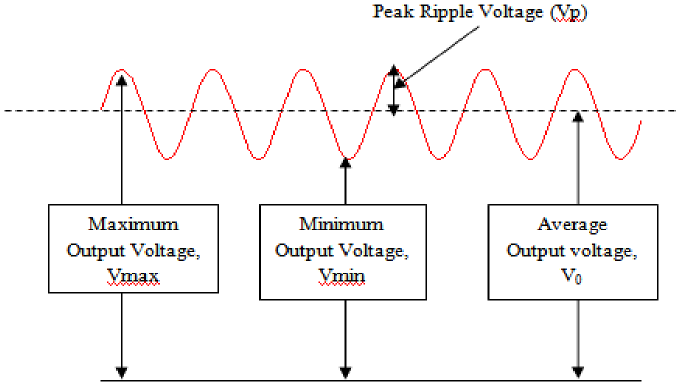

Figure 1. Ripple

The ripple factor is a ratio of the rms value of the ripple voltage Vrms to the average value V_0 at the output of a rectifier filter [4]. Fig 1 indicates the parameters needed to determine the ripple factor graphically. It is assumed that the ripple voltage has sinusoidal waveform. The formula for determining the percentage of ripple is

Percentage of ripple = (RMS value of ripple/Average DC output) x 100
= (Vrms/ V_0) x 100
where; Vrms = 0.707 x Vp
Vp = peak value of ripple voltage

A circuit that minimizes or eliminates the ripple component from the rectified output is called a filter. Filter systems in general are composed of a capacitor, an inductor, or both. Capacitor filters are used for lower-power applications . On the other hand, inductor filters are used in high-power applications [5].
Depending upon the passive element used, the filters can be classified as

1. Capacitor filter
2. Inductor filter
3. Capacitor-Inductor filter

In this paper, each of above filters is modeled for full-wave bridge rectifier and waveforms are obtained in Alternative Transients Program (ATP) [6].

II. CAPACITOR FILTER

A rectifier circuit without a filter produces pulses at the output. The fluctuations can be reduced if some of the energy can be stored in a capacitor while the rectifier is producing pulses and is allowed to discharge from the capacitor between pulses [4].

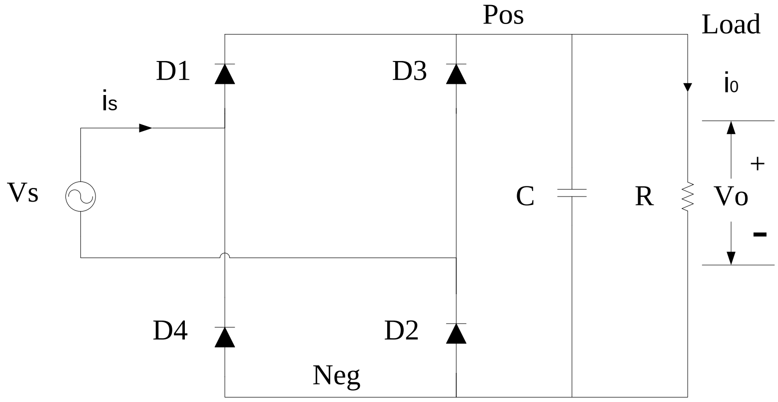

Figure 2a. Full-wave bridge rectifier with a capacitor filter

Fig 2a shows a full-wave bridge rectifier with a capacitor filter. Vs is rms value of source voltage and is equal to 120 V. Frequency of the source is 60 Hz. Time varying source current is represented by is and load current by io. Diodes are represented as D1, D2, D3, and D4. During positive half cycle of the source, D1 and D2 conduct. During negative half cycle, D3 and D4 conduct. Filter capacitor is represented by C and the load is represented by R. The value of load is 10 Ohm. Value of C is calculated in this section for different values of ripple. The output waveforms are plotted in ATP for 3% ripple and the ATP model is verified with the formula for calculating the ripple.

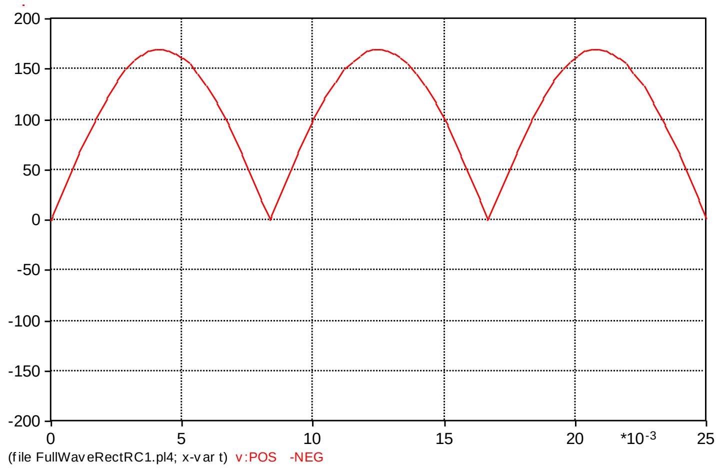

Figure 2b. Full-wave output without a filter

Fig 2b shows the voltage output of the full-wave bridge rectifier across point POS and NEG of Fig 2a without the filter capacitor. This pulsating voltage is applied to the filter capacitor represented by C in Fig 2a. The capacitor will react to any change in circuit voltage. Because the rate of capacitor charging is limited only by the impedance in the source side which is pretty low, the voltage across the capacitor can rise nearly as fast as the half sine wave voltage from the rectifier. In other words, the RC charge time is relatively short. The charge on the capacitor represents storage of energy. When the rectifier output drops to zero, the voltage across the capacitor does not fall immediately. Instead, the energy stored in the capacitor is discharged through the load during the time that the rectifier is not supplying energy.

The voltage across the capacitor and the load falls off very slowly if it is assumed that a large capacitor and relatively large value of load resistance are used. In other words, the RC discharge time is relatively long. Therefore, the amplitude of the ripple is greatly decreased as shown in Fig 2c. Waveform v:POS -NEG represents the output without a filter and waveform v:LOAD –NEG represents the output with a filter.

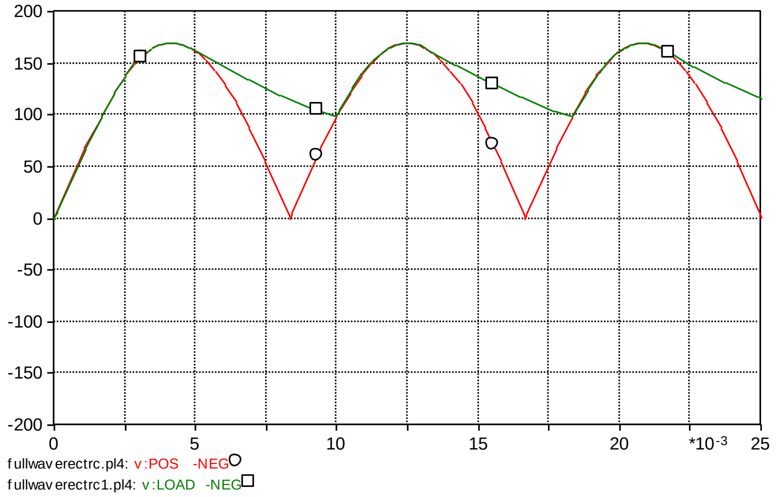

Figure 2c. Output for full-wave bridge rectifier

After the capacitor has been discharged, the rectifier does not begin to pass current until the output voaltage of the rectifier exceeds the voltage across the capacitor. This occurs at 10 ms in Fig 2c. Current flows in the rectifier until slightly after the peak of the half sine wave at 13 ms. At this time the sine wave is falling faster than the capacitor can discharge. A short pulse of current beginning at 10 ms and ending at 13 ms is therefore supplied to the capacitor by power source.

The average voltage, Vo, of the full-wave bridge rectifier output is 0.636xVm [5]. Vm is peak value of Vs and is equal to √2 xVs. From Fig 2b it can be seen that the average value is 0.636x√2x120 V= 108 V. Because the capacitor abosorbs energy during the pulse and delivers this energy to the load between pulses, the output voltage can never fall to zero. Hence the average votage of the filter otuput as shwon in Fig 2c is graeter than that of the unfiltered output shown in Fig 2b. However, if the resistance of the load is small, a heavy current will be drawn by the load and the average output votlage will fall. Also, the fitler capacitor acts like a short circuit across the rectifier while the capacitor is being charged. Due to these reasons, a simple capacitor filter is not suitable for rectifiers in higher power applications.

In practice, the ripple factor can be found from [5]

$$RF = 1/[\sqrt{2}\,(2f_rRC-1)] \quad (1)$$

where f_r is the output ripple frequency.

From Fig 2b, it can be seen that there are 2 otuput pulses for each cycle of supply voltage. Therefore the frequency of output ripple, f_r, is 120 Hz. Using equation (1) the value of capacitor is calculated for different values of ripple and the results are tabulated in Table 1.

Table 1

RF %	R Ohms	fr Hz	C mF
1	10	120	29.880
2	10	120	15.148
3	10	120	10.238
4	10	120	7.782
5	10	120	6.309

Using the capacitor value of 10.238 mF for 3% ripple, the voltage waveforms are plotted in Fig 2d.

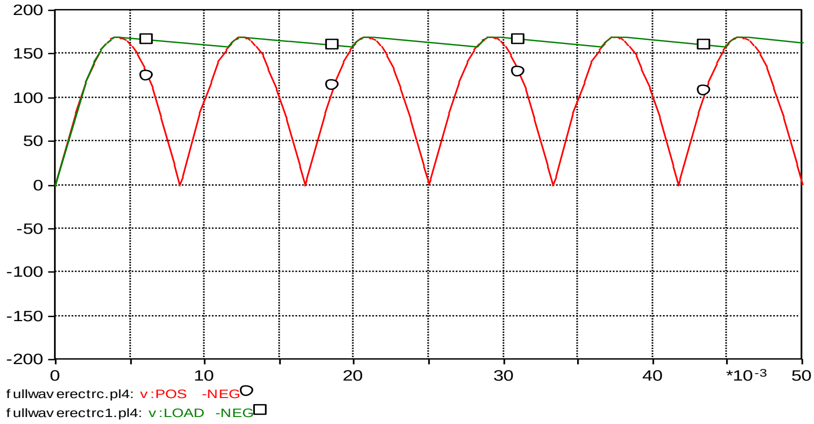

Figure 2d. Output voltage waveform for 3% ripple with 10.238 mF capacitor

From Fig 2d, Vmax = 170 Volts, Vmin = 156 Volts, Vo = 163 Volts, Vp= 7 Volts
Vrms of ripple = 0.707x7 Volts= 4.95 Volts.
Ripple percentage = (Vrms/Vo) x 100
= 3%

Since the same value of percentage ripple is obtained from simulation as well as from the equation (1), the ATP model has been verified with fromula given in equation (1).

III. INDUCTOR FILTER

From above we know that a capacitor is a device that reacts to variation in voltage and are connected across the load. The inductor is a device that reacts to changes in current. The inductor causes delay in current. Since the current is same in all parts of the series circuit, an inductor L is connected in series with the load as shown in Fig 3a. Circuit nomenclature and circuit parameters are the same as those in capacitor filter. Output of the rectifier without the inductor filter will be the same as shown in Fig 2b. The sequence of operation of diodes is also the same as those in capacitor filter. In this section the value of inductor required for different value of ripple are calculated and results are tabulated in Table 2. The output waveforms are plotted using ATP for 3% ripple and the ATP model has been verified with the formula given in equation (2).

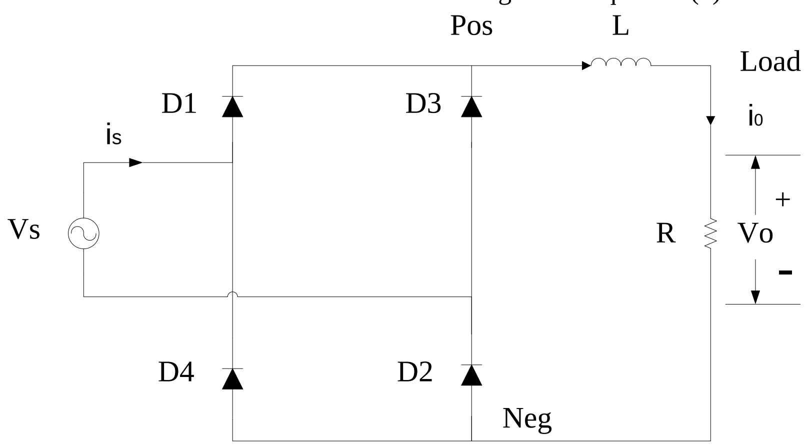

Figure 3a. Full-wave bridge rectifier with an inductor filter

The use of an inductor prevents the current from building up or dying down too quickly. If the inductor is made large enough, the current becomes continuous and nearly constant. The inductor prevents the current from ever reaching the peak value which would otherwise be reached without a filter inductor. Consequently, the output voltage never reaches the peak value of the applied sine wave. Thus, a rectifier whose output is filtered by an inductor cannot produce as high a voltage as that could be produced by a rectifier filtered by a capacitor. However, this disadvantage is partly compensated because the inductor filter permits a larger current without a serious change in output voltage. This is the reason that an inductor filter is suitable for high power applications.

A typical output waveforms are shown in Fig 3b. Waveform that has a peak value of 17 A is the current without the inductor filter. The waveform that has a peak value of 12.6 A is the current with the inductor filter.

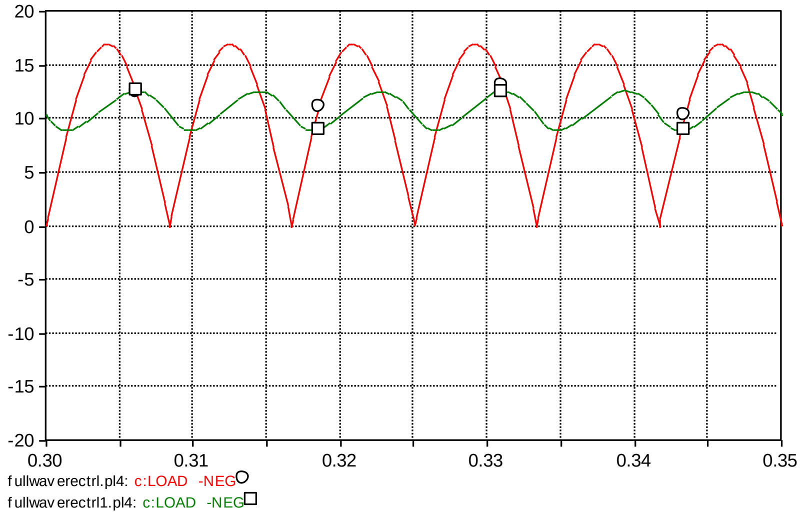

Figure 3b. Load current

In practice, the ripple factor can be found from [5]

$$RF = 0.4714/\sqrt{[1+(4\pi f_i L/R)^2]} \quad (2)$$

where f_i is the input frequency

It should be noted that in equation (2) for inductor filter, input line frequency is used for calculation unlike the case of capacitor filter where output ripple frequency was used in equation (1). Using formula shown above, the value of inductor is calculated for different values of ripple and the results are tabulated in Table 2.

Table 2

RF %	R Ohms	fi	L mH
1	10	60	624.821
2	10	60	312.200
3	10	60	207.898
4	10	60	155.677
5	10	60	124.287

Using the inductor value of 207.898 for 3% ripple, the current waveform are plotted as shown in Fig 3c. From Fig 3c, Imax = 11.25 A, Imin = 10.34 A, Io = 10.79 A, Ip = 0.46

Irms of ripple = 0.707 x 0.46 A = 0.325 A

Ripple percentage = (Irms/Io) x 100

= 3 %

Since the same value of percentage ripple is obtained from computer simulation as that was calculated using equation (2), the ATP model has been verified with the formula.

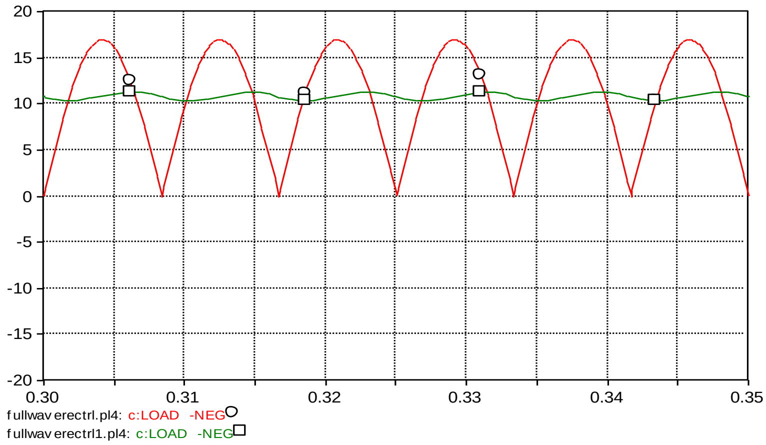

Fig 3c. Output current waveform for 3% ripple with 207.898 mH inductor

IV. CAPACITOR-INDUCTOR FILTER

A capacitor-inductor filter is used to improve the filtering action of rectified voltage and current. We saw in above sections that the capacitor alone or the inductor alone cannot perform the filter action satisfactorily as former is suitable for low-power applications and the latter is suitable for high-power applications. However, if both the capacitor and inductor are combined, they produce high quality dc voltage and current. The function of the capacitor is to smooth out the variations in voltage while the inductor is used to smooth out the variations in current. Because of the uniform flow of current, the capacitor-inductor filter is used widely in high-power applications. Fig 4a shows a full-wave bridge rectifier with a capacitor-inductor filter.

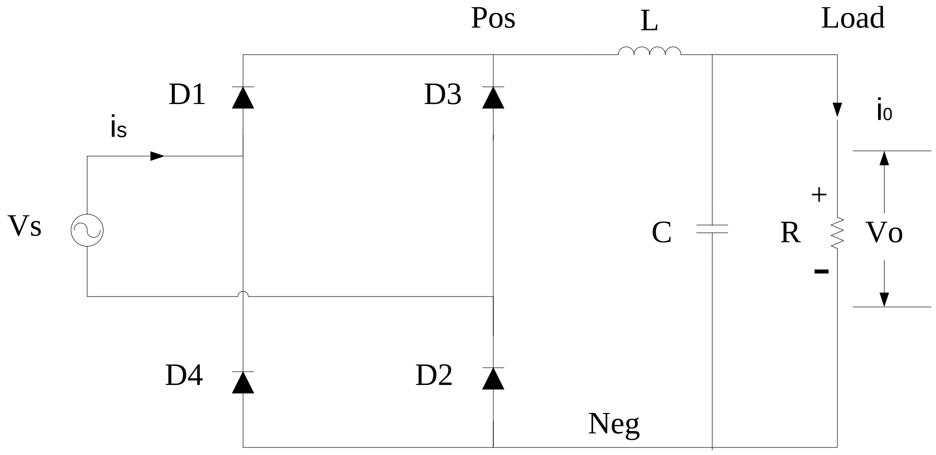

Figure 4a. Full-wave bridge rectifier with a capacitor-inductor filter

From previous sections we know that, if used alone, a 10.238 mF capacitor is needed to reduce the ripple to 3% in the circuit under consideration. Similarly, if used alone, a 207.898 mH inductor is needed to reduce the ripple to 3%. The aim of this section is to find out the value of a capacitor and an inductor used together in the way shown in Fig 4a to reduce the ripple to 3%.

The approach taken to design the filter is to select an arbitrary value of capacitor; about 25% of the value that was needed to reduce the ripple to 3% when used alone and then vary the value of inductor until a 3% ripple is obtained. The values are obtained by trial and error using the verified ATP model. The results from the simulations are tabulated in Table 3. Terminologies used in Table 3 are same as those shown in Fig 1. Terminologies in Fig 1 are shown for voltage ripple but they are also applicable for current ripple.

Table 3

C mF	L mH	I max Amp	I min Amp	I ave Amp	Peak ripple	I rms Amp	I ripple %
2.5	5	13.20	11.50	12.35	0.85	0.60	4.87
2.5	10	11.38	10.28	10.83	0.55	0.39	3.59
2.5	15	11.18	10.46	10.82	0.36	0.25	2.35
2.5	20	11.08	10.55	10.82	0.26	0.19	1.73
2.5	25	11.02	10.60	10.81	0.21	0.15	1.37

Current ripple in percentage as a function of inductor in mH is plotted in Fig 4b. From Fig 4b it is clear that 3% current ripple is obtained when a capacitor of 2.5 mF and an inductor of 12.5 mH are used. Using this value the voltage and current waveforms are obtained from ATP as shown in Fig 4c.

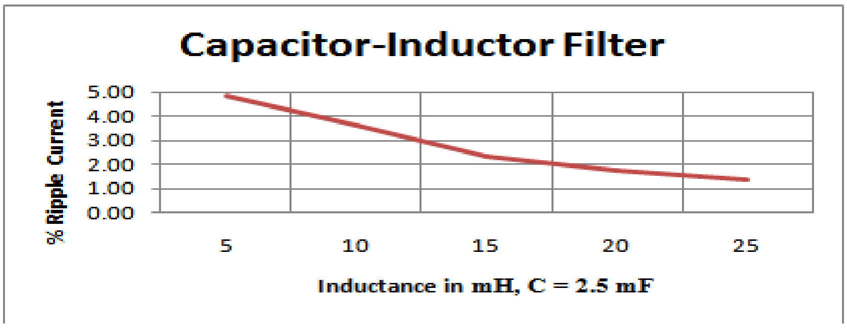

Figure 4b. Percentage Current ripple v/s Inductance

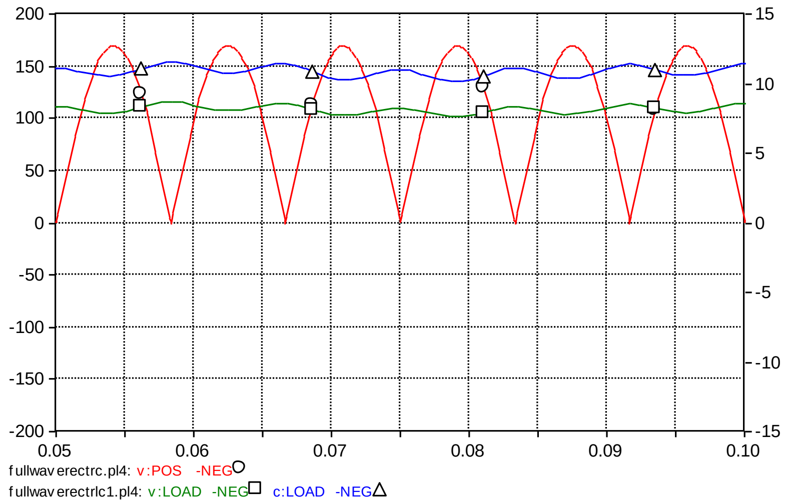

Figure 4c. Voltage and current waveform for a capacitor and an inductor filter with 3% ripple

In Fig 4c there are three different waveforms plotted. There are two voltage waveforms and one current waveform. Voltage waveforms are plotted on left y-axis and the current waveform is plotted on right y-axis. For clarity, x-axis is shown only between 0.05 sec to 0.10 sec. The waveform v:POS –NEG is the output voltage waveform from the rectifier before the filter. The waveform v:LOAD – NEG is the load voltage waveform after the filter. The waveform c: LOAD –NEG is the current waveform through the load. It should be noted that, since the load is purely resistive, the load current waveform follows the load voltage waveform. For percentage ripple calculation, we can use either load voltage waveform or load current waveform; both will end up with the same result.

Using voltage waveform from figure 4c, we have

Vmax = 112.57 Volts, Vmin = 103.90 Volts, Vo = 108.24 Volts, Vp= 4.34 Volts

Vrms of ripple = 0.707 x 4.34 Volts= 3.07 Volts.

Ripple percentage = (Vrms/Vo) x 100

= 3%

Using current waveform from Fig 3c, we have

Imax = 11.26 A, Imin = 10.39 A, Io = 10.83 A, Ip = 0.44

Irms of ripple = 0.707 x 0.44 A = 0.311 A

Ripple percentage = (Irms/Io) x 100

= 3 %

Percentage ripple obtained from both the voltage waveform as well as the current waveforms are same. Therefore, it can be noted that the Fig 1 is applicable for both the voltage ripple as well as the current ripple.

V. RESULTS

The values of capacitor and/or inductor needed for various type of filter to limit the dc ripple to 3% is shown in Table 4. It is clear from Table 4 that significantly larger value of capacitor or inductor is needed when they are used alone to achieve the same result than their values when they are used together. Capacitor needed when used alone is 10.238 mF and Inductor needed when used alone is 207.898 mH for 3% ripple. On the other hand, when they are used together, the value of capacitor needed is 2.5 mH (compared to 10.238 mF) and the value of inductor needed is 12.5 mH (compared to 207.898 mH) for the same percentage of ripple.

Table 4

Filter Type	Capacitor in mF	Inductor in mH
Capacitor Filter	10.238	N/A
Inductor Filter	N/A	207.898
Capacitor-Inductor Filter	2.500	12.500

VI. CONCLUSION

ATP model and the mathematical equations for percentage ripple for capacitor filter or inductor filter were verified. Based on verified ATP model, a capacitor-inductor filter was designed to achieve the specified ripple percentage. It has been shown that the effective control of ripple can be achieved by choosing proper values of capacitor and inductor for a filter in AC to DC rectifier.

Since there is no mathematical formula available for designing a combined capacitor-inductor filter, the verified ATP model will help seniors, graduate students, and design engineers to design a filter to limit the ripple to a specified value in an AC to DC converter.

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