A Comparative Study of Small Voltage Rectification Circuits for Implanted Devices

Samnan Haider$^{1}$, Hasmah Mansor$^{1}$, Sheroz Khan$^{1}$, Atika Arshad$^{1}$, Mohammed M. Shobaki$^{1}$ and Rumana Tasnim$^{1}$

$^{1}$Department of Electrical and Computer Engineering
International Islamic University
53100 Kuala Lumpur, Malaysia
Email: syedsamnanhaider855@gmail.com

E-mail: syedsamnanhaider855@gmail.com

Abstract: Biomedical implants have acquired an invulnerable and significant importance over the recent years due to their low voltage requirements and trifling dimensions. Biomedical implants are being widely employed for the continuous monitoring of intended parameters as well as stimulation of target organs in patient’s body. Being low power devices, the continuous powering without using battery dependent sources necessitates the alternative sources such as energy harvesting from the surroundings. Harvested output needs to be processed before using it for powering purposes, particularly in harsh and challenging premises. Even after processing, it needs to be made robust against the contiguous hazards so that maximum power is transferred to the load. A rectifier is employed to make this harvested energy usable. This paper compares the rectifier circuits, comparing their simulation output in terms of regulation, stability and power transferred. The rectification of small voltages is usually confronted by the threshold voltage drops that affect the output causing an effective drop in the power transfer efficiency and other parameters related. The solution to this problem has been suggested comparing the previous approaches with some modifications. Obtained results have been plotted in terms of ripple factor comparing them with the analytical calculations in order to show the role of capacitance in the reduction of ripple factor.

1. Introduction

Undoubtedly, technological development has bequeathed the innovations to all fields of science but has imparted the biomedical domain with bamboozling novelty [1]. This origination not only whirls around the miniaturization of implantable devices but also spurs towards the development of sensing networks in order to collect the data from subject and process it for monitoring purposes [2-3]. Automated sensing networks have attained an invulnerable importance in biomedical implanted devices as they provide the facility to monitor the intended parameters [4].

Biomedical implanted devices help in performing a number of tasks efficiently such as the collection of data from different body parts for monitoring purposes and to rejuvenate the lost functionality of organs by stimulating the muscular tissues [5-6]. The stimulation of tissues by
electrical means in biomedical implants has always been a field of interest, as this technique has
remained helpful in restoring organs’ lost functionality in the aftermath of injuries received in
accidental situations [7]. However, it has been taken under serious consideration recently, for using the
electrical stimulation as a permanent source for impaired tissue operations [8].

Although biomedical implants perform efficiently in fulfilling the intended tasks, but it is quite
difficult to meet the power requirements for these devices. Batteries cannot be used for this because of
longevity issues and the unacceptable sizes. Therefore energy harvesting is considered as an effective
alternative that replaces the batteries fulfilling the energy requirements. Energy obtained as a result of
energy harvesting process is not readily usable because of its too small amplitude therefore it needs to
be processed by using some amplification and regulatory circuits that bring it to an operating level.
Mainly, it suffers of continuity and stability and issues related to power transfer efficiency, which can
be overcome by implementing different circuits proposed recently by contemporary researches.

A contemporary research claims to enhance the power transfer efficiency by using a model of
Printed Spiral Coil PSC applying an algorithm to make this PSC operate at a frequency of 13.56MHz
[11]. The suggested algorithm improves the efficiency and stabilizes the output as well. Class-E
oscillator [12] has been implemented in order to enhance the power transfer efficiency. The paper
endorses to use the same link for powering as well as for communication purposes at the same time
avoiding the switches and connectors. This technique not only ameliorates the power transfer
efficiency but regulates the output as well. A neoteric approach in [13] proposed a full wave CMOS
rectifier for non-invasive powering of low voltage biomedical implants. Bootstrapped capacitors are
used for the reduction of threshold voltage drops to overcome the start-up voltage of selected
transistor. This technique improves the power efficiency minimizing the voltage drop.

This paper focuses on the rectification and regulation aspects of the low power output produced as
a result of energy harvesting. It compares a number of rectification circuits proposed by contemporary
researches on the basis of output power and regulation of output voltage making such small voltage
usable by bringing it to an operational level.

2. Methodology

Harvesting energy using thermal and other sources like solar, vibrational etc. produces an output of
minimal value. Fig. 1 exhibits the basic concept behind energy harvesting using two sources only i.e.
thermal and vibrational. The output produced as a result of energy harvesting cannot be directly
utilized to power up the buried implant, so it needs to be amplified, regulated and stabilized. In the
recent past, many researches have proposed visible solutions to enhance the power received. This
paper is a comparative study of a number of approaches based on rectifiers used in different
topologies, in terms of all the tasks quoted above.

Circuits including Full wave bridge rectifier, Gate cross coupled, fully cross coupled rectifier and
bootstrapping capacitor based rectifier have been simulated for an input of 3V, f= 50Hz. Simulation
plots for input and output currents, voltages and power have been obtained comparing them in the light
of regulation and power transferred consequently in order to know that how much power is transferred
over a small distance using CMOS transistors. Circuits have been compared on the basis of ripple
factor and hence categorized by calculating the values for each circuit. The role of a capacitor filter in
reduction of the ripple factor has been shown via simulations by connecting a capacitor of a value
equal to 100uF at the output.

3. Results and Discussion

Generally, the betrothed applications for rectifier are low voltage energy harvesters with very low
output voltage amplitudes of around 500 mV generally. Usually, these rectifiers are used in biomedical
implants in order to rectify the harvested output and regulate it to a usable level. Dealing with such a
small voltage demands an efficient circuit in terms of power conversion i.e. lesser threshold voltage
drops. Recent reported researches have considered this issue vitally and many solutions have been
proposed to for the minimal threshold voltage drop resulting in the enhanced output. This section is based on the simulation results of all the circuits mentioned in section II chronologically.

Fig. 1 represents a conventional full wave bridge rectifier circuit with 4 diodes connected in such a way that D1 and D3 conduct during the positive half cycle whereas the other pair D2 and D4 conduct in the negative half cycle. It rectifies the input voltage and brings the negative half above zero. Currently, a 3V input is applied to this circuit and the rectified output v/s input voltage is shown in fig. 2.

![Fig. 1: Full wave bridge Rectifier](image)

A full wave rectified output approx. equal to 2.8V is produced as a result of rectification process. The loss is because of threshold voltage drops in diodes. This drop affects the output power as well that can be observed in Fig. 3. An output power of 12mW is obtained for an input of 15mW. Also the output voltage constitutes of a vigilant AC part which is not suitable for powering small voltage devices such as biomedical implants. So a capacitor is added in parallel to the load and the output becomes more regulated with less ripples and smaller ripple factor.

![Fig. 2: Full wave rectified output](image)

Adding a capacitor regulates the output and brings it near to DC which is shown in Fig. 4, hence such regulated voltage can be used directly to power up the biomedical devices.

![Fig. 3: Input power v/s Output power](image)
Fig. 4: Output voltage with a capacitor filter

Fig. 4 shows the result in case of a capacitor connected in parallel to the load. The output is more regulated and near to DC voltage as compared to the Fig. 2. Preemptively, looking at the waveform gives an idea that the ripple factor has been reduced as well. This can be vindicated by a very simple calculation. First of all, the ripple factor for Fig. 2 needs to be calculated. The peak amplitude for the input voltage is 3V. The output DC voltage is $V_{\text{avg}} = \frac{2V_m}{\pi} = \frac{6}{\pi} = 1.90V$. The peak-to-peak ripple voltage is the difference between the maximum and the minimum in the $v_o$ waveform that means $V_{p-p} = V_m - 0 = 3V$. The percentage ripple factor equals $\frac{V_{p-p}}{V_{\text{avg}}} \times 100 = 157\%$ for frequency of 50Hz. The ripple factor for the waveform in Fig. 9 can be calculated as under

As the output Dc voltage is equal to $V_{\text{avg}} = 2V_m = 5V$ in this case.

The load current $I_L$ is given by $I_L = \frac{V_{\text{avg}}}{R_L} = 5/500 = 0.01A$.

The capacitor discharges between T1 and T2 which is 20msec for a frequency of 50Hz so the charge supplied by the capacitor to the output resistor during this period is given as Eq.1.

$$\Delta Q = I_L \times T = 0.01 \times 20 \times 10^{-3} = 0.0002 \text{ Coulomb}$$ (1)

Peak to peak ripple voltage is $V_{p-p} = \Delta Q / C = 2V$. This is almost 80% of the value of ripple factor for Fig. 2 so it has reduced almost more than 50% compared to the case when capacitor is not used. A small capacitor of value equal to 100uF has reduced the ripple factor to the half of the original value and it will go down some more if the capacitance value is increased.

A gate cross coupled rectifier is shown in Fig. 5 that has a pair of switch connected NMOS transistors at the input and a pair of diode connected PMOS transistors at the output. The working principle of this rectifier is quiet simple. The switch connected PMOS helps to overcome the threshold voltage drop during each half cycle. The rectified output is shown in Fig. 6 where it has been compared with the input voltage as well to show the drop caused due to the threshold voltage.
An output of 2.6 V approx. is produced after the rectification process but it contains a delay as the active area is reduced as compared to the input waveform. This is because of leakage current and it can be eradicated by using a comparator proposed in [9-10]. The output contains a noticeable AC part that can be suppressed easily by using the same capacitor as added in the previous cases. Adding a capacitor caused a visible drop in the ripple factor in this circuit as well. Output for this case is shown in Fig. 7. The percentage drop can be calculated by using the same method and for these waveforms, it has been dropped from 157% to 82% approx. for a value of C=100uF. It can be reduced even more by using a higher value of capacitance.

This threshold voltage drop due to the diode connected transistors causes the power to decrease as well which is shown in Fig. 13 where an output power of 10mW is produced against an input of 13mW.

Fig. 6: Input voltage v/s output voltage

Fig. 7: Output voltage with a capacitor filter

Fig. 8: Input power v/s output power

Fig. 9 shows another topology of full wave rectifier with two pairs of transistors i.e a pair of NMOS switches at the input and a pair of PMOS switches at the output. This circuit overcomes the threshold voltage drop to a higher level as compared to the previous configuration because the threshold drop is replaced by switches during each half cycle. The resulting output after rectification is shown in comparison with the input voltage in Fig. 10. A subsequent Fig. 11 shows the plots for input and output power as well to show the efficiency of the circuit. Output power is almost 16mW in this case. The output voltage in this case also needs to be regulated in order to suppress the AC portion in it, hence it is passed through a capacitor filter for a value of C=100uF and the resulting output is shown in Fig. 12.
After adding a capacitor in parallel to the load resistor, the output becomes more regulated and it is averaged to a value that equals approx. 2.5 V. The ripple factor is reduced as well and by calculation it comes out to be 80% of the value for ripple factor in the normal case without using a capacitor.
Fig. 13 shows a contemporary design of a full wave rectifier with functionality based upon the dynamic bulk biasing and bootstrapping capacitors. The dynamic bulk solves the problem of leakage current through the bulk whereas small bootstrapping capacitors not only reduce the effective threshold voltage of the main pass transistor; hence this circuit proves to be the most efficient amongst all the configurations discussed in this paper. Simulations results for input voltage v/s output voltage have been shown in Fig. 14 where an output voltage equal to 2.9 V approx. is produced by this circuit. Plots for input v/s output power are shown in Fig. 14; this circuit produces an output power equal to 17mW which is almost the highest in all the discussed configurations. Similar to the other cases, the output voltage contains an AC portion which is regulated by using the same value of capacitor as used for the other circuits. Fig. 16 shows the output for this case. The output produced is enhanced and more ripple free compared to all other techniques.
The capacitor filter reduces the ripples to a higher extent and makes this voltage regulated, bringing it closer to DC. An average voltage equal to 2.8V is produced in this case and the ripple factor has reduced to almost 85% compared to the original rectified voltage waveform.

Fig. 16: Output voltage with a capacitor filter

4. Conclusion

Low power devices require a regulated input for their proper functioning. Energy harvesting is preferred over batteries due to the low voltage requirements but the output of energy harvesting system is so small that it needs to be regulated to usable level. Rectifiers are used to fulfil this job usually. Although these circuits rectify the output but it contains AC ripples that can interlude the operation of the device, so a solution has been proposed to cope against this problem. The output becomes more regulated if a capacitor is connected in parallel to the load resistor. The larger the value of capacitor, the more regulated output is. This paper compared the contemporary rectifier approaches in terms of output voltage, output power and the ripple factor. All above mentioned parameters have been plotted and compared. The ripple factor for each case has been calculated using analytical approach as well. Results show that the last circuit with bootstrapping capacitors performs best in terms of achieving all the intended parameters.

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