Comparison between Active AC-DC Converters For Low Power Energy Harvesting Systems

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Abstract— **Low power energy harvesting systems research is increasing in recent years due to many applications such as wireless sensor node, biomedical implants, highway traffic sensor and demand for increasing the battery life. One of the major challenges of the energy harvesting systems is to convert and store usable power efficiently. This paper presented a survey about several commonly used active AC-DC converter circuits that is based on active diodes such as negative voltage converter with active diode, cross-coupled active full bridge and active bridge voltage doubler. Our study shows that the most efficient rectifying circuit among the surveyed AC-DC converter circuits is the active bridge voltage doubler. It provides a minimum voltage drop compared to other two AC-DC converter circuits. In additions, it provides 2X the amount of electrical power.**

Index Terms—**Energy Harvesting, Active AC-DC, Comparator**

I. INTRODUCTION

AC-DC Converter converts AC signal produced by different energy harvester sensors [1] such as piezoelectric, electromagnetic and electrostatic to DC signal suitable for powering wireless sensors and other systems without the need to external DC power supply. Conventional rectifiers [2] suffer from high diode voltage drop that leads to power loss during the rectification stage. Recently, active diodes are used at low power applications to overcome the voltage drop of the conventional diodes. In this paper, the comparison between active AC-DC converters for low power energy harvesting systems is presented.

The main rectification challenges of junction diodes are the forward voltage drop and the reverse leakage current of junction diodes. On the other hand, active diodes have shown great promise in replacing conventional diodes in low-voltage and low-current applications. As shown in Figure 1, active AC-DC converter is a comparator-controlled switch, whose ON/OFF state is determined by the polarity of the voltage across it, generates low or high voltage at the output terminal.

The behavior of an active diode is similar to an ideal diode, but the comparator requires a power supply. Fortunately, the power consumption of the active diode is quite low. Several commonly used active AC-DC converter circuits are discussed according to efficiency and area. Our study shows that the most efficient rectifying circuit among the surveyed circuits is the active bridge voltage doubler.

The rest of the paper is organized as follows. Section II introduces the surveyed circuits. Section III introduces the simulation results and discussion. Finally, some conclusions are drawn in Section IV.

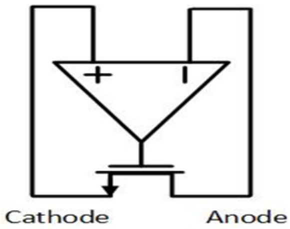


Fig. 1: Schematic of an active diode using PMOS switch [3].

II. SURVEYED CIRCUITS

A. Negative voltage converter with active diode

The proposed active rectifier [3]-[5] is realized using two stages as shown in Figure 2 .The first stage, Negative Voltage Converter "NVC", is used to convert the negative wave of the input AC signal to positive by using two PMOS and two NMOS connected as shown in Figure 3. During the positive wave of the input AC signal ($V_{in1}>V_{in2}$), MP1 and MN1 will be active when the input voltage becomes greater than V_{thn} and V_{thp}. Then, terminal (1) becomes high "V_{in1}" and terminal (2) becomes low "V_{in2}". At the negative wave of the input ($V_{in2}>V_{in1}$), MP2 and MN2 will be active then terminal (1) becomes high "V_{in2}" and terminal (2) becomes low "V_{in1}".

Therefore, terminal (1) is always high "positive" during the positive and the negative cycle of the AC input signal while terminal (2) is always low, the voltage drops of the first stage reach to ($V_{thn}+V_{thp}$) across NMOS and PMOS transistors. Further increasing of the transistor width decreases the resistance to get a smaller voltage drop at the expense of higher power consumption.

The first stage itself cannot control the direction of the current. Therefore, the active diode second stage will be used. This active diode consists of PMOS switch, which is driven by the comparator. The width of the PMOS switch has a great effect on the performance of the active AC-DC converter. Increasing the transistor width decreases the resistance to obtain a smaller voltage drop. On the other hand, this results in larger area and power consumption [6].

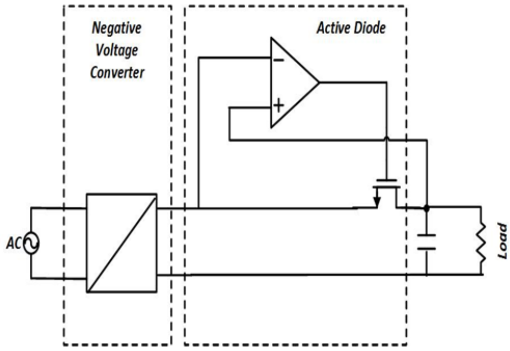


Fig. 2: Negative voltage converter with active diode [5].

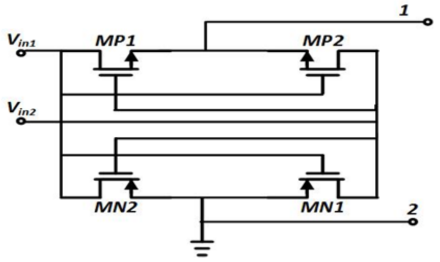


Fig. 3: Negative voltage converter schematic [5].

The comparator should be designed with low power consumption and low input voltage. The circuit implementation of low input voltage comparator , shown in Figure 4, consists of six transistors (M4-M9) work as a comparator to control the gate voltage of the PMOS switch M1. The main drawback of the comparator is the need for an external power supply that can be achieved easily by using current mirroring circuits. Transistors (M10-M12) are used to design two current mirrors for powering the comparator.

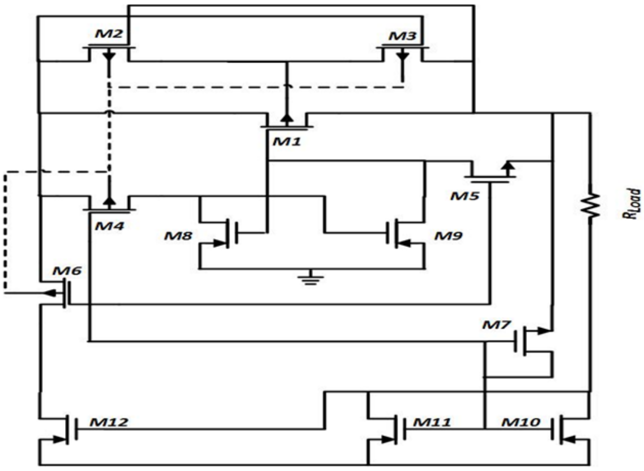


Fig. 4: Schematic of the comparator design [5].

Transistors (M2-M3) work as an active body biasing block to prevent the PMOS switch M1 body-junction from turning ON during start-up for better design reliability. The sizes of these transistors should be designed as small as possible to provide a low current flow during start up.

The total voltage drop of the negative voltage converter with active diodes is ($V_{thn}+V_{thp}+V_{thp\ (switch)}$).

B. Cross-coupled active full bridge

The proposed cross-coupled active full bridge [7-8], displayed in Figure 5, consists of two cross-coupled inverters and two active diodes. During the positive wave of the input AC signal ($V_{in1}>V_{in2}$), MP1 will be active when the input voltage becomes greater than V_{thp}. The voltage at the negative input port of the left comparator becomes low "V_{in2}". Correspondingly, the output of the left comparator becomes high which turns the transistor MN2 ON. Thus, the current flowing though (MP1-MN2) charges the loading capacitor CL.

During the negative wave of the input AC signal ($V_{in2}> V_{in1}$) MP2 will be active when the input voltage becomes greater than V_{thp}. While the voltage at the negative input port of the right comparator becomes low "V_{in1}". Correspondingly, the output of the comparator is high which turns the transistor MN1 ON. Thus, the current flowing though (MP2-MN1) charges the loading capacitor CL.

The comparator implementation, shown in Figure 6, consists of three parts (common gate amplifier-current mirror-inverter). Transistors (M8, M10) and transistors (M7, M12) are common gate amplifier while transistors (M9, M13) are used to design current mirror. Transistors (M14-M17) are two inverters driving large gate capacitance for the NMOS switch.

The total voltage drop of the cross coupled active full bridge is ($V_{thn}+V_{thp}$).

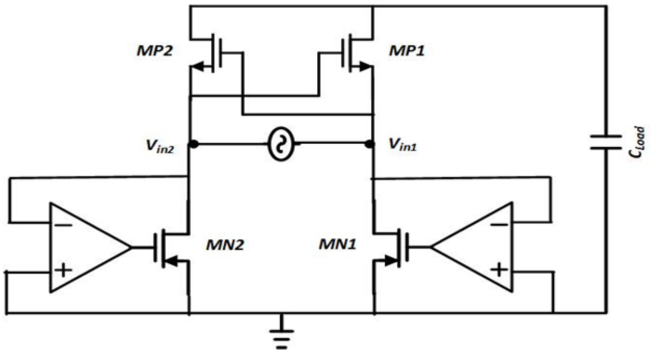


Fig. 5: Cross-coupled with active diode [7].

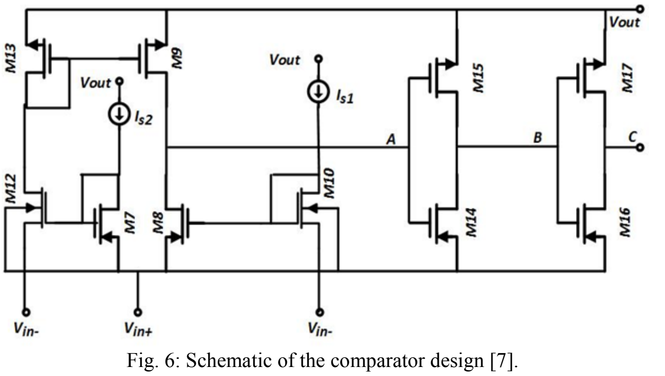


Fig. 6: Schematic of the comparator design [7].

C. *Active bridge voltage doubler*

The active bridge voltage doubler [9-10], shown in Figure 7, consists of positive and negative peak detectors that generate DC voltages that track the positive and the negative voltage of the input AC signal.

During the positive wave of the input AC signal the voltage at the negative input port of the comparators is greater than 0V. Correspondingly, the comparator output becomes low which turns the PMOS switch ON and turns the NMOS switch OFF. Thus, the current flowing through the PMOS switch charges the loading capacitor C_{load}. During the negative wave of the input AC signal, the voltage at the negative input port of the comparator is lower than 0V. Correspondingly, the comparator output becomes high which turns the NMOS switch ON and turns the PMOS switch OFF. Therefore, the current flowing through the NMOS switch charges the loading capacitor C_{load}. The total voltage drop of the active bridge doubler is $V_{th(switch)}$. The main advantage of this circuit is providing two positive and negative DC output voltages.

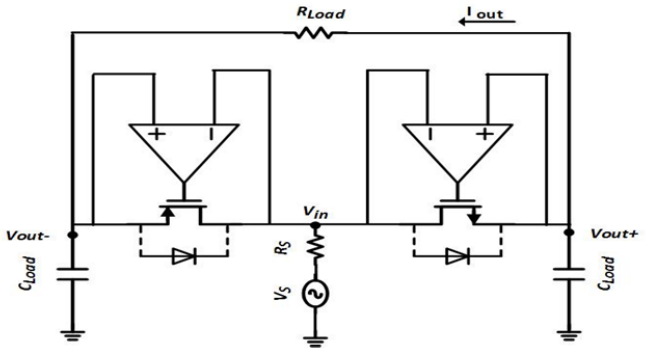
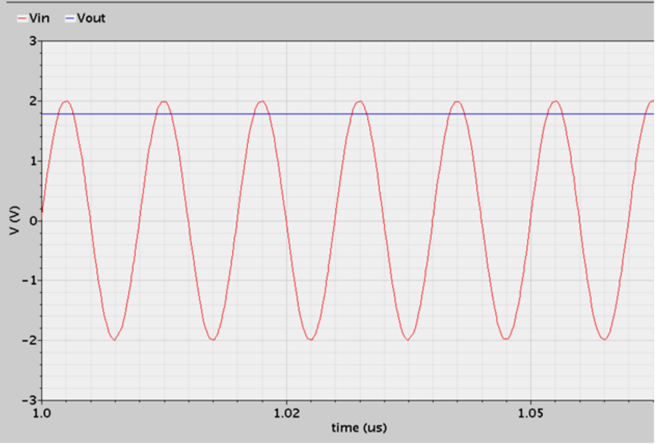


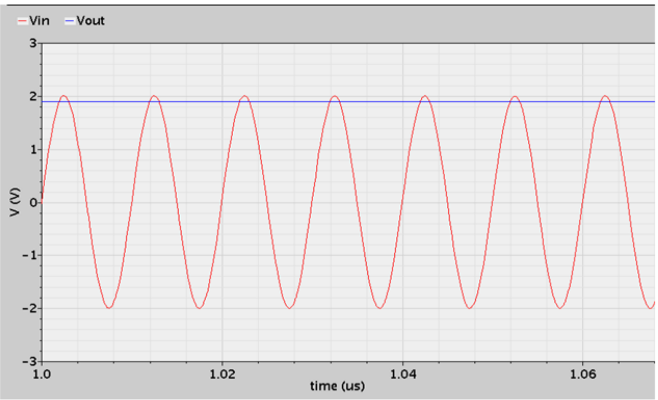
Fig. 7: Active bridge voltage doubler [9].

III. SIMULATION RESULTS

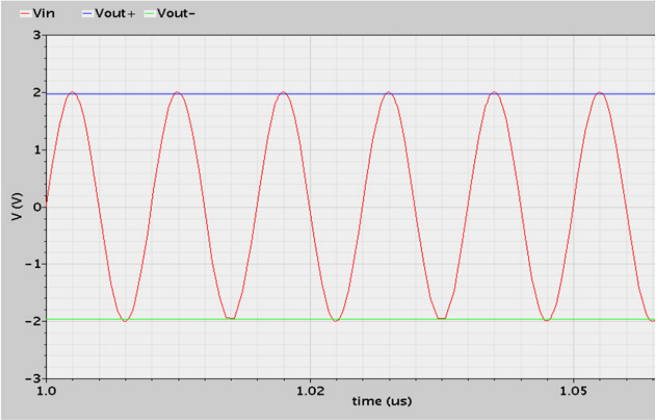
Negative voltage converter with active diode, cross-coupled active full bridge and active bridge voltage doubler are simulated by using Cadence Spectre and hardware -calibrated 130nm CMOS technology provided by UMC. The transient behaviors of the discussed AC-DC converters are shown in Figure 8.



(a)



(b)



(c)

Fig. 8: Transient behavior of discussed rectifiers (a) Negative voltage converter with active diode (b) Cross-coupled active full bridge (c) Active bridge voltage doubler

It is obvious that the active bridge voltage doubler circuit provides two output voltages (V_{out+}, V_{out-}) with a smaller voltage drop compared with other two AC-DC converters.

The power obtained at the output of the rectifier for the three AC-DC converters portrayed in Figure 9. The active bridge voltage doubler is able to provide 2X the amount of electrical power that was provided by the cross-coupled active full bridge and the negative voltage converter with active diode when a load resistance of 80kΩ load is used.

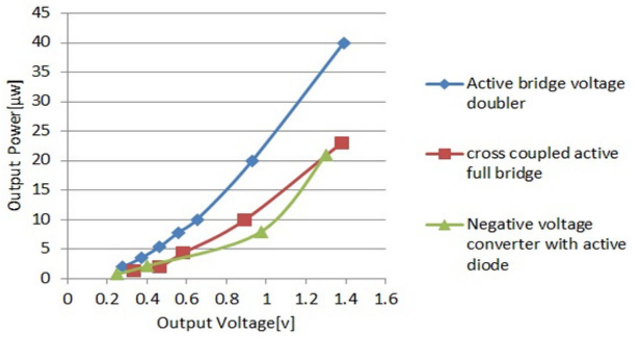


Fig. 9: Simulated power obtained at the output of the Negative voltage converter with active diode, Cross-coupled active full bridge and active bridge voltage doubler.

The voltage efficiency versus different input voltage amplitudes "unloaded" for the three AC-DC converters is shown in Figure 10. At an input voltage of 2.5V, the efficiencies of the active bridge voltage doubler, the cross-coupled active full bridge and the active bridge voltage doubler are 98.8%, 98.2%, and 85% respectively.

Figure 11 displays the voltage efficiency versus different input voltage amplitude with ohmic load 80kΩ for the three AC-DC converters. At an input voltage of 2.5V, the efficiencies of the active bridge voltage doubler, the cross-coupled active full bridge and the active bridge voltage doubler are 96%, 94%, and 84% respectively

Table I presents a comparison between the discussed AC-DC converters according to efficiency and area. Where (a): Negative voltage converter with active diode, (b): Cross-coupled active full bridge and (c): Active bridge voltage doubler.

TABLE I
COMPARISON BETWEEN THE DISCUSSED
AC-DC CONVERTERS

	η	**Area**
(a)	Low	1 comparator+1 switch+4 transistor (Small)
(b)	Moderate	2 comparator+2 switch+2 transistor (Large)
(c)	High	2 comparator+2 switch (Moderate)

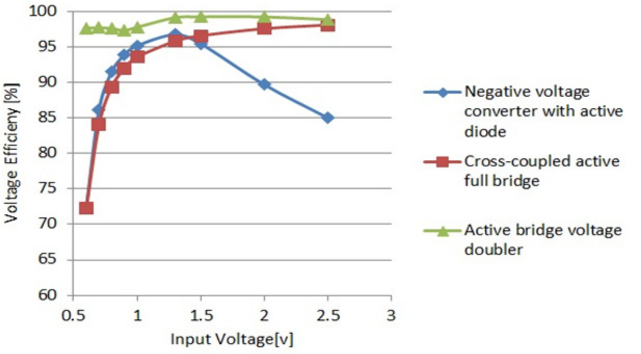


Fig. 10: Simulated voltage efficiency versus input voltage amplitude unloaded

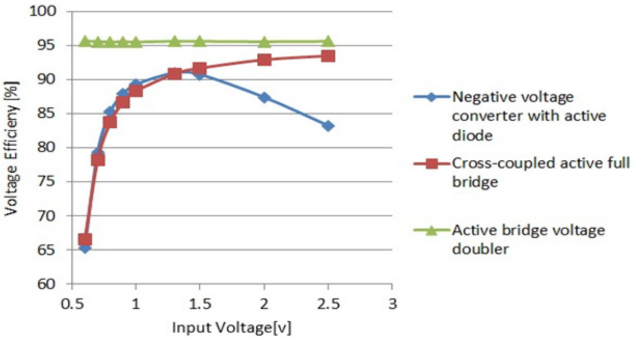


Fig. 11: Simulated voltage efficiency versus input voltage amplitude with 80KΩ ohmic load

It is obvious that the active bridge voltage doubler is the highest efficiency compared with other two AC-DC converters because the total voltage drop of the active bridge voltage doubler across only the PMOS switch, which is the smallest voltage drop compared with other two AC-DC converters. In additions, it provides two output voltages (V_{out+}, V_{out-}). On the other hand, the area of active bridge voltage doubler is a moderate area compared with other two AC-DC converters.

IV. CONCLUSION

This paper presented a survey about several commonly used active AC-DC converter circuits that is based on active diodes such as negative voltage converter with active diode, cross-coupled active full bridge and active bridge voltage doubler to perform signal rectification. Our study shows that the most efficient rectifying circuit among the surveyed AC-DC converter circuits is the active bridge voltage doubler. This is because it provides minimum voltage drop compared to other two AC-DC converter circuits. In additions, it provides 2X the amount of electrical power. Its voltage efficiency reaches 98.8% "unloaded" and reaches 96% with a load of 80KΩ.

V. ACKNOWLEDGEMENT

This research was partially funded by Cairo University, ITIDA, NTRA, NSERC, Zewail City of Science and Technology, AUC, the STDF, Intel, Mentor Graphics, SRC, ASRT and MCIT.

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