Hybrid Boost-SEPIC Converter with BLDC motor for Wearable Artificial Kidney

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Abstract

This work aims to implement a hybrid Boost-SEPIC converter fed brushless DC motor (BLDC) for continuous operation of blood pump in wearable artificial kidney. Wearable artificial kidney will help patients with end stage kidney disease to receive dialysis while undergoing everyday activity. In this paper, a hybrid Boost-SEPIC converter has been proposed and designed for BLDC motor drive. A comparative analysis of the proposed converter with its other counterparts has been presented. The proposed hybrid Boost-SEPIC converter fed BLDC drive has been simulated in MATLAB.

Keywords: DC-DC Converter; Artificial Kidney; Boost-SEPIC Converter; BLDC Motor; Wearable device

DOI Number: 10.14704/nq.2022.20.9.NQ44238 **Neuro Quantology 2022; 20(9):2058-2064**

1 Introduction

The renal System consists of two kidneys, ureters, bladder and urethra. The main purpose of the renal system is to remove waste from human body, regulate blood pressure and blood volume. It also helps to regulate blood electrolyte and maintain blood pH level. The kidney receives blood supply from renal arteries that leaves via renal vein, Miroslav Markovic (2013).

Renal failure is a medical condition in which kidneys fails to adequately filter waste products from the blood. Renal replacement therapy is a term used for life-supporting treatment for renal failure. The treatment can be of three types – Hemodialysis, Peritoneal Dialysis and Renal transplantation Miroslav Markovic (2013) - C. Vidhya1(2021).

Even today increased and prolonged dialysis is considered as a treatment for improving quality of life and longevity of end stage renal disease (ESRD). Though frequent dialysis is desirable as a treatment yet it is logically difficult. A wearable artificial kidney (WAK) provides practical solution and it may solve many issues. Research on WAK is going on since more than two decades. Ideal WAK would be wearable, comfortable and light weight. It would be highly efficient as it is expected to operate like a real kidney. In WAK, a blood pump is used to pass blood through tubes of the circulation tools. In standard renal treatment therapy lightweight miniature pumps are required to reduce complexity load of the entire circuit Donya Nias (2018) - Arunabha Mitra(2015).

Brushless DC Motor (BLDC) have been widely used in various medical applications like positive airways pressure (PAP) for Sleep Apnea treatment, in medical analyzer of human body fluid. BLDC motors are brushless motors and runs with low noise. Therefore, BLDC motors are appropriate for noise sensitive environment. The high efficiency and lower maintenance cost of Brushless DC motor makes it an attractive option to be used in Blood pump of WAK. Power converters plays a vital role in control of BLDC motor drives. Therefore, now-a-days advancement in research is being carried out for the BLDC motor drive and its control techniques for wearable artificial kidney blood pump Arunabha Mitra(2015)- K. I. Hwu (2014). In this paper, a hybrid Boost-SEPIC converter is presented for control of a BLDC motor. The proposed hybrid Boost-SEPIC converter fed

BLDC drive can be used for continuous operation of blood pump for WAK.

2 Wearable Artificial Kidney

Principle of operation

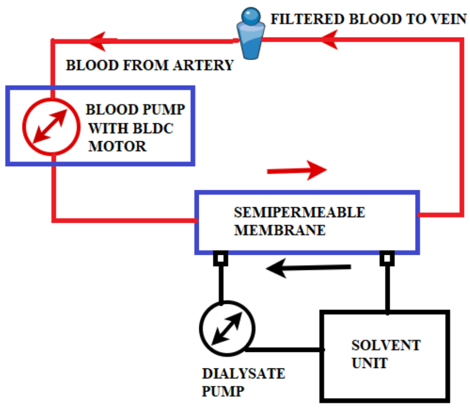
The operating principle of a wearable artificial kidney is presented in figure 1(a). It is a dialysis machine in which human blood is continuously circulated through a membrane using a blood pump and returned back to the human body. The opposite side of the membrane is washed with an electrolyte solution. The flow of water and waste from blood is carried out by two mechanisms of diffusion and convection. A dialysate pump is used to circulate the dialysate. The wastes are removed from the dialysate by using a filter Miroslav Markovic (2013) - Paolo Armignacco(2015).

Blood pump

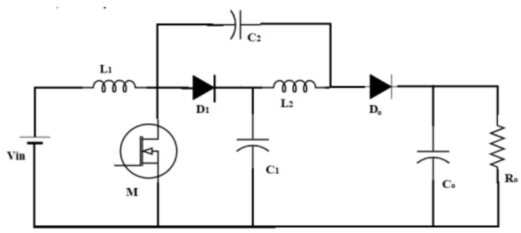
Blood is a complicated fluid. It comprises of red blood corpuscles (RBC), which consists of hemoglobin. The hemoglobin may get damaged by mechanical force, sudden changes in temperature and pressure. Therefore, design of blood pump needs to done carefully. Firstly, the temperature of the pump should not exceed 45°C. Destruction of RBS is called hemolysis. Normalized index of hemolysis (NIH) is a medical measure of concentration of hemoglobin in blood. 100mg per 100L of pumped blood is the critical measure of NIH, which should not be exceeded. The mean blood pressure in arteries are100mmHg in veins are 40mmHg respectively. The membrane for dialysis will exert opposition to blood flow, which will result in pressure drop. The blood pump should be designed to compensate the pressure drop and maintain appropriate blood pressure. Also, thrombosis (formation of blood clot) is another concern. If blood remains immovable during a short period, there is an involved risk of thrombosis Miroslav Markovic (2013), M. Lakshmi (2018), Farhan Mumtaz (2021). The blood pump must be designed taking all the above points into consideration. Another important feature is pump must be blood tight, which means no blood leakage or air bubble formation should be there.

Brushless DC motor for blood pump

BLDC motor can be used in a peristaltic pump or rotary pump. A peristaltic pump is a type of positive displacement pump used in hemodialysis. Peristaltic pump comes with BLDC motor at the pump head, which enables the pump to work smoothly and efficiently. Rotary pumps are most commonly used in hemodialysis. BLDC motor have better life expectancy than its other counterpart due to the absence of brushes. Also, BLDC motor helps to transfer heat away from the motor, which helps the pump to run cool at difficult environment. BLDC motors offers larger torque and higher operating speed range. Most importantly, BLDC motors are good for noise sensitive environment Paolo Armignacco (2015), Mauricio Dalla Vecchia (2018).



(a)



(b)

Figure 1. (a) Block Diagram representation of Wearable artificial kidney (b) Hybrid Boost-SEPIC Converter

3 Hybrid Boost-SEPIC Converter

The DC-DC converter plays an important role in determining the performance of the motor. For a BLDC motor, DC-DC converter provides the switched mode regulation which in turn feeds the voltage source inverter. A DC- DC converter is one which provides regulated DC output from an unregulated DC input. The DC-DC converter helps in speed regulation of the motor by controlling the DC link voltage Mauricio Dalla Vecchia (2018) - M. Nilanjan (2016).

Hybrid Boost-SEPIC (HBS) is a combination of boost and SEPIC converter comprising of a single switch. The circuit diagram of the HBS converter is presented in figure 1(b). The operation of hybrid boost-SEPIC converter is divided into two modes – continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The Continuous conduction mode is again divided into two modes based upon the switching condition of the MOSFET (M).

When the MOSFET is turned on, diodes D1 and Do are in reverse biased condition. The inductors L1 and L2 magnetizes and stores energy. The maximum voltage across the two diodes and the MOSFET is equal to the voltage across the capacitor C1. The output voltage is equal to the sum of the voltages across both the capacitors

When the MOSFET is off, the energy stored in the inductor L1 is transferred to the output through the capacitor C2 and output diode Do and also is transferred to the C1 through D1. The energy stored in the inductor L2 is transferred to the output through the diode Do. Applying voltage second balance across inductor L1 and L2, we get equation (1)

$$\frac{V_o}{V_{in}} = \frac{1+D}{1-D} \tag{1}$$

4 Design consideration of the proposed converter

Inductance (L1 and L2): Here, the inductor L1 and L2 are considered equal. The current ripple (△iL) value of the inductor L1 and L2, can be considered same for both the inductor. The inductance can be calculated using the equation (2).

$$L_1 = L_2 = \frac{V_{in}DT}{\Delta i_L} \tag{2}$$

Critical value of inductance: The selection of the inductance not only depends on the duty ratio, switching frequency and the load, but also on the critical value of inductance. The critical value of inductance (Lx) can be determined from equation (3)

$$L_X = \frac{D(1-D)^2 RT}{2(1+\mathrm{D})^2} \tag{3}$$

For, continuous conduction, the inductance must be selected greater than the critical value of inductance.

Capacitance (C1 and C2): The value of the capacitance can be calculated using the charge variations of the capacitor. Considering the capacitor voltage ripple △Vc to be 10% of the nominal voltage of the capacitor C1. The value of the capacitance is calculated by equation (4).

$$C_1 = C_2 = \frac{I_o T}{\Delta V_c} \tag{4}$$

Table 1

Parameters used for Circuit Design

Parameter	Value
Inductor (L1)	64µH
Inductor (L2)	64µH
Capacitor (C1)	0.3µF
Capacitor (C2)	15µF
Capacitor (C0)	15µF
Resistor (R0)	350Ω
Duty Ratio (D)	0.8
Frequency	50kHz

Table 2

Comparative analysis of proposed converter with SEPIC converter

Parameter	Proposed converter	SEPIC
Total Harmonic Distortion	14.72%	27.10%
Rise Time	281.06usec	658.759
Settling time	1.484msec	9.1msec
Overshoot	10.56%	44.20%
Undershoot	0.61%	0.04%
Voltage Gain	7.3	5.1

5 Results and Discussion

The Proposed hybrid boost-SEPIC converter has been designed using MATLAB using the parameters mentioned in table 1. For analyzing the converter performance, the proposed converter has been compared with conventional SEPIC converter. The comparative analysis on different performance parameters of the proposed converter with SEPIC converter has been presented in table 2. The proposed hybrid boost-SEPIC converter has also been compared with other similar converters available in literature M. R. Banaei (2018) - Y. Tang (2014). The comparative analysis has been presented in the table 3.

Table 3

Comparative analysis of the proposed converter with similar converter

Converter Topologies	Numbers L	S	D	C	Gain (CCM)	Vs
[7]	4	1	3	6	3D/(1-D)	Vo/2
[8]	1	1	4	4	(3-D)/(1-D)	Vo/(3-D)
[9]	1	1	3	3	2/(1-D)	Vo/2
[10]	2	2	3	3	(2+D)/(1-D)	Vo/(2+D)
Proposed	2	1	2	2	(1+D)/(1-D)	Vo/(1+D)

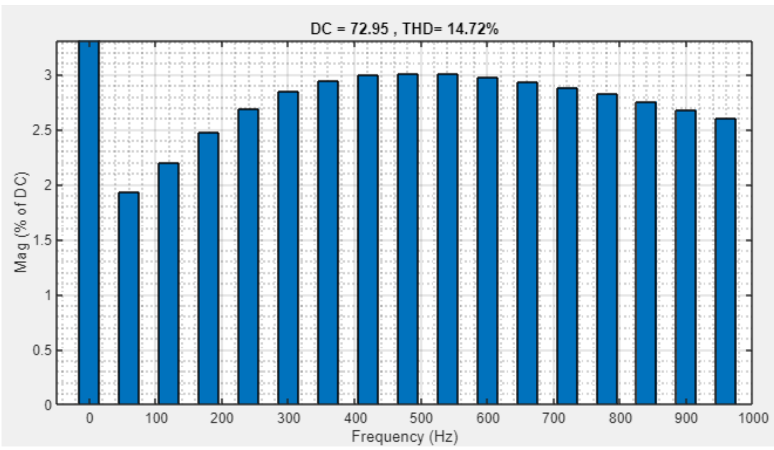


Figure 2. FFT analysis of the output voltage of the proposed converter

The Fast Fourier Transform (FFT) analysis has been done on the output voltage of the proposed converter. The FFT analysis has been presented in the figure 4. The voltage across the MOSFET has been presented in the figure 5. The current through the inductor L1 and L2 has been shown in the figure 6 and 7 respectively. The voltage across the capacitor C1 and C2 has been presented in the figure 8 and 9 respectively.

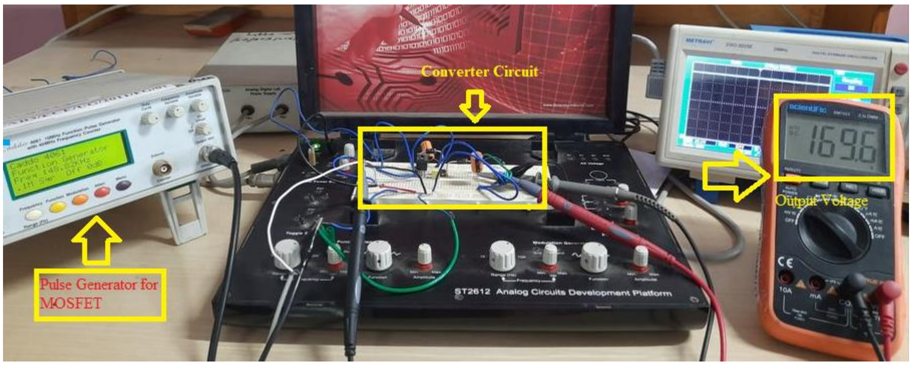
The maximum voltage across the switch is equal to the voltage across the capacitor C1. Therefore, voltage across the switch is lower than the output voltage which results in lower voltage stress across the switch.

Hardware Design

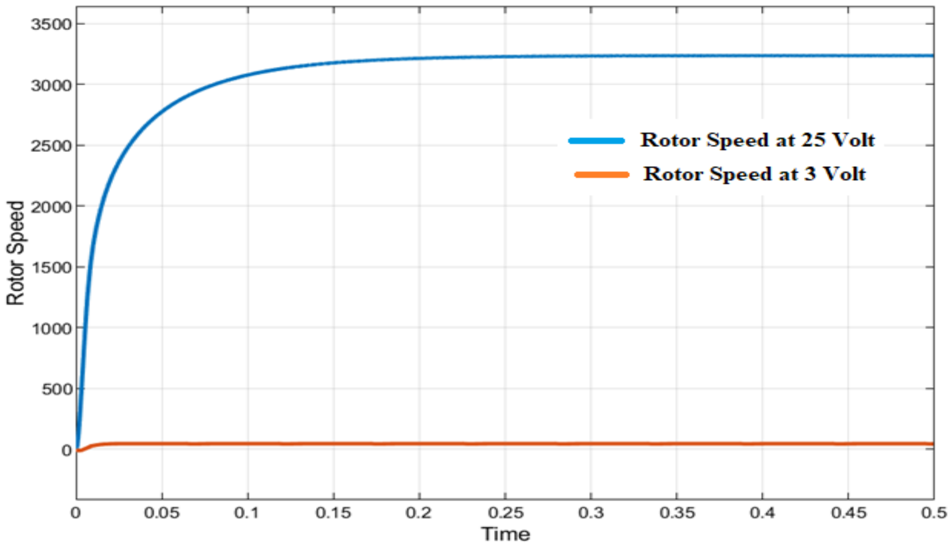
The proposed circuit has been designed in the laboratory. Figure 3(a) shows the hardware setup of the experiment conducted for the proposed converter. The output voltage obtained with 0.82 duty ratio for an input of 20 Volt was 169.6 Volt. The voltage across the MOSFET was 94 Volt (approx.).

Hybrid Boost-SEPIC Converter fed BLDC drive

The Hybrid Boost-SEPIC converter fed BLDC motor for artificial wearable kidney has been designed using MATLAB Simulink. The simulation has been presented in the figure 4. The proposed drive for blood pump offers wide range of speed control with a single switch. As the number of switches used is less, the control circuit involved in the drive circuit has also been reduced. Figure 3(b) shows the rotor speed at two different input voltage.



(a)



(b)

Figure 3. (a) Hardware design of the proposed converter(b) Rotor Speed of BLDC Motor

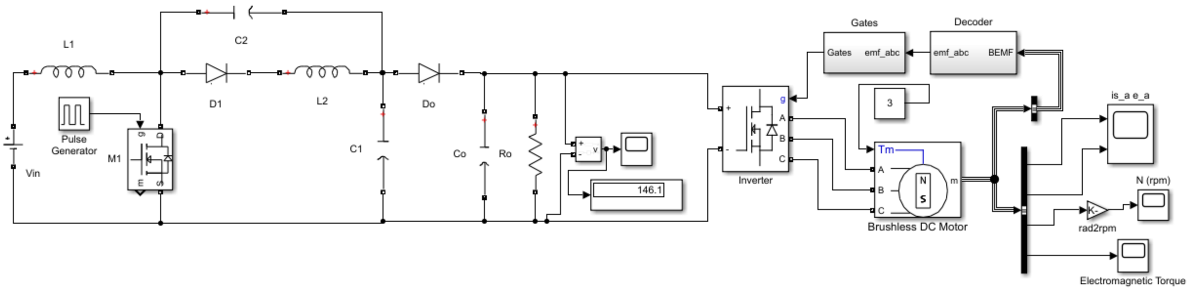


Figure 4. Hybrid Boost-SEPIC converter fed BLDC motor

For a blood flow rate of 350ml/min with a 15-gauge needle having radius of 0.0004cm, the motor for the blood pump is expected to rotate at a speed of 135rpm. From the figure 3(b), we can say that the proposed BLDC motor drive can offer the required constant speed operation for the pump with a minimal input voltage of 5 Volt.

6 Conclusion

It has been observed that the proposed hybrid Boost-SEPIC converter topology offers higher gain with minimum voltage stress across the switch. Also, from table 3, we can say, the number of components used for the converter design is minimum as compared to other Boost-SEPIC converter present in the literature. The proposed converter has been simulated in MATLAB and also designed in hardware. From the table 2, it can be said that the proposed converter offers less THD, with lesser settling time and rise time as compared to SEPIC converter. Here, BLDC motor has been fed with the proposed converter. The proposed BLDC drive has been simulated in MATLAB. The proposed drive offers a constant speed with a range of 50 rpm to 3000 rpm for an input voltage of 3 Volt to 25 Volt. Based on the higher efficiency and life expectancy of BLDC motor and observations of drive performance, it can be concluded that the drive is a suitable option for continuous operation in blood pump of the artificial wearable kidney.

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