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A Non-isolated Modified Zeta Converter-fed DC Motor under Load Condition

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HIGHLIGHTS

- Use of boost power stage ensures improved voltage gain for the existing Zeta converter.
- The proposed Zeta topology produces high voltage gain at low duty ratio itself.
- Low voltage stress is observed on both power switches.
- Characteristics of the DC motor-generator set are obtained by duty ratio adjustment.

Abstract: In this paper, the steady state performance characteristics of a separately excited DC motor fed by a non-isolated positive output DC-DC converter of high voltage gain Zeta topology are presented. The suggested Zeta converter configuration energized by a DC source is operated in continuous inductor current mode. The DC motor is mechanically coupled with a DC generator. The armature voltage and hence the speed of the motor is controlled by varying the duty ratio (k) of the converter for the given converter input voltage and generator-side load resistance. The proposed DC motor speed control scheme is simulated in MATLAB/SIMULINK platform for performance validation. The various performance measures such as torque, speed, armature current, armature voltage, load current, and efficiency for the motor-generator set are explored. The comparison of voltage gain of existing Zeta topologies and the voltage stress calculation are also illustrated.

Keywords: Continuous inductor current mode; DC motor-generator set; Duty ratio; MATLAB/SIMULINK; Performance characteristics; Zeta topology.

INTRODUCTION

Recently, DC-DC converters are found to play significant role for regulating the lower input voltage delivered by renewable energy sources. The two categories of DC-DC conversion topologies are isolated and non-isolated configurations respectively [1]. Even though the isolated structures can generate regulated DC output voltage for wide range of DC input voltages, it has certain limitations such as surges developed across the power switches, effect of leakage flux, undesirable magnetic core saturation, and increased cost due to large size [2]. The non-isolated structures too have certain disadvantages like increased switching losses due to converter operation nearer to unity duty cycle ratio and poor voltage conversion ratio. Further, the addition of switches and passive components may improve the voltage gain. Hence, both the topologies have their own merits and demerits. The application requirements dictate the choice of particular converter structure [3]-[4].

The positive output Zeta converter is a non-isolated DC-DC converter capable to produce a wide range of regulated DC output voltages from unregulated DC input voltages. It can be operated at both buck and boost modes with varying duty cycle ratio and switching frequencies [5]. It is a high-efficiency converter with continuous output current suitable for renewable energy based power generation and Electric Vehicle (EV) applications that require quick response times due to its significant advantage that it has lower amount of ripples present in the output voltage compared to that of non-isolated SEPIC (Single ended primary inductor converter) [6]-[8].

A highly efficient non-coupled inductor-based hybrid Zeta converter with features of reduced components and continuous input current is proposed in [9] that can achieve high voltage gain at low duty cycle. A new non-isolated single switch Zeta converter with high voltage gain and low switch voltage stress is proposed in [10]. This converter has the capability to operate in both buck and boost configurations with simple control technique. Further, the converter has continuous output current and reduced switching losses.

Due to the above advantages of Zeta converter, it finds applications for controlling the speed of a sensorless control technique based PMBLDC motor and power factor correction on the AC side [11], in which the closed loop operation of the converter operating in continuous inductor current mode helps to achieve wide range of motor speed control by appropriate variation of DC link capacitor voltage. In [12], a step-up-down DC-DC converter is analyzed for DC motor speed control. The DC drive model, steady state behaviour, feed forward control features, and experimental results are presented in [12].

Some authors suggested BLDC motors for control of Electric Vehicles fed by bidirectional DC-DC converters [13]. Both simulation and prototype model results are presented to validate the effectiveness of the converter. The features of the work described in [13] include reduced number of power devices and passive components, and efficient converter operation. In [14], a Chopper is used as converter of Zeta topology for wide range of speed control up to rated speed of a separately excited DC motor. The speed controller is implemented using conventional PI (Proportional + Integral) type in view of obtaining reduced steady state error and fast settlement of motor speed.

The comparative performance analysis of KY converter and four quadrant converter fed BLDC motor is presented in [15]. Both the converters are operated at duty ratio of 0.5. The authors proved that the KY converter exhibits better performance in terms of improved electromagnetic torque and low Total Harmonic Distortion (THD) at low duty ratio itself. The authors of [16] summarized the working principles, advantages, limitations, and applications of various AC-DC and DC-DC converter topologies suitable for speed control of DC motor drives.

A robust adaptive intelligent controller is employed to vary the armature voltage of a DC motor fed by a DC-DC converter, by adjusting the duty ratio of the converter [17]. The armature voltage variation causes the motor speed regulation. The simulation and the prototype model results are presented in [17] to validate the performance of the controller. As DC motors find applications in many industries, their speed control is viewed as an important issue. The speed of a DC motor can be varied either by field flux control method or by armature voltage control method. The work presented in this paper explores the armature voltage method of speed control scheme for a Zeta converter-fed DC motor under load condition. The speed regulation of the motor is achieved by variation of motor armature voltage due to change in duty cycle ratio of the converter. The various performance characteristics such as electromagnetic torque, speed, load current, and efficiency of the motor-generator set are measured and plotted with respect to duty ratio (k) of the power switch.

The proposed work is organized as follows: The following Section presents a brief report on Zeta converter and speed control scheme of DC motor. The proposed high gain Zeta converter-fed DC motor is simulated in MATLAB/SIMULINK platform and the performance characteristics are discussed in next Section. The features of the proposed research work are summarized in the conclusion section.

The proposed high gain zeta converter-fed dc motor: speed control scheme

In this research work, a modified Zeta converter with high voltage gain is proposed. The proposed converter is capable of providing high voltage gain at low duty ratio itself. The performance characteristics of a DC motor fed by the converter are measured at different duty ratios (k) by means of MATLAB/SIMULINK tool.

High gain Zeta Converter topology:

A separately excited DC motor coupled with a DC generator is fed by a non-isolated positive output DC-DC converter of Zeta topology as shown in Figure 1. In the proposed research work, the load resistor ‘R’ is replaced by a DC motor loaded with DC generator. The operation of the Zeta converter is briefly explained in this section [11] and the motor speed control scheme is presented in next section.

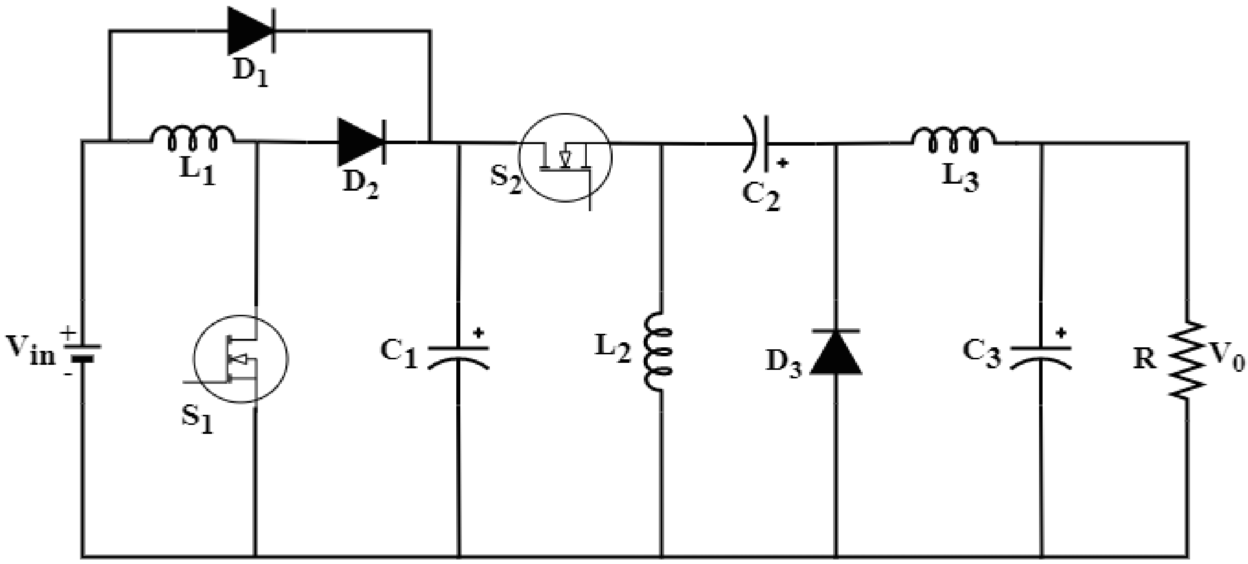

Figure 1. Power circuit diagram of Zeta converter-fed Separately excited DC motor coupled with DC generator

The working of the Zeta converter topology in continuous conduction mode (CCM) is explained in this section. The Zeta configuration can act as buck-boost converter based on duty ratio (k). To achieve higher output voltage, ‘k’ must be greater than 0.5. The converter is operated in three modes: Mode-I: Switches S1 and S2 are turned ON, Mode-II: Switches S1 and S2 are turned OFF, and Mode-III: Switch S1 is turned OFF and S2 is turned ON.

In mode-I operation, the switches S_1 and S_2 are turned ON and the input supply (V_{in}) energizes the input inductor L_1. The diode D_1 is forward biased. The diodes D_2 and D_3 get reverse biased. The capacitor C_1 transfers the energy directly to the inductor L_2 and capacitor C_2 charges the inductor L_3. The motor current is supplied by the output capacitor C_3. The converter output voltage (V_0) is applied as input voltage (V_{am}) across the motor armature. The equivalent circuit of the converter during mode-I is given in Figure 2. The voltages across the inductors are represented as Equation (1) as shown below:

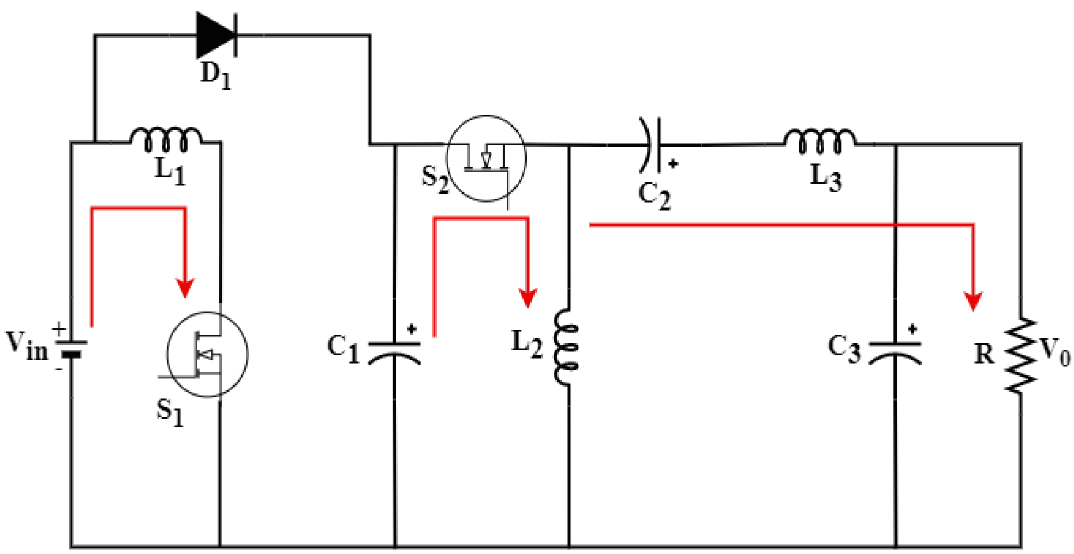

Figure 2. Equivalent circuit of the converter during Mode-I

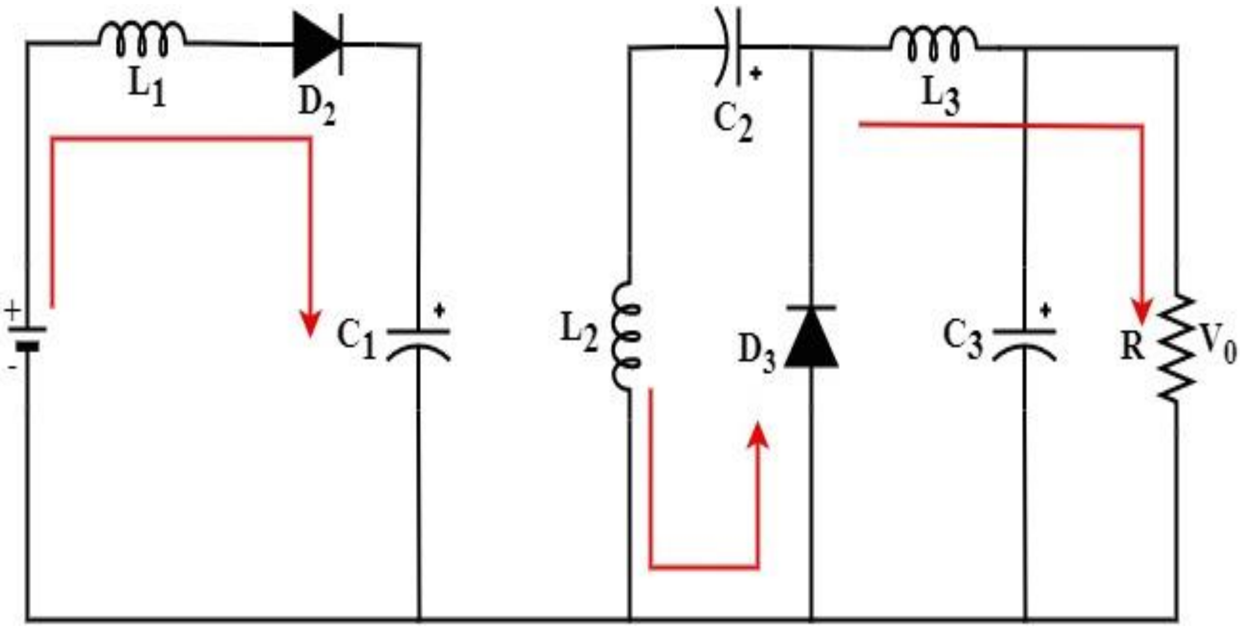

Figure 3. Equivalent circuit of the converter during Mode-II

$$\left.\begin{aligned} V_{L1} &= V_{in} \\ V_{L2} &= V_{C1} \\ V_{L3} &= V_{C2} + V_{in} - V_0 \end{aligned}\right\} \qquad (1)$$

During mode-II operation, both switches are turned OFF. The diode D_1 is reverse biased. The diodes D_2 and D_3 are forward biased. The inductor L_1 discharges and hence energizes the capacitor C_1. The inductor L_2 charges the capacitor C_2 and the inductor L_3 discharges its energy through the motor armature. The equivalent circuit of the converter during mode-II is shown in Figure 3. The Equation (2) represents the inductor voltages during mode-II. Then the volt-second balance principle is applied to the three inductors using Equations (1) and (2) to derive the voltage gain (G_{CCM}) Equation (4) for the proposed high gain Zeta topology. The Equation (4) indicates that the low duty cycle ratio itself can produce higher output voltage V_0.

$$\left.\begin{aligned} V_{L1} &= V_{in} - V_{C1} \\ V_{L2} &= -V_{C2} \\ V_{L3} &= -V_0 \end{aligned}\right\} \qquad (2)$$

During mode-III operation, the switch S_1 is turned OFF and the switch S_2 is turned ON. The diode D_2 is forward biased. The diodes D_1 and D_3 are reverse biased. The inductor L_1 discharges and hence energizes the capacitor C_1 and the inductor L_2. The inductor L_3 discharges its energy through the motor armature. The Equation (3) represents the inductor voltages during mode-III. Figure 4 illustrates the equivalent circuit.

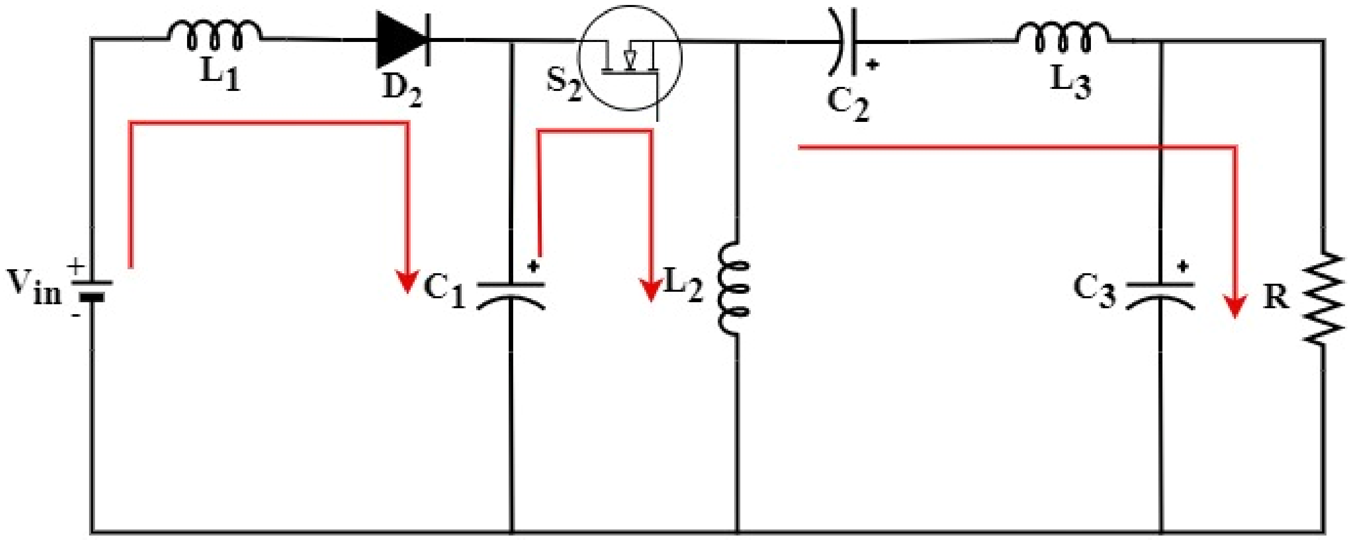

Figure 4. Equivalent circuit of the converter during Mode-III

$$\left.\begin{aligned} V_{L1} &= V_{in} - V_{C1} \\ V_{L2} &= V_{C2} \\ V_{L3} &= V_{C2} + V_{C1} - V_0 \end{aligned}\right\} \quad (3)$$

$$G_{CCM} = \frac{V_0}{V_{in}} = \frac{k(k^2 - 2k + 2)}{(1-k)^2} \quad (4)$$

The above voltage gain (G_{CCM}) of the proposed converter is compared with that of existing Zeta topologies [3, 10, 18] as shown in Figure 5. It illustrates that the proposed Zeta converter structure shows enhanced voltage gain at low duty ratio (k) itself compared to the other existing Zeta topologies. Moreover, low voltage stress is observed on both the power switches.

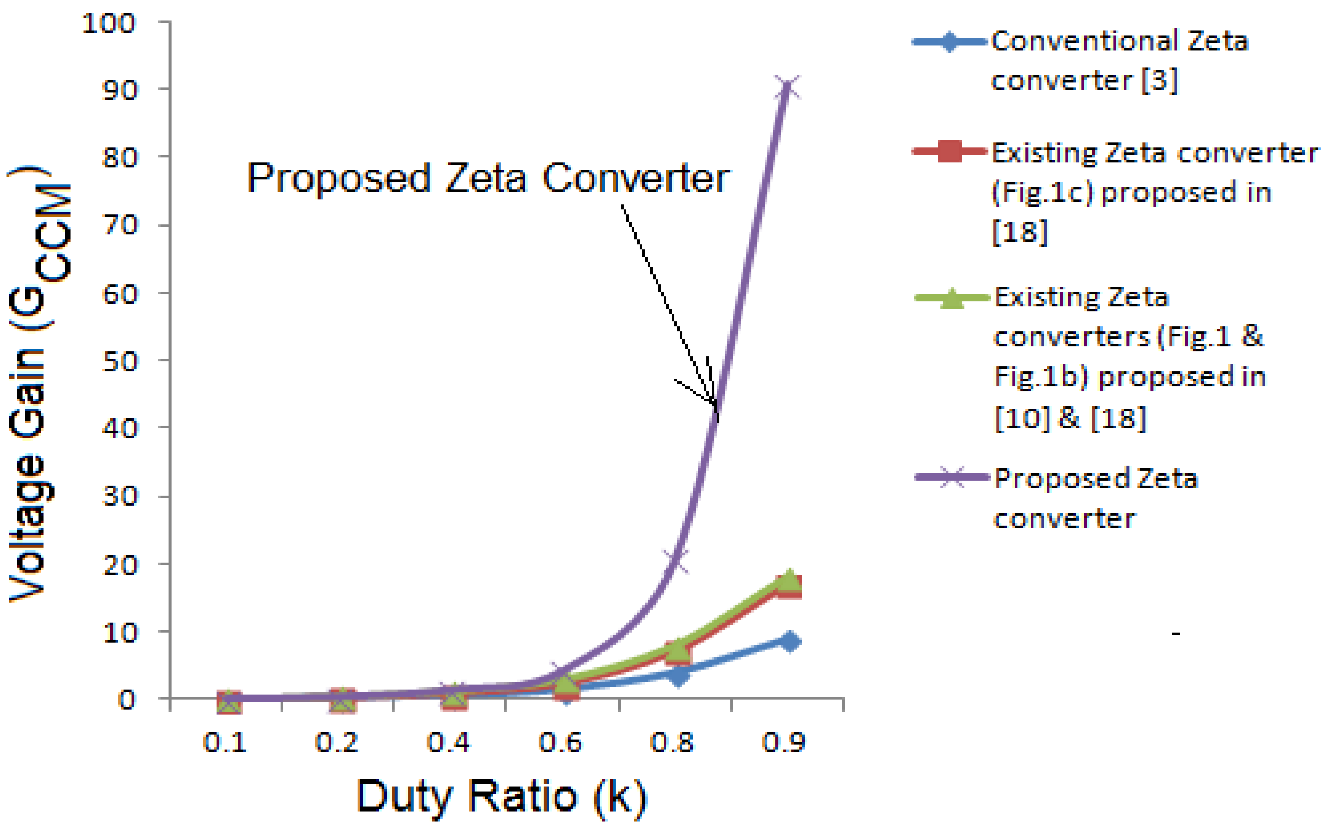

Figure 5. Comparison of proposed Zeta converter with other Zeta topologies

Voltage stress calculation of the proposed converter topology:

Assuming the duty ratio k = 0.7 and the input voltage V_{in} = 60 V, the voltage stresses across the power switches S_1 and S_2, and the diodes D_1, D_2, and D_3 are calculated as follows:

Voltage stress across the Switch S_1 = V_{S1} = V_{C1} = $\frac{V_{in}}{1-k} = \frac{60}{1-0.7} = 200V$

Voltage stress across the Switch S_2 = V_{S2} = V_{C1} + V_{C2} = $\frac{V_{in}}{1-k} + \frac{V_{in}k}{(1-k)^2} = 60\left(\frac{1}{1-0.7} + \frac{0.7}{(1-0.7)^2}\right)$ = 666.7 V

Voltage stress across the diode D_1 = V_{D1} = $-V_{L1} = V_{C1} - V_{in} = 200 - 60 = 140\,\mathrm{V}$

Voltage stress across the diode D_2 = V_{D2} = $-V_{C1} = -200\,\mathrm{V}$

Voltage stress across the diode D_3 = V_{D3} = $V_{C1} + V_{C2} = 200 + 466.7 = 666.7\,\mathrm{V}$

Speed control scheme of the proposed Zeta converter-fed DC Motor:

There are two important methods of speed control scheme for a DC motor; (i). Field flux control, and (ii). Armature voltage control respectively. In the proposed work, as field windings of both the motor and the generator are energized by constant DC voltage sources, the speed of the motor and hence that of generator can be controlled by varying the motor armature voltage (V_{am}). The duty cycle ratio (k) is in turn adjusted to get variable motor armature voltage for a fixed DC input voltage (V_{in}). The low duty ratio k = 0.6 is responsible for producing approximately the rated voltage of the motor. The coupled DC generator with a load resistor 'R' is acting as load for the motor.

SIMULATION RESULTS AND DISCUSSION

The proposed high gain Zeta converter-fed DC motor speed control scheme is simulated using MATLAB/SIMULINK software tool as illustrated in Figure 6. The simulation model is developed using the Simulink library and 'ode15s' solver is used for simulation with stop time of 5 sec. The switching frequency of the converter is chosen as 50 kHz. The converter DC input voltage (V_{in}) is 60 V. Table 1 shows the values of circuit parameters of proposed converter. Table 2 summarizes the specifications of separately excited DC motor. Table 3 illustrates the performance characteristics of DC motor-generator set for the optimum value of load resistor R = 100 Ω. The range of duty cycle ratio (k) is selected as $0.5<k<0.8$ for obtaining the performance characteristics of the motor-generator set. The gate pulse waveforms, converter input and output voltages are shown in Figure 7, Figure 8 and Figure 9 respectively. As the duty ratio 'k' is varied in the above range, the converter output voltage (V_0) and hence the motor armature voltage (V_{am}) are varying according to equation (3) with the fixed DC input voltage (V_{in}) of 60 V. Thus, the motor armature voltage variation causes the changes in speed (ω) of the motor and hence that of generator. The speed (ω) and electromagnetic torque (T) characteristics of the motor are plotted with respect to time for different values of duty ratio (k) as shown in Figure 10 and Figure 11. The variations of motor armature voltage and hence the armature current with duty ratio (k) as the independent variable are shown in Figure 12 and Figure 13. As the speed of the motor is variable, the induced EMF in the generator armature winding is also varying with duty ratio. This variation of EMF causes the changes in generator output current (load current) with duty ratio as shown in Figure 14. The efficiency characteristic of the motor-generator set is plotted with respect to generator output power as shown in Figure15.

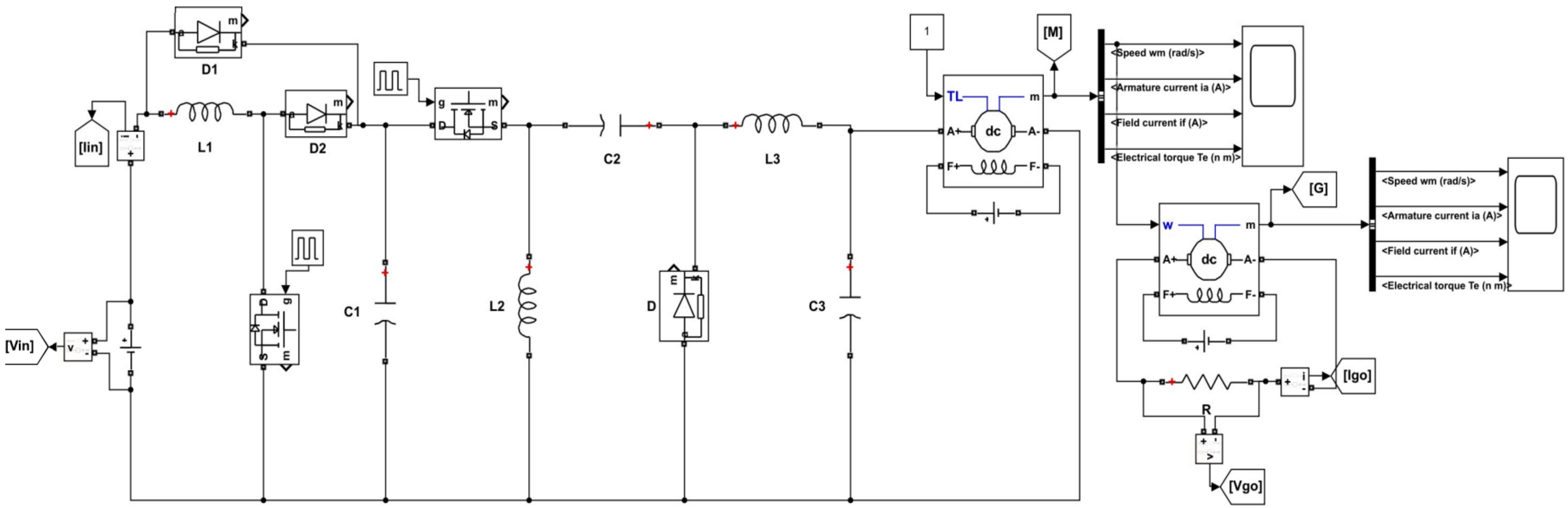

Figure 6. Simulation model of Zeta converter-fed Separately excited DC motor coupled with DC generator

Table 1. Converter circuit Parameters

Parameters	Symbol	Value
Converter Input voltage	V_{in}	60 V (DC)
Inductors	L_1, L_2, L_3	0.45 mH each
Capacitors	C_1, C_2	1.7 µF each
Capacitor	C_3	100 µF
Switching frequency	f_s	50 kHz
Duty ratio of the switch	D	0.4 - 0.8

Table 2. DC motor specifications

Parameters	Symbol	Value
Power rating	P_m	5 HP
Armature voltage	V_{am}	240 V
Field winding voltage	V_f	150 V
Speed	N	1750 rpm

Table 3. Performance characteristics of the DC motor-generator set

Motor performance characteristics						Generator performance characteristics						
Duty ratio, k	Input voltage, V_{min} (V)	Speed, ω_m (rad/sec)	Armature current, I_{ma} (A)	Field current, I_{mf} (A)	Torque, T_{me} (N-m)	Speed, ω_{gm} (rad/sec)	Armature current, I_{ga} (A)	Field current, I_{gf} (A)	Torque, T_{ge} (N-m)	Generator output voltage, V_{go} (V)	Generator output current, I_{go} (A)	M-G (Motor-Generator) set efficiency, η (%)
0.4	109.6	87.89	1.523	1	1.879	87.89	0.866	1.066	0.876	86.65	0.8665	45.01
0.5	117.2	94.29	1.57	1	1.937	94.29	0.929	1.066	0.940	92.96	0.9296	46.96
0.6	219.8	176.7	2.196	1	2.71	176.7	1.744	1.066	1.764	174.4	1.744	63.02
0.7	433	348.8	3.757	1	4.637	348.8	3.439	1.066	3.478	343.9	3.439	72.71
0.75	637.1	512.8	5.06	1	6.244	512.8	5.055	1.066	5.113	505.3	5.055	79.28
0.8	917.1	737.8	6.942	1	8.567	737.8	7.274	1.066	7.356	727.4	7.274	83.1

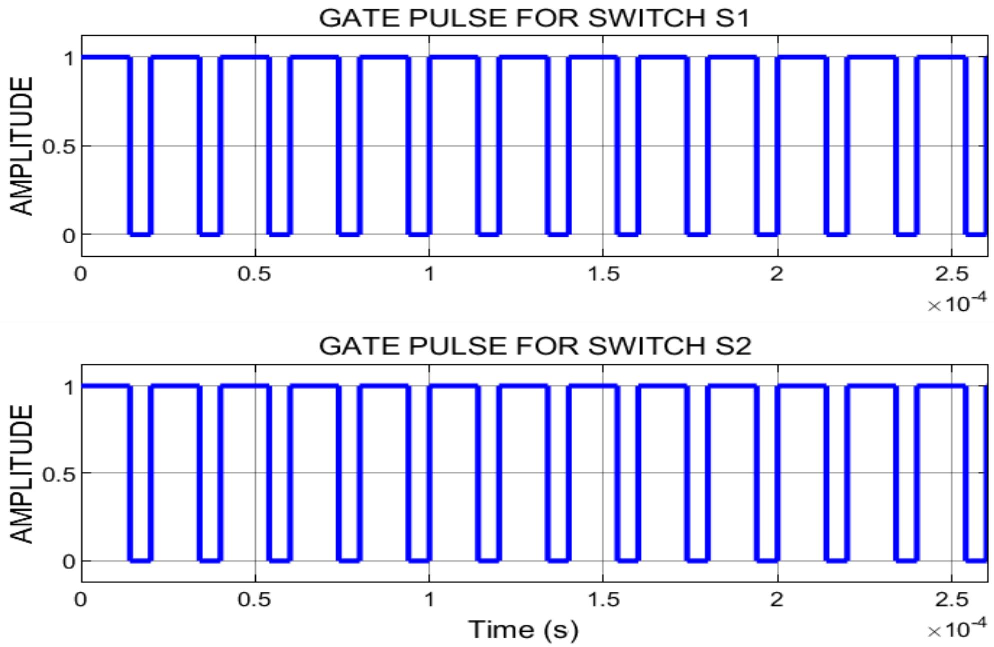

Figure 7. Gate pulse waveforms for the switches S_1 and S_2

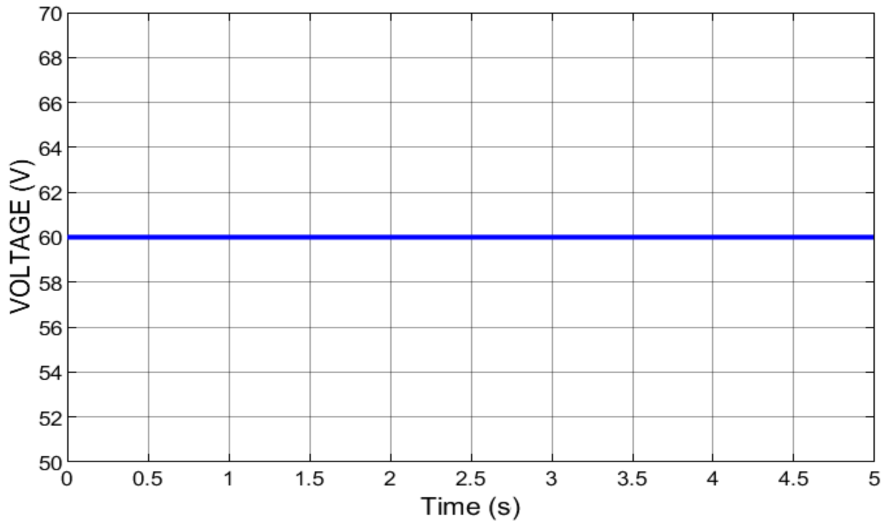

Figure 8. Converter Input voltage (V_{in})

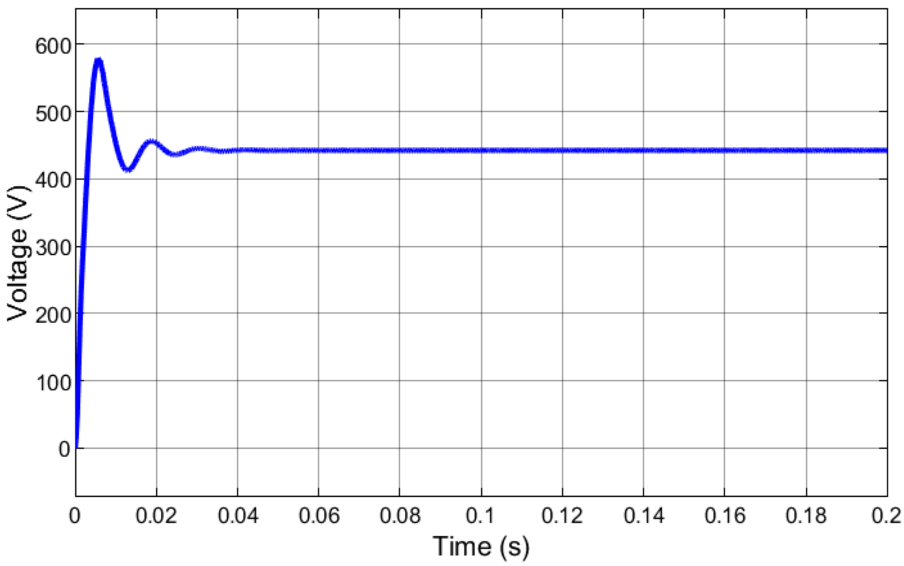

Figure 9. Converter Output voltage (V_0)

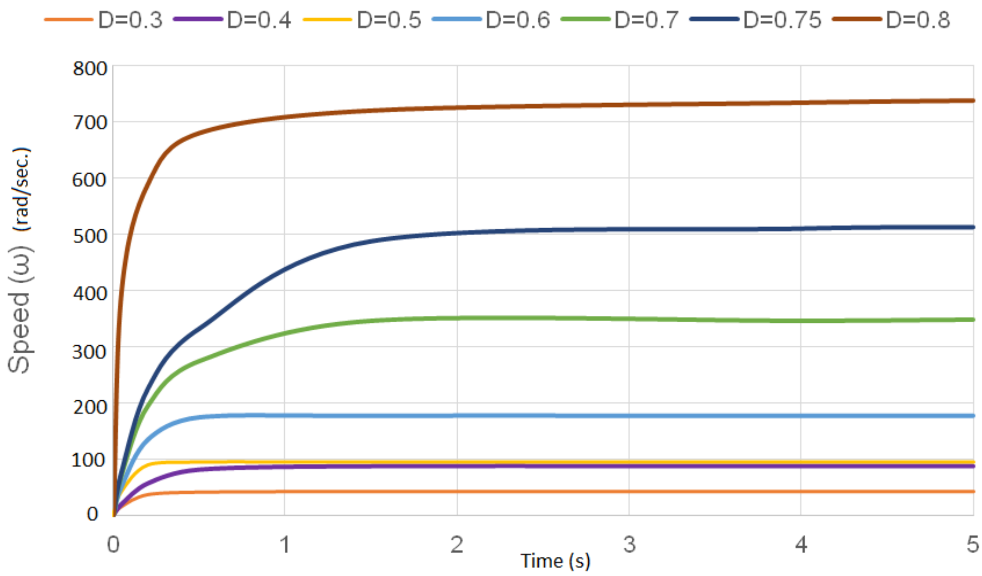

Figure 10. Variation of motor speed (rad/sec) with duty ratio (k)

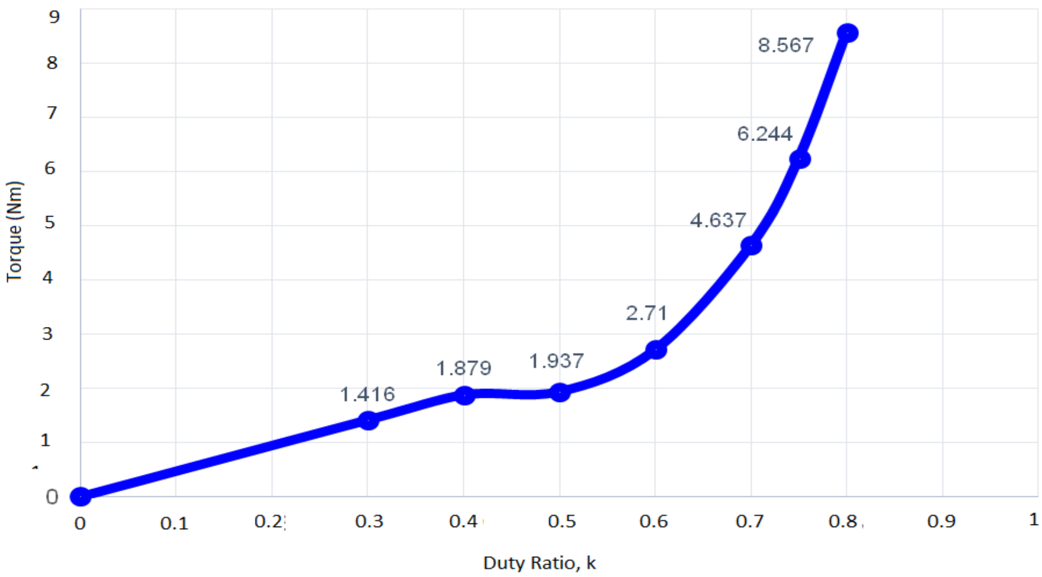

Figure 11. Variation of motor torque (Nm) with duty ratio (k)

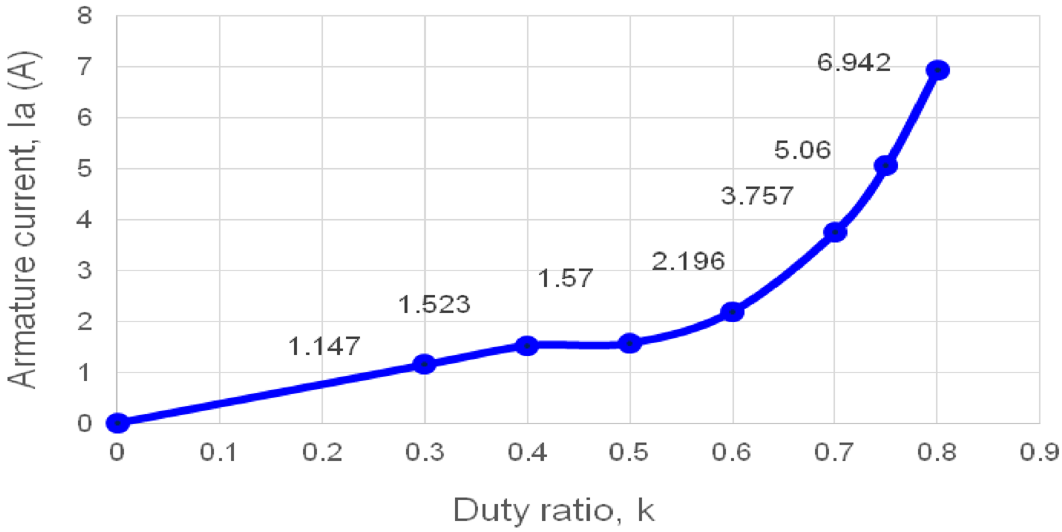

Figure 12. Variation of motor armature current with duty ratio (k)

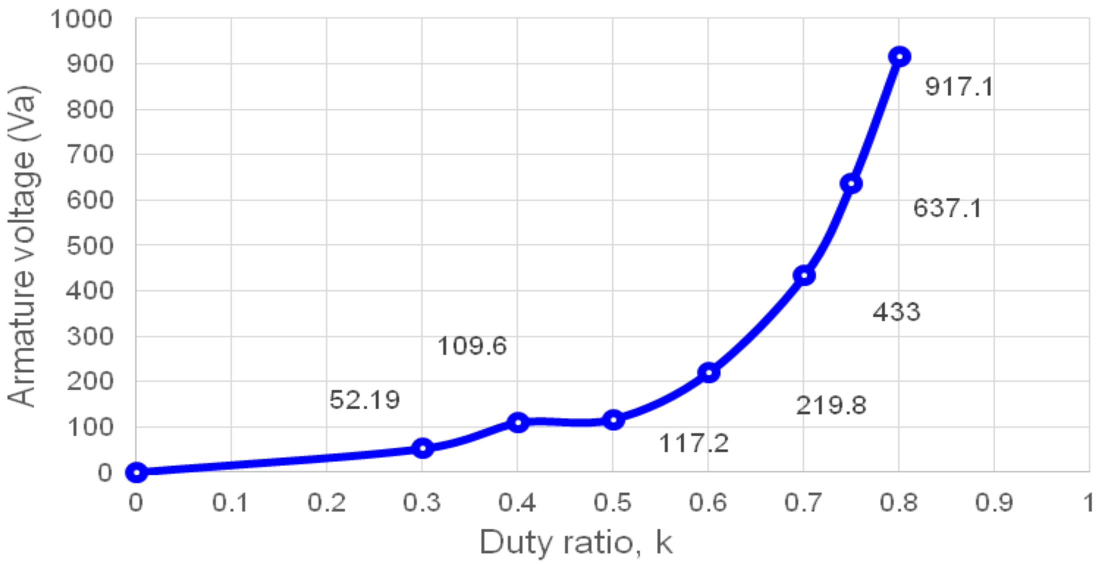

Figure 13. Variation of motor armature voltage with duty ratio (k)

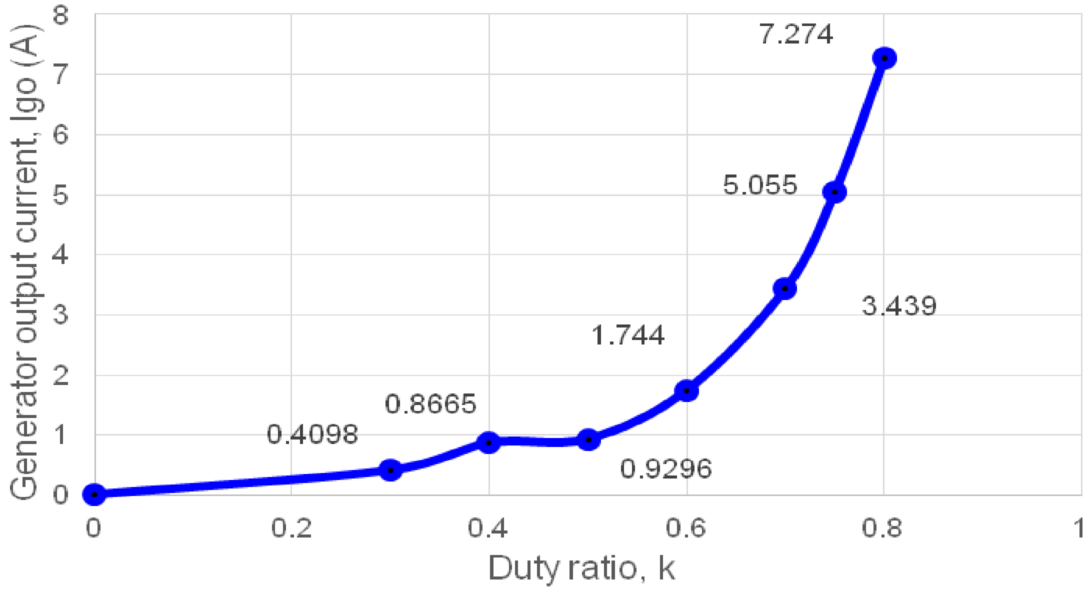

Figure 14. Variation of generator load current with duty ratio (k)

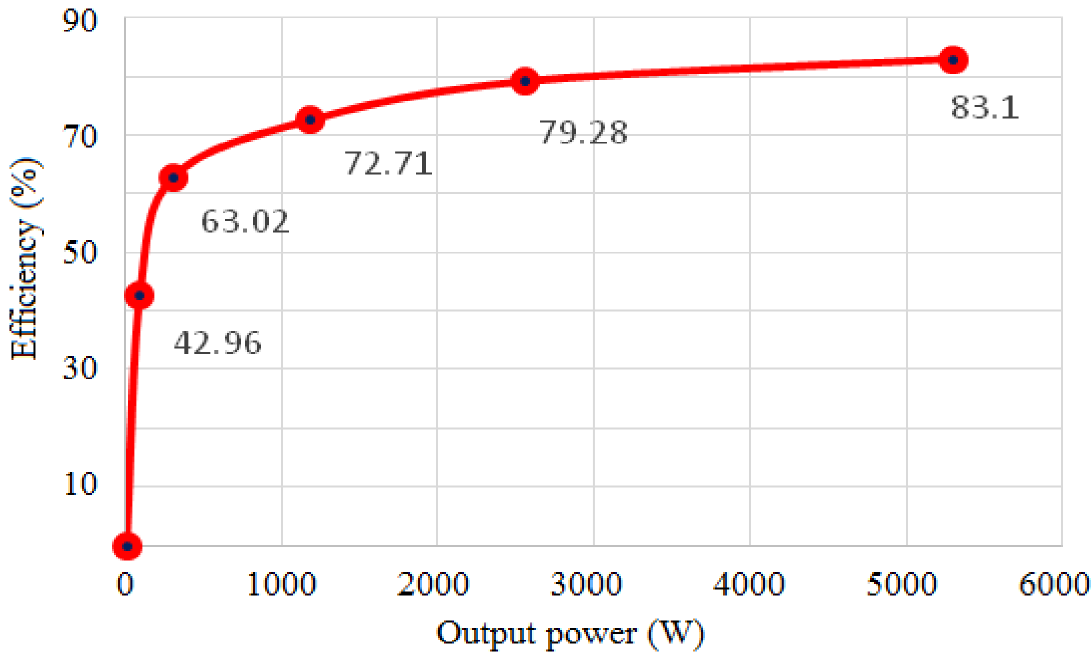

Figure 15. Efficiency characteristic of motor-generator set

CONCLUSION

In this research article, the speed control scheme for a high gain Zeta converter-fed separately excited DC motor under load condition is proposed. The various performance characteristics such as speed, torque, armature voltage, armature current, output current, and efficiency of the DC motor-Generator set are presented by taking duty ratio (k) as the variable parameter. The voltage stresses across the various power switches and the diodes are also calculated. The features of the proposed research work are that (i). Wide range of speed control of DC motor with respect to motor armature voltage variation due to the change of duty ratio from 0.4 to 0.8, (ii). The proposed Zeta topology has high voltage gain (at low duty ratio) compared to that of conventional Zeta converter, (iii). As higher amount of ripples are present in output voltage and output current of SEPIC topology, the proposed work employs Zeta topology as it contains lower amount of ripples in voltage and current, and (iv). The motor-generator efficiency is around 83%. The proposed open loop based converter-fed speed control approach for DC motor is applicable in paper mills and steel rolling mills.

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Conflicts of Interest: The authors declare no conflict of interest.

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