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Modeling and simulation of ac–dc buck-boost converter fed dc motor with uniform PWM technique

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Abstract

PWM controlled rectifiers can efficiently and economically be employed in low and medium power applications of dc drives and in front-end converters of rectifier–inverter systems while maintaining the advantages of design simplicity and operation reliability of naturally commutated schemes. Due to the high dc voltage that is produced which is greater than the peak voltage of the utility supply, the ac–dc buck-boost converter is especially suited as a front-end power source in variable-speed drive systems to convert the utility supply voltage into a variable dc link voltage where a single-phase or a three-phase utilities power supply is available. In this paper, the dynamic model and steady state equivalent circuit of a single-phase ac–dc buck-boost converter fed dc motor with uniform PWM control is presented. The waveforms of voltage and current, the input and output characteristics of the converter are discussed and verified. Measured, computed and simulated results are shown to be very close and the model is proved to be efficient and accurate.

Keywords: Buck-boost; ac–dc converter; Uniform PWM; dc motor

1. Introduction

Traditionally, the conversion of ac power (from utilities or generators) to dc power has been carried out by using a diode bridge and a large dc capacitor connected to a rectifier output. Such approach has many disadvantages, including high input current harmonic components, a maximum input power factor of approximately 0.5 and an invariable output dc voltage, with the usual bridge connection of diodes. Many attempts have been made to minimize the harmonic current components and improve the input power factor [1,2]. The ac–dc converters with thyristor bridge have the advantage of simple configuration. However, it has the characteristics of lower input power factor and much generation of lower-order harmonics. The power converter composed of a diode bridge and a dc chopper [3] has the advantage of higher input power factor than that of the thyristor bridge. However, the source current is also distorted due to the lower-order harmonics.

To improve these shortcomings, various circuit configurations have been presented using pulse-width modulation (PWM) techniques employing high frequency switching power devices [4–7]. The bridge connection of diodes, combined with boost type dc chopper [8], requires many devices. Analysis of pulse-width controlled ac–dc converter was reported in [9], only passive R-L loads were considered. In [10,11] an attempt of steady-state modeling of uniform pulse-width modulated single-phase ac–dc step down converter fed dc motor drive is presented. The operation of dc motor supplied from an ac–dc converter of Cuk type and boost converter has been studied in both steady state and transient cases [12,13].

In this paper, a single-phase PWM ac–dc buck-boost converter with only one switching device is proposed. The control of the ac–dc converter is based on uniform PWM strategy, which is simple and easy to implement. The performance of the converter is analyzed and clarified, and the PWM control

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strategy, the dc voltage control method and the simulation method are presented. The input and output characteristics of the converter, waveforms of the voltage and current and the dynamic characteristics are discussed in details.

Besides the wide range of the dc output voltage, which is controllable from zero to more than the maximum value of the ac source voltage, the proposed ac–dc converter has only one switching device. The proposed converter contributes to a reduced number of power switching devices. This may result in advantages such as small installation size and less energy loss. It is clear that the number of switches does not highly affect the characteristics of the ac–dc converters so that the one-switch converter is very convenient for an economical variable dc voltage supply. However, the use of many switches increases the switching losses and the cost of the system. Moreover, an incompatible installation is inevitable.

2. Circuit description and principles of operation

Fig. 1 schematically represents a separately excited dc motor fed from an ac–dc buck-boost converter. The proposed PWM buck-boost converter comprises a diode bridge with only one switching device as shown in Fig. 1, reactor in the dc link, a series connection of a diode and a capacitor parallel to the dc reactor. The proposed converter is an application of the step-up and step-down chopper. In this configuration, the inductor acts as an energy storage/transfer element and step-up and step-down characteristics of the output voltage can be easily obtained by an appropriate switching scheme for the controlled power semiconductor switch.

The conversion process is accomplished through two different power stages, which are the rectification and the control stages. In the first stage, a simple diode bridge rectifier is employed to unify the direction of motor current and the supply voltage. An IGBT operating in the chopping mode and employing symmetrical PWM strategy is used in the second stage to control the amplitude of the output average voltage. As a result of the rectification stage, the waveforms of the load voltage and current are repetitive at a frequency equals double the supply frequency.

2.1. PWM switching strategy and dc voltage control

The generation of the IGBT driving signal is accomplished by comparing a dc reference signal, having a variable amplitude v_c, with a saw tooth carrier wave, having a fixed amplitude v_r and frequency f_s, known as the switching frequency. The ratio between v_c and v_r is called the duty cycle, $D = v_c/v_r$, which is defined as the ratio of the on time T_{on} to the total switching period $T_s = T_{on} + T_{off}$. The average output voltage is varied by changing through the variable v_c to control the duty cycle D (Fig. 2).

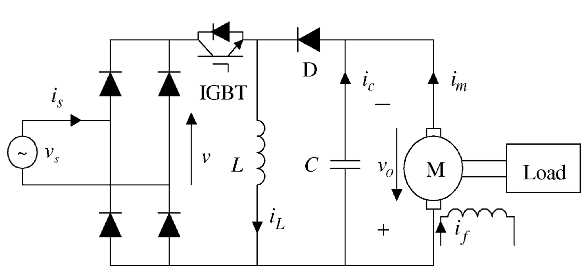


Fig. 1. Schematic diagram of ac–dc buck-boost converter fed dc motor.

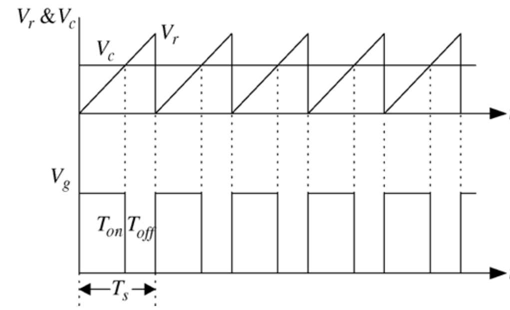


Fig. 2. Generation of PWM gating signals.

3. Operation modes

The operation modes and the equivalent circuits during these modes of the buck-boost converter fed dc motor depend on the switching conditions of both the switching device and the diode D. Depending on the state of the switching device and the diode, each chopping cycle comprises two or three different sub modes of conduction. Fig. 3 shows these three possible modes for one switching cycle for positive supply voltage. These modes are as follows.

3.1. Charging mode (mode 1)

During the charging mode, the switching device is turned on, therefore, the diode D is reverse biased so the absolute value of the supply voltage appears across the inductor. The inductor current i_L will rise and flows through the input side, as shown in Fig. 3a, causing energy to be stored in the inductor. In this mode, the loop of the motor terminals and the output capacitor are isolated from the supply. Therefore, the capacitor charge, accumulated from the previous period, will be discharged through the armature winding. The system will stay in this mode for the turn on period of the switching function of the switching device. The bold lines in Fig. 3a show the possible current paths of the inductor and motor currents during the charging mode.

3.2. Discharging mode (mode 2)

The discharging mode is complementary to the charging mode. The system is transferred to this mode when the switching device is turned off and the diode D will be forward biased. The inductor current i_L falls through the output side and flows through the output capacitor C and the dc motor as shown in

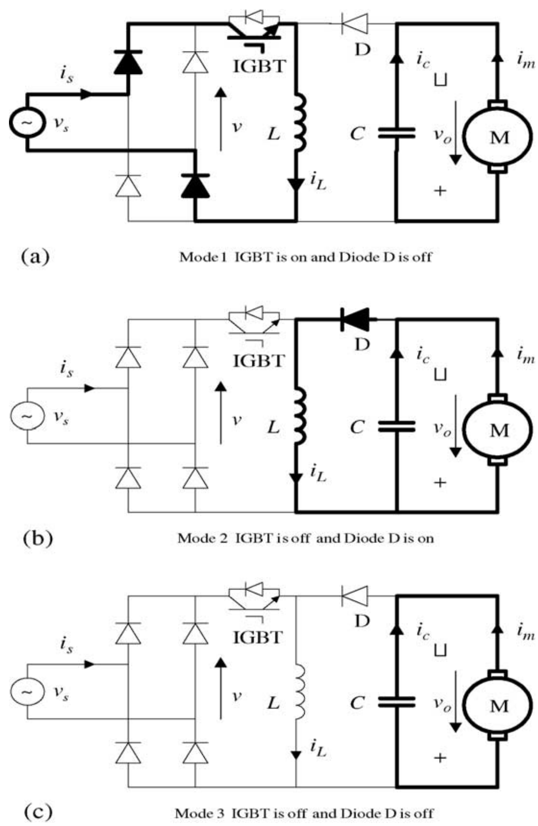


Fig. 3. Operation modes and current paths for positive half-cycle.

Fig. 3b. The inductor voltage reverses its polarity and it forward biases the diode D. The energy stored in the inductor would be transferred to the motor and the inductor current will fall until the switching device is switched on again in the next cycle or until inductor current decreases to zero (mode 3). The capacitor is charged according to a decrease in the inductor current.

3.3. Mode 3

In mode 3, the switching device is still off but the circuit conditions may cause the inductor current i_L to fall to zero such that the diode D becomes reverse biased. This mode lasts until the switching device is turned on again. The system will stay in the discharging mode for a period determined by the system parameters. Of course, this period does not exceed the off period of the switching device. If the inductor current i_L is assumed flows continuously, mode 3 disappears. Fig. 3c shows the equivalent circuit during this operation mode.

4. Model formulation

In this section, the transient and steady state analysis of the ac–dc buck-boost converter will be discussed. The power electronic components are assumed ideal and the switching frequency is assumed much greater than the supply frequency, so that during each switching cycle the input and output voltages can be considered constant.

4.1. Transient analysis

The state variables describing the dynamic behavior of a separately excited dc motor fed from buck-boost converter depend on the switching conditions of both the switching device and the diode D. Three modes of operation are considered as illustrated in Fig. 3. In the all of the above three operating modes, the diode bridge output voltage is given by

$$v = |v_{\mathrm{s}}| = |V_{\mathrm{sm}}\ \sin(wt)| \tag{1}$$

The general voltage equation of a separately excited dc motor can be written as

$$v_{\mathrm{o}} = R_{\mathrm{m}} i_{\mathrm{m}} + L_{\mathrm{m}}\frac{\mathrm{d}i_{\mathrm{m}}}{\mathrm{d}t} + k_{\mathrm{m}}\omega_{\mathrm{m}} \tag{2}$$

While the electromagnetic torque equation is written as

$$T_{\mathrm{e}} = T_{\mathrm{L}} + J\frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{d}t} + B\omega_{\mathrm{m}} \tag{3}$$

where k_m is the motor constant and given by

$$k_{\mathrm{m}} = k_v i_{\mathrm{f}} \tag{4}$$

and the developed electromagnetic torque T_{e} is given by

$$T_{\mathrm{e}} = k_{\mathrm{m}} i_{\mathrm{m}} \tag{5}$$

The analysis is formed in a generalized form that is applicable irrespective of the number of pulses per supply cycle. The developed analysis and solution are experimentally verified. For analysis purposes the supply voltage is assumed sinusoidal.

According to the selected current directions shown in Fig. 3, the following state/performance equations in the different modes can be found as follows:

Mode 1

$$v = L\frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t} \tag{6}$$

$$i_{\mathrm{s}} = i_{\mathrm{L}} \tag{7}$$

$$i_{\mathrm{c}} = -i_{\mathrm{m}} \tag{8}$$

$$i_{\mathrm{c}} = C\frac{\mathrm{d}v_{\mathrm{o}}}{\mathrm{d}t} \tag{9}$$

Mode 2

$$L\frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t} = -v_{\mathrm{o}} \tag{10}$$

$$i_{\mathrm{s}} = 0 \tag{11}$$

$$i_{\mathrm{L}} = i_{\mathrm{c}} + i_{\mathrm{m}} \tag{12}$$

$$i_{\mathrm{c}} = C\frac{\mathrm{d}v_{\mathrm{o}}}{\mathrm{d}t} \tag{13}$$

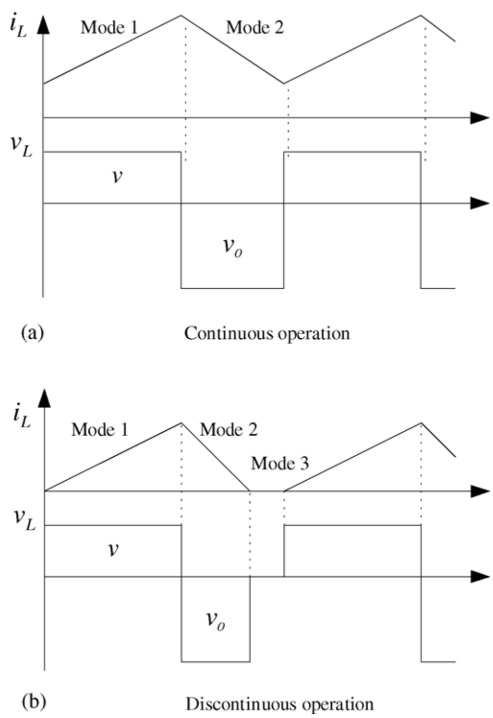


Fig. 4. Inductor current and voltage waveforms during one switching cycle.

Mode 3

$$i_c = -i_m \tag{14}$$

$$i_s = i_L = 0 \tag{15}$$

$$i_c = C\frac{dv_o}{dt} \tag{16}$$

4.2. Steady state analysis

The steady state analysis procedure is aimed at modeling the converter in order to obtain an approximate equivalent circuit for ac–dc buck-boost converter.

Fig. 4 shows the steady state inductor current and voltage waveforms during one complete switching cycle for a continuous and discontinuous inductor current. Due to the use of high switching frequency, the input voltage can be assumed constant during the switching period.

The inductor voltage v_L is the input voltage v during the charging mode and is the output voltage v_o during the discharging mode. For constant switching frequency and quasi steady state analysis of the switching converter, the average inductor voltage during each switching cycle can be given as a function of the chopper duty cycle D by

$$v_L(t) = Dv(t) + (1-D)v_o(t) \tag{17}$$

where $v(t)$ and $v_o(t)$ are the average rectified voltage and dc converter output voltage during one switching period, respectively, provided that $v_o(t)$ is of opposite polarity with respect to $v(t)$. The inductor voltage is given by

$$v_L(t) = L\frac{di_L}{dt} \tag{18}$$

where $i_L(t)$ is the average inductor current during each switching period.

The inductor current, which produces the output current during the discharging mode, is caused by the input current during the charging mode. Hence, the following relations are obtained for the input and output currents:

$$i_s(t) = Di_L(t) \tag{19}$$

$$i_o(t) = (1-D)i_L(t) \tag{20}$$

where $i_s(t)$and $i_o(t)$ are the average input and output currents, respectively, during one switching period.

From Eqs. (17) and (18), the following relation is obtained:

$$Dv(t) = L\frac{di_L}{dt} - (1-D)v_o(t) \tag{21}$$

Substituting from Eq. (20) into Eq. (21) results

$$\frac{D}{1-D}v(t) = \frac{L}{(1-D)^2}\frac{di_o}{dt} - v_o(t) \tag{22}$$

Eq. (22) represents a steady state equivalent circuit for the buck-boost ac–dc converter shown in Fig. 5. From which, the following current relation can be obtained:

$$C\frac{dv_o(t)}{dt} = i_o(t) - i_m(t) \tag{23}$$

It must be noted that the output capacitor has to be sufficiently large to smooth the dc output voltage, which fluctuates at twice the supply frequency, as in the conventional diode bridge rectifier. At steady state and for a sufficiently large value of the output capacitor C, the average values of the output voltage $v_o(t)$ and current $i_o(t)$ can be assumed constant; the average value of the second component of Eq. (22) is equal to zero; and the transfer function of the output voltage with respect to the input voltage is obtained as

$$\left|\frac{v_o(t)}{v(t)}\right| = \frac{D}{1-D} \tag{24}$$

The above equation results in a relationship between the output voltage and the dc rectified voltage. From Eq. (24), it is clear to note that the proposed converter operates in the

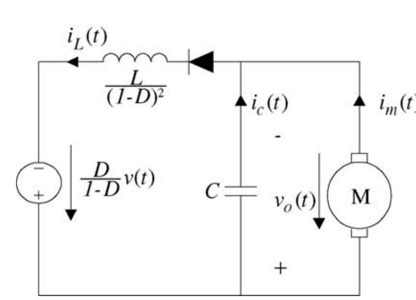


Fig. 5. Approximate dc equivalent circuit of ac–dc buck-boost converter.

Table 1
Simulated circuit and test motor parameters

Parameter	Symbol	Value
Maximum supply voltage	V_{sm}	70.69 V
Supply frequency	f	50 Hz
Switching frequency	f_s	1.8 kHz
Capacitor	C	330 μF
Armature resistance	R_m	2.95 Ω
Armature inductor	L_m	6.0 mH
Motor constant	K_m	2.11 V/(rad/s)
Inductor	L	95.8 mH
Moment of inertia	J	0.25 kg m^2

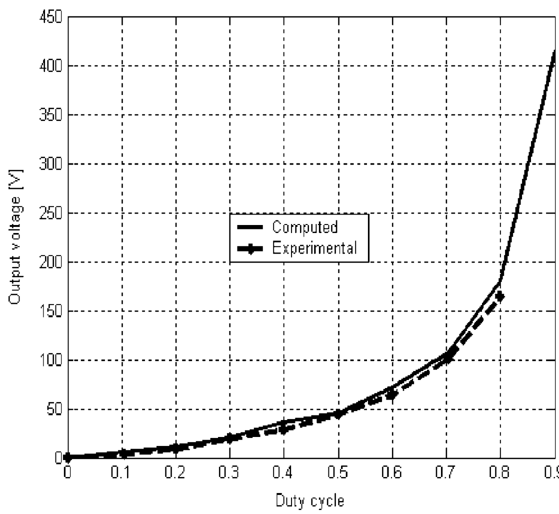


Fig. 6. Computed and experimental variation of output voltage.

stepping-up mode for duty cycle D >0.5 and in the stepping down mode for D <0.5. For D = 0.5, the output voltage is equal to the dc rectified voltage.

In practice the interval of mode 3 is very short, if it exists, when the switching frequency is sufficiently high as described in this paper. Neglecting the operations corresponding to mode 3, the ac–dc converter shown in Fig. 1 can be represented by the dc equivalent circuit shown in Fig. 5 and the converter can be taken to be a dc–dc converter in which the supply is the fully rectified voltage $v(t)$ and D is the duty cycle of the switching device. A buck-boost regulator provides an output voltage which may be less or greater than the input voltage-hence the name buck-boost. This converter is

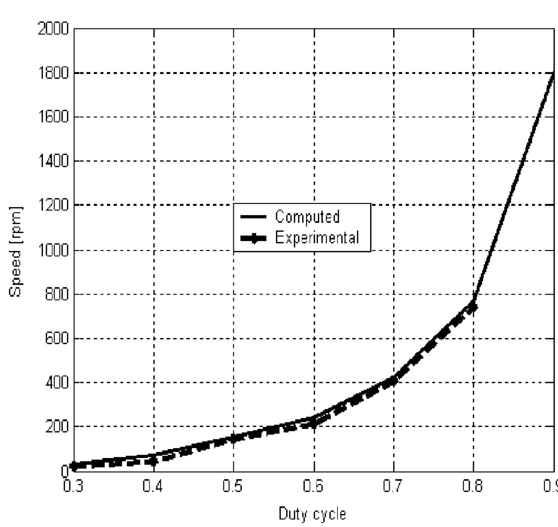


Fig. 7. Computed and experimental variation of motor speed.

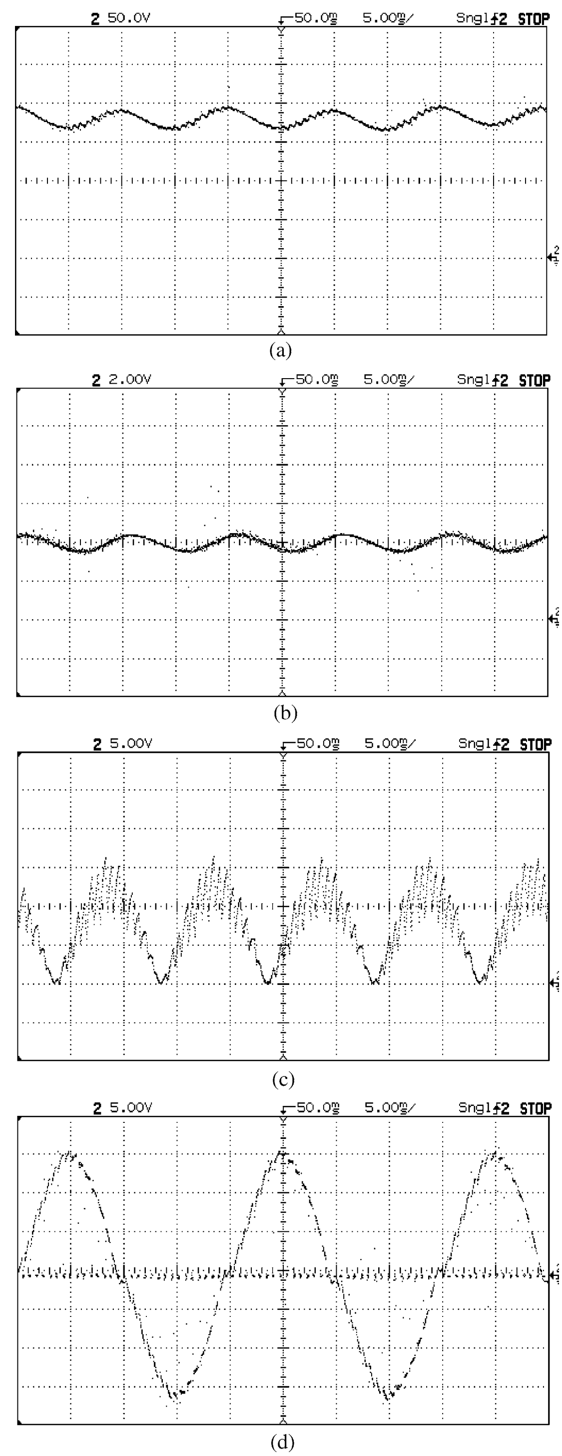


Fig. 8. Experimental voltage and current waveforms: (a) armature voltage; (b) armature current; (c) inductor current; (d) supply current.

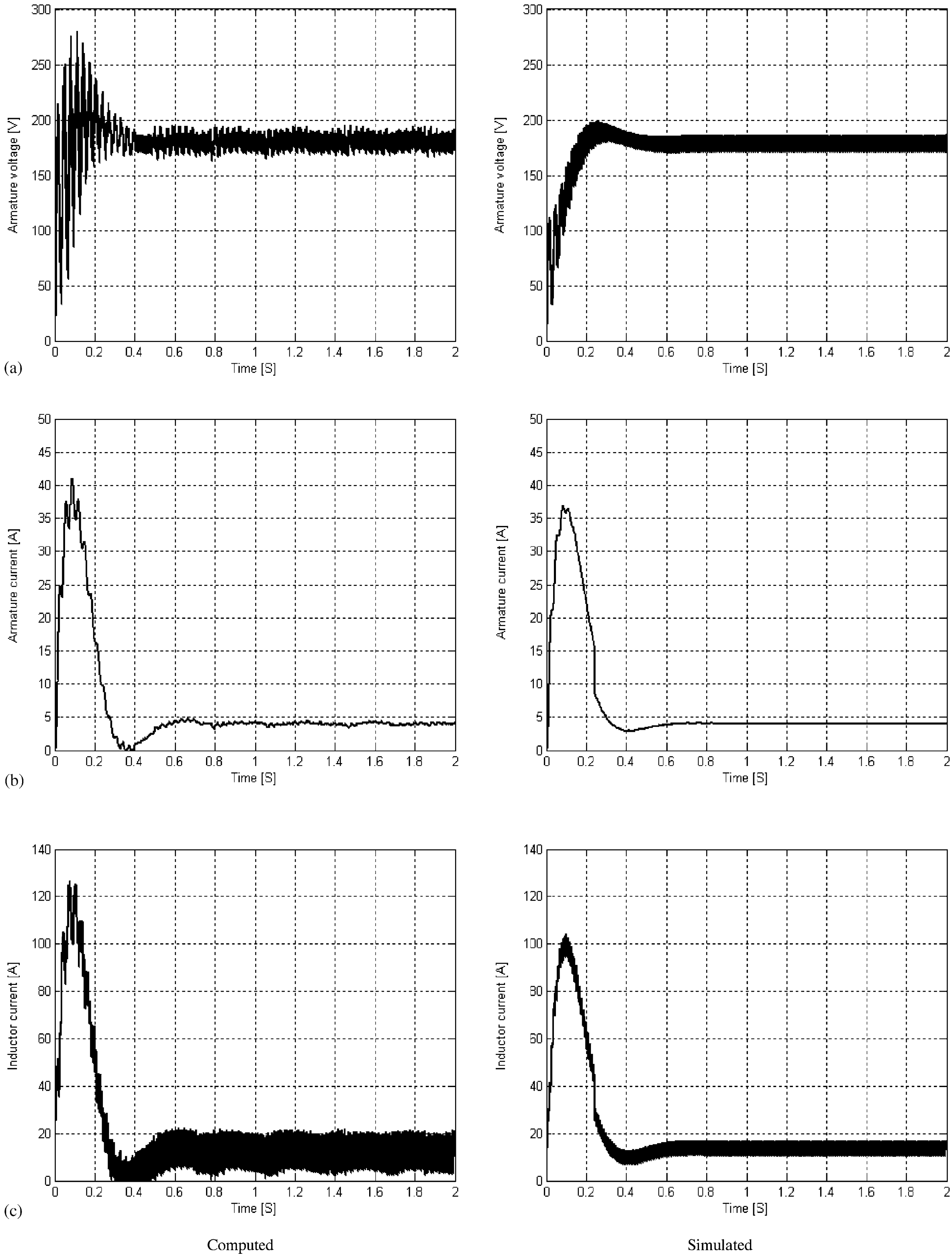
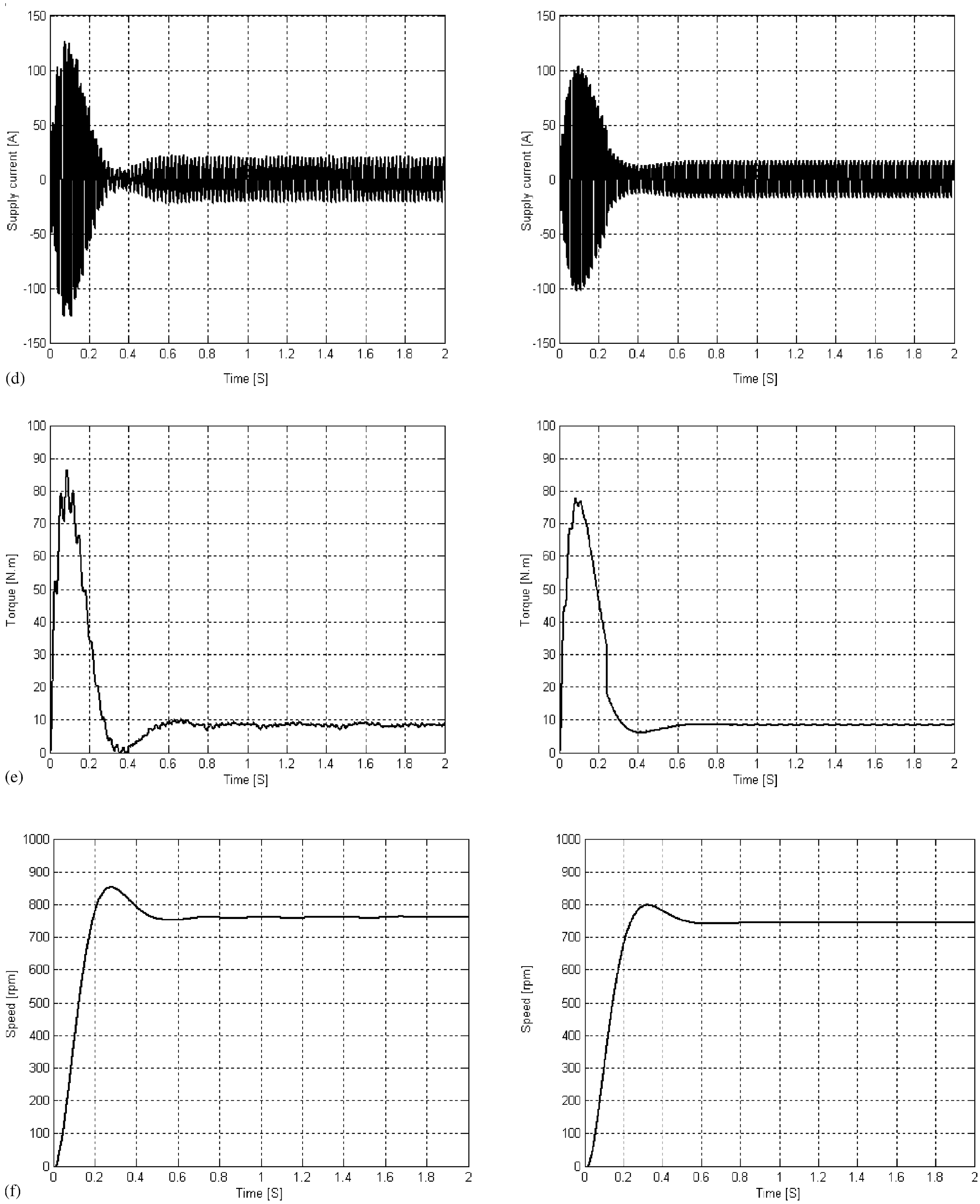


Fig. 9. Comparison between computed and simulated transient run up characteristics: (a) armature voltage; (b) armature current; (c) inductor current; (d) supply current; (e) developed torque; (f) motor speed.



Computed

Simulated

Fig. 9. (*Continued*)

also known as inverting converter because the output voltage polarity is opposite to that of the rectification stage output voltage.

5. Simulation and experimental results

Simulation studies: As shown in the analysis, the converter is assumed to operate with ideal circuit elements and switches. The state Eqs. (6)–(16) which describe all the operating modes of the converter are solved numerically using fourth order Rung-Kutta method. In order to ensure the proper transition of the operating modes, the initial conditions of the state variables at the beginning of each mode are computed from the final conditions of the state variables of the previous one. Simulation results based on MATLAB-SIMULINK software are used too and the results are nearly agreed.

In order to verify experimentally the principle of operation and the validity of theoretical analysis results, a small power prototype rating 2.2 kV A (220 V, 10 A) has been implemented in laboratory. The power stage of the experimental system of the PWM ac–dc converter shown in Fig. 1 composed of the following components: the main power circuit, a PSB 35/14 (1400 V, 35 A) diode bridge rectifier, a MG50J2YS1 (600 V, 50 A) insulated gate bipolar transistor (IGBT) used as a switching device, a dc motor rated 1.25 kW, 180 V, 8.6 A, 735 rpm coupled to a dc generator which represents an electric load for the motor. An output capacitor of 330 μF is chosen in order to have a near free-ripple output dc voltage. The simulated and experimental circuit constants and conditions are listed in Table 1. the switching frequency used is 1.8 kHz. The maximum ac supply voltage is chosen to be 70.69 V to give the motor rated voltage of 180 V at a duty cycle of 0.8.

The computed, simulated and experimental obtained average output voltage characteristics against the duty cycle are represented by the curves shown in Fig. 6. It is clear that the output voltage can be regulated from zero value to greater than the peak value of the supply voltage by controlling the duty cycle. The average output voltage is very sensitive to changes in duty cycle and the average output current is less than the average inductor current by a factor of $(1 - D)$. It must be noted that, the buck-boost converter provides output voltage polarity reversal without a transform and it has high efficiency due to the fact of using only one switching devise.

Fig. 7 shows the computed and experimental variations of the motor speed with the duty cycle. A wide control range can be obtained by controlling the duty cycle.

From Fig. 6 it is clear to note that, the output voltage is controlled theoretically from 0 to 410 V by controlling the duty cycle from $D = 0$ to $D = 0.9$ and is controlled experimentally from 0 to 180 V; the rated motor voltage; by controlling the duty cycle from 0 to 0.8. Also, as shown in Fig. 7, the motor speed is controlled theoretically and experimentally from zero speed at $D = 0$ to the rated speed of 765 rpm at $D = 0.8$.

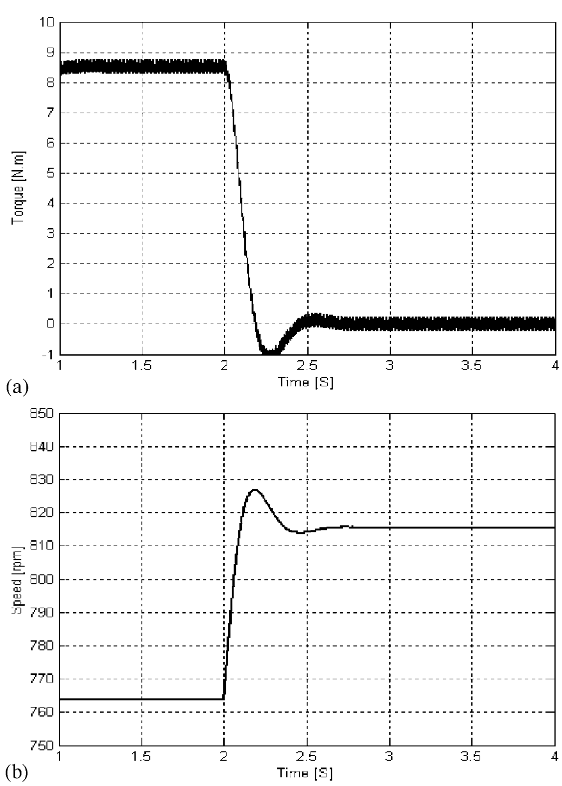


Fig. 10. Negative disturbance in load torque from 8.5 N m to no load at time of 2.0 s for a duty cycle of $D = 0.8$: (a) developed torque and (b) motor speed.

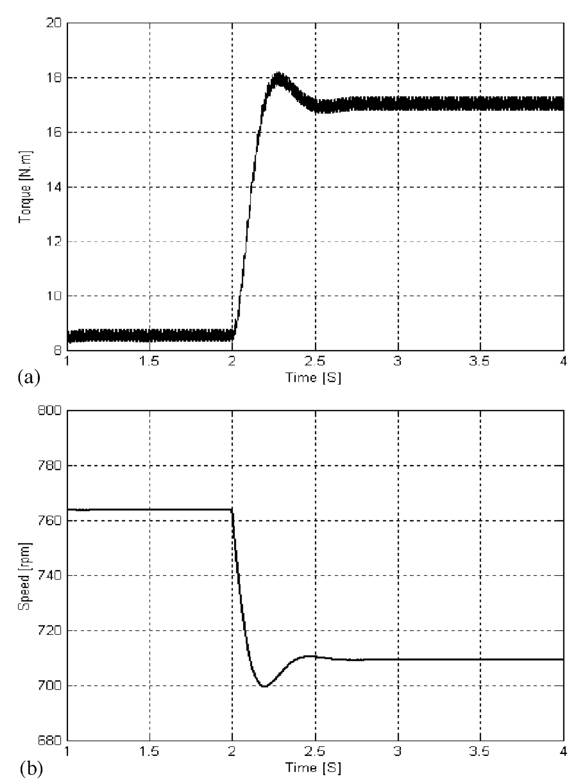


Fig. 11. Positive disturbance in load torque from 8.5 to 17.0 N m at time of 2.0 s for a duty cycle of $D = 0.8$: (a) armature voltage and (b) motor speed.

Fig. 6 proves that the proposed work involves a step up/down operation.

Fig. 8 shows the experimental steady state voltage and current waveforms. The motor applied voltage can be made continuous and more ripples free by using a large capacitor instead of 330 μF used capacitor and the motor current is continuous and almost ripples free as shown in Fig. 8b. The inductor current is also continuous; it increases during the charging mode (mode 1) and gradually decreases during the discharging mode (mode 2). Mode 3 is absent due to the use of high switching frequency. However, the input current is discontinuous; it equals the inductor current during the charging mode and equals zero during the discharging mode.

Fig. 9 shows the transient run up characteristics of the motor applied voltage, motor current, inductor current, supply current, developed torque and motor speed, respectively, computed from the mathematical model described by the state Eqs. (6)–(16) at a duty cycle of 0.8 and at half the full load torque (8.5 N m) as compared with those obtained from the MATLAB-SIMULINK software. The difference between computed and simulated characteristics is mainly caused by the switching device losses, not taken into account in the analytical model.

The transients due to sudden load changes of the motor at steady state are shown in Figs. 10 and 11. Fig. 10 shows the computed system response of developed torque and motor speed for a step change in load torque from half load (8.5 N m) to no load at time of 2 s. The motor speed is increased from 765 to 815 rpm. Fig. 11 shows the same quantities for a step change in load torque from half load (8.5 N m) to full load (17.0 N m) at time of 2 s, where the motor speed is decreased from 765 to 710 rpm. The results of the two figures are at duty cycle 0.8. Also, the effect of the change in the duty cycle on the steady state characteristics of the motor is investigated in Fig. 12, which shows the change in the motor armature voltage and the speed when the duty cycle is changed from 0.8 to 0.7 at time of 2 s. The average motor armature voltage is decreased from 180 V at duty cycle of 0.8 to 105 V at duty cycle of 0.7 and the motor speed is reduced from 765 rpm at duty cycle of 0.8 to 423 rpm at duty cycle of 0.7.

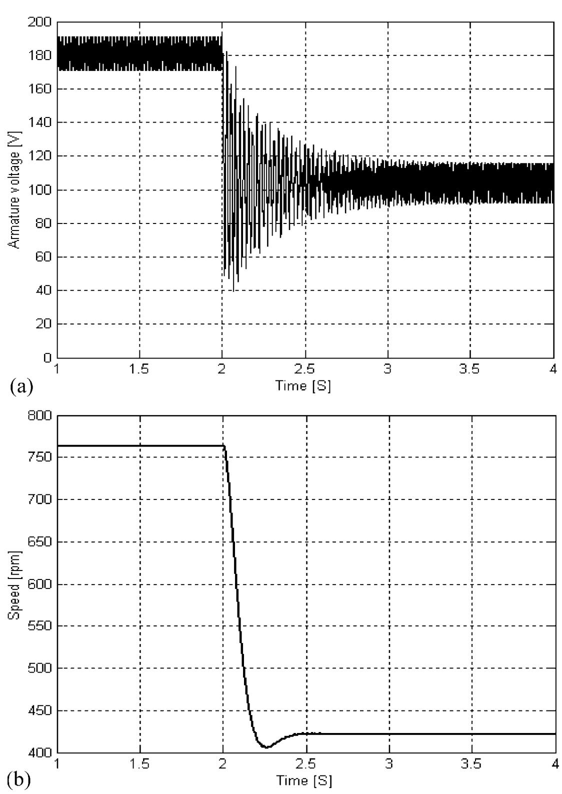


Fig. 12. The effect of step change in the duty cycle from 0.8 to 0.7 at time of 2.0 s for load of half the rated value: (a) armature voltage and (b) motor speed.

The proposed topology of buck-boost converter is appropriate for low and medium power applications, such as power supplies and motor drives. It is also can be used for starting of dc motors to limit the starting current to the desired value by controlling the duty cycle to give the required armature voltage at starting period.

6. Conclusions

The paper presents a steady state equivalent circuit and a dynamic model for the transient analysis of a single-phase ac–dc buck-boost converter fed dc motor with uniform PWM control technique. The waveforms of the motor voltage, motor current, inductor current and the input and output characteristics of the converter are discussed and verified. Measured, simulated and computed results are shown to be very close and the model is proved to be efficient and accurate. The transients during starting period and those due to sudden load changes of the motor at steady state and the effect of the duty cycle on the steady state characteristics of the motor are investigated.

Due to the high dc voltage which is greater than the peak voltage of the utility supply, the ac–dc buck-boost converter can be especially suited as a front-end power source in variable-speed drive systems to convert the utility supply voltage into a variable dc link voltage where a single-phase or a three-phase utilities power supply is available.

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