Driving the universal motors through a universal pulse-width-modulated converter

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The name universal motor stems from the fact that such motor can be operated from either DC or single phase AC source. This paper introduces a Pulse Width Modulated (PWM) converter that can operate from DC or AC supply, hence may be also named as universal converter. Motor performance and dynamic model have been discussed. Waveforms analysis of different motor-converter combinations has been illustrated using simulation model based on Matlab package. Simulation results have been obtained and analyzed, showing the similarity of the proposed universal converter with the conventional transistor DC chopper (when being fed from DC) and the superiority over the conventional thyristor AC voltage controller (when being fed from AC). Experimental setup has been implemented and the actual motor speed, voltage and current waveforms have been obtained. The setup has been tested for the speed step variation, soft start and soft stop in both cases of DC and AC supplying operations. Simulation and experimental results showed the simplicity and the effectiveness of the proposed motor-converter configuration.

تستمد المحركات الكهربية العامة اسمها من إمكانية التشغيل عن طريق التغذية من مصدر كهربي مستمر أو متردد. وفى هذا البحث يتم عرض تصميم وتنفيذ واختبار مغير يعمل بنظام التغير في عرض النبضة بحيث يمكن توظيفه أيضاً للعمل مع أي من المصدرين الكهربيين المستمر أو المتردد. وبذلك يُكوّن المحرك والمغير نظام تشغيل عام من أي مصدر كهربي متاح. وقد تم عمل محاكاة للنظام المقترح وكذلك تحليل النتائج النظرية وتم تصميم وتنفيذ نموذج معملي وكذلك اختباره عملياً وأظهرت النتائج العملية تطابق مع النتائج النظرية والتي أوضحت سهولة وفاعلية النظام المقترح ليس فقط في إمكانية التشغيل من مصدر مستمر أو متردد ولكن أيضاً في تحسين الوظائف العامة لنظام التسير الكهربي.

Keywords: Simulation, Implementation, Universal-motor, Power-electronics, Electrical-drives

1. Introduction

A small DC series motor specially designed to operate from either AC or DC supplies is usually named a universal motor. It is used quite extensively in domestic appliances and applications that may require speed variation with load torque such as routers, sewing, portable machine tools and vacuum cleaners [1– 2]. Design approach of the universal motor for performance improvement and reduction of the volume/power ratio has been introduced [3]. Power electronics revolutionized the concept of power control for power conversion and for control of electrical machine drives. The power electronic circuits may be classified into main four ty pes [4]:

1- AC to DC converters; referred as controlled rectifiers and usually utilize Thyristor devices.
2- AC to AC converters; referred as AC voltage controllers and usually utilize Thyristor devices.
3- DC to DC converters; referred as choppers and usually utilize Transistor devices.
4- DC to AC converters; referred as inverters and usually utilize Transistor devices.

The conventional drives of the universal motors are based on choppers or AC voltage controllers when being fed from DC or AC supplies respectively.

This paper proposed a motor-converter combination that can be operated from either DC or AC supplies. Universal motor characteristics and operation are discussed. Converter analysis is introduced. Simulation model of the proposed setup is developed. Experimental results are obtained to verify the effectiveness of the system.

2. Universal motor

Single-phase series motors can be fed either from a DC source or a single phase AC source, and therefore are called universal motors. Universal motors can developed higher torques, can accelerate to higher speeds, and have a higher power-to-weight ratio than induction motors of the same power ratings [5]. They are usually operated at high speeds (1500 up to 10000 rpm) and are widely used in fractional horsepower ratings in many domestic applications, such as portable tools, drills, mixers, blenders and vacuum cleaners. Large universal motors (series DC motors) in the range of 500 hp are used for traction applications [6]. Connections, phasor diagram, characteristics and waveforms of a typical universal motor are depicted in fig. 1. Following equations can be written for the universal motor [6]:

$$T_m = K_a \phi_d i_a \,. \tag{1}$$

And

$$e_a = K_a \phi_d \omega_m \,. \tag{2}$$

For AC excitation

$$i_a = I_{a(\max)} \cos \omega t \,. \tag{3}$$

And

$$\phi_d = \phi_{d(\max)} \cos \omega t \,. \tag{4}$$

Substituting from (3 and 4) in (1):

$$T_m = K_a I_{a(\max)} \phi_{d(\max)} \cos^2 \omega t = \frac{K_a}{2} I_{a(\max)} \phi_{d(\max)} (1 + \cos 2\omega t) \,. \tag{5}$$

Also from (2) and referring to the phasor diagram shown in fig. 1-b:

$$\frac{E_{a(DC)}}{E_{a(AC)}} = \frac{K_a \phi_{d(DC)} \omega_{m(DC)}}{K_a \phi_{d(AC)} \omega_{m(AC)}} = \frac{1 - (\frac{I_a}{V_m})(R_a + R_f)}{\cos\theta_s - (\frac{I_a}{V_m})(R_a + R_f)} \,. \tag{6}$$

Since $(\frac{I_a}{V_m})(R_a + R_f) < 1$, and assuming $\phi_{d\,(DC)}$ = $\phi_{d\,(AC)}$, eq. (6) maybe simplified as:

$$\frac{E_{a(DC)}}{E_{a(AC)}} \approx \frac{\omega_{m(DC)}}{\omega_{m(AC)}} \approx \frac{1}{\cos\theta_s} > 1 \,. \tag{7}$$

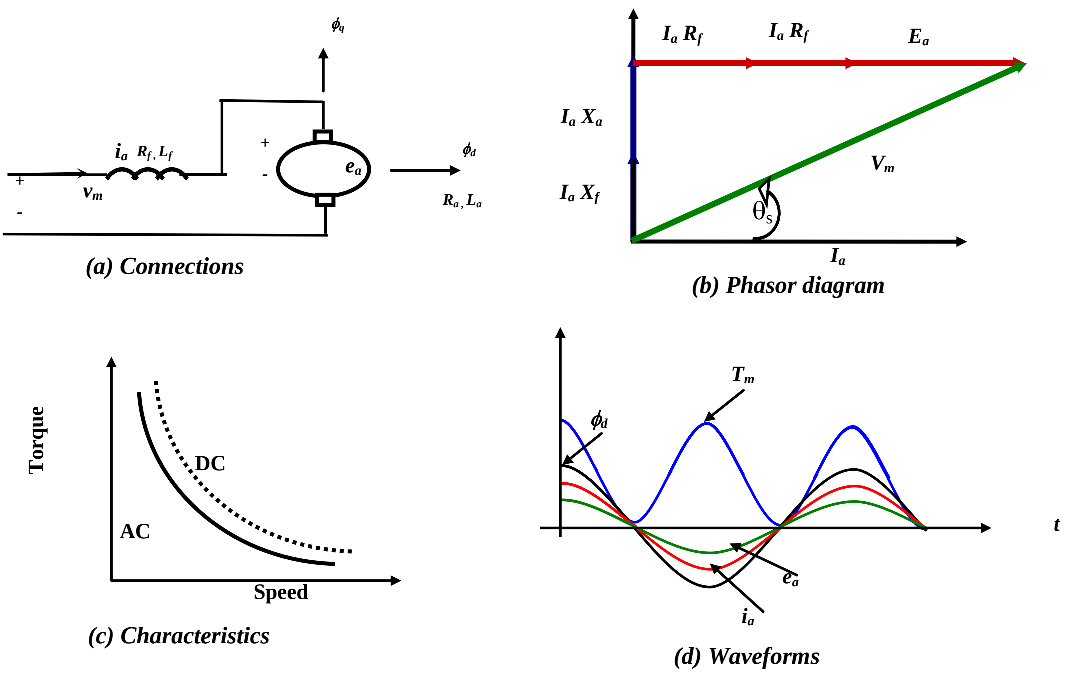


Fig. 1. Typical universal motor.

It can be seen from eq. (5) that the AC motor torque has a unipolar direction and varies at twice the supply frequency see fig. 2d. Eq. (7) shows that for same terminal voltage and motor current (i.e. same load torque), the speed will be lower for AC excitation see fig. 2-c.

This could be improved by adding a compensating winding in the q-axis to reduce the effective inductance, hence increasing the corresponding $E_{a\,(AC)}$ and consequently $\omega_{m\,(AC)}$. The motor speed and current are determined by motor parameters, applied terminal voltage, and mechanical load according to the following linear Laplace eqs. [7]:

$$\omega_m = \frac{K_a i_a i_f - T_L - \beta\omega_m}{sJ}\,, \tag{8}$$

$$i_a = i_f = \frac{v_m}{(R_f + R_a) + s(L_f + L_a) + K_a\omega_m}\,. \tag{9}$$

3. Universal converter

Speed control of universal motor may be required in many applications such as blenders and machine tools. Such control can be easily achieved by controlling the motor terminal voltage, hence motor current and developed torque, consequently the load speed. The Pulse Width Modulated (PWM) DC chopper, shown in fig. 2-a, is conventionally used if the application is fed from a DC source. This chopper cannot be effectively operated if it is fed from AC source due to the transistor direction polarity. Another configuration, shown in fig. 2-b, is the phase controlled AC voltage controller utilizes two back to back Thyristors (two SCR's and maybe one TRIAC) and only can be operated from AC source, else additional forced commutation circuit is required to turn off the SCR in case of DC source. Two possible configurations as shown in fig. 2-c and fig. 2-d are proposed through this paper. Each of them can be effectively operated from either DC or AC supplies, hence may be named as universal converter. The first proposed converter, shown in fig. 2-c, consists of two transistors in conjunction with two H-bridge diode rectifiers and two isolating transistor gate drive circuits. A simple generated pulse width modulated signal (Q) drives the first transistor (TR_1), while the complement of such gate ($\overline{Q}$) drives the other transistor (TR_2). In case of AC supply and in the positive half cycle, the current will pass through D_1, TR_1 and D_2 during the on-period while it will be freewheeled through D_{M1}, TR_2 and D_{M2} during the off-period. In the next negative half cycle, the current will pass through D_3, TR_1 and D_4 during the on-period while it will be freewheeled through D_{M3}, TR_2 and D_{M4} during the off-period. The second proposed universal converter, shown in fig. 2-d, utilizes an H-bridge diode rectifier, a single transistor switch and a single freewheeling diode. In case of AC operation and during the on-periods, the positive half cycle current passes through D_1, TR and D_2 while the negative half cycle current passes through D_3, TR and D_4. During the off-periods of both positive and negative cycles, the current will be freewheeled through D_M. In case of feeding from DC supply, the operation of both proposed converters will be as described in the case of AC source but only during the positive half cycles. The instantaneous output voltage of each converter, which is the terminal voltage of the motor, may be defined as follows:

For DC chopper in fig. 2-a,

$v_m(t) = V_s$: During on-periods. (10)

For AC voltage controller in fig. 2-b,

$v_m(t) = V_{s(\max)} \sin \omega t$: During the conduction angle (δ), where $\delta = \beta - \alpha$. (11)

For universal converter in fig. 2-c,

$v_m(t) = V_s$: During on-periods while feeding from DC source. (12)

$v_m(t) = V_{s(\max)} \sin \omega t$: During on-periods while feeding from AC source. (13)

For universal converter in fig. 2-d,

$v_m(t) = V_s$: During on-periods while feeding from DC source. (14)

$v_m(t) = abs[V_{s(\max)} \sin \omega t]$: During on-periods while feeding from AC source. (15)

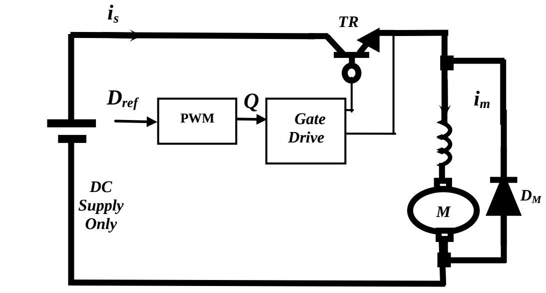
For the four converters in figs. 2-a, 2-b, 2-c and 2-d,

$v_m(t) = 0$: During off-periods (16)

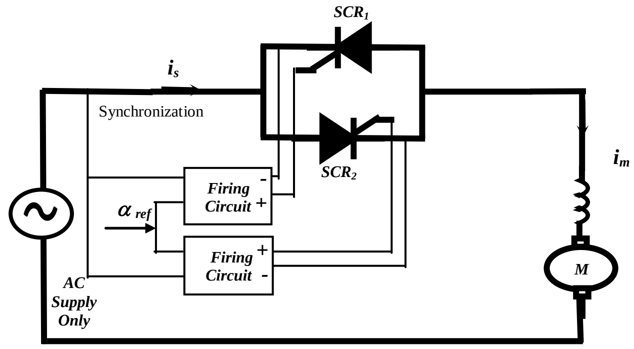
Changing the firing delay angle (α) for the AC voltage controller or changing the duty cycle ($D = \frac{T_{ON}}{T_{ON} + T_{OFF}}$) for other PWM converters will vary the motor voltage, current and speed in both AC and DC operations, that will be demonstrated in the next simulation section.

4. Simulatiom analysis

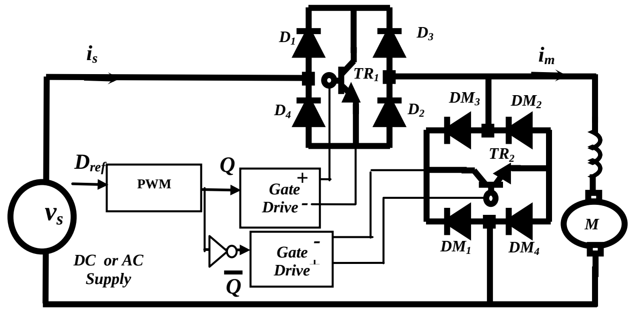
The dynamic performance of a DC motor can be modeled using different mathematical techniques, such as equivalent circuit [8], differential equations, transfer function, state space variable analysis [7] or d-q model based on the generalized machine theory [9]. Finite element packages have been also used for the simulation analysis of the magnetic circuit of universal motors [10]. Matlab software has been introduced as a powerful package to simulate the dynamic performance of many electric machines [11]. Different motor-converter combinations discussed in section 3 have been simulated using Simulink program under the Matlab package R13. Fig. 3 shows an example of Simulink connection diagram of the proposed universal converter shown before in fig. 2-c. Converters shown in fig. 2 are individually simulated and figs. 4-a, 4-b, 4-c and 4-d show the simulated waveforms of control gate signals ($Q1$ and $Q2$), supply voltage and current (v_s and i_s), motor voltage and current (v_m and i_m) and finally motor speed and torque (ω_m and T_m). The simulation waveforms of converters in figs. 2-a, 2-c and 2-d have been found almost typical when being fed from DC source and are as shown in fig. 4-a. Table1 depicts a comparison results obtained between such conventional phase controlled and the proposed PWM drive for different firing angles (α) and duty cycles (D) respectively at same motor speed and load torque. Fourier analysis has been utilized and



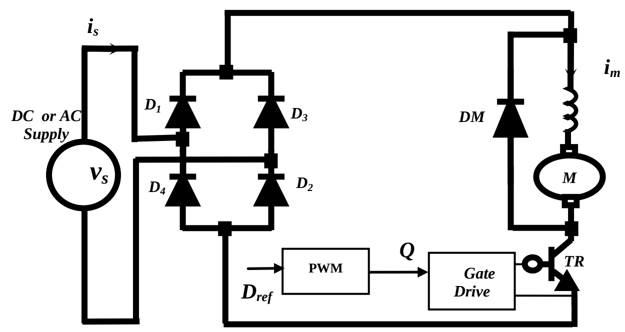
a) Conventional DC chopper (can be only fed from DC)



(b) Conventional AC voltage controller (can be only fed from AC)



(c) Proposed universal converter conf. 1 (can be fed from AC or DC)



(d) Proposed universal converter conf. 2 (can be fed from AC or DC)

Fig. 2. Connections of different motor- converter combinations.

the harmonic spectrum of the supply current is plotted as shown in fig. 5. The supply power factor, current total harmonic distortion and motor torque ripple factor are then calculated as [4]:

$$SPF = \frac{I_{s1}}{I_s} \cos \theta_{s1} \, . \tag{17}$$

$$THD = \sqrt{\left(\frac{I_{s1}}{I_s}\right)^2 - 1} \, . \tag{18}$$

$$TRF = \sqrt{\left(\frac{T_{m(rms)}}{T_{m(av)}}\right)^2 - 1} \, . \tag{19}$$

Table 1
Comparison between the conventional and the proposed drives for different delay angles (α) and duty cycles (D), respectively

		ω_m	$T_{m(av)}$	$T_{m(rms)}$	$V_{s(rms)}$	$I_{s(rms)}$	I_{s1}	θ_{s1}	SPF	THD	TRF
		rad/s	*Nm*	*Nm*	*V*	*A*	*A*	*Deg*	*pu*	*pu*	*pu*
Conventional	α =83°	67.8	0.5	0.78	75	1.12	1.44	-29.2	0.79	0.47	1.2
Proposed	D = 75%	67.7	0.5	0.65	75	1.14	1.49	-6.7	0.91	0.42	0.83
Conventional	α =108°	27.6	0.5	0.87	75	1.12	1.26	-46.1	0.56	0.76	1.42
Proposed	D = 50%	27.4	0.5	0.67	75	1.0	1.08	-8.4	0.77	0.74	0.87

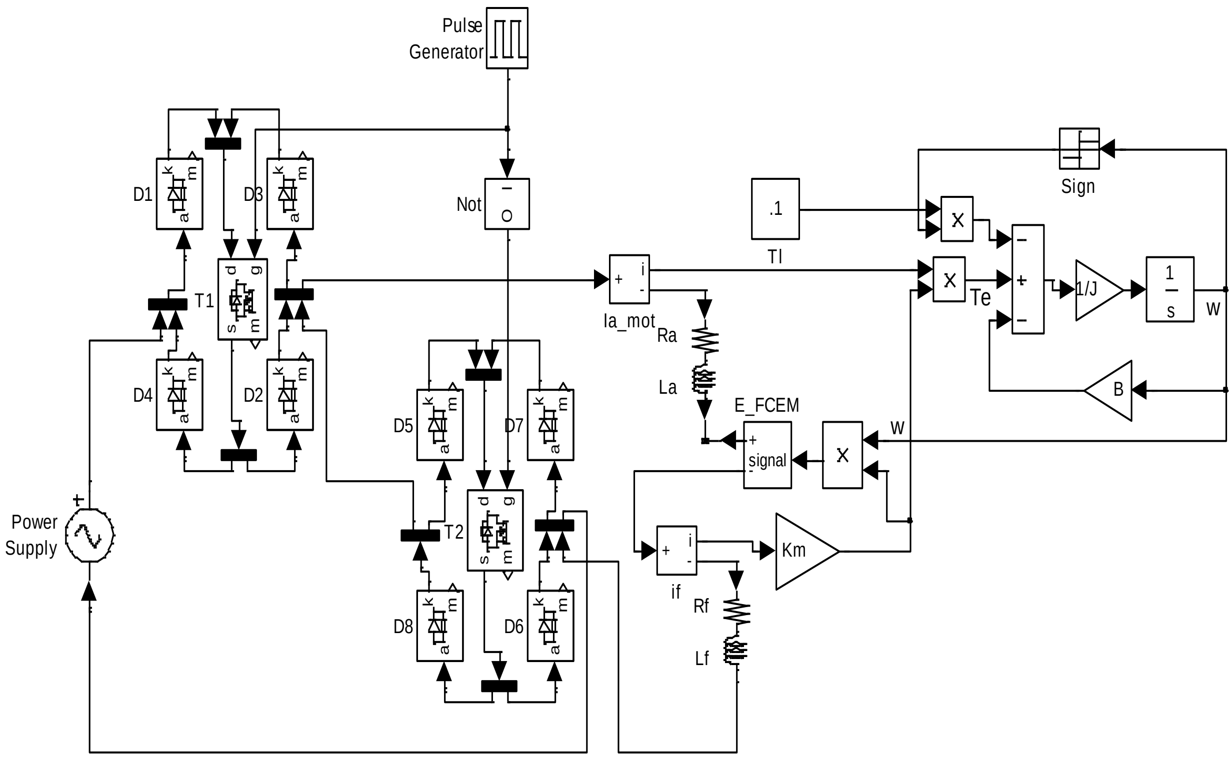


Fig. 3. Simulink simulated program (configuration in fig. 2-c as an example).

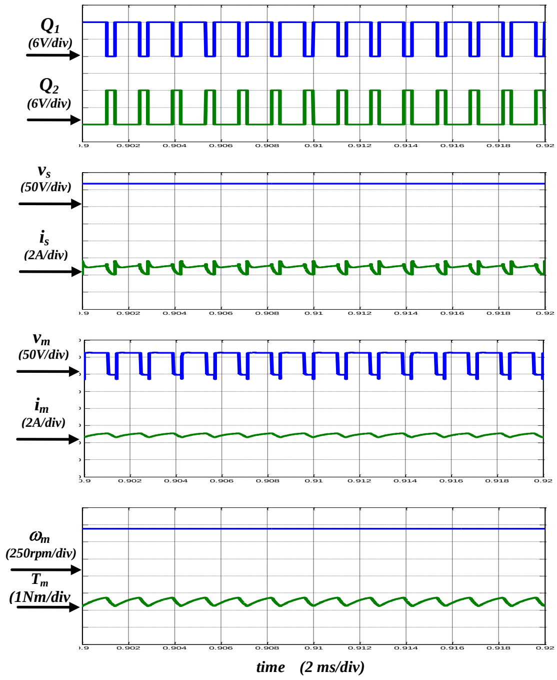
Simulation results obtained for the two proposed universal converters in figs. 4-c and 4-d are found nearly equal as depicted in table 1. Practically, difference may be found between the two converters due to the fact that dead time should be introduced between the gate signals of *TR*1 and *TR*2 in order to prevent possible supply short circuit in case of both transistors are on in the same time. Proposed universal converter in fig. 4-d is cheaper than that in fig. 4-c since it requires less switching devices, hence it will be the first choice to be used in practical applications. From table1, it can be seen that the proposed configuration operates with higher supply power factor (0.91 or 0.77) rather than the conventional one (0.79 or 0.56). Also it has lower motor torque ripple factor (0.83 or 0.87 rather than 1.2 or 1.42, respectively). Focusing views of motor speed for both drives, shown in fig. 6, indicates the reduction of speed ripple for the proposed converter. The harmonic spectrum of the supply current in case of the phase controlled converter, contains all the odd frequencies while the proposed PWM converter introduces only two harmonic components around (*chopping frequency/supply frequency*), see fig. 5. The Total Harmonic Distortion (THD) of the proposed drive is slightly lower (better) than the conventional for the given chopping frequency of 700Hz. This could be improved by increasing the chopping frequency [12]. The obtained simulation results reflect the better performance of the proposed drive from the point of view of both supply and motor sides. Comparing to the conventional AC voltage regulator, the proposed universal converters do not require any synchronization with the input supply and also do not depend on the load power factor. It can be seen that the proposed system can be successfully operated from the DC and AC supply with the same PWM gate signal, so it can be named as a universal motor-converter combination drive.

5. Experimental validation

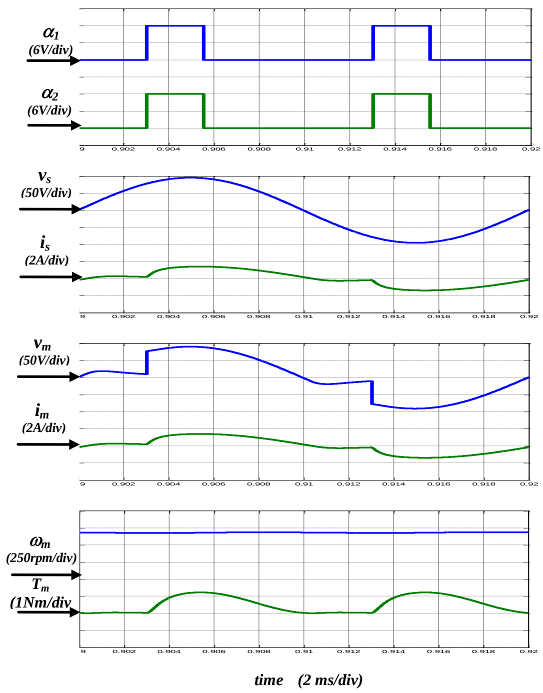
Through the experimental work, the actual voltage and current waveforms for different motor-converter combinations described in section 3 are investigated. The AC voltage controller has been implemented using two TIC126N SCRs, synchronizing circuit for delay firing angle (α) and isolating gate circuit based on pulse transformer isolation technique. The DC chopper has been implemented using an IRF740 MOSFET transistor and an IXYS fast recovery diode. The proposed system, shown in fig. 4-c, has been implemented using two IRF740 power transistors in conjunction with two H-bridge power rectifiers while configuration shown in fig. 4-d has been implemented using a single H-bridge KBPC3505 rectifier, a single IRF740 MOSFET and an IXYS fast recovery diode. A pulse width modulation circuit is implemented to feed the MOSFETs with controlled PWM gate signal through a gate drive circuit, designed based on opto-coupler technique, at suitable current drive level and isolated drive voltage. It should be noted that the gate signal is simply generated, as it does not need any synchronization with the supply voltage, as in case of the conventional AC voltage controller. A universal motor with specifications depicted in table 2 is driven with the each individual converter configuration and experimental waveforms have been obtained using digital scope. Fig. 7 shows actual motor voltage and current, for each converter, during different delay angle α fig. 7-b or duty cycles *D* figs. 7-a, 7-c and 7-d. It should be noted that the proposed universal converters produced typical waveforms, as depicted in fig. 7-a, to that of DC chopper in case of being fed from DC supply. For the proposed universal converter, motor speed and current are shown in fig. 8 for step speed variation (from 750 rpm to 250 rpm then back to 750 rpm) by controlling the duty cycle, and also during soft

Table 2
Motor specifications

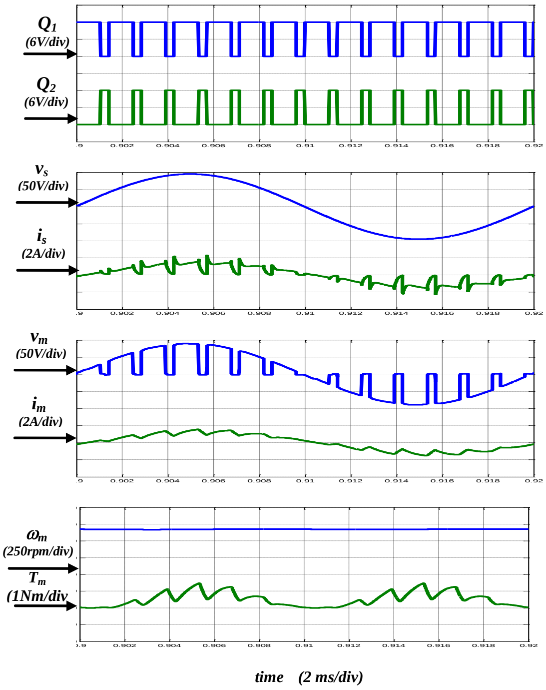
P_m	ω_m	V_m	I_m	R_a+R_f	L_a+L_f	K_a	J
W	*rpm*	*V*	*A*	*Ω*	*mH*	*Nm/A²*	*Kg.m²*
175	1500	220	1.5	22	23	0.4	0.002



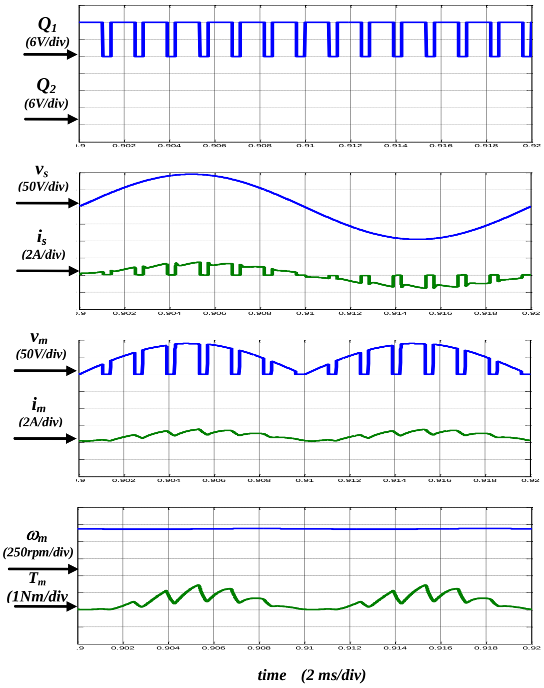
(a) DC Chopper in figure 2a (also same for configurations in figures 2c and 2d while being fed from DC)



(b) Ac voltage controller in figure 2b

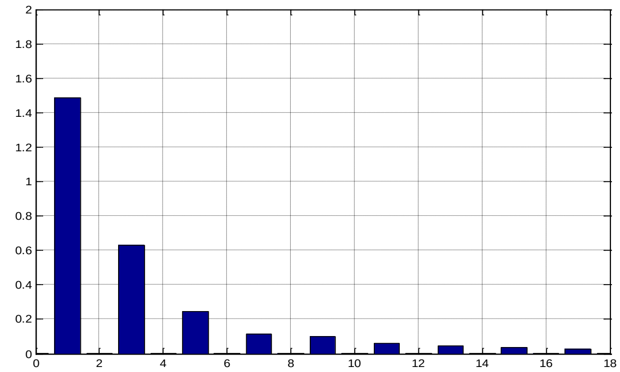


(c) Configuration in figure 2c while being fed from AC

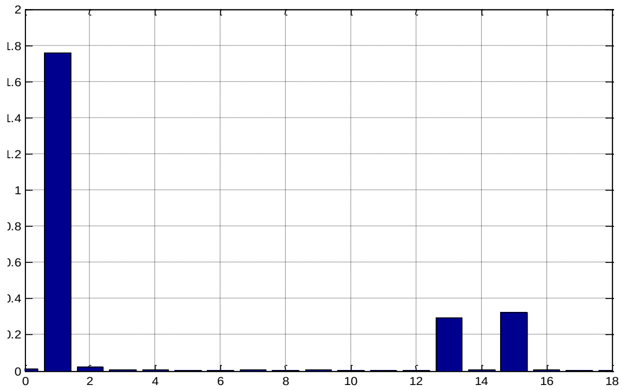


(d) Configuration in figure 2d while being fed from AC

Fig. 4. Simulated waveforms of different motor - converter combinations.



(a) conventional AC voltage controller



(b) proposed universal converter

Fig. 5. Harmonic spectrum of the supply current.

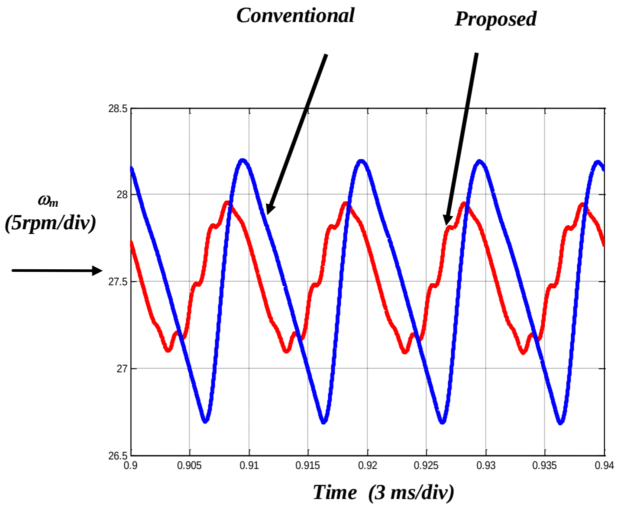
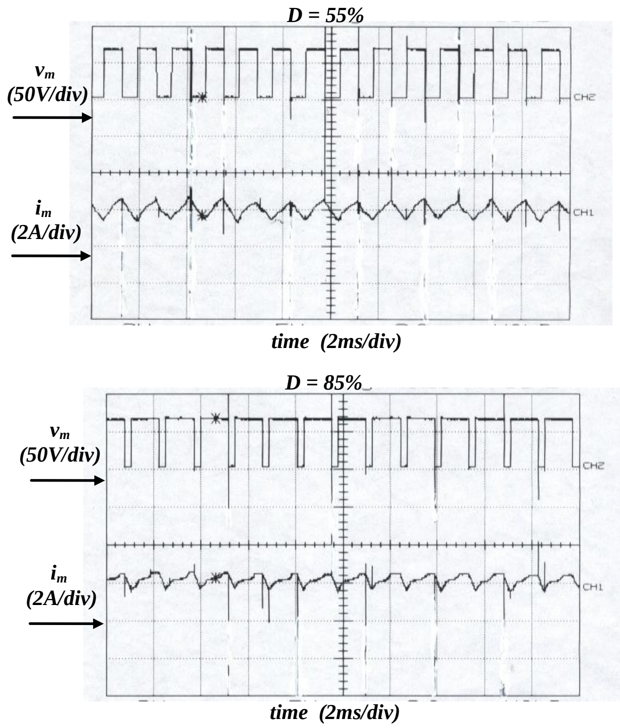
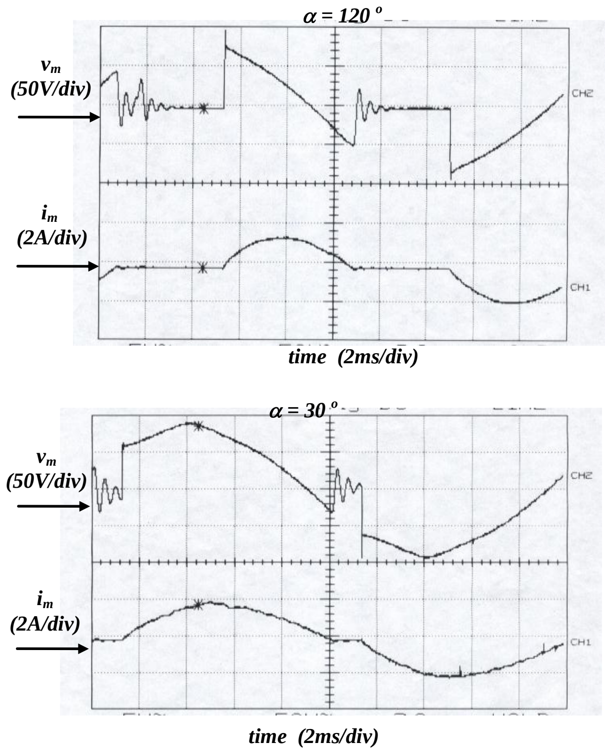


Fig. 6. Focusing the motor speed ripple.

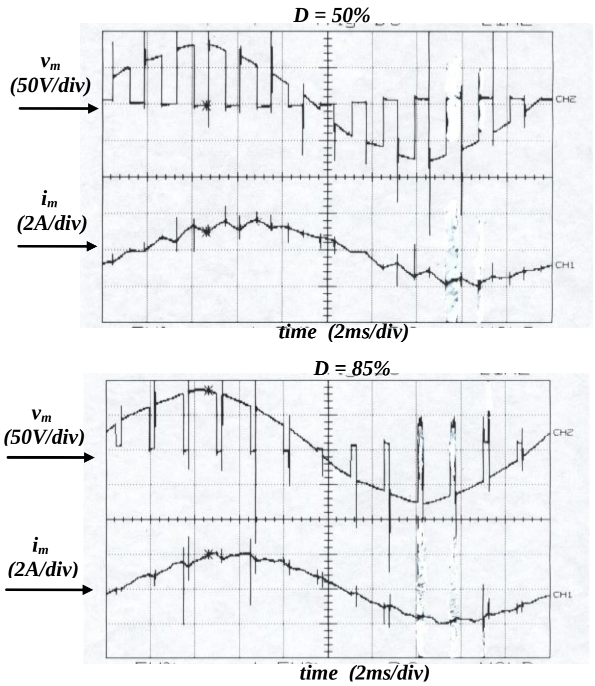


(a) DC Chopper (also for the proposed conf. 1 & 2 fed from DC)

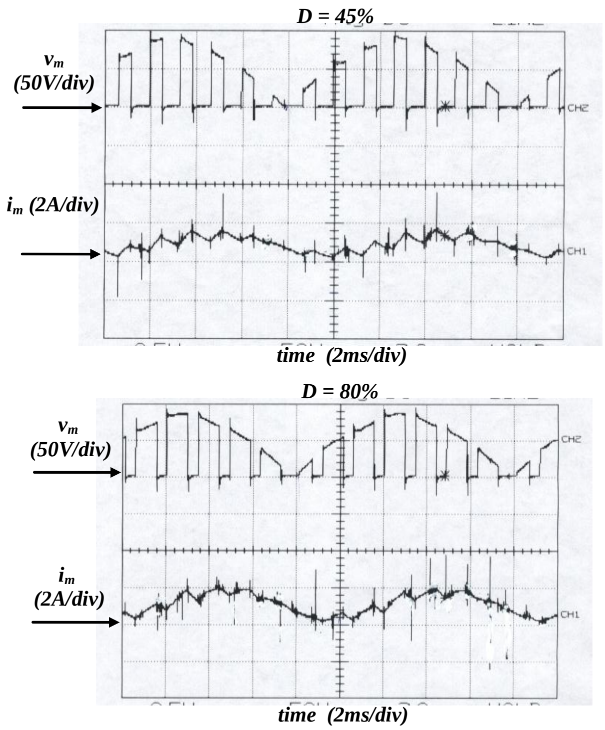


(b) AC Voltage controller

Fig. 7. Experimental motor voltage and current waveforms of different motor - converter combinations at different operating conditions.

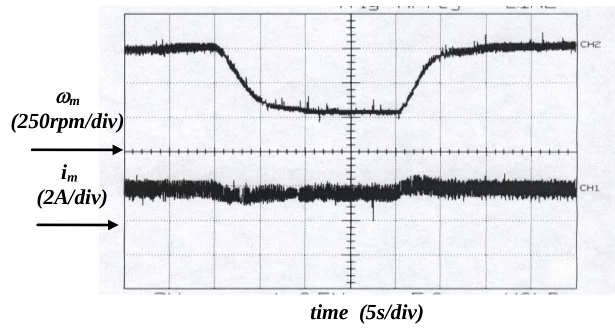


(c) Proposed conf. 1 fed from AC

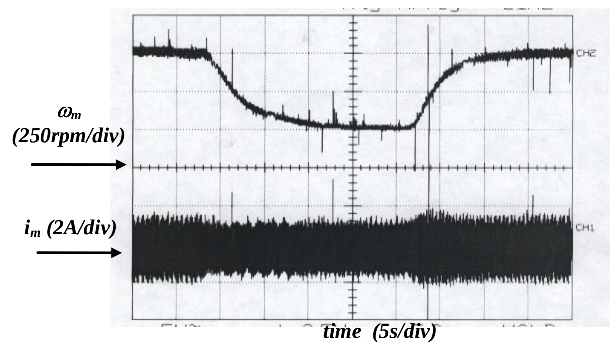


(d) Proposed conf. 2 fed from AC

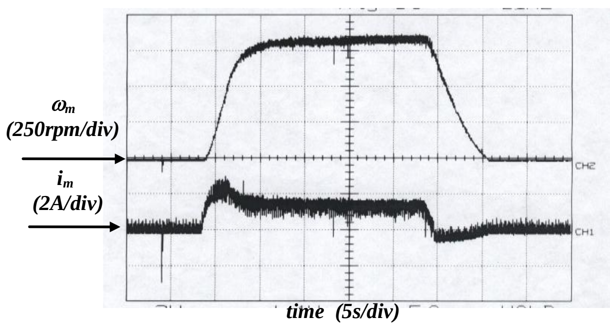
Fig. 7 (Cont.). Experimental motor voltage and current waveforms of different motor - converter combinations at different operating conditions.



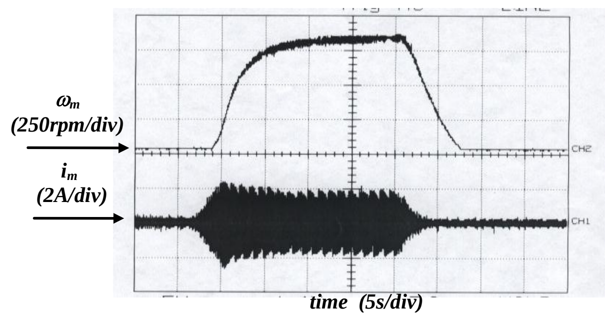
(a) Step change from 750rpm to 250rpm then back to 750 while feeding from DC



(b) Step change from 750rpm to 250rpm then back to 750 while feeding from AC



(c) Soft-start and soft-stop while feeding from DC



(d) Soft-start and soft-stop while feeding from AC

Fig. 8. Experimental motor speed and current response with the proposed universal converter by controlling the duty cycle for different operating conditions.

starting then soft stopping (in order to reduce starting current and mechanical stress) for DC and AC supply operations. Experimental waveforms in fig. 7 are well correlated with the corresponding simulated waveforms shown in fig. 4. From such results it can be seen that the proposed universal motor-converter combination can simply and effectively provide speed control and soft start/soft stop operation by simple control of the chopping duty cycle regardless of the supply type (DC or AC), validating such combination for practical applications, such as blenders, washing machines, vacuum cleaners and tractions. It should be noted that most practical applications of the universal motors are open loop controlled, however closed loop control for the proposed motor-converter combination can be simply achieved with simple speed tacho-meter and *PI* controller to adjust the duty cycle according to the required load speed.

6. Conclusions

A configuration of MOSFET's and full rectifier bridge has been introduced through this paper to control and drive the universal motor. Such configuration permits the simple and effective motor operation from either DC or AC supplies using the PWM technique. Simulation and experimental results showed the similarity with the conventional transistor DC chopper drive and the superiority over the conventional thyristor AC voltage controlled drive due to the higher supply power factor and lower total harmonic distortion, and also lower motor torque and speed pulsation for the proposed configuration particularly at lower speeds without the need of any synchronization with the input supply.

Nomenclatures

P_m, T_m, ω_m, v_m	are the motor power, torque, speed and voltage,
K_a, i_a, e_a	are the armature constant, current and induced voltage,
R_a, L_a, X_a	are the armature resistance, inductance and reactance,
R_f, L_f, X_f	are the field resistance, inductance and reactance,
v_s, i_s	are the supply voltage and current,
I_{s1}, θ_{s1}	are the first harmonic magnitude and phase shift,
T_{ON}, T_{OFF}, D	are the chopper on-period, off-period and duty cycle,
T_L, J, B	are the load torque, moment of inertia and viscous friction constants,
ϕ_d	is the direct axis flux,
s	is the laplace operator,
SPF, θ_s	are the supply power factor and power factor angle,
THD	is the total harmonic distortion,
TRF	is the torque ripple factor, and
α, β, δ	are the delay, extinction and conduction angles.

References

[1] B.S. Guru and H.R. Hiziroglu, "Electric Machinery and Transformers", Oxford Univ. Press, Inc., 3rd Edition (2001).

[2] R.N. Tuncay, M. Yilmaz and C. Onculoglu, "The Design Methodology to Developed New-Generation Universal Motors for Vacuum Cleaners", IEMDC, IEEE International Conference, USA, pp. 926-930 (2001).

[3] J. Cros. P. Viarouge P. Chalifour and J. Figueroa, "A New Structure of Universal Motor Using Soft Magnetic Composites", IEEE Trans. on Industrial Applications, Vol. 40 (2), pp. 550-557 (2004).

[4] M.H. Rashid, Power Electronics: Circuits, Devices and Applications, Pearson Prentice Hall, Inc., 3rd Edition (2004).

[5] C.I. Hubert, "Electrical Machines: Theory, Operation, Applications Adjustment, and Control", Maxwell Macmillan, Inc. (1991).

[6] P.C. Sen, "Principles of Electric Machines and Electronics", John Wiley and Sons, Inc., 2nd Edition (1997).

[7] I.J. Nagrath and M. Gopal, Control Systems Engineering, John Wiley and Sons, Inc., 2nd Edition (1982).

[8] A. Di Gerlando. R. Perini and G. Rapi, "Equivalent Circuit for the Performance Analysis of Universal Motors", IEEE Trans. on Energy Conversion, Vol. 19 (1), pp. 18-27 (2004).

[9] A.K. Mukhopadhyay, Matrix Analysis of Electrical Machines, New Age Publisher, Inc., 2nd Edition (2003).
[10] R.H. Wang, and R.T. Walte, "Modeling of Universal Motor Performance and Brush Commutation Using Finite Element Computed Inductance and Resistance Matrices", IEEE Trans. on Energy Conversion, Vol. 15 (3), pp. 257-263 (2000).
[11] C.M. Ong, Dynamic Simulation of Electric Machinery Using Matlab/ Simulink, Prentice Hall, Inc., 1st Edition (1998).
[12] K.E. Addoweesh and A.L. Mohamadein, "Microprocessor Based Harmonic Elimination in Chopper Type AC Voltage Regulators", IEEE Trans. on Power Electronics, Vol. 5 (2), pp. 191-200 (1990).

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