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A FIVE PHASE SWITCHED RELUCTANCE MOTOR PART 2: POWER CONVERTER AND SWITCHING CONTROL

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ABSTRACT

This paper describes the development of an economical and reliable unipolar power converter for switched reluctance machine with a relatively high number of phases. The developed converter uses minimum number of switching devices with full capability to control phase current waveforms. The experimental load test of a five-phase switched reluctance motor shows that the developed converter matches, if not superior to, the conventional asymmetric half bridge one over a very wide speed range.

1. INTRODUCTION

Recent years have recorded a surge of interest with switched reluctance SR machines in both academic and industry centres[15]. The rugged construction and simple converter configurations are among many potential advantages of this new machine. In its basic form, SR motor consists of a doubly salient variable reluctance structure fed by an electronic power converter. Essentially, this converter should be synchronized with the rotor position via a feedback signal provided by a position transducer mounted on the motor shaft[1].

In spite of the growing interest of SR machine, it still has urgent problems need to be dealt with before being fully accepted. Torque pulsations is one of these problems. Torque pulsations are dependent on various interrelated factors among them number of phases, number of poles, pole geometric dimensions, operating speed and converter control parameters. In an accompanying paper [Part 1] the use of high number of phases with high inductance overlap ratio has been proposed to reduce the torque ripple content on the motor shaft. To the date, existing power converters are not suitable for such increase of phase numbers. Some of these converters have restrictions on phase numbers, others have limited capability to handle overlapped phases, while the third group requires unreasonable high number of switching devices. For the proposed category of SR machines, the principle of *Pollock and Williams*[12] is used, in this paper, to develop a compact five phase power converter with only six switching devices.

2. BASIC REQUIREMENTS AND IDEAL SPECIFICATIONS

SR machine has its own converter specification requirements which, to some extent, are different from other conventional electrical machines. To have a clear understanding of the basic requirements let us use the linear model of SR motor. If one phase winding is modeled as a resistance R and an inductor L in series, the voltage equation may be written as,

$$V = R.i + \frac{d\psi}{dt} \tag{1}$$

Assuming magnetic linearity and negligible resistance,

$$V = \frac{d(L.i)}{dt} = L\frac{di}{dt} + i\frac{dL}{dt} \tag{2}$$

Which may be rewritten as,

$$V = L\frac{di}{dt} + \frac{i}{2}\frac{dL}{dt} + \frac{i}{2}\frac{dL}{dt} \tag{3}$$

The rate of flow of energy is obtained by multiplying both sides of equation(3) by the current i,

$$Vi = \left(Li\frac{di}{dt} + \frac{i^2}{2}\frac{dL}{dt}\right) + \frac{i^2}{2}\frac{dL}{d\theta}\frac{d\theta}{dt} \tag{4}$$

Which also may be rewritten as,

$$Vi = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + \frac{i^2}{2}\frac{dL}{d\theta}\omega = P_{mag} + P_{mech} \quad (5)$$

Two points could be observed in this equation. The first one is that besides the mechanical power P_{mech}, the power converter should be able to handle the floating magnetic power P_{mag}. In the idealized case magnetic energy is, according to the energy flow, exactly half of the energy supplied by the source in each stroke. Converter configurations are mainly distinguished by the way in which this energy is managed. The second point is that the power flow is independent of current direction. Based on this advantage a simple and reliable unidirectional converter circuit is required in contrast to the most complicated and costly bidirectional inverter circuits required for ac machines.

An ideal power converter circuit for SR motor would satisfy the following conditions:

1. The ability of fast establish the current pulse.
2. The ability of fast recover magnetic energy.
3. To be able to control the current pulse level.
4. No restrictions on phase numbers.
5. Uses a low switch/phase ratio.
6. Switching devices are rated close to supply voltage.
7. The use of full supply voltage across each phase.

Only if all these conditions are met, SR drive would become comparable with conventional inverter-driven induction machine.

3. AN OVERVIEW OF EXISTING SR CONVERTER TOPOLOGIES

Numerous circuit configurations are developed for SR machines. Each of these circuits has its own merits. In this section, most popular configurations are briefly reviewed. In all these circuits, main switches, referred to by S, could be any of different electronic switches such as thyristors, bipolar transistors, darlingtons, gate turn-off thyristors (GTO), MOSFETs or isolated gate bipolar transistors (IGBTs).

3.1. *EXTERNAL RESISTANCE DUMP CIRCUIT*[5,7].

This circuit is shown in figure(1). It is simple, cheap and suitable for low power applications. The voltage rating of the electronic switch depends on the value of the external resistance used. The efficiency of this circuit is low as some of the input energy is wasted in the external resistance and regeneration is not possible.

3.2. *BIFILAR WINDING CIRCUIT*[2,3].

As shown in figure(2), each phase requires one electronic switch, a diode and an auxiliary winding. When the electronic switch is turned-off, the stored magnetic energy is recovered by the secondary coil. It meets the minimum switch requirement with one switch/phase ratio; however,the voltage spikes resulting from imperfect magnetic coupling increase the switch voltage ratings to twice phase voltage or even higher. It also suffers from poor copper utilization and the need of many connections to the motor.

3.3. *SPLIT SUPPLY CIRCUIT*[14].

This circuit is suitable for SR motors with even number of phases and high voltage applications. Its configuration is shown in figure(3), in which centre tap is formed using two capacitors. It meets the minimum switch requirement but a dual dc supply is necessary.

3.4. *THE H-SCHEME CIRCUIT*[5,14].

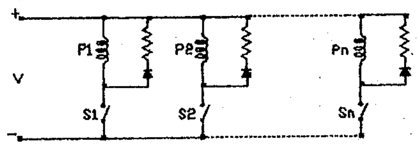
This scheme is shown in figure(4). It is a modified version of split supply circuit, but, at least 4 phases (or multiple) are required. It needs complex control strategy to maintain current balance between phases.

3.5. *CAPACITOR DUMP CIRCUIT*[14].

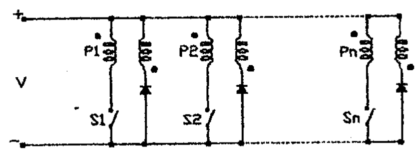
This circuit is shown in figure(5), in which the advantage of using one switch per phase is retained but it requires a chopper for energy recovery and additional common capacitor for dumping magnetic energy of the off going phase. Main devices voltage rating is in excess of double the supply voltage and it is complex and costly.

3.6. *A COMMON SWITCH CIRCUIT*[6,10].

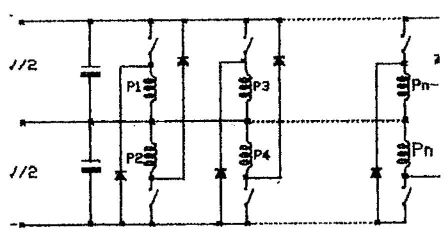
Figure(6) shows a sketch of this circuit. It has one switch per phase and a common switch for all phases. It uses only PWM voltage control and overlap between phases is not possible. Voltage rating of each switch is the dc link voltage.



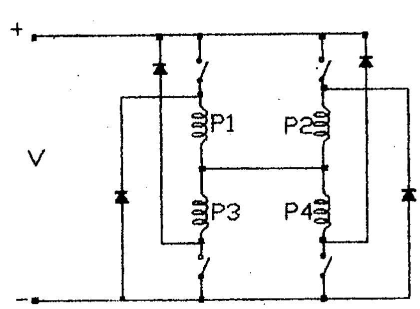
Figure(1) External resistance dump circuit



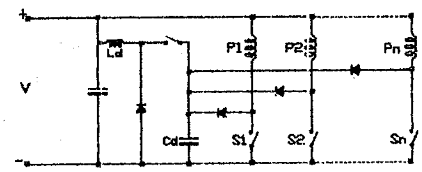
Figure(2) Bifilar winding circuit



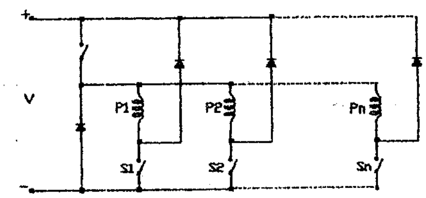
Figure(3) Split supply circuit



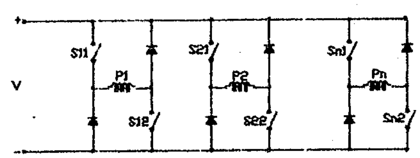
Figure(4) The H-scheme circuit



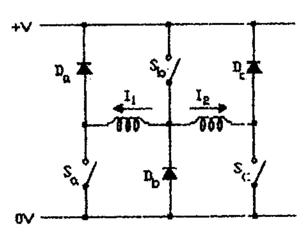
Figure(5) Capacitor dump circuit



Figure(6) A common switch circuit



Figure(7) Asymmetric half bridge converter



Figure(8) Section of the proposed converter

3.7. *ASYMMETRIC HALF BRIDGE CONVERTER*[9,12]

This circuit is shown in figure(7). It is identical to that one used by ac machines, except that with SR drives phase windings are connected in series with top and bottom switches of the same leg rather than connecting these windings between the mid-points of different legs. This circuit meets most of the requirements mentioned in section(3). The only drawback of this configuration is its high switch/phase ratio. The new configuration proposed in this paper attempts to improve the switch utilization of this circuit.

4. PROPOSED FIVE-PHASE CONVERTER WITH MINIMUM SWITCHES

The proposed five-phase converter is based on the principle of *Pollock and Williams*[12], which is summarized here. Figure(8) shows a general section of two phases connected to three switching devices. The central switch S_b is connected to two phase windings, rather than one as in the conventional asymmetric half bridge in figure(7). The opposite ends of each phase are connected to one upper and one lower switching devices. Each of these switches may also be connected to other phase windings.

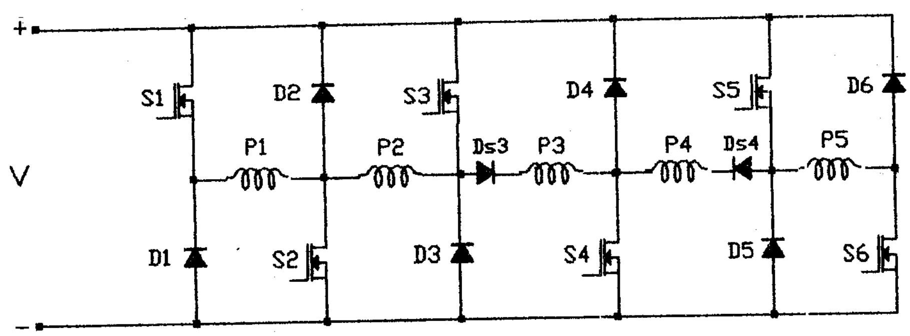
I_1	I_2	S_a	S_b	S_c
increase	zero	on	on	off
hold	zero	on	chop	off
hold	increase	chop	on	on
hold	hold	chop	on	chop
decrease	hold	off	off	on

Table(1) Operation of switches of Fig.8 for one pulse of I_1

The switching algorithm is summarized in Table(1), where each switching device takes into account the current demand of each phase winding connected to it. To increase the current in the first phase winding, both switches S_a and S_b are turned on. When this current reaches the chopping level S_b starts to modulate to hold I_1 constant. When the rotor turns one step angle from the start of I_1, the next phase will need to start. At this moment S_a and S_b exchange modulation such that I_2 is allowed to increase through S_b and S_c. When I_2 reaches the chopping level S_c starts to modulate. Sometime later the first phase would need to be turned off. At this moment S_a turns off and S_b exchange modulation with S_c such that the first phase winding is exposed to a voltage which alternates between zero and full negative value. After one step angle from the turn-off of S_a, S_b would be turned-off and the first phase is now exposed to the full negative supply voltage to collapse any current still flowing in that winding.

At high speeds, the induced back emf in the winding would be sufficient to maintain the current within its level without chopping. In this case each positive voltage pulse would be followed by a zero volt period while the next phase is in duty. After that period the full negative voltage would be applied across the first phase. to complete the collapse of its current.

The circuit diagram of the proposed five-phase converter is shown in figure(9). In this circuit only six switches and six freewheeling diodes are required. Since S_1 overlaps S_6 and S_2 overlaps S_5, two series diodes are needed to block unwanted currents between both sides of the configuration.



Figure(9) The proposed 5-phase converter for SR motor.

Under chopping this circuit passes through 20 different switching modes of operation, and this cycle is repeated for every rotor pole. These modes are summarized in table(2), where {0} stands for {*off*}, {1} stands for {*on*} and {1/0} is a chopping mode.

Switching algorithm given in table(2) is formulated into six logic equations, one for each switch, to govern the switching process of the converter. these equations are functions of phase position and current control signals. The following equations are obtained for the forward direction of rotation. Another similar six equations could be written for the reverse direction.

M	P1	P2	P3	P4	P5	C1	C2	C3	C4	C5	S1	S2	S3	S4	S5	S6
1	1	0	0	0	1	1	0	0	0	1/0	1	1	0	0	0	1
2	1	0	0	0	1	1/0	0	0	0	1/0	1	1/0	0	0	0	1
3	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0	0	0
4	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0	0	0
5	1	1	0	0	0	1/0	1	0	0	0	1/0	1	1	0	0	0
6	1	1	0	0	0	1/0	1/0	0	0	0	1/0	1	1/0	0	0	0
7	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0	0
8	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0	0
9	0	1	1	0	0	0	1/0	1	0	0	0	1/0	1	1	0	0
10	0	1	1	0	0	0	1/0	1/0	0	0	0	1/0	1	1/0	0	0
11	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0
12	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0	0
13	0	0	1	1	0	0	0	1/0	1	0	0	0	1/0	1	1	0
14	0	0	1	1	0	0	0	1/0	1/0	0	0	0	1/0	1	1/0	0
15	0	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0
16	0	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1	0
17	0	0	0	1	1	0	0	0	1/0	1	0	0	0	1/0	1	1
18	0	0	0	1	1	0	0	0	1/0	1/0	0	0	0	1/0	1	1/0
19	0	0	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1
20	0	0	0	0	1	0	0	0	0	1/0	0	0	0	0	1/0	1

Table(2) Summary of switching modes for the proposed converter.

$$S_1 = P_1 \cdot \overline{P_2} \cdot P_5 + C_1 \cdot P_1 \cdot \overline{P_2} \cdot \overline{P_5} + C_1 \cdot P_1 \cdot P_2 \quad (6)$$

$$S_2 = C_1 \cdot P_5 \cdot P_2 \cdot \overline{P_2} + C_1 \cdot \overline{P_1} \cdot P_2 \cdot \overline{P_3} + C_2 \cdot P_2 \cdot P_3 + \overline{P_5} \cdot P_1 \cdot \overline{P_2} + P_1 \cdot P_2 \cdot \overline{P_3} \quad (7)$$

$$S_3 = C_2 \cdot P_1 \cdot P_2 \cdot \overline{P_3} + C_3 \cdot \overline{P_2} \cdot P_3 \cdot \overline{P_4} + C_3 \cdot P_3 \cdot P_4 + \overline{P_1} \cdot P_2 \cdot \overline{P_3} + P_2 \cdot P_3 \cdot \overline{P_4} \quad (8)$$

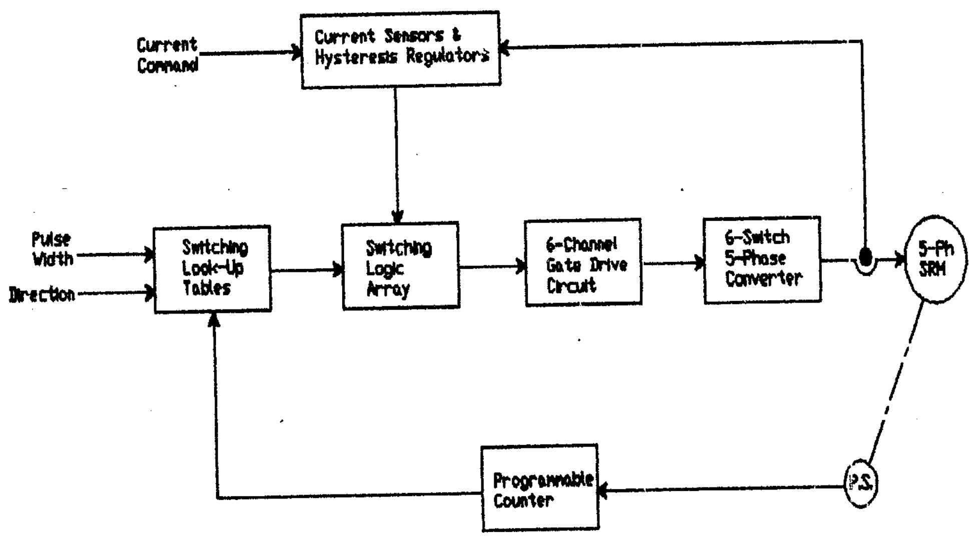
$$S_4 = C_3 \cdot P_2 \cdot P_3 \cdot \overline{P_4} + C_4 \cdot \overline{P_3} \cdot P_4 \cdot \overline{P_5} + C_4 \cdot P_4 \cdot P_5 + \overline{P_2} \cdot P_3 \cdot \overline{P_4} + P_3 \cdot P_4 \cdot \overline{P_5} \quad (9)$$

$$S_5 = C_4 . P_3 . P_4 . \overline{P_5} + C_5 . \overline{P_4} . P_5 . \overline{P_1} + C_5 . P_5 . P_1 + \overline{P_3} . P_4 . \overline{P_5} + P_4 . P_5 . \overline{P_1} \quad (10)$$

$$S_6 = C_5 . P_4 . P_5 . \overline{P_1} + \overline{P_4} . P_5 . \overline{P_1} + P_5 . P_1 . \overline{P_2} \quad (11)$$

5. PRACTICAL IMPLEMENTATION AND EXPERIMENTAL RESULTS

A laboratory prototype 5-phase SR drive fed by the proposed converter has been built and experimentally investigated. A block diagram of this system is shown in figure(10). The main parts of this system are briefly described here.



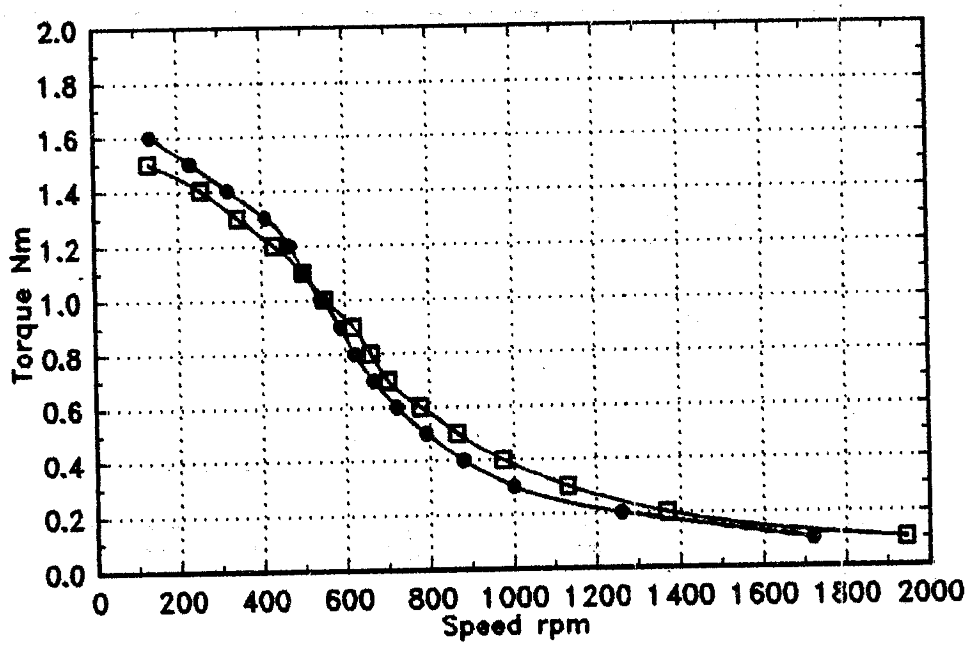
Figure(10) A block diagram of the 5-phase drive system under investigation

The position feedback is obtained by an optical *shaft encoder* of 500 pulses per revolution, mounted on the motor shaft. A resolution of 0.72° could be obtained with this encoder and this resolution is sufficient to study the system performance. The output of the encoder is used to clock a *programmable up/down counter*. The function of this counter is to generate a binary code for each rotor position. This code is later combined with more data about pulse width and direction of rotation. The whole binary word is used to address a pre-loaded 5-phase switching pattern from an EPROM look-up tables. A hall-effect 5-channel *current sensors* are used to measure phase currents. These measured values are compared with a reference current command to generate current control signals for the logic circuit.

The switching algorithm defined by equations(6) through(11) is combined with another similar set of equations for the opposite direction and the whole set is programmed on an Erasable Programable Logic Device (EPLD) chip. The output of this stage is the switching commands for the six switches. These commands are sent to six MOSFETs through six channel gate drive circuit. A new 5-phase SR motor is designed for this system and its specifications are given in accompanying paper[Part 1].

As explained in section(5), depending on the operating conditions, a positive voltage pulse is followed by either zero or reduced negative voltage period. This will increase the time taken to reduce phase current to zero. To eliminate any negative torque on the shaft, shorter conduction pulses would be necessary. This might raise a question about a possibility of high derating of system performance. To investigate this point, the torque-speed characteristics are recorded for both the proposed converter and a fully independent 10-switch asymmetric half bridge one and the results are given in figure(11). This test is carried for both converters at the same switching conditions. A very little derating of machine torque is observed at high speeds, but the proposed converter gives better torque performance at low speeds. At high speeds a little negative torque is produced at the end of each pulse and this negative torque reduces the whole average torque slightly. At low speeds the case is much better since there is enough time to reduce the current to zero before the negative torque region. The proposed converter is superior than the conventional one at low speeds since the recovered magnetic energy partially produces torque instead of wholly sent back to the supply. This explains why the proposed converter produced higher torque at low speeds. Besides torque performance improvement converter *volt ampere requirement* and *energy ratio* would be improved.

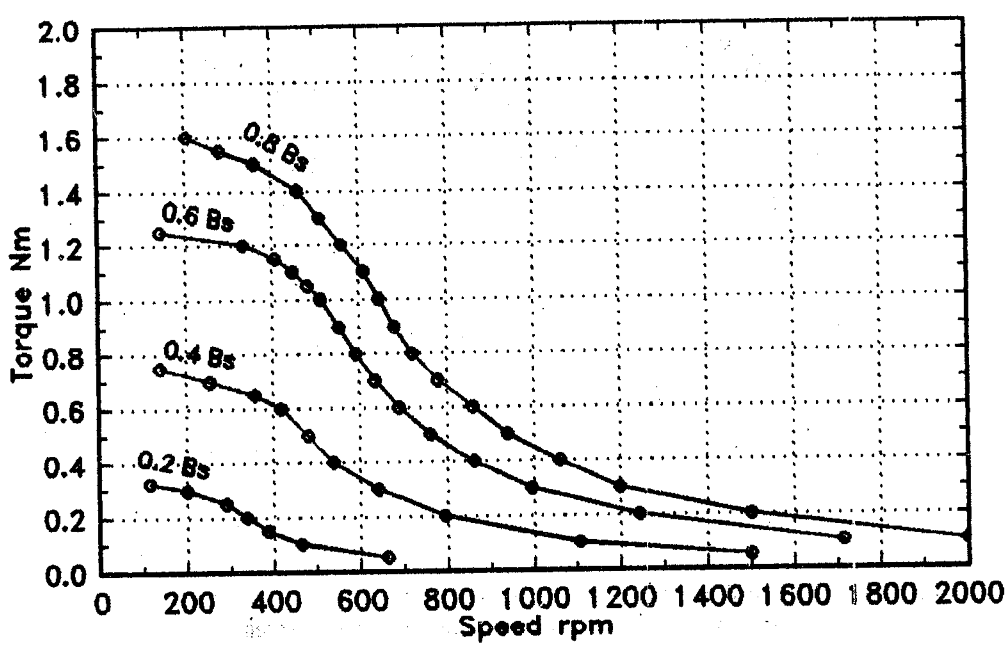
A further experimental investigation is carried to test the ability of the new converter and the proposed switching algorithm to control either conduction pulse width or current chopping level. Figures (12) and (13) are recorded from these test experiments. The phase voltage and current waveforms for the loaded machine, under chopping and no-chopping are shown in figures (14) and (15).



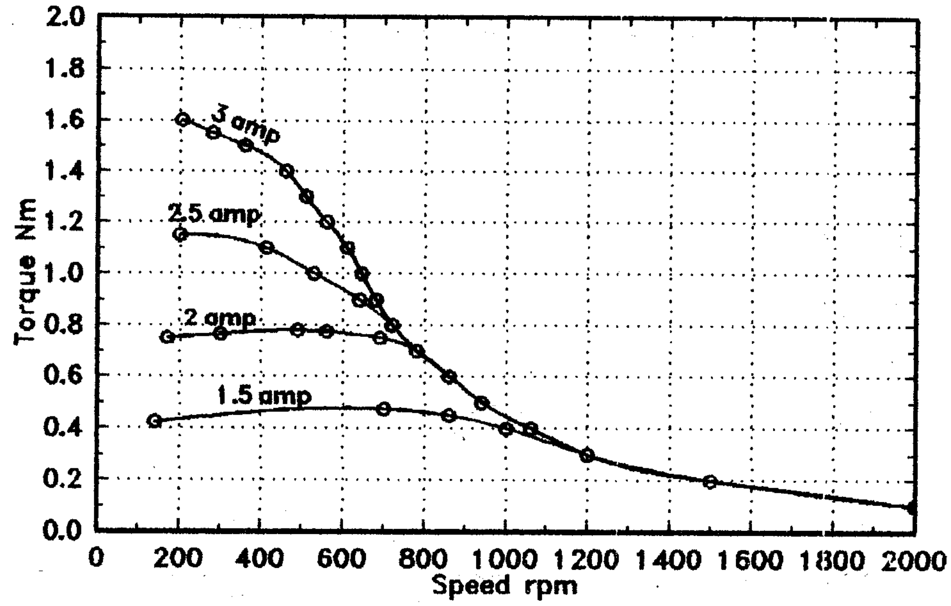
Figure(11) Experimental torque-speed for both conventional and developed converters.

• Developed converter.

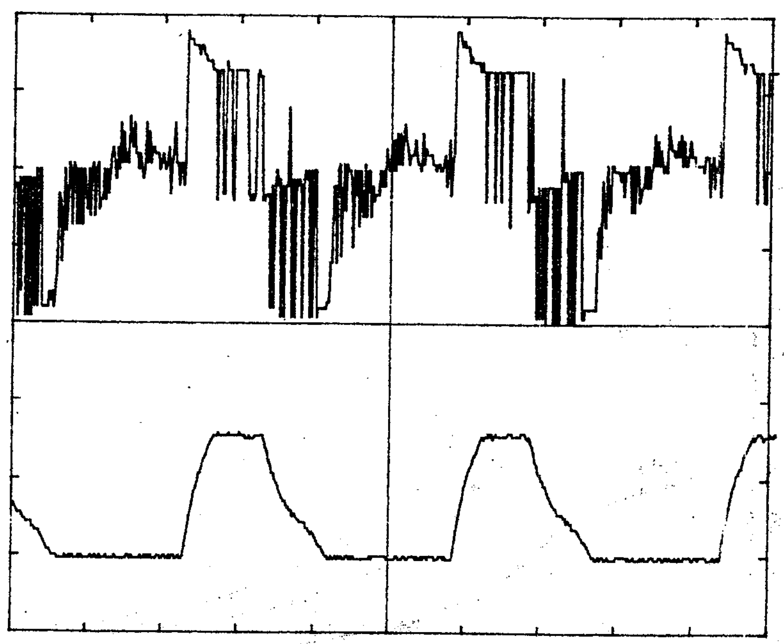
▯ Conventional converter.



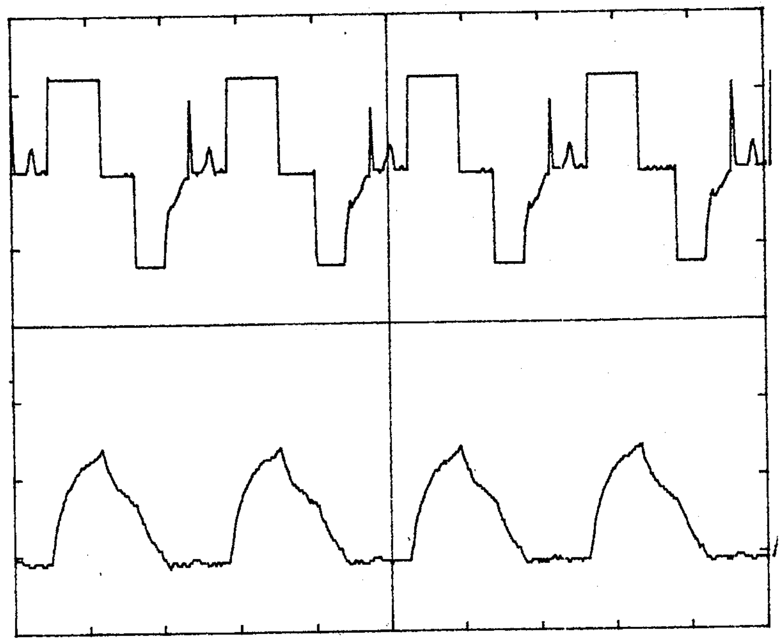
Figure(12) Experimental torque-speed for the developed system for different pulse width.



Figure(13) Experimental torque-speed for the developed system under different chopping levels.



Figure(14) Recorded voltage and current waveforms on one phase winding under chopping.
Top: Phase voltage 50 V/Div & Bottom: Phase current 2 amp/Div.
Horizontal: 5 mSec/Div.



Figure(15) Recorded voltage and current waveforms on one phase winding without chopping.
Top: Phase voltage 50 V/Div & Bottom: Phase current 2 amp/Div.
Horizontal: 10 mSec/Div.

6. CONCLUSION

This paper provides an experimental investigation study of new power converter for a switched reluctance machine with a relatively high number of phases. The proposed converter uses minimum number of switching devices but it still retains the potential advantages of half bridge asymmetric circuit and sometimes superior to it. A slight torque derating could be faced at high speeds but with the careful choice of both *switch on* and *switch off* angles the system performance could be greatly improved. The proposed scheme have been tested under both variable conduction angles and different current levels. A combination between both these approaches would result in a very wide range of system performance to suit a specific application.

7. LIST OF SYMBOLS

C_{1-5} Current control binary signals.
P_{1-5} Phase reference patterns binary signals.
S_{1-6} Switches binary command signals.

V Supply voltage.
R Resistance of phase winding.
i Phase current.
L Phase inductance.
ψ Flux linkage.
ω Rotor angular speed.
θ Rotor position.
β_s Stator pole arc in rad.

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محرك الممانعة المغناطيسية المتغيرة خماسي الأوجه المغذى بنبضات
الجزء الثاني: المغذى الإلكترونى وآليات التحكم فيه

مع بدايات العقد الماضي وفي ظل التطور الهائل في مجال تكنولوجيا إلكترونيات القوى ظهر إلى الوجود محرك الممانعة المغناطيسية المتغيرة المغذى بنبضات، وهذا المحرك ذو طبيعة خاصة تختلف عن المحركات الكهربية التقليدية، فهو يحتاج دائما إلى مغذى إلكترونى ليقوم بمهمة توصيل وتبديل أطراف تغذية المحرك أثناء الدوران.

ونظرا لأن المغذى الإلكترونى يمثل جزء أساسي من منظومة محرك الممانعة المغناطيسية المتغيرة، فإن خصائص هذا المغذى تنعكس مباشرة على أداء المنظومة كلها، وفي مقالة أخرى للمؤلفين (في نفس هذا العدد) تم بيان الفائدة الكبيرة من زيادة عدد أوجه المحرك، ولكن المغذيات المتوفرة حاليا – بصفة عامة –لاتتناسب مع مثل هذه الزيادة في عدد الأوجه، حيث بعضها يقصر إستخدامه على عدد أوجه محدد والبعض الآخر لايفي بمتطلبات تغذية الأوجه المتراكبة معا، أما البعض الثالث فيستخدم عددا كبيرا جدا من وحدات المفاتيح الإلكترونية التى تزيد من تكلفة بناء المظومة، وتقدم هذه المقالة دراسة تحليلية وعملية لمغذى إلكترونى جديد لهذا النوع من المحركات يستخدم أقل عدد من مفاتيح التغذية الإلكترونية مع التغلب على عيوب المغذيات الموجودة حاليا، وقد تم تصميم أسلوب تتابع التشغيل لهذا المغذى الجديد ثم صياغته في صورة معادلات منطقية، وتم أيضا برمجة هذه المعادلات علي وحدات شرائح السيليكون الرقمية (EPLD) والتى تتلقى إشارات التشغيل من أسلوب نمطي تم أيضا تصميمه لهذا الغرض وتخزينه على وحدات الذاكرة الإلكترونية (EPROM) والتى بدورها تعطى إشارات التشغيل تبعا لبيانات الموضع التى يتم أيضا قياسها بطريقة إلكترونية عالية التحليل.

تخلص هذه الدراسة إلي أن المغذى الجديد المقترح يفي بجميع متطلبات تغذية المحرك من حيث التحكم في كل من عرض وموضع النبضة و مستوى تيار التغذية، كما أنه – وبعدد أقل من مفاتيح التغذية الإلكترونية – يعطي خصائص عزم وسرعة للمحرك قريبة جدا من تلك التى يعطيها أحد المغذيات المشهورة في هذا الصدد، ويتفوق عليه عند السرعات المنخفضة.