Mansoura Engineering Journal

Volume 13 | Issue 1 Article 18

6-1-2021

# Design and Application of a Transistorised Inverter Suitable for Switched Reluctance Drives.

M. El-Khazendar
*Assistant Professor, AMIEE., Electrical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt.*

A. Kalas
*Assistant Professor, Suez Canal University, Egypt.*

M. Abuzeid
*Assistant Professor, Tanta University, Egypt.*



## Recommended Citation

El-Khazendar, M.; Kalas, A.; and Abuzeid, M. (2021) "Design and Application of a Transistorised Inverter Suitable for Switched Reluctance Drives.," *Mansoura Engineering Journal*: Vol. 13 : Iss. 1 , Article 18.
Available at: https://doi.org/10.21608/bfemu.2021.189371

# DESIGN AND APPLICATION OF A TRANSISTORISED INVERTER SUITABLE FOR SWITCHED RELUCTANCE DRIVES

تصميم و تطبيق دائرة الكترونية تعمل بالترانزستور لادارة محركات الممانعة المغناطيسية المتقطعة

M.A.EL-Khazendar
B.Sc., Ph.D., AMIEE
Tanta University,
EGYPT

A.H.M.Kalas
B.Sc., M.Sc.
Suez Canal University,
EGYPT

M.S.Abuzeid
B.Sc., M.Sc.
Tanta University,
EGYPT

خلاصة : يغطى هذا البحث خطوات تصميم و اختبار دائرة الكترونية اقتصادية و بسيطة احادية القطب. وقد استخدمت هذه الدائرة مع حساس الكترونى للوضع لادارة محرك قرصى ذو ممانعة مغناطيسية متغيرة وثنائى الطور. هذه الدائرة الالكترونية التجريبية تحتوى على ترانزيستور واحد فى كل طور و مقاومة خارجية لامتصاص الطاقة المغناطيسية المخزونة. وقد تم حساب قيمة كل عنصر مستخدم فى مكونات هذه الدائرة الالكترونية وهى : دائرة الفتح الرئيسية ـ دائرة التعشيق ـ دائرة الحماية ـ دائرة التحكم. وقد تم استخلاص النتائج الديناميكية لهذا النظام مع الحصول على منحنيات مختلفة للعزم بالنسبة للسرعة من خلال التحكم فى زاويتى التحكم والبدء. وقد ادت هذه الدراسة الى أن أداء هذا النظام لازال غير مرضى فى هذه المرحلة الاولى من البحث ولكنه قابل للتطور بصوره مشجعة.

## ABSTRACT

This paper gives the design procedure and testing results of an economical unipolar inverter circuit. This circuit together with a simple but reliable position transducer had been used to drive a 2-phase variable reluctance disc motor. The prototype switching circuit has one bipolar power transistor per phase and an external resistor for dumping the stored magnetic energy. The different components of the main switching circuit, the interface circuit, the control logic circuit and the electronic protection circuit have been worked out. The running performance of this drive system has been investigated through several experimental results. Different torque-speed characteristics are shown to be obtainable by controlling both switch-on angle and conduction angle. The overall performance of the system is still rather poor but it is considered to be satisfactory for this stage of development.

## 1. INTRODUCTION

Power electronic circuits have been developed so fast such that semiconductor devices having higher blocking voltages, more current carrying capability, shorter turn-off time, lower driving signals, wider safe operating areas, higher switching frequencies and lower cost are available. The progress is very fast and many new types of static switching devices are emerging from time to time. Nowadays there are different switching devices suitable for electrical machinee, such as: thyristors (SCR), bipolar junction transistors (BJT) , Darlingtons, gate turn off (GTO), metal oxide semiconductor field effect transistors (MOSFET) and insulated gate transistors (IGT). Each switching device has its own distinct features which make it suitable for certain application more economically than other types.

Many novel power electronic circuits have been introduced to drive the different types of the well known machines (dc machines, synchronous machines, and induction machines). Also a considerable research effort has been devoted to the design of new forms of special electrical machines and their appropriate switching circuits such as : Stepping motors, Switched Reluctance Drives (SRD) and Permanent Magnet brushless machines (PM). But, in contrast with the conventional machines, Steppers and SRD do not work without employing suitable types of electronic circuits. Also, these special machines and their drive circuits are completely interactive and the whole system characteristics are greatly affected with the type of the switching circuit used.

It must be noted that the power electronic designer must choose the proper switching device which satisfies the required application more economically and due to the rapid development in this field he must develop the comparison criterion from time to time. As an example, at the begining of 1970, with the devices available at that time, a comparison showed that transistors represent the most cost effective solution for inverter circuits up to 2 KW rating and above this level the SCR was dominated. Nowadays the picture is completely different.

The main concern of this paper is to demonstrate the design and building of a switching circuit which can be used to energise an SR disc motor. The next Section reviews the different components of a switched reluctance drive system (the variable reluctance motor, the position sensor and the complete switching circuit). A prototype switching circuit consisting of the main switching circuit, interface circuit, control logic circuit and protection circuit, is described in details in Section 3. The experimental running performance of the whole drive system is given in Section 4.

## 2. AN SRD SYSTEM

A Switched Reluctance Drive system is one of the recent development in the field of electronically controlled variable speed drive systems. It has many advantages over the conventional types such as:

1) Being brushless which makes it suitable for hazardous areas.
2) Its torque is independent of the current direction so, a simple and reliable unidirectional switching circuit is required in contrast with the most complicated and costly bidirectional switching circuits required by AC or PM machines.
3) The system is completely controllable in the four quadrant of operation.
4) It is a highly efficient system and can produce more than 50% higher in output torque than a conventional system in the same frame size.

An SRD consists of a variable reluctance machine (cylindrical or disc), position sensor and switching circuit. A brief description of these different components will be given:

### 2.1 The Motor

The variable reluctance motor used in the work presented here is a disc type which is simply constructed from two fixed discs carrying the exciting coils wound on a number of poles. The rotor is a disc mounted on a shaft and has a related number of poles on both sides but it does not carry any winding of any type. The number of rotor poles depends upon number of stator poles and number of phases. It must be noted that the rotor disc is made of a non-magnetic material which makes this motor suitable for servo applications (very good dynamic performance). The details and design method of this motor is given in / 1 /.

The disc motor is a 2-phase motor with 4 stator poles for each stator disc and 2 rotor poles on each side of the rotor disc. This motor is inherently non-selfstarting as at least 3 phases are required to obtain a self-starting motor. So, a special means is required to give the 2-phase motor its starting capability. The method used was to reshape the poles and create a step in the air-gap area to extend the positive inductance variation angle / 1 /.

2.2 Position Sensor

The main function of the position sensor is to detect the position of the rotor poles relative to the stator poles and transfers it to an electronic signal. This signal is used to control the switching of the appropriate transistor. Two optical heads were mounted on one of the fixed discs with the facility to control the angle between them (this angle is defined as the conduction angle). Also the two optical heads can be moved together in order to switch on the phase winding before the start of the rising inductance region (this is called the early turn-on angle). A vane with two sectors each of 90 deg. was fixed on the rotor shaft to interupt the two optical heads. The vane was fixed in a position such that its leading edge coincides with the leading edge of one of the rotor poles / 2 /. Output signals of the optical heads are shown in Fig. 1, where both switch-on angle and conduction angle can be controlled.

2.3 Switching Circuits

There are several switching circuit configurations suitable for energising a variable reluctance motor working as an SRD system; each has its own merits. The main factors which determine the choice of the right configuration are the power rating of the drive system, the dc link voltage, cost, and type of application / 3,4 /.

It must be noted that in all the switching circuits required by an SRD, a phase winding is connected in series with the main switch(s) thus preventing the "shoot-through" failure which is usually unavoidable in most bipolar switching circuits.

The most commonly used circuits are:

(i) External resistance-dump circuit / 3 /.

This circuit is shown in Fig. 2. Each phase winding is connected in series with one BJT and in parallel with a branch consisting of a diode and an external resistance ($r_e$). When the BJT is conducting, the dc link voltage is applied across the phase winding and when it is switched off, its collector voltage rises until the diode becomes forward biased and the winding current circulates in the circuit consisted of the winding resistance (R), the external resistance ($r_e$), and the diode, thus dissipating the stored magnetic energy as heat in these resistances. This circuit is simple, cheap, and suitable for low power application. The voltage rating of the BJT depends on the value of the external resistance used. The efficiency is low as some of the input energy is wasted in $r_e$ , also it is not capable of regeneration.

(ii) Asymmetric bridge circuit / 5,6 /.

This circuit is shown in Fig.3. It is identical to that used by AC motors or PM motors except that with SRD's phase windings are connected in series with top and bottom switches of the same leg rather than connecting the windings betwaen the mid points of the different legs. The circuit is costly requiring drivers isolation for the top floating switches. Two possible control strategies could be employed, either current regulator control (wide-bandwidth current sensor is required in series with each phase winding) or voltage-PWM control (only one low-bandwidth current sensor is required for over current protection). For current control, there are three modes of operation: the first is the conduction mode where both switches are closed and the current builds up in the phase winding with + $V_s$ impressed. The second is the freewheeling mode, where one switch is opened and the other is closed allowing the current to circulate with zero applied voltage through the closed switch, the phase winding, and a diode. The third is the switching off mode, where both switches are opened and a -ve voltage (- $V_s$) is applied allowing the current to decay fast through the phase winding, the two diodes and back to the supply. Voltage rating of each switch is equal to the dc link voltage ($V_s$).

## 3. PROTOTYPE INVERTER CIRCUIT

After careful identification of the different switching circuit topologies; the external resistance-dump configuration was chosen to drive the 2-phase SR disc motor, whose details and static performance are given in Reference / 1 /.

The following conditions have to be met:

a) The drive should be connected to the single phase main supply in order to be used in domestic applications.
b) The conversion process (from AC to DC) should be carried out in as few stages as possible.
c) The number of main switches should be kept to minimum.
d) The motor should be of the simplest possible kind in order to reduce the cost and maintenance.
e) Torque should be available at standstill from any position and the motor is unidirectional.
f) Overall efficiency of the system is of low importance.

The designed switching circuit can be devided into the following four parts:

1- Main switching circuit.
2- Interface circuit.
3- Protection circuit.
4- Control logic circuit.

The design procedure of each circuit will be given in the following sub-Section.

### 3.1 Main Switching Circuit

As the required rating is low (less than 500 W), transistors are the best solution to be used as the main switches. For the two phases, 2 transistors are required. One for each phase. Transistor type 2scl413, its blocking voltage, $V_{CE}$ equals to 400 V, and its average collector current ( $I_C$ ) is equal to 4 A , is considered to be suitable compared with what was available in the local market.

Two fast recovery diodes (4G2/06 sK) were employed to give the facility of freewheeling the stored magnetic energy.

The single phase main supply is rectified using a full-wave bridge (S5VB 1043) and the output is smoothed using an electrolytic capacitor (1200 $\mu$F). This value is calculated to smooth the ripple, less than 10% , and high reliability is achieved by correctly rating the capacitor for its rms current ripple according to the published data. The dc link voltage $V_s$ is 150 Volt.

The main switching circuit for the 2-phase disc motor with the value of each component indicated is shown in Fig. 4.

The voltage equation of a phase winding when it is conducting is given by:

$$V_s = i\,R + \frac{d\psi}{d\,t} \qquad (1)$$

Where: $\psi$ is flux-linkage; R is phase winding resistance; i is the instantaneous current and $V_s$ is the dc link voltage.

During switching-off the voltage equation is given by:

$$0 = i\,(R + r_e) + \frac{d\psi}{d\,t} \qquad (2)$$

At switching on the main transistor is driven in the quasi-saturation region where the collector-emitter voltage is the saturation voltage. When the main transistor is switched off its collector voltage rises and it depends on the value of the external resistance $r_e$ and the commutated current at the instant of switching off ( $I_p$ ), thus the voltage rating of the transistor used is given by:

$$V_{CE} = V_s + i_p r_e \qquad (3)$$

This implies that in order to reduce the voltage rating of the main transistor it is necessary to use the minimum possible value of $r_e$. On the other hand, higher rate of change of flux-linkage (good commutation) requires higher value of $r_e$ (see equation 2 ). So, the external resistance has to be designed for a good compromise between these two conflicting requirements.

As the phase winding resistance ( R ) is 10 Ohm, and the peak current at switch-off has been required not to be higher than 2 Amp, and according to the above two conditions, the external resistance has been chosen to be 25 Ohm , 6 W resistor.

### 3.2 Interface Circuit

In order to operate the main transistor in the saturation region, it must be over-driven. So, each transistor has to be driven by an interface circuit which operates from signals obtained from the control logic circuit. The output of this control logic circuit is in the order of 200 $\mu$A, which is not enough to drive the main transistor. For this reason the circuit shown in Fig. 5 has been designed and built. it consists of two stages of amplification, each consists of two transistors connected in Darlington ( 2SC 945, 2SC1104 ). The different values of the resistors appeared in this circuit are calculated in such a manner to switch on the main transistor hardly into saturation.

### 3.3 Control Logic Circuit

The aim of this circuit is to energise the interface circuit connected to the main transistor of the appropriate phase according to signals from the two optical heads. As shown in Fig. 6, it consists of two optical heads comprising a gallium arsenide infrared emitting diode coupled to a silicon photo-transistor in a plastic housing, and a logic circuit. A 5 volt supply is used to supply this circuit. The logic can be reconstructed to catter for both starting signals and running signals, but at this stage the control of these two mode of operations were made manually. Also a microprocessor can be used to perform the control laws.

### 3.4 Protection circuit

Protection of power transistors is not an easy task because usual fuses are not fast enough to remove the faulty part of the circuit without damaging the main transistor. So, an electronic protection method must be employed. The resistance detection method is used to protect the power transistors of the main switching circuit. In this method the main transistors are protected from overcurrent by comparing the voltage drop across a resistor connected in series with the main winding with a reference voltage using a comparator, as shown in Fig. 7. This reference value represents the maximum allowable current that the transistor could handle without failure. When the voltage drop exceeds the reference value, the comparator goes low and the main transistor is switched off.

It must be noted that the 2-phase SR motor requires only one resistor for protecting both transistors as there is no overlap between phases could happen.

## 4. EXPERIMENTAL TEST RESULTS AND EVALUATION

One of the main advantage of SR motors is that they can be designed to have different characteristics to suit the required application. Also, an SR motor can run in two different modes of operation, these are: / 7 /

1) The chopping mode of operation, normally at low speed and the torque is controlled through the adjustment of the chopped current level. Fig. 8 shows a chopped waveform.
2) The single-pulse mode, at higher speeds where the motional emf prevents the rapid build up of the current at the start of the rising inductance, thus reducing the positive torque and slowing down its decay. Hence, incrsasing the negative torque. Through this mode of operation it is necessary to switch on earlier and change the conduction angle to produce the optimum current wave-form which maximise the output torque or give better efficiency. A single pulse current waveform is given in Fig. 9.

There is an optimum speed to switch over from mode (1) to mode (2). Determining this speed is beyond the scope of this paper.

The experimental rig used in the work presented here is shown in Fig. 10. The main results of the extensive tests are summarised as follows:

1) The effect of both switch-on angle and conduction angle on the voltage-speed characteristic at 0.5 Nm is given in Fig. 11. As depicted it is a linear characteristic.

2) Fig. 12 shows the torque-speed characteristics at different switching angles. Both constant torque region and constant power region are clear. Also, the effect of the switching angles on controlling the speed of the motor in the constant power region is shown.

3) Optimising the system efficiency is depicted using Fig. 13 (a), (b). The maximum overall efficiency for an output of 0.5 Nm at 300 rpm is 42 %.

## 5. CONCLUSIONS

A unipolar switching circuit which has one main transistor per phase winding and an external resistance to dissipate the stored magnetic energy has been designed and built. The different components of this circuit have been given in details. This prototype circuit has been used to drive a 2-phase SR disc motor. The torque-speed characteristics of this drive system have been experimentally investigated. The effect of two control parameters, namely the switch-on angle and the conduction angle, on volt-speed relation and speed range has been shown. This switching circuit is cheap, simple and suitable for driving SR motors used in domestic applications. But it suffers from being low efficient circuit.

## 6. ACKNOWLEDGEMENT

The authors wish to thank Prof. A. Ibrahim Head of Electronic Engineering Department, EL-Mansoura University, Egypt for his helpful discussion and continuous supervision of this project.

## 7. REFERENCES


1) EL-Khazendar, M.A. and Abuzeid, M.S.: 'An axial field switched reluctance diec motor', ICEM'88 Conf., Italy, Sept. 1988, (under publication).

2) Kalas, A.H.M.: 'Running Performance of Switched Variable Reluctance Motors', M.Sc. Thesis, Suez Canal University, 1987, Egypt.

3) Ehsani, M., Bass, J.T., Miller, T.J.E., and Steigerwald, R.L.: 'Development of a unipolar converter for variable reluctance motor drives', IEEE Trans., Vol IA-23, No. 3, 1987, pp. 545-553.

4) Ray, W.F. , and Davis, R.M.: 'Inverter drive for doubly sallent reluctance motor: its fundamental behaviour, linear analysis and cost implications', IEE Proc., EPA, Vol. 2, No. 6, 1979, pp. 185- 193.

5) Sugden, D.M., Blake, R.J., Randall, S.P., Stephenson, J.M., and Lawrenson, P.J. : ' High performance MOSFET switched reluctance drives', IEEE IA annual meeting, 1987, pp. 481 - 486.

6) Miller, T.J. : 'Brushless reluctance-motor drives', Power Eng. Journal, Nov. 1987, PP. 325 - 331

7) Lawrenson, P.J., Stephenson, J.M., Blenkinsop, P.T., Corda, J., and Fulton, N.N. : ' Variable speed switched reluctance motors ', IEE Proc., EPA, Vol. 127, Pt. B, No. 4, 1980, pp. 253 - 265.


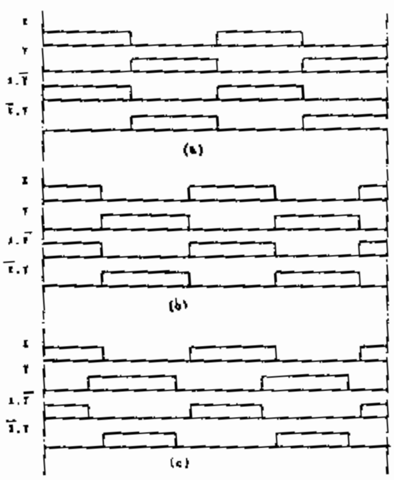

Fig. 1 Optical heads output signals X and Y and running mode switching signals (X.Y and X.Y) for three different switch-on angles and conduction angles.

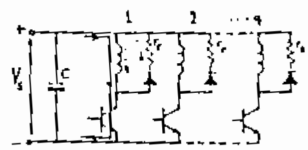

Fig. 2 External resistance dump circuit

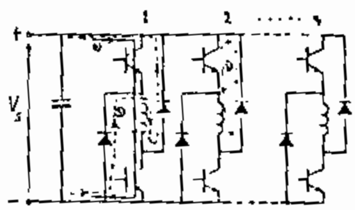

Fig. 3 Asymmetric bridge circuit

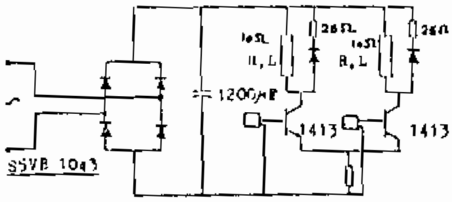


Fig. 4 Main switching circuit and un controlled bridge rectifier.

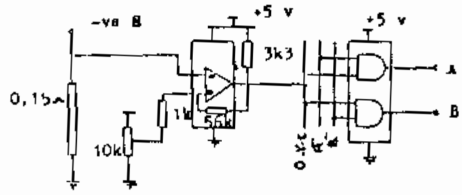


Fig. 7 Electronic protection circuit.

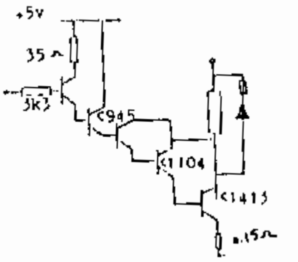


Fig. 5 Interface circuit.

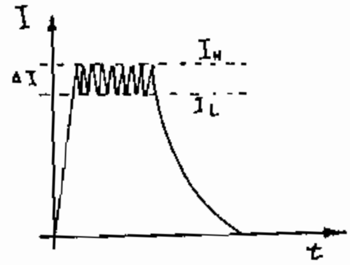


Fig. 8 Chopped current wave-form

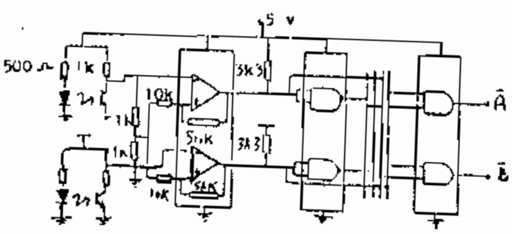


Fig. 6 Position sensor and control logic circuit.

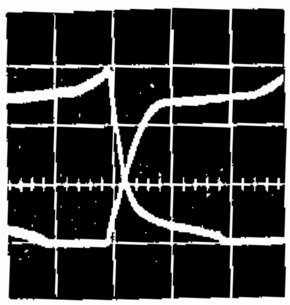

Fig. 9 Single pulse current wave-form
Scale: Horizontal axis 20 ms/div
Vertical axis 0.5 A/div.

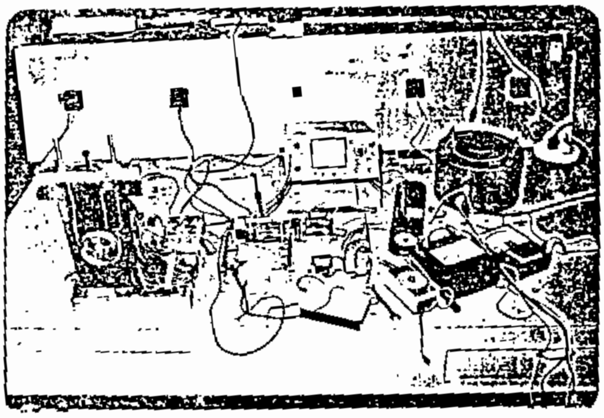

Fig. 10 The experimental rig showing loading instrument, the prototype switching circuit, and measuring equipments.

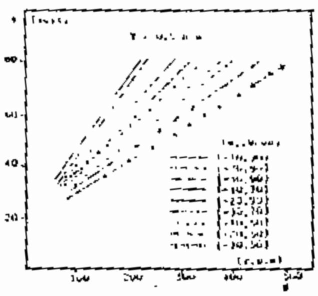

Fig. 11 Voltage-speed characteristics for different switching angles.

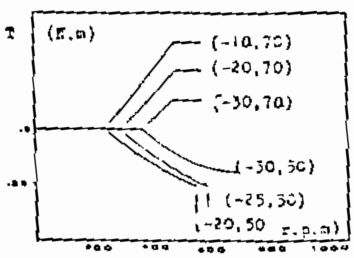


Fig. 12 Torque-speed characteristcs at different switching angles.

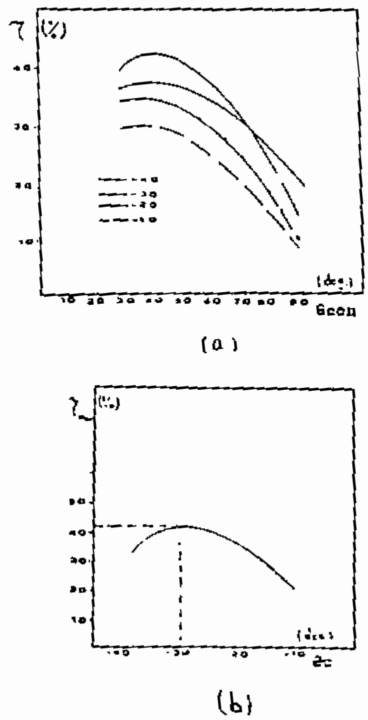


Fig. 13 Optimising system efficiency using the switching angles.