1. G. Sree Lakshmi[1] 2. E. Sreeshobha[2], 3. Malladi Lakshmi Swarupa[3] 4. Vinodh Kumar Pandraka[4]

Professor, CVR College of Engineering/EEE. Department, Hyderabad, India (1,3).
Assistant Professor, University College of Engineering, Osmania University (2)
Assistant Professor, CVR College of Engineering/EEE. Department, Hyderabad, India (4).
ORCID: 1. https://orcid.org/0000-0001-5049-5011

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Bi-directional DC-DC Converter and Fuzzy Logic Controller Based Switched Reluctance Motor for EV Applications

***Abstract**. This work is done on the performance of the switched reluctance motor drives for electric vehicles that are driven by a bi-directional DC-DC converter. SRMs are becoming more and more in demand for use in electric vehicle applications due to their superior speed-power characteristics, stable structure, low production costs, absence of permanent magnets, robustness, and fault-tolerance abilities. DC-DC converter with dual direction operation (forward and backward). Thus, this can be used to recharge the battery when backward operation is used. The Switched Reluctance Motor exhibits fault-tolerant behavior and good dynamic response. Performance metrics like speed, torque, fluxes, and state of charge (SOC) were used to assess an electric vehicle powered by an SRM. The analysis was based on a 6/4 SRM simulation that was run in MATLAB/Simulink.*

Streszczenie.** Praca ta dotyczy wydajności silników reluktancyjnych z przełączaniem dla pojazdów elektrycznych, które są napędzane przez dwukierunkowy przetwornik DC-DC. Silniki SRM stają się coraz bardziej pożądane do zastosowań w pojazdach elektrycznych ze względu na ich lepsze charakterystyki prędkości i mocy, stabilną strukturę, niskie koszty produkcji, brak magnesów trwałych, wytrzymałość i zdolność do tolerancji błędów. Przetwornica DC-DC z pracą w dwóch kierunkach (do przodu i do tyłu). Dzięki temu można jej używać do ładowania akumulatora, gdy używana jest praca wsteczna. Silnik reluktancyjny z przełączaniem wykazuje zachowanie odporne na błędy i dobrą reakcję dynamiczną. Do oceny pojazdu elektrycznego zasilanego przez silnik SRM wykorzystano takie wskaźniki wydajności, jak prędkość, moment obrotowy, strumienie i stan naładowania (SOC). Analiza została oparta na symulacji SRM 6/4, która została uruchomiona w programie MATLAB/Simulink.* (Dwukierunkowy przetwornik DC-DC i sterownik logiki rozmytej oparty na silniku reluktancyjnym z przełączaną modulacją do zastosowań w pojazdach elektrycznych***)

Keywords: Switch Reluctance Motor (SRM) Drive, Regenerative braking, DC-DC Converter, MATLAB..
Słowa kluczowe: **n**apęd silnika reluktancyjnego przełączalnego (SRM), hamowanie regeneracyjne, przetwornik DC-DC, MATLAB
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Introduction

Electric cars have the most advanced technologies in the world. The primary problem the world is currently experiencing in the twenty-first century is pollution, which is caused by cars burning fuel and releasing pollutants into the atmosphere. These cars can be replaced with zero-emission electric vehicles.

It was discovered that motor propulsion was more comfortable and user-friendly than gasoline propulsion in the middle of the 19th century, which led to the invention of electric vehicles. Within the last hundred years, internal combustion engines have ruled the automotive industry; however, electric vehicles continue to exist in a variety of forms, such as electric trains and small cars [1]-[2].

A growing emphasis on renewable energy sources and the potential reduction of their influence on the transportation system, coupled with electric vehicles' reputation as one of the best ways to combat climate change, have led to a renaissance of the vehicle in the twenty-first century [3]-[4].

The term "electric vehicle" also applies to a vehicle that is propelled by one or more motors. Fuel cells, batteries, solar panels, electric generators that convert gasoline into electricity via collector systems, or electricity from off-vehicle sources can all power an electric vehicle [5]-[6].

Electric vehicles (EVs), sometimes referred to as electric cars, are automobiles that are propelled by one or more traction motors or electric motors. An electric vehicle can run on gasoline alone by using a battery, solar panels, fuel cells, electric generator, or other self-contained technology, or it can run on electricity from external sources via a collector system. Examples of electric vehicles (EVs) include electric cars and trains, electric spacecraft, electric airplanes, and surface and underwater watercraft [7]-[8].

When electricity became one of the most widely used sources of power for motor vehicles in the middle of the 19th century, electric vehicles made their debut. Back then, gasoline-powered cars couldn't compete with the level of comfort and convenience they provided. Electric power has been widely used in other vehicle types, such as railways and smaller vehicles of different kinds, but modern internal combustion engines have dominated the propulsion of motor vehicles for nearly a century [9]-[10].

The switching reluctance motor has garnered renewed interest in the last four decades. Its rapid adoption and development enabled a multitude of industrial applications for SRM [9]. Switched reluctance motors offer excellent fault tolerance for high levels of dependability in electric drive applications [11]. Unlike SRM, some types of motors have more serious consequences when they break down. Because of mutual coupling, any malfunction on one phase has a significant effect on the other phases' ability to function [12]. However, due to the magnetic independence of the SRM phases, a defect can be isolated from the other phases without affecting them. The design of the SRMs is simple, low cost, and robust, but they also generate a great deal of noise and torque ripples [13]. The popularity of SRM drives in traction applications, such as electric vehicles, can be attributed to numerous studies that attempted to mitigate these problems. The behavior of Switched Reluctance Drives (SRD) in electric vehicle applications is examined in this paper under different open/short circuit fault scenarios [14]-[15].

Methodology

An electric motor that creates non-permanent magnetic poles on its ferromagnetic rotor is called a reluctance motor. There are no windings on the rotor. It employs magnetic reluctance to produce torque. A motor with a non-symmetric rotor that is singly excited is called a reluctance motor. Variable, switched, synchronous, and variable stepping are the subtypes of resistive motors. Reluctance motors are appealing for a variety of applications because they can provide high power density at a low cost. High torque ripple (the difference between the maximum and minimum torque during one revolution) and noise from torque ripple are drawbacks when operating at low speeds. Their use was restricted until the early 21st century due to the difficulty of creating and managing them. These challenges were overcome by developments in theory, computer design tools, and affordable embedded control systems. Microcontrollers adjust drive waveforms in response to rotor position and current/voltage feedback using real-time computing control algorithms. The control electronics were unaffordable prior to the creation of large-scale integrated circuits.

Fig. 1. A 6/4 configuration of switched reluctance motor drive

As illustrated in Figure 2, the SRM drive is composed of a switched reluctance motor, supply, driver circuit, position sensor, current controller, and speed controller. To power the stator winding, an asymmetric bridge arrangement is utilized as an inverter circuit. The rotor position is sensed by the position sensor, which could be a Hall Effect sensor. The shaft position encoder then uses this information to switch the converter devices, thereby cyclically energizing different phases. The output speed is controlled by the proportional-integral controller, and the current is limited within reference values by the hysteresis current controller.

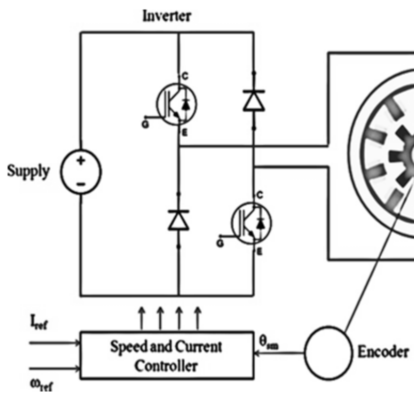

Fig. 2. Switched Reluctance Motor Speed Control

Table I Switched reluctance motor parameters

S. No.	SRM parameter	Values
1.	Model (Generic)	10/8
2.	Stator resistance (ohm)	0.05
3.	Stator inductance	970
4.	FRICTION (Nm-s)	0.005
5.	Inertia (kg.m2)	0.0082
6.	Unaligned inductance (H)	0.00067
7.	Aligned inductance (H)	0.0236
8.	Saturated aligned inductance (H)	0.00015
9.	Maximum current (A)	400
10.	Maximum flux linkage (V.s)	0.486

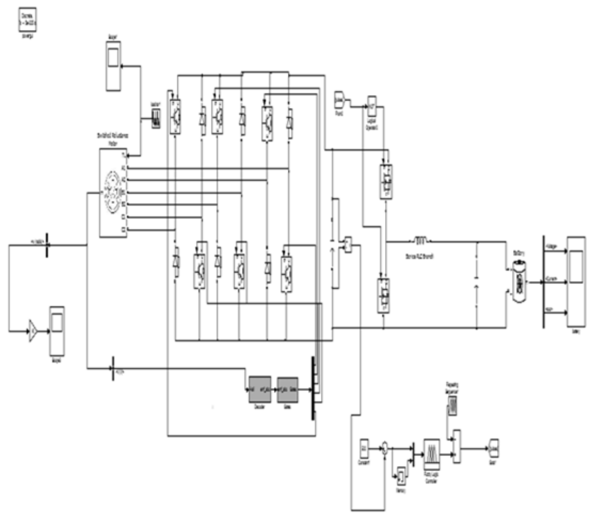

Fig. 3. Simulation of SRM with Speed Control loop

Battery Storage System

A battery is a device that powers electrical devices like cell phones, flashlights, and electric cars. It is made up of one or more electrochemical cells that are connected to the outside world. When a battery is supplying electricity, its positive terminal is called the cathode and its negative terminal is called the anode. Electrons that travel from the negative terminal to the positive terminal via an external electric circuit originate at the negative terminal. When a battery is connected to an external electric load, a redox reaction takes place. High-energy reactants are transformed into lower-energy products, and the free energy difference is sent as electrical energy to the external circuit. A device made in the past was referred to as a "battery".

Rechargeable batteries, sometimes referred to as secondary batteries or secondary cells, need to be charged before being used for the first time because their active parts are frequently depleted. Rechargeable batteries are refilled with electric current, which undoes the chemical reactions that take place during use or discharge.

Devices that supply the required current are called chargers. Because of usually irreversible side reactions that deplete charge carriers without creating current, batteries lose capacity when stored for extended periods of time or when discharged to a very small percentage of their capacity. We call this phenomenon internal self-discharge. Additionally, when batteries are recharged, more adverse reactions could happen, which would reduce their ability to discharge further. The battery stops producing power when its capacity is exhausted after a predetermined number of recharges.

Design of DC-DC converter

Buck Boost converter

A switch mode DC to DC converter that can change the output voltage to be greater or lower than the input voltage is called a Buck converter. The output voltage is determined by the duty cycle of the switch. Another name for it is a step-down or step-up converter. The fact that the input voltage can be stepped up or down to a level greater or lower than the input voltage, much like a step up/step down transformer, gives rise to the moniker "steps up/step down converter." The principle of conservation of energy states that the input power and output power (assuming no losses in the circuit) must match.

(1) Input power (P_{in}) = output power (P_{out})

In step up mode V_{in} < V_{out} in a Buck Boost converter, it follows then that the output current will be less than the input current. Therefore, for a Buck Boost converter in step up mode.

(2) $V_{in} < V_{out}$ and $I_{in} > I_{out}$

In step down mode V_{in} > V_{out} in a Buck Boost converter, it follows then that the output current will be greater than the input current. Therefore, for a Buck Boost converter in step down mode

(3) $V_{in} > V_{out}$ and $I_{in} < I_{out}$

Continuous Conduction Mode

case-1: When switch S is ON

Since the diode prevents currents from flowing from input to output in the opposite direction, it will become open circuited when the switch is turned on for a period of time. Consequently, the Buck Boost converter can be redrawn as follows.

Both the charges and the inductor current increase in this state. The following formula is used to determine the inductor's current flow:

(4) $$I_L = \left(\frac{1}{L}\right) * \int V * dt$$

Assume that prior to the opening of switch the inductor current is I'L, off. Since the input voltage is constant.

(5) $$I_{L,on} = \left(\frac{1}{L}\right) * \int V_{in} * dt + I'_{L,on}$$

Assume the switch is open for a specified number of seconds, D*Ts, where D is the duty cycle and Ts is the switching time period. At the conclusion of the switch-on state, the current through the inductor is given as

(6) $$I_{L,on} = \left(\frac{1}{L}\right) * \int V_{in} * D * T_s + I'_{L,on}$$

Hence

(7) $$\Delta I_{L,on} = \left(\frac{1}{L}\right) * \int V_{in} * D * T_s$$

case 2: When switch is off

When the switch is turned off, the diode will be forward biased because it allows current to flow from the output to the input (p to n terminal). The Buck Boost converter circuit can then be rebuilt in the manner described below.

Now the RC and diode combination is used to discharge the inductor. Presume that before the switch is closed, the inductor current is I"L, off. The following formula is used to determine the inductor's current flow:

(8) $$I'''_{L,off} = -\left(\frac{1}{L}\right) * \int V_{out} * dt + I''_{L,off}$$

The negative sign in the equation's beginning indicates that the inductor is discharging. Since D is the duty cycle and Ts is the switching time period, let's say the switch is open for toff seconds, or (1-D)*Ts. After the switch-off state is over, the inductor's current is expressed as

(9) $$I'''_{L,off} = -\left(\frac{1}{L}\right) * V_{out} * (1-D) * T_s + I''_{L,off}$$

In a steady state situation, the current through the inductor does not vary abruptly, so it should be equal at the end of the switch on state and the end of the switch off state. It should be the case that the currents at the beginning and end of the switch off and switch on states are equal.

Thus

(10) $$I'''_{L,off} = I_{L,on} \; also \; I'_{L,off} = I'''_{L,off}$$

Using the equations 6 and 10 we get

(11) $$\left(\frac{1}{L}\right) * V_{in} * D * T_s = \left(\frac{1}{L}\right) * V_{out} * (1-D) * T_s$$

(12) $$V_{in} * D = V_{out} * (1-D)$$

(13) $$\frac{V_{out}}{V_{in}} = \frac{D}{(1-D)}$$

Since D < 1, Vout can be greater than or less than V_{in}. For D>0.5 the Buck boost converter acts as boost converter with V_{out} >V_{in}. For D<0.5 the Buck boost converter acts as buck converter with V_{out} >V_{in}. Assuming no losses in the circuit and applying the law of conservation of energy

(14) $$V_{out} * I_{out} = V_{in} * I_{in}$$

This implies

(15) $$\frac{I_{out}}{I_{in}} = \frac{(1-D)}{D}$$

Thus I_{out} > I_{in} for D<0.5 and Iout < Iin for D<0.5. As the duty cycle increases the output voltage increases and output current decreases.

Pulse Width Modulation

PWM offers very little power loss in the switching devices, which is its main advantage. Turning off a switch results in almost no current flow, and turning it on to transfer power to the load causes almost no voltage drop across the switch. Since voltage and current are the products of one another, power loss is almost always close to zero. Digital controllers, on/off characteristics enable them to rapidly determine the necessary duty cycle, are another device with which PWM functions well.

The average value of the waveform fluctuates as a result of pulse-width modulation, which uses a rectangular pulse wave with a modulated pulse width. The average value of a pulse waveform with period, low value, high value, and duty cycle D (refer to figure 1) can be obtained by:

(16) $$\bar{y} = \frac{1}{T}\int_0^T f(t)dt.$$

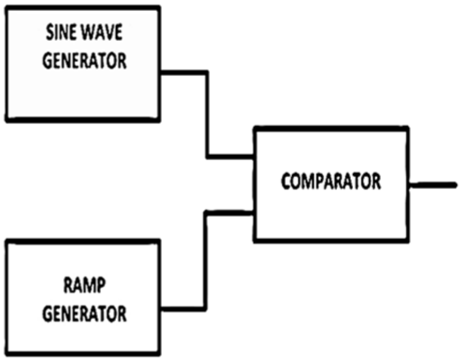

Fig. 4. Block Diagram of PWM

SPWM Block Diagram

PWM has long been a popular technique for driving inertial loads. One simple illustration of an inertial load is a motor. A motor that has been powered for a very short period of time should be turned off, but it will still continue to run after the power is removed. The significance of this aspect, which has to do with the motor's inertia, is that those kinds of devices don't need constant power to run. While delivering the same amount of power to the load overall, burst power can outperform continuous power.

It is necessary for the PWM's switching frequency to be substantially higher than the load's (the device that uses the power) in order for the load to observe a smooth waveform. Electric stoves have numerous times per minute switching; a lamp dimmer operates at 120 Hz; a motor drive operates at a frequency of a few kilohertz (kHz) to tens of kHz; and audio amplifiers and computer power supplies operate at a frequency of tens to hundreds of kHz.

The most straightforward method for producing a PWM signal is the interceptive technique, which just needs a comparator and a saw tooth or triangle waveform (which can be made with a simple oscillator). When the value of the reference signal (the red sine wave in figure 2) is greater than the modulation waveform (blue), the PWM signal (magenta) is in the high state; otherwise, it is in the low state.

Fuzzy Logic

Fuzzy logic is widely used in machine control. The term "fuzzy" suggests that the logic at play might deal with concepts that are "partially true" as opposed to "true" or "false." In many cases, fuzzy logic alternatives like neural networks and evolutionary algorithms can perform equally well.

Fuzzy logic is widely used in machine control. The word "fuzzy" suggests that the reasoning at play might deal with ideas that are "partially true," rather than "true" or "false." Fuzzy logic is often inferior to other methods such as neural networks and genetic algorithms.

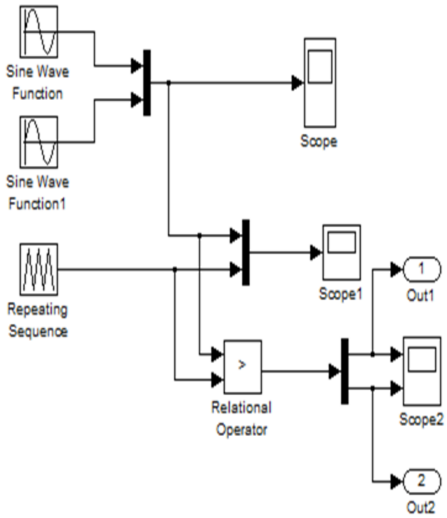

Fig. 5. Simulation of PWM technique

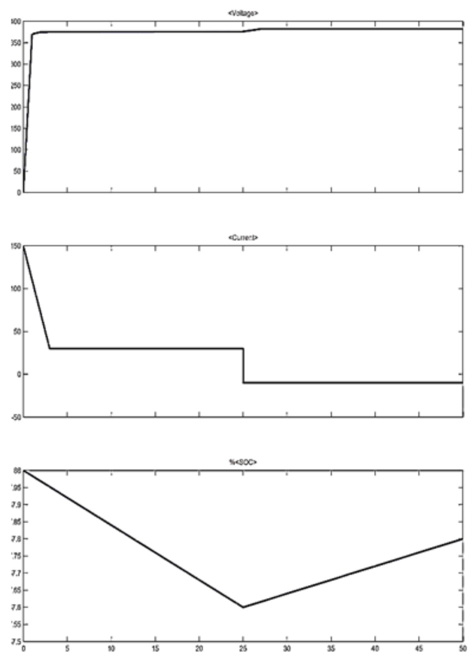

Fig. 6. Output Voltage, Current and Speed of SRM

Fuzzy rule sets, in practice, usually consist of a large number of antecedents that are combined using fuzzy operators such as AND, OR, and NOT. There are different interpretations of these operators; for example, one common definition of AND uses the smallest weight of the antecedents, while OR uses the largest value. The "complementary" function is obtained by subtracting a membership function from 1 using a NOT operator.

Simulation Results

The fundamental data element of MATLAB, which is an interactive system, is an array; therefore, it does not require dimensioning. In a fraction of the time it would take to develop a program in a scalar non-interactive language like C or FORTRAN, many technical computing problems, especially those involving matrix and vector formulations, may now be solved. After simulating SRM with a bi-directional DC-DC converter and fuzzy controller, the output voltage, current, and motor speed are displayed in Fig. 6.

Conclusions

The design and control of a bi-directional DC-DC converter for an all-electric vehicle is presented in this paper. The bi-directional dc-dc converter operates in boost mode and the SRM machine operates in motor mode when the battery is discharged. The SRM machine is subjected to variable positive torque values, and the battery's condition is monitored. The simulation results show that the voltage of the DC machine remains constant at 500 V and that the battery SoC decreases from %88 to %87.337. The machine runs in generator mode and the bi-directional DC-DC converter runs in buck mode when the battery is charged. The SRM machine is subjected to varying negative torque values, and the battery's response is monitored. The simulation result indicates that the battery SoC has increased from 87.337 to 87.245 percent. This is the state of regenerative breaking in an all-electric vehicle. The battery's charge and discharge conditions are the most crucial factors in determining distance.

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