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Critical Review of Converter Topologies for Switched Reluctance Motor Drives

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Abstract – *This paper represents an overall literature review of SRM convenient drive circuit topologies with the proposal of a new topology utilizing switched capacitance circuit. The known topologies of SRM drive circuits were critically reviewed and compared. The main configurations and classifications of SRM and the principle of switched capacitance circuit with double capacitors, double switches are reviewed as well.* ***Copyright © 2007 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords: *switched reluctance motor, switched capacitance, drive circuit*

I. Introduction

Switched reluctance motors (SRM) and their drives for industrial applications are considered in many references to be of recent origin. Krishnan, referred the first proposal of a variable reluctance motor for variable speed application to 1969, and the originality of the motor itself to 1842[1].

Some other authors dated back the first acknowledged application of Switched Reluctance Motor to the late 1830s[2]. Since that date, the Switched Reluctance Motor was proposed but with major drawbacks, which severely limited the applications of this motor in industry, these major drawbacks are :

- Necessity of electronic commutation[3].
- Complicated analysis due to non-linear characteristics.
- Difficulty of control.
- Need to shaft position sensor.
- Torque ripples.
- Acoustic noise.

However, if considering the fact that the Switched Reluctance Motor together with its drive and control circuits should be designed as one single block, it can be appreciated why the SRM was not applicable since the early date on which it was invented; that is because of the unavailability of fast, inexpensive, high-power switching devices and control techniques at that time till the late 1960s, at which, most of the SRM drawbacks could be overcome [2]. Many researchers paid attention to the analysis and modelling of the SRM since that date, specially with the great development of software packages, which helped with accurate modelling of the machine parameters such as PSPICE and MATLAB[4-25].

This fact is more appreciated when one knows that unlike DC or induction motors, the Switched Reluctance Motor can't run directly neither from a DC nor an AC supply, instead, a power converter must supply unipolar current pulses, timed accurately according to the inductance profile to produce positive torque in the motoring operation mode[26].

It is of great importance to overview the various designs of Switched Reluctance Motors as both the motor design and its drive circuit are severely inseparable.

II. Configurations of Switched Reluctance Motor

The Switched Reluctance Motor is a doubly salient, single excited machine, which has a number of critical parameters should be considered in its design process; these parameters are : the dimensions of stator and rotor laminations, winding details, number of poles, pole arcs, and number of phases [1]. These critical parameters determine the electrical, magnetic, mechanical, and thermal capabilities of the Switched Reluctance Motor.

The variety of combinations of number of phases with stator and rotor number and shapes of poles led to a wide range of possible designs of the SRM. The Rotary Switched Reluctance Motors, which is the scope of this research, could primarily be divided into Radial field and Axial field machines, Fig. 1.

Within the radial field rotary machines, there are two possible designs, if the stator and the rotor of the machine are symmetrical about their centre lines and equally spaced around their periphery, this may be referred to as a regular structured machine as this term was first adopted by T. Miller [26].

In the early 1990s, an alternative arrangement, called the dual rotor pitch machine was introduced in the design of a five-phase 10/8 SRM but with its rotor having two separate pole pitches, the authors introduced the position theory as an extension to the basic modelling theory to encompass the boarder range of SRMs [26]. The position theory added a new

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categorization concept to SRMs on basis of the relative position of rotor poles with respect to the nearest stator poles, according to which, machines could be categorized to one position, two positions, or four positions machine [26].

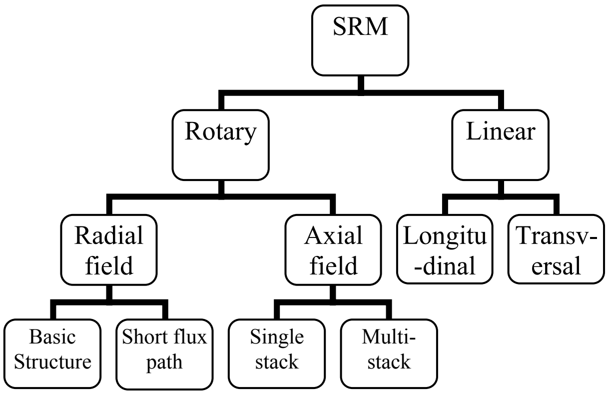

Fig. 1. Basic Configurations of SRM

Researches related to the machine design have been carried out to overcome the major drawbacks of SRM, specially those related to acoustic noise and torque ripples. One other problem with the SRM arises only in single and two phase machines, which is the existence of dead zones which may lead to the failure of the motor to self start at certain positions of the rotor.

The hybrid SRM was proposed to overcome this problem in the late 1980s, this type of motor utilizes a PM inserted either in the rotor or in the stator iron in order to guarantee the possibility of providing starting torque at all rotor positions. The idea of hybrid or PM SRM was applied later to multi phase (3 and above) machines to enhance the torque/volume ratio and to boost the efficiency of the machine [27, 28]. Other solutions were proposed to solve the self starting problem such as, the stepped-gap motor, Fig. 2, which was proposed in 1986 [29], and the homopolar SRM, which was applied to a two phase SRM design [30].

The axial field SRM in which the flux path is parallel to the shaft was proposed in the early 1970s to meet the applications in which the total length may be constrained, such as ceiling fans. The axial field SRMs have the advantage of lower core losses than the radial field motors, however, they have higher mutual inductance and higher magnetic pull on the rotor [1].

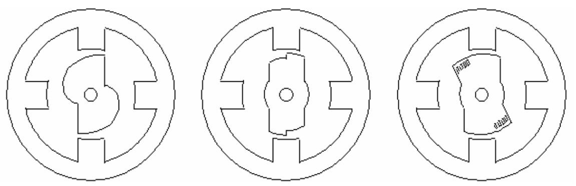

Fig. 2. Different implementations of Stepped- gap Switched Reluctance Motors

There are various configurations of SRM designs which were proposed to improve the overall performance of the machine, e.g. a c-core stator was proposed in [31] to increase torque capability and efficiency and also to provide a higher flexibility in winding design, while a new pole tip shape was suggested in [32], and a new notched teeth rotor shape was suggested in [33] to reduce the torque ripple rate.

In [34], a novel SRM with wound-cores which is made of grain-oriented silicon steel was proposed to reduce the weight and volume of the SRM, hence increasing the power/weight and power/volume capability.

III. Converter Topologies for Switched Reluctance Motor Drives

It is essential before considering the different topologies of Switched Reluctance Motor drive circuits to introduce the following features of the motor which give it an attractive advance over other types of AC machines; and affects the design of the drive circuit, these features are:

1. The torque in a SRM is independent of the polarity of the phase excitation current, which means only one switch per phase winding is required to energize or de-energize this phase.
2. there is always one switch connected in series with a phase winding, which makes the SRM self protected against shoot-through fault.
3. The phases of the SRM are electrically and magnetically independent, which allows separate control of current and torque for each phase, and also allows possible operation of the machine in case of one phase winding failure, although with reduced output power.
4. The mutual coupling between phases in a SRM can be neglected, this also gives an advance for independent phase current and torque control.
5. The phase inductance of the SRM varies with the rotor position in either a linear or a nonlinear profile.

The previous facts about the SRM explain the expected function of the drive circuit for this type of AC machines, which could be concluded in three tasks; first, is to divert current into the phase only in the positive gradient period of its inductance profile. Second, is to shape the energizing current of each phase, including its amount and its rise and fall times, of course less rise and fall times are desired to maximize the torque productivity during motoring operation[3, 15]. Third task is to provide a path for the stored magnetic energy in the phase winding during the commutation period, otherwise it will result in excessive voltage stress across the phase winding, hence across the semiconductor switching element leading to its failure, this energy could be freewheeled, or returned to the DC source either by electronic or electromagnetic means.

There are several topologies suggested to achieve the above function of the drive circuit. These topologies are well classified in [1] based on the number of switches used to energize and commutate each phase.

The most common configuration of SRM drive circuit is the asymmetric type with freewheeling and regeneration capability, Fig. 3. The performance of this converter depends on the switching strategy, which varies between simultaneous switching of T1 and T2, or switching one switch ON and OFF while the other is ON all time. Selecting the proper switching strategy, dwell angle and control technique (usually hysteresis current control) will define the efficiency and application of this converter. The asymmetric converter is the most common for voltage source operation for low power levels [35].

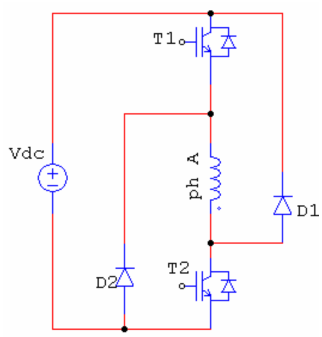

Fig. 3. Asymmetric Bridge Converter

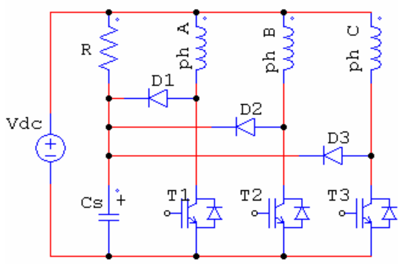

Fig. 4. R-Dump Converter

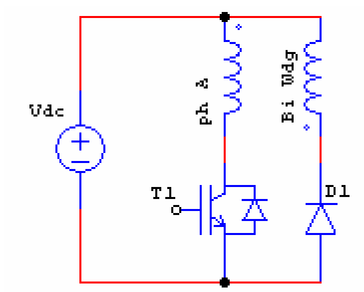

Fig. 5. Bifilar Type Converter

The R-dump converter, Fig. 4, is one of the configurations which has one switch and one diode per phase. The value of R determines the power dissipation and the switch voltage. A compromise of R value should be done to achieve both reasonable stress on the switch (increases with higher R), and appropriate fall time of the current (increases with lower R). Analysis and detailed design procedure of this converter is explained in [36].

The Bifilar type converter, Fig. 5, also has one switch and one diode per phase but with the capability of regenerating the stored magnetic energy to the supply by the bifilar winding. This converter is also utilizing one switch per phase. The bifilar converter has the drawbacks of reduced power density, and the high stress on the switching elements due to the bifilar windings inductance.

Fig. 6 shows the split DC supply converter which allows freewheeling and regeneration. proper design of the values of C_1 and C_2 should be done carefully to achieve charge balancing across the DC link. However, this converter utilizes only half the value of the DC supply, and also it is suitable only for motors with even number of phases.

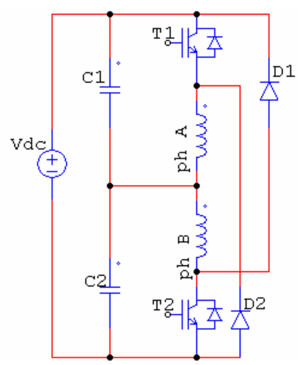

Fig. 6. Split DC Supply Converter

One of the earliest drive circuits introduced for switched reluctance machines is the C-dump converter, shown in Fig. 7. In this converter, the stored magnetic energy is partially diverted to the dump capacitor and recovered by a single chopper and sent to the DC source.

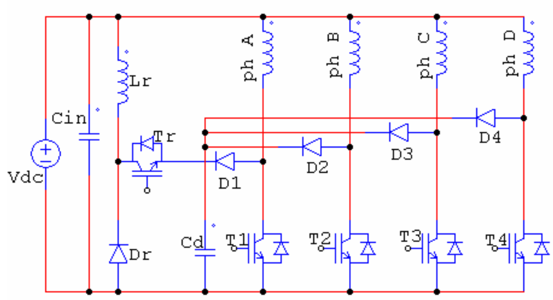

Fig. 7. C – Dump Converter

The C-dump converter has the drawback of disability to provide zero voltage across the phase winding during commutation period, which results in increased acoustic noise, and deterioration of the winding insulation. These drawbacks were overcome by adding a freewheeling transistor, which may be used for active energy recovery replacing the energy recovery coil further modifications were proposed to the conventional C-dump converter to eliminate its drawbacks while maintaining its attractive advantages[37, 38].

The variable DC link converter is an attractive configuration of SRM drives due to its advantages and its ability of operation in four-quadrant sensor-less applications.

The variable DC link could be achieved by inserting a front end converter which may be a buck or a buck-boost converter.

Fig. 8 shows a variable DC link converter with a buck-boost front end stage. The machine input voltage can be varied from zero to twice the supply voltage, further, faster commutation of the current is achieved. A combination of the C-dump and the buck front end converters was proposed in [39]as a hybrid converter that possesses the advantages of both topologies and overcomes their major drawbacks.

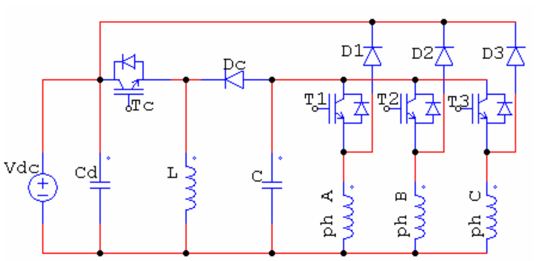

Fig. 8. Variable DC Link Converter

All the above converter topologies are known as hard switching topologies, since the power switches and diodes are switched ON and OFF while their voltages and currents are nonzero. The converter topologies that enable soft switching are known as resonant topologies, one of which is shown in Fig. 9.

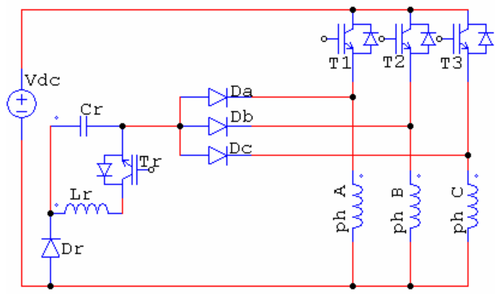

Fig. 9. Resonant Converter

The attractive advantage of zero switching losses which could be offered by the resonant circuit is contradicted by the losses in its passive elements, and the electromagnetic interference, EMI influenced by such circuits. There are several configurations within the resonant converter topology, depending on the resonance elements arrangement, (series or parallel), the soft switching technique (ZCS or ZVS), and the application (is phase current overlap required or not)[40, 41].

Few researches paid attention to the resonant converter topology because of the un-encouraging experimental studies[1].

More detailed study and suggestion of a new configuration based on the resonance principle and utilizing a switched capacitance circuit to perform as a variable capacitor will be proposed by the end of this paper.

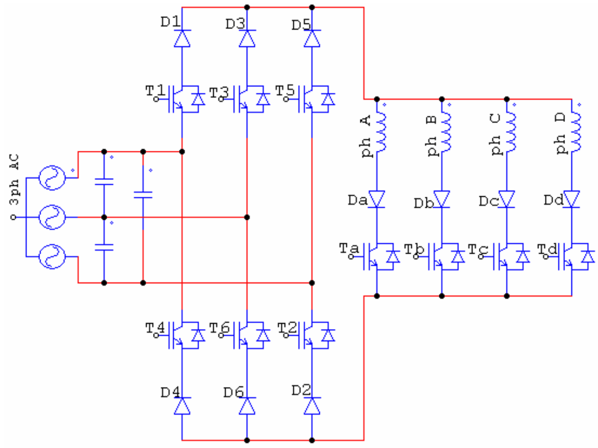

Fig. 10. Two Stage Power Converter

The last converter topology to be presented in this section is the two stage power converter, Fig. 10, in which, the three phase AC supply is converted to a single phase variable frequency via a controlled rectifier/inverter, the other stage is the commutating stage which energizes phase windings[1].

The two stage converter has the advantage of being capable of returning the power from the machine to the supply side directly with no limitations and eliminates the DC link capacitor. A comparison of the above discussed topologies showing the advantages and disadvantages together with useful application notes is presented in Table I.

IV. Control of Switched Reluctance Motor Drives

There are different well known strategies of machine control depending on the application, these are, position, speed, current, and torque control. The switched reluctance machine is different from other types of DC and AC machines because of its poles saliency and nonlinearity. Further more, the current control strategy in SRM is different from torque control while these two are synonyms in DC drives.

The SRM produces discrete pulses of torque, and the proper design of the machine which allows overlapping inductance profile could make it possible to produce continuous torque. The developed torque is controlled by adjusting the magnitude of the phase current or by varying the dwell angle, which is recommended to be kept constant in order to reduce the torque ripples[1].

The control operation may be done using a position sensor feedback signal, or using sensorless operation, by estimating the position from the magnetic characteristics of the machine[43-48].

TABLE I
COMPARISON OF COMMON SRM DRIVE CIRCUITS

Type	Switches/ phase	Diodes/ phase	Advantages	Disadvantages	Application Notes
Asymmetric Bridge	2	2	-Ideal for high performance current and torque control. -Allows greater flexibility in controlling machine current. -Capable of +ve, -ve, and zero voltage output. -Voltage stress across the switching element is restricted to V_{dc}.	-High switching losses. -Larger Heat sinks. -Not suitable for high power applications.	Low power levels inverters fed from a voltage source.
R- Dump	1	1	-Compactness of converter package. -Lower cost due to minimum number of switches and diodes.	-Unable to apply zero voltage output during current conduction. -Reduced system efficiency. -Rate of change of phase voltage is doubled.	Low speed, low switching frequencies.
Bifilar	1	1	-Compactness of converter package. -Lower cost due to minimum number of switches and diodes. -Capability of regeneration of stored energy.	-High stress on switching element. -Reduced power density [1].	Not economical for large motors.
Split DC supply	1	1	-Compactness of converter package. -Lower cost due to minimum number of switches and diodes. -Capability of regeneration of stored energy.	-De-rating of the supply voltage. -Suitable only for motors with an even number of phases.	Fractional hp motors with even number of phases.
C –Dump	1	1	-Minimum switches number. -Independent phase current control.	-Current commutation is limited by the difference between the voltage across C_d and the DC link. -Not suitable for high speeds. -Lower efficiency. -Unable to provide zero voltage.	Low speed applications
C –Dump with freewheeling transistor	1	1	-Minimum switches number. -Independent phase current control. -Lower cost than C-dump. -Higher power density than C-dump. -Less ripple on DC link capacitor. -Able to provide zero voltage.	-Only motoring operation is possible. -High rating of the freewheeling switch. -complexity of control when phase currents overlap.	Suitable only for motoring operation.
Minimum switch with variable DC-link	1	1	-Higher DC source can be adopted -Lower core losses[39],[1]. -Lower switching losses. -Reduced acoustic noise.	-Lower commutation voltage. -Lower overall system efficiency. -Unsuitable for continuous generative operation [1].	-Suitable for four quadrant sensor-less applications. -Preferred in generation mode of operation.
Resonant converter	1	1	-Low switching losses (theoretically zero). -Superior quality of current waveform. -High switching frequency capability.	-Lower power density. -EMI influence. -Higher rating of switching elements.	Suitable for high frequency applications (f>20kHz).
Two –stage power converter	1(+6)	1(+6)	-Lower cost. -Higher reliability. -Higher power density.	-Higher number of switches. -Not economical if regenerative operation is not substantial.	Suitable for variable speed, constant frequency generation using wind energy[42].

In the following sections, a brief overview of the control principle of each scheme is presented.

IV.1. Speed Control

The speed control scheme, Fig. 11, consists of two loops, current loop and speed loop through which the speed error is processed and conditioned with the speed controller to obtain the current command signal, i^*, this current command is compared to the actual phase current feedback signal to generate the current error signal. This later is processed through the current controller to produce the command signal for the converter, v^*, and the switching of the phase is determined according to a predetermined window, Δi, of the hysteresis current controller. The currents are diverted into each phase according to its position information which maybe measured or estimated. In general, the speed control strategy consists of two actions, the first is to regulate the motor speed by adjusting the duty cycle of a PWM signal that activates the power converter, and the second action is to adjust the advanced firing angle as a function of the motor speed to improve motor efficiency and performance specially at high speeds [49].

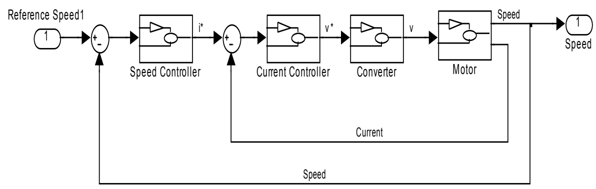

Fig. 11. Speed Control Closed-loop Block Diagram

IV.2. Current Control

The SRM is operated either in current control or voltage control mode. The voltage control operation mode is cheaper in implementation but is not convenient for servo-type applications, in this case current control operation mode is essential [50].

The most significant parameter in the current control loop is the hysteresis band, which is desired to be as small as possible in order to reduce current ripples and to increase the bandwidth of the current loop, however the residual current ripple content, the high-variable switching frequency are the un-encouraging drawbacks of this approach [50].

IV.3. Torque Control

Unlike DC and AC machines, the air-gap torque in the SRM has a nonlinear relationship with the excitation current which makes the control system more complex, since the torque is depending not only on the excitation current but on the rotor position as well. The method of torque control depends on the number of phases which are excited at the same instant, which severely affects the torque ripple content and consequently the speed ripples which in turn reduce the overall efficiency and performance of the drive system [1].

The designer of a SRM drive system has to aim at one of two conflicting concerns, maximizing the output torque, or maximizing the efficiency. The efficiency is maximized by minimizing the dwell (conduction) angle of the phase, while maximum torque is obtained when the dwell angle is maximized. In general, two strategies of dwell angle are followed, either constant or variable dwell angle, depending on the application. Different modes of SRM commutation are given in [35].

V. New Converter Topology

The new converter proposed in this paper depends on the switched capacitance circuit technique, Fig. 12, where the equivalent capacitance between points A and B could be varied by varying the duty cycle of the switching elements, in other words, it works as a variable capacitance, which varies with the duty cycle, D according to equation (1) [51] which is plotted in Fig. 13 for different values of C_1 and C_2.

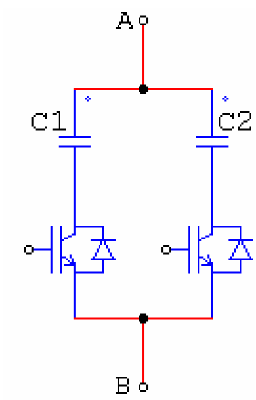

Fig. 12. Switching Capacitance Circuit

$$C_e = \frac{C_1}{D^2 + (1-D)^2 (C_1/C_2)} \quad (1)$$

where:

C_e is the effective capacitance between points A and B, D is the duty cycle of the switching element in C_1 branch.

The advantage of using the switched capacitance circuit in SRM drive is to obtain fast rising and falling edges of the current through the motor, which maximizes the produced torque even at high speeds, where most of the conventional methods fail [51]. The proposed technique depends on varying the capacitance to follow the profile of variation of the phase inductance in order to keep the impedance of the phase current path as low as possible to assure fast rising and falling of the phase current.

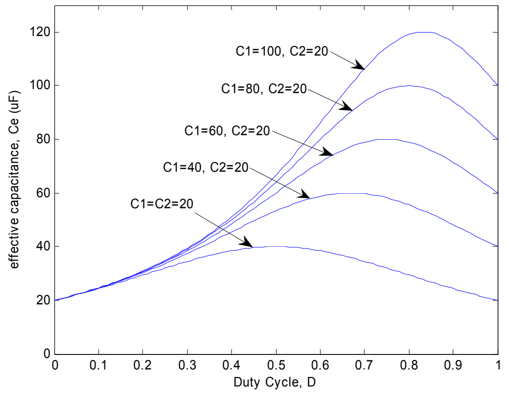

Fig. 13. Variation of C with Duty Cycle

The schematic diagram of the drive circuit is shown in Fig. 14, where the switched capacitance circuit of Fig. 12 is connected between points A and B. The drive circuit consists of an asymmetric converter with the utilization of a double capacitor, double switch (DCDS), switched capacitance circuit.

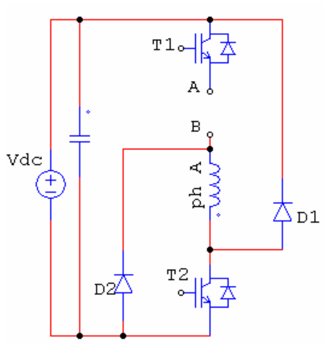

Fig. 14. Proposed Drive Circuit

The capacitance profile may be either increasing or decreasing while the phase inductance is increasing, depending on the desired damping factor, and the application speed (if the capacitance is increasing with the inductance increase, high damping factor is obtained [51].

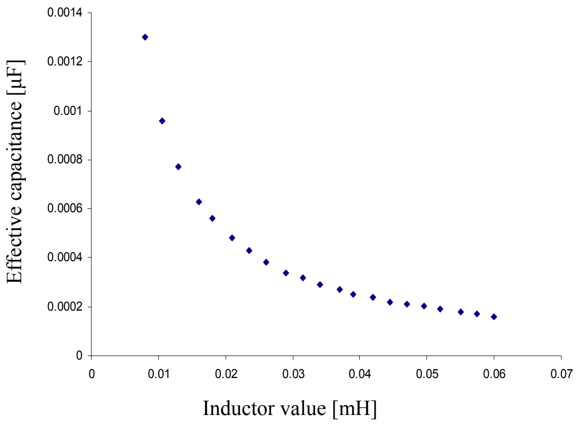

Fig. 15. Inductor/capacitor profile

Fig. 15 illustrates the simulation results of how the profile of the capacitance is varied with the motor inductance during the positive gradient region.

There are several configurations of the switched capacitance circuit depending on the number of capacitors and number of switching elements. The proposed circuit is a double capacitance double switch (DCDS) circuit.

VI. Conclusions

The basic configurations of SRM designs were critically reviewed together with the known topologies of drive circuits for this type of AC machines. The major advantages and drawbacks of each drive topology were presented and summarized. Useful application notes which is needed for decision making by the drive circuit designer are stated for each circuit. Principle of switched capacitance circuit was briefly presented. Finally, a new drive circuit topology using the switched capacitance circuit was proposed for a SRM drive system.

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