Abstract—This paper is related to comparison of two switching techniques that can be applied to asymmetric bridge converter driven switched reluctance machine. Switched reluctance motor operation principles are discussed. Theoretical circuit operation description and Matlab simulation software are used for switching technique comparison. After analysis shows that modification of switching technique have following advantages: lower semiconductor commutation losses, lower current pulsations, reduced voltage stress.

I. INTRODUCTION

The switched reluctance motor drive has outstanding features like high robustness level, simple structure, low cost, high efficiency and power/weight ratio.

Switched reluctance motor has salient laminated poles on both rotor and stator. The rotor is made of laminated steel. It does not contain any permanent magnet or winding, therefore, it has smaller size and weight that leads to low inertia. On one hand this construction property has disadvantage, because power density of permanent magnet machines could not be obtained by switched reluctance motor, on the other hand switched reluctance motor is simple and inexpensive in construction and manufacturing; other advantage of this kind of machines is ability to work in harsh environment conditions and high temperature at high speed without malfunctioning and machine parameter changes, as it is for permanent magnet machines (high temperature is demagnetizing permanent magnets), for example. Winding absence in rotor is good for cases when high load torque is applied to rotor or it is stalled, because there is no conductor with high current and respectively high losses that takes the form of heat in rotor; the curves of machine is rather synchronous type and therefore are much flatter than ones for induction motors. Stator windings are insulated one from other and mutual influence is negligible. For this reason electrical fault of one phase does not influence other phases.

The operation of motor is based on sequential energizing pairs of stator opposite windings, while rotors opposite poles get moved by magnetic force in order to get position with minimal reluctance (Fig. 1). This way of driving has several significant disadvantages: such operation produces torque ripple and acoustic noise as consequence.[1]-[3]

II. SWITCHED RELUCTANCE MOTOR OPERATION PRINCIPLES AND MATHEMATICAL ANALYSIS

As phases of the Switched reluctance motor are excited independently and their positions are not parallel, we can assume that voltage of each phase is equal to:

\[ u_{ph} = R_{ph}i_{ph} + \frac{d\psi(i_{ph}, \theta)}{dt}. \]  

(1)

Equation (1) describes phase voltage \( u_{ph} \) as resistive voltage drop of winding and derivative of flux linkage. Flux linkage \( \psi \) is related to phase current \( i_{ph} \) and position angle \( \theta \) function. Flux linkage equation is:

\[ \psi(i_{ph}, \theta) = i_{ph}L(\theta, i_{ph}). \]  

(2)

which is product of current and induction \( L \) as function of current and rotor position angle. If magnetic non-linearity of material is not considered, induction becomes a function of angle only and phase voltage can be described as:

\[ u_{ph} = R_{ph}i_{ph} + L(\theta)\frac{di_{ph}}{dt} + i_{ph}\frac{dL(\theta)}{d\theta}. \]  

(3)

Electromagnetic torque equation for switched reluctance motor in this case is equal to:

\[ T_{oph} = \frac{1}{2} i_{ph}^{2} \frac{dL(\theta)}{d\theta}. \]  

(4)

Considering that switched reluctance motor has only one region, where inductance derivative of angle is positive, the torque is produced only during inductance positive slope no matter which polarity current have (Fig. 1).

If there is current flow in winding during negative inductance slope then negative torque is produced. That means the total torque will have pulsations that have negative influence on mechanical curves, shaft torque curve in the time and make vibrations and acoustic noise that are main problems of switched reluctance drives. Therefore, stator and rotor arcs should be chosen very carefully with respect of application of the drive. Aligned region should be big enough to discharge current within the time required for motor pole to pass by the stator pole and small enough to avoid regions where no torque is produced in any of phases as in Fig. 2 otherwise negative torque is generated as in Fig. 3. In other words any of phases should consequentially keep motor torque at rated value without pulsation caused by negative torque production. For this reason mechanical structure of motor should be designed with considering final rates of power, voltage, speed and current that are necessary for certain application range drive is designed for.[1], [2], [4], [6].

One more significant problem is motor magnetic non-linearity that makes motor mathematical description complex because it directly affects flux linkage and torque production. There is two ways to achieve better performance considering
this issue: using magnetization look-up tables or/and intelligent control.

![Fig 2. Effect of rotor pole arc greater than the stator pole arc on torque generation](image)

![Fig 3. Effect of equal stator and rotor pole arcs on torque generation](image)

- Converter configuration with \( q \) switches and \( 2q \) diodes;
- Converter configuration with \( q \) switches and \( 2q \) diodes with independent current control;
- Converter configuration with \((q+1)\) switches and diodes
- Minimum switch topology with variable DC-link
- Converter configuration with \((1.5q)\) switches and diodes

One of the most popular converters is asymmetric bridge due to simple construction and resistance to shoot-through faults.

Asymmetric bridge converter consists of two switches and two diodes. As topology is different to classic bridge scheme, the diodes are connected to switches differently to avoid induction kick (Fig. 4).

![Fig 4. Circuit of three-phase asymmetric bridge converter](image)

Each phase of SRM is energized independently and shoot through fault are eliminated by converter structure. In case of insulation fault of one of the phases other phases of bridge are not involved in current leakage process. This converter structure property have significant role in malfunction detection and repair.

While both switches are in conduction mode SRM phase that could be considered as inductor gets energized. Then one or both of the switches gets to non-conduction mode and current of inductor (winding) that could not be stopped instantly discharges through diodes and DC-link and transistors in case of special switching techniques. The way current of inductor is discharged depends on switching technique.

## IV. Switching strategy description

There is two switching techniques could be applied for asymmetric bridge Fig. 4 converter control. During first step VT1 and VT2 are in conduction mode and winding of SRM is energized by flowing current (Fig. 5, b)). When level of desired current is reached there is two ways to de-energize the winding.

First (switching technique I or conventional): both transistors are closed and winding is discharged through diodes VD1, VD2 and DC-link. That mean that reverse voltage is applied to winding. Then after current have reached level above desired VT1 and VT2 are conducting current again and reverse DC-link voltage is applied till next switching (Fig. 5, c), Fig. 6, a)).

Second (switching technique I or modified): VT2 is in conduction mode all the time the current should flow in phase and VT1 is working in PWM mode to obtain desired current form, this mean when upper switched is turned off, current is discharged through switch lower switch VT2 and VT2. This
way of switching allows decreasing switching losses in one of the semiconductor switches, increasing its life cycle and decreasing voltage stress of motor windings. Keeping VT2 switched on is keeping winding from discharging through DC-link and diodes what means reverse voltage is not applied and current pulsations have smaller amplitude and current of motor phase is closer to reference value (Fig. 5, d), Fig. 6, b).

Fig. 5. a) Circuit of one phase of the asymmetric bridge converter; b) Energizing of motor winding; c) Path of current flow in switching technique I; d) Winding current discharging if switching technique 2 is applied

Another benefit of proposed switching technique II is possibility to choose transistor in lower price range and decrease price of converter, as there is much lower switching losses. [1]

Fig 6. Comparison phase current of asymmetric bridge converter for conventional (a) and modified switching technique (b)

When aligned inductance is reached both of techniques provides discharging at reverse DC-link voltage to decrease current after aligned position is reached. Current flow in winding during after rotor have reached aligned position is producing negative torque. Phase A and VT2 switch currents are figured in Fig. 7.

As it is seen from graphic in Fig. 7, phase current shapes of conventional and modified switching techniques are very close each to other, but if shape of current is magnified to resolution it is obvious that current of modified switching techniques has less pulsations. More significant current shape difference between switching techniques could be observed in VT2 switch current shape (Fig. 6). Magnitudes of current shapes are close as it is seen in Fig. 7. While current of switching technique I is discontinuous, current shape of switching technique II is not interrupted. Phase voltage of switching techniques is not equal as well, as it is proposed in theoretical graphics of Fig. 6. Phase voltage graphic is shown in Fig. 7, shows that Modified switching technique is using only positive voltage pulses and only at aligned position negative voltage is applied. Voltage of switching technique I consists of positive and negative voltage pulses.

Fig. 8. Comparison of phase current, phase voltage and transistor TR2 of asymmetric bridge converter for conventional (A) and modified switching technique (B) during small time period.

V. SIMULATION OF SWITCHED RELUCTANCE DRIVE

Simulation graphics of Fig. 7 and Fig. 8 are based on MATLAB model. To model switched reluctance motor according motor block is used. The block has signals of rotor position angle (theta), phase currents and speed that are involved in control process. Reference speed multiplied by ramp shape forms speed reference signal. Speed error
calculated from speed reference and speed actual values and processed by PI regulator gives out reference current value. Current reference value gets compared with triangular waveform or processed through PWM generator.

Control block needs turn-on and turn-off angles to keep the winding excited only during motor positive inductance slope as well. Excitation signal is in On-state during positive inductance slope region. This signal is generated by processing position angle of rotor.

PWM signal and excitation signal logically multiplied by AND gate. In case of switching technique I obtained signal controls both transistors VT1 and VT2. In case of modified switching technique obtained signal controls only VT1 and VT2 is controlled by excitation region signal directly.[1], [5]

When aligned inductance is reached both of techniques provides discharging at reverse DC-link voltage to decrease current after aligned position is reached. Phase current shape in total is approximately the same for both techniques if phase current pulsations are ignored, therefore Fig. 9 shows graphs of flux linkage, current, torque and speed only for switching technique II.

![Fig 9. Simulation results of switched reluctance motor driven by asymmetric bridge converter that is controlled by modified switching technique](image)

Simulation is made for load-less switched reluctance motor with speed 1000 rpm and DC voltage of 240 V.

Drive performance could be improved if induction measurement and prediction techniques are implemented. These drive improvements are able to provide better turn-on and turn-off angles, encoder-less position detection. [3]

VI. CONCLUSION

As follows from the theoretical analysis and simulation results, modified switching technique for asymmetric bridge converter has several advantages comparing to the switching technique using PWM signal for both transistors. The modified technique is able to provide less current and torque micro-pulsations, reduce losses. It does not change operation of switched reluctance drive dramatically and way of circuit operation is close to the common switching technique, but it makes possible to reduce asymmetric bridge converter hardware costs because of reduced losses of semiconductor switches. Operation in proposed switching technique is not reducing number of advantages of asymmetric bridge converter.

For these reasons modified switching technique can be proposed as recommended method of asymmetric bridge converter transistor control.

REFERENCES


