COMPARATIVE STUDY OF DIFFERENT TYPES OF CONVERTERS FOR SWITCHED RELUCTANCE MOTOR DRIVE

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ABSTRACT
Switched Reluctance Motor (SRM) is a competition for many applications of electric drive system due to its simple construction and robustness. This paper presents a comparison between different types of conventional converters with a new Bridgeless SEPIC converter. The conventional converter topologies employed for SRM drive are R-dump, C-dump, H-bridge, series and parallel type converters. The SRM with 6/4 pole is analyzed with a Bridgeless SEPIC converter by using Matlab/Simulink packages and operating principles of various converters also described. This paper provides the results of Bridgeless SEPIC converter yields reduced current, torque ripples with a constant speed used in medical application particularly for Sleep Apnea Treatment.

Index Terms - Switched Reluctance Motor (SRM), Single Ended Primary Inductor Converter (SEPIC), R-dump, C-dump, H-bridge, series and parallel converter.

I. INTRODUCTION
Switched Reluctance Motor is a doubly salient machine in which the electromagnetic torque is developed owing to reluctance principle. The stator and rotor has salient poles but only stator carries windings and rotor does not have any attached coils or magnets. Due to the presence of independent SRM phases the failure of one winding does not affect the continuous operation of the drive, but power output from the drive is reduced. The various drawbacks of SRM drive are acoustic noise, torque ripples and position sensing. The Bridgeless Single Ended Primary Inductor Converter (SEPIC) with open and closed loop is proposed to overcome these drawbacks. The advantages of proposed converter are continuous output current, reduced switching stress and smaller voltage ripples compared to conventional converters.

The proposed converter has three identical inductors which are coupled to the circuit for reducing the ripples and it can operate as capacitor diode voltage multiplier. The controller gives command to power converter unit to activate the phases of drive. The regulation of phase current and performance of motor is achieved by the controller to meet the specific requirements of drive. The drive system for three phase 6/4 pole SRM with H-bridge converter is shown in Fig.1.

The continuous torque can be obtained by synchronizing excitation phases with rotor position. The current flowing through the windings of SRM drive is controlled by power electronic switches. Power converter is the most important part of drive [1]. Based on the selection of converter type, the performance, cost and size of the drive gets varied. The identification of best drive for motor performance is obtained by comparison of converters. The basic requirements of SRM drive converters are as follows [3];

- The converter should be able to excite the phases before it enters into generating or demagnetization region.
- Each phase of motor has at least one switch to conduct independently.

II. TYPES OF SRM CONVERTERS
The fixed DC link voltage for SRM drive is obtained by using AC/DC converter. Based on the performance and application, the suitable type of power converter and control scheme is selected. Some of the features of SRM drive are summarized as follows [3];

- The maximum torque is accomplished during energizing of motor phase.
- The magnetic energy stored during commutation period should be free wheeled or returned to source.
- The supply of current to phase is made only at positive gradient duration of inductance profile.

A. R-Dump Converter
The R-dump converter is shown in Fig.2. It consists of one switch and one diode per phase. The power dissipation and switching voltage is determined by the value of resistance R. The change in value of R should be done to achieve both stress on the switch and fall time of the current. When the switch T1 is turned off, the current freewheels through diode D1, charging capacitor C and external resistor R. This resistor
dissipates the stored energy in energized phase [3]. The drawback of this converter is that current in any phase will take longer time to extinguish. It reduces overall efficiency of the motor and dissipates more energy in a resistor [5].

**B.C-Dump Converter**

The C-dump converter is shown in Fig.3. It consists of one switch and one diode per phase and has one additional dump capacitor to dissipate the stored energy back to the supply. The phase A is energized when the switch $T_1$ is turned on. When the switch $T_1$ is turned off, the phase current $i_a$ exceeds the reference value. Due to this the diode $D_1$ is forward biased and current path closed through dump capacitor $C_d$ to achieve fast demagnetization. The dump switch $T_1$ operates at higher frequency compared to other phase switches.

The advantages of C-dump converter are reduced number of switching devices, independent phase current control, regenerative capability and fast winding demagnetization. The major drawback of this converter is use of capacitor and an inductor in the dump circuit which increases the voltage to twice the bus voltage [5]. The efficiency of the drive gets decreased due to energy circulation between dump capacitor and dc link voltage which also results in additional losses.

**C.H-Bridge converter**

The H-bridge converter is shown in Fig.4. It consists of two switches and two diodes per phase to achieve unipolar strategy. The unipolar switching strategy is used to obtain less current ripple and better frequency response. In each phase, PWM switching control is performed by upper switches such as $T_1$, $T_3$ and $T_5$ and charge of commutation by lower switches such as $T_2$, $T_4$ and $T_6$. The three modes of operation of this converter are magnetization, freewheeling and demagnetization mode [5,10].

By using H-bridge converter, the SRM is controlled either by voltage control or current control. Compared to voltage control, current control is advantageous because it provides possibility of reduction in torque ripples and noise [14]. The advantageous of this converter is that it provides greater flexibility in controlling the machine current. The major drawback of this converter is that two devices are always in series with the motor winding which leads to increase the conduction losses as well as size and cost of the drive gets increased.

**D. Series Converter**

The series converter is shown in Fig.5. The series converter is modified from the H-bridge converter by adding one diode and boosting capacitor in series with the phase windings of SRM to achieve voltage boosting capability [7]. The three modes of operation are magnetization, freewheeling and demagnetization mode. In magnetization mode $T_1$ and $T_2$ are turned on and phase winding A is energized with the current flow through the path of $V$, $D_a$, $T_1$, $L_1$, $T_2$ and $V$. In free wheeling mode when the winding current exceeds the reference value, either $T_1$ or $T_2$ is turned off.

The flow of current in winding is freewheeling in one path $L_1$, $D_1$, and $T_1$ or the path of $L_1$, $T_2$ and $D_2$. In the demagnetization mode the incoming phase winding is charged by stored magnetic energy of energized winding [2]. The advantages of this converter are higher efficiency and simple control. The major drawback is that the torque per ampere is medium.

**E. Parallel Converter**

The parallel type of converter is shown in Fig.6. The parallel type converter is modified from H-bridge...
converter by adding one boost capacitor in parallel with phase windings to achieve voltage boosting capability [6]. The three modes of operation are magnetization, demagnetization and freewheeling mode. In magnetization mode $T_1$ and $T_2$ are turned on and phase A winding is energized with current flow through the path of $V$, $D_a$, $T_1$, $L_1$, $T_2$ and $V$. In freewheeling mode, when the winding current exceeds the reference value either $T_1$ or $T_2$ is turned off.

The flow of current in winding is freewheeling in one path $L_1$, $D_c$ and $T_1$ or with the path of $L_1$, $T_2$ and $D_2$. In demagnetization mode the incoming phase winding is charged by the stored magnetic energy of energized winding [3]. The major advantages of this converter are high reliability and better performance

### F. Bridgeless SEPIC Converter

The circuit diagram of bridgeless SEPIC converter is shown in Fig.7. The auxiliary circuit includes an additional winding $N_s$ of input inductor $L_s$, auxiliary inductor $L_c$ and a capacitor $C_a$. The coupled inductor $L_c$ can be modeled as a magnetizing inductance $L_m$ and an ideal transformer which has a turns ratio of $1:n$ ($n = N_a/N_o$). The leakage inductance of the coupled inductor $L_c$ is included in auxiliary inductor $L_a$. The capacitance $C_a$ is considered as a voltage source $V_a$ during a switching period. By volt-second balance law, the average input voltage should be zero and average capacitor voltage $V_{ca}$ is equal to the input voltage $V_m$ during a switching period under steady state [13]. Likewise average capacitor voltage $V_{cl}$ is equal to the input voltage $V_{in}$. The diodes $D_1$ and $D_2$ are input rectifiers. The intrinsic body diodes $D_{a1}$ and $D_{a2}$ are switches of $s_1$ and $s_2$ which operated by gate signals.

The operation of proposed converter is symmetrical in both half cycles of input voltage. So, the converter operation is analyzed during the positive half-line cycle of input voltage [12]. The output diode $D_o$ is turned off before the main switch gets turned on [15]. The gate driving signals for the proposed converter is shown in Fig.8.

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**III. BRIDGELESS SEPIC CONVERTER – MODES OF OPERATION**

**Mode 1** $[t_0, t_1]$ In Fig. 9, at the time instant $t_0$, the switch $S_1$ is turned on and switch $S_2$ is conducting.

The magnetizing current $i_m$ increases from its minimum value of $i_{m0}$ linearly with a slope of $V_m/L_m$ due to the voltage $V_p$ across magnetizing inductance $L_m$ is $(1-n)V_m$. The voltage $V_{LS}$ across $L_s$ is $V_m$ and therefore current $i_s$ increases from its minimum value of $L_2$ linearly with a slope of $(1-n)V_m/L_s$. Mode 2 $[t_1, t_2]$ In Fig.10, at the time instant $t_1$, the switch $S_1$ is turned on and switch $S_2$ is conducting.

The voltage $V_p$ across magnetizing inductance $L_m$ is $-V_m$. The magnetizing current $i_m$ decreases from its minimum value of $L_{m1}$ linearly with a slope of $-V_m/L_m$. The voltage $V_{Is}$ across $L_s$ is $-(1-n)V_a$ and the current $i_s$ decreases from maximum value $L_{s1}$ linearly with a slope of $-V_m/L_s$.

**Mode 3** $[t_2, t_0]$ In Fig.11, at the time instant $t_2$, diode $D_o$ is turned off and current $i_{do}$ becomes zero. The freewheeling currents $i_{a2}$ and $i_{d0}$ makes the sum of input current $i_{in}$. The input current is given as $i_{in} = i_{m0} - nis = i_{in} - i_{t1}$. 

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**Fig.6 Circuit Diagram of Parallel converter**

**Fig.7 Circuit Diagram of Bridgeless SEPIC converter.**

**Fig.8 Gate driving signals a). Conventional gate signals for $S_1$ and $S_2$. B) Proposed gate signals for $S_1$ and $S_2$.**
IV. SIMULATION RESULTS AND DISCUSSION

A. Results R-Dump Converter

The simulation model using R-dump converter is shown in Fig.12. The output parameters such as flux, current, torque and speed are shown in Fig.13. During steady state operation, the flux is 1.5 Wb, maximum phase current is 300A. The torque developed by motor is 250 N-m with a speed of 3000 rpm.

B. Results for C-Dump Converter

The complete simulation model using C-dump converter is shown in Fig.14. The output parameters of SRM such as flux, current, torque and speed is shown in Fig.15. During steady state operation, the flux obtained is 0.7 Wb, the maximum phase current is 500A. The torque developed by a motor is 270 N-m with speed of 4000 rpm.

C. Results for H-Bridge Converter

The complete simulation model using H-bridge converter is shown in Fig.16. The simulink results of SRM with flux, current, torque and speed are shown in Fig.17. During steady state operation, the maximum current is 400A with flux 0.5 Wb. The torque developed by motor is 300 N-m with a speed of 5000 rpm.

D. Results for Series Converter

The complete simulation model of series converter is shown in Fig.18. The variations of flux, current, torque and speed are shown in Fig.19. During steady state operation, flux obtained is 0.5 Wb with maximum phase current of 350A. The torque developed by motor is 250 N-m with speed of 4500 rpm.
E. Results for Parallel Converter

The complete simulation model of parallel converter is shown in Fig.20. The simulation results of flux, current, torque and speed are shown in Fig.21. During steady state operation, the flux is 0.5 Wb, the maximum phase current is 300A. The torque developed is 250 N-m with a speed of 4500 rpm.

![Fig.20 Simulink model of 3 phase 6/4 SRM using Parallel Converter](image)

![Fig.21 Simulation results of Parallel Converter a). Flux, b). Current, c). Torque, d). Speed](image)

F. Results for Bridgeless SEPIC Converter

- Open loop SRM
- Closed loop SRM

(i). Open loop Bridgeless SEPIC Converter fed SRM Drive

The complete simulation model of open loop Bridgeless SEPIC converter fed SRM drive is shown in Fig.22. The variations of flux, current, torque and speed is shown in Fig.23. During steady state operation, the flux obtained is 0.4 Wb, the maximum phase current is 50A. The torque developed by motor is 25 N-m with a speed of 2000 rpm.

![Fig.22 Simulation model of 3 phase 6/4 pole SRM using open loop Bridgeless SEPIC Converter](image)

![Fig.23 Simulation results of Open loop Bridgeless SEPIC Converter fed SRM drive a). Flux, b). Current, c). Torque, d). Speed](image)

(ii). Closed loop Bridgeless SEPIC Converter fed SRM Drive

The complete simulation model using closed loop Bridgeless SEPIC converter fed SRM drive is shown in Fig.24.

![Fig.24 Simulation model of 3 phase 6/4 pole SRM using Closed loop Bridgeless SEPIC Converter](image)

![Fig.25 Simulation results of closed loop Bridgeless SEPIC Converter a). Flux, b). Current, c). Torque, d). Speed](image)

The output parameters of flux, current, torque and speed are shown in Fig.25. During steady state operation, the flux is 0.3 Wb with maximum current of 40A. The torque developed by motor is 20 N-m with a speed of 1400 rpm.

![Fig.26 Subsystem model of Bridgeless SEPIC Converter for 3 phase 6/4 pole SRM](image)
TABLE 1. COMPARISON OF SIMULATION RESULTS OF SRM CONVERTERS

<table>
<thead>
<tr>
<th>Converter</th>
<th>Flux (weber)</th>
<th>Current (A)</th>
<th>Torque (N-m)</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-dump</td>
<td>1.5</td>
<td>300</td>
<td>250</td>
<td>3500</td>
</tr>
<tr>
<td>C-dump</td>
<td>0.7</td>
<td>500</td>
<td>270</td>
<td>4000</td>
</tr>
<tr>
<td>H-bridge</td>
<td>0.5</td>
<td>400</td>
<td>300</td>
<td>5000</td>
</tr>
<tr>
<td>Series</td>
<td>0.5</td>
<td>350</td>
<td>250</td>
<td>4500</td>
</tr>
<tr>
<td>Parallel</td>
<td>0.5</td>
<td>300</td>
<td>250</td>
<td>4500</td>
</tr>
<tr>
<td>Open loop Bridgeless SEPIC</td>
<td>0.4</td>
<td>50</td>
<td>25</td>
<td>2000</td>
</tr>
<tr>
<td>Closed loop Bridgeless SEPIC</td>
<td>0.3</td>
<td>40</td>
<td>20</td>
<td>1400</td>
</tr>
</tbody>
</table>

The comparison of various converters such as R-dump, C-dump, H-bridge, series, parallel and Bridgeless SEPIC converter with Open loop and Closed loop topologies for SRM drive is represented in Table 1. The comparison of various parameters such as flux, current, torque and speed shows that Bridgeless SEPIC Converter with closed loop produces better results with reduced current and torque ripples.

V. CONCLUSION

The most flexible and versatile converter for SRM drive is Bridgeless SEPIC converter with closed loop which produces reduced current and torque ripples compared to conventional converters employed for SRM drive. By comparing various converter topologies from Table 1, it is found that Bridgeless SEPIC converter with closed loop produces better results and performance. The Bridgeless SEPIC Converter topology is more beneficial in low-voltage high-current applications. Thus the simulation and its output have a tendency of improved performance with reduced current and torque ripples throughout the operation.

REFERENCES