The Journal of Energy: Engineering & Management
Vol. 12, No. 4, Winter 2023, P. 68-79
Research Article

A Modified SRM Drive Structure Based on Conventional Inverter and DTC Strategy to Reduce Torque Ripple

Majid Ghanizadeh[1], Seyed Reza Mousavi-Aghdam[2*], Majid Hosseinpour[3]

[1] Department of Electrical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
majid13730204@gmail.com
[2] Department of Electrical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
R.mousaviaghdam@uma.ac.ir
[3] Department of Electrical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
hoseinpour.majid@uma.ac.ir

Received: 29/09/2021 **Accepted:** 27/08/2022

Abstract
This paper proposes a modified drive structure for switched reluctance motors considering a direct torque control strategy. In the proposed converter structure, standard inverter topologies are used with a few additional components to make the total SRM drive cost-effective. Like drives with conventional inverters, proposing a new general converter structure, appropriate regarding its total cost and controllability, has been one of the most critical challenges of the last two decades for switched reluctance motors. The use of such conventional three-phase inverters instead of SRM (Switched Reluctance Motor) exclusive converters, due to low cost and greater availability, has been analyzed and effectively implemented in this paper. The analysis showed that driving switched reluctance motors using conventional inverters could possibly lead to a high torque performance. In this paper, two new converter structures, based on conventional three and one phase inverters, are presented for a four-phase switched reluctance motor. In addition, the direct torque control strategy is used to reduce torque ripple sufficiently. The results showed the effectiveness of the proposed drive structure.

Keywords: switched reluctance motor, converter, three-phase inverter, direct torque control, torque ripple.

* Corresponding author
doi: 10.22052/JEEM.2023.113683

1. Introduction

The applications of switched reluctance motor (SRM) drives have increased in recent years because of advantages such as simple and robust construction, high torque capability, and low manufacturing costs. SRMs are one of the most straightforward electrical machines, at which only the stator has windings, and there is no winding or magnetic material on the rotor [1-2]. Hence, it possesses a high application potential, particularly for high-torque and speed driving and operating at high-temperature environments [3-4]. SRM drives always need a sensor to detect the rotor position. The position information is used to energize SRM phases using a unique converter [5]. Some studies [6–9] indicated that the SRM possesses some driving characteristics comparable, for example, to PMSMs in many applications. However, it was bounded by some limitations. Additionally, SRMs have some disadvantages that should be overcome such as high torque ripple and acoustic noise [10–15].

SRMs can be directly operated neither from a DC nor from an AC supply, and they must be electronically commutated all the time. On the other side, the SRM converter is not a standard three-phase inverter. The converter is the heart of the SRM drive. The performance, cost, and size of the SRM drive mainly depend on the selected converter type of the drive circuit. Many converter topologies have been introduced to drive the SRM [16-20]. In addition, there are several works presented on reducing drawbacks through improving the SRM structure or improving its control [21-24]. Any improvement of the controller is deeply dependent on converter capabilities. In any SRM drive, continuous torque ought to be produced by synchronizing phase excitation with the rotor position [25]. R-dump converter type is one of the structures which have one switch and one diode per phase. One of the drawbacks of this converter is that the current in any of the SRM phases will take longer to become zero in comparison to recharging the source, and the energy is dissipated in a resistor; it, thus, reduces the total efficiency of the SRM drive. C-Dump converter type is used as a converter of auxiliary voltage supply [26]. The advantages of a C-dump converter include a lower number of switching devices, full regenerative capability, fast demagnetization during commutation, and phase commutation advancing capability. The significant disadvantages of the C-dump converter are an additional capacitor and an inductor in the dump circuit. The drawback of a conventional C-dump converter can be overcome by adding a freewheeling transistor. However, freewheeling is necessarily limited in this converter [26-28].

In most cases, an asymmetric bridge converter is used in SRM drives. Typically, a high switching voltage is required to establish a fast build-up of the excitation current. The uni-polar switching strategy can be obtained by the converter consisting of two switches and diodes per phase. For each phase, the upper switch acts as PWM switching control, and the lower one for commutation. SRM phases are controlled independently. There are three modes of operation classified as magnetization, freewheeling, and demagnetization mode [29]. In this converter, one switch is always in the current conduction path increasing the losses in the converter and causing the cooling problems. This type of converter generates a relatively low demagnetizing voltage at high speeds [30-32]. The passive converters of series or parallel may be used to achieve voltage-boosting capability during turn-off periods [33].

As introduced in some literature, SRM's conventional converters may be improved in structure. However, it will be more attractive and also cost-effective if the standard three-phase inverter can be utilized for SRMs. In [34], a new control strategy is proposed to extend the conduction angle of delta-connected SRM driven by a three-phase full-bridge inverter. Also, in [35], a three-phase inverter is proposed to drive six-phase SRM. The inverter produces three positive half-waves and three negative half-waves. Each of these half-waves is considered to excite the corresponding phase. However, due to the sinusoidal output voltage of the inverter, the voltage applied to the SRM phases is decreased, which is one of the disadvantages of this structure.

A significant challenge which limits the application of SRMs is that they are subjected to torque ripple and that they result in noise and maintenance difficulty. There have been many control strategies to reduce the torque ripple of SRM. In the last decades, researchers mainly used conventional strategies including current chopper control (CCC) [36] and angle position control (APC) [37]. However, none of the control strategies can effectively reduce the torque ripple, and this problem has still remained an issue. To reduce torque ripple effectively, many new control methods have been introduced with advances in computing technology [38]. The torque sharing function (TSF) control is a new method to mitigate torque ripple [39].

Nevertheless, with an increased number of phases, it may unavoidably complicate the control and result in instability. Direct torque control (DTC), which is used in induction motor control, is recently considered in SRMs. DTC is a new control strategy in SRMs and may bring some advantages, especially for the novel SRM drive structures [40-41].

According to the aforementioned research challenges of SRM machines, this paper intends first to present a new drive topology, which is more cost-effective in terms of implementation and cost; it, then, proposes a method for direct torque control for the new drive to minimize the resulting torque ripple effectively.

2. Initially Proposed Drive Topology for Four-Phase SRM Using Standard Inverters

So far, the converters which have been designed to be used in SRM drives have been mentioned earlier. Due to the particular application and uncommonness of such converters in other machine drives, the cost of these converters is high in comparison with three-phase standard inverters, which are very common and widely used. Therefore, it can be concluded that the use of a three-phase inverter in an SRM drive structure can be cost-effective; that is, because these inverters use a well-known structure and control scheme, they are cheaper and more accessible than other converters. In the previous section, some articles that dealt with SRM energizing through a standard three-phase inverter were totally introduced. This section discusses the initially proposed drive in which the standard inverter is used in a suitable way for SRMs. Fig. 1 depicts the initially proposed drive topology.

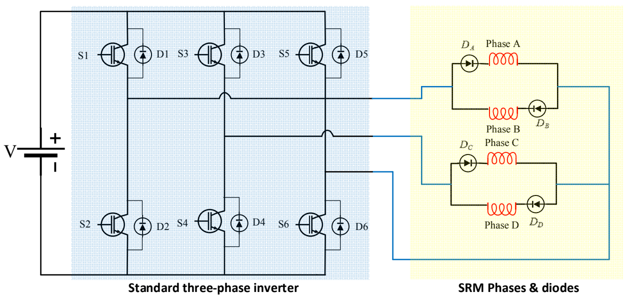
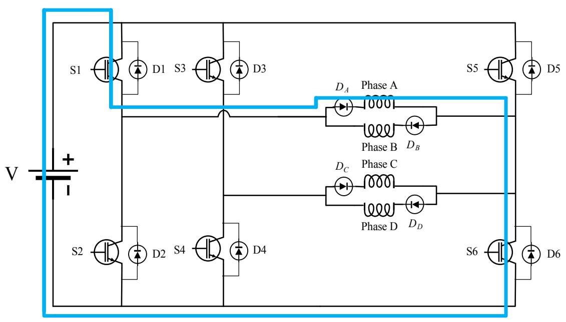
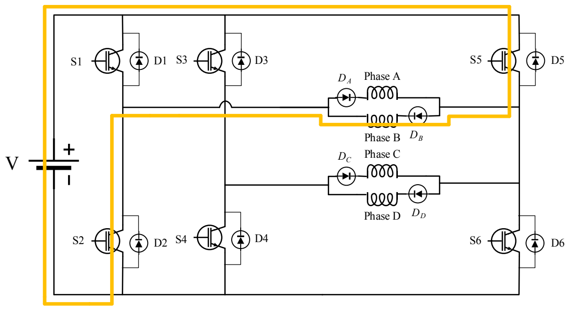


Fig. 1: The initial proposed drive topology using (three-phase) standard inverter for four-phase SRM

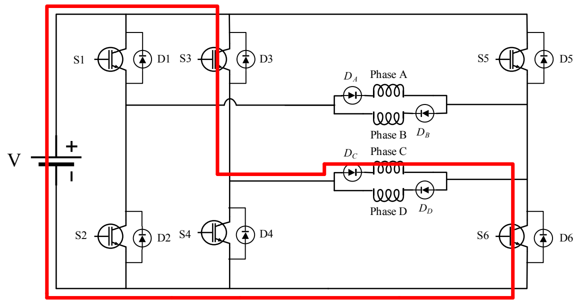
The working principles of the initially proposed SRM drive are illustrated in Fig. 2 for different modes of operation in detail. As shown in Fig 2 (a), phase A can be excited along the current path through switch S_1, diode D_A, phase A, and switch S_6. In this mode, D_B diode blocks the current flow through phase B and acts as a current blocker. Considering D_B diode as a current blocker, it is essential to know how much voltage may be applied to this diode inversely. The reverse voltage on the D_B in this mode is equal to the input voltage.



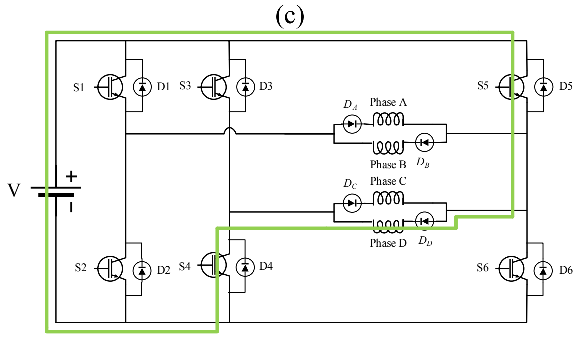
(a)



(b)



(c)



(d)

Fig. 2: Different modes of operation in the initiallyproposed drive topology

Furthermore, phase B can be energized along the current path through switch S_5, diode D_B, phase B, and switch S_2. In this mode (Fig. 2(b)), diode D_A blocks the current flow through phase A and acts as a current blocker. The reverse voltage imposed on the diode D_A in this mode is the same as the one mentioned in the previous mode. As you can see in Fig.2 (c), to excite phase C, it should close its current path through switch S_3, diode D_C, phase C, and switch S_6. In this mode, diode D_D blocks the current flow through phase D and acts as a current blocker. The reverse voltage on diode D_D has no change compared with the previous modes. Finally, as in Fig. 2(d), phase D is energized when its current path through switch S_5, diode D_D, phase D, and switch S_4 is closed. In this mode, the D_C diode blocks the current flow through phase C. The reverse voltage applied on diode D_C in this mode is equal to the input voltage as well.

Earlier, the direct torque control method and its efficiency in reducing torque ripple of the switched reluctance motor were introduced. Now, in the second step, the implementation of the DTC method is considered in the initially proposed drive. The principles of the direct torque control strategy for the proposed four-phase SRM are thoroughly discussed in the subsequent section.

3. Principle of DTC for SRM

3.1. Voltage and Torque Equations

The general equations for voltage and torque of the switched reluctance motor are given here. Based on energy conversion principles, the electromagnetic torque can be written as follows:

$$T=\left.\frac{dW_m}{d\theta}\right|_{i=const}=\left.\frac{d(W_e-W_f)}{d\theta}\right|_{i=const}=i_k\frac{d\psi(i_k,\theta)}{d\theta}-\frac{dW_f}{d\theta}\approx i\frac{d\psi(i,\theta)}{d\theta} \quad (1)$$

In this equation, W_e and W_m are the electrical and mechanical energy, and W_f is the magnetic field energy. $W_f/d\theta$ can be ignored due to the usual magnetic saturation in SRMs. Considering the aforementioned equation, it can be seen that SRM torque is dependent on the variation tendency of $d\psi/d\theta$. It means that if $d\psi/d\theta>0$, the torque will be positive, and while $d\psi/d\theta<0$, the torque will be negative. Hence, the electromagnetic torque can be controlled via modifying the flux linkage gradient.

The stator flux vector can be expressed as:

$$\vec{\psi}(i,\theta)=\int_0^t\left(\vec{V}-R_s\vec{i}\right)+\vec{\psi_0} \quad (2)$$

ψ_0 is the initial magnetic flux of the SRM, which equals zero, and if the term $R_s i$ is considered to be ignored, the equation will, then, be written as:

$$\Delta\vec{\psi}(i,\theta)=u\Delta t \quad (3)$$

According to (3), it is observed that the flux linkage vector may be modified by providing a different stator voltage vector. The resultant torque can, then, be controlled by acceleration/deceleration of the flux linkage vector, as shown in Fig.3.

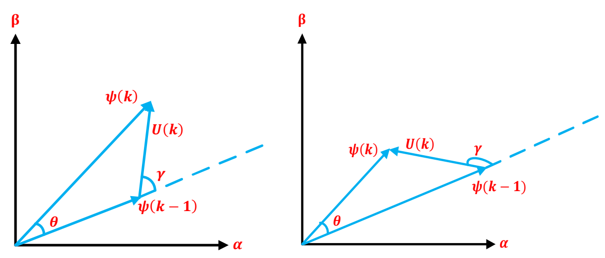


Fig. 3: Illustration of voltage vector and modification of the flux linkage

For a four-phase SRM, the flux linkage can be expressed as follows:

$$\begin{cases}\psi_\alpha=\psi_a-\psi_c\\ \psi_\beta=\psi_b-\psi_d\end{cases},\quad \begin{cases}\psi_s=\sqrt{\psi_\alpha^{\,2}+\psi_\beta^{\,2}}\\ \delta=\arctan\dfrac{\psi_b}{\psi_\alpha}\end{cases} \quad (4)$$

Any phase of the proposed SRM has a mutual angle of 90°. Therefore, the space requires to be divided into eight regions and, here, eight corresponding voltage vectors are needed. As a result, the selection of the magnetic flux and voltage vector, based on the SRM structure and practical requirements, should be performed as in Fig.4.

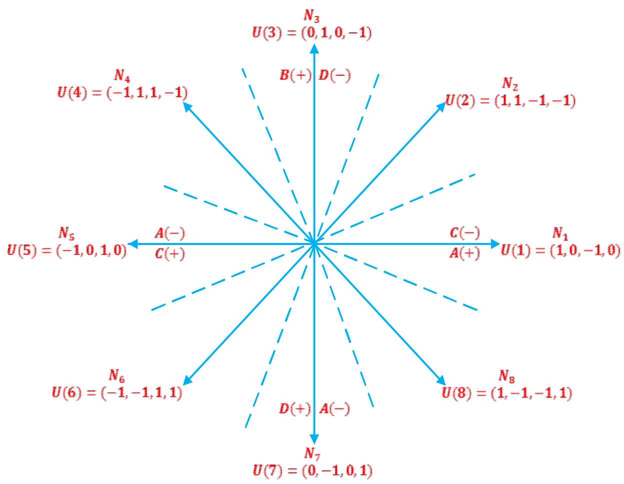


Fig. 4: Space voltage vector and zones for the initial proposed four-phase SRM

As shown in Fig. 3, one can see that if the angle between voltage vector $U(k)$ and magnetic flux vector $\psi(k-1)$ is an acute angle (U_{k+1}, U_{k-1}), the magnetic flux amplitude ψ_s will be increased. On the other hand, if the angle between voltage vector and magnetic flux vector is obtuse (U_{k-3}, U_{k+3}), the magnetic flux amplitude ψ_s will be decreased. Furthermore, any increase/decrease of electromagnetic torque will be determined by advancing or delaying the magnetic flux vector. In addition, the torque control can be carried out by choosing the appropriate voltage vector. The voltage vector in the advance mode of the magnetic flux vectors (U_{k+1}, U_{k+3}) can increase the motor torque, while the voltage vector in the delay mode of the magnetic flux vector (U_{k-1}, U_{k-3}) can decrease the motor torque. Thus, one can attain a selection table for the space voltage vector based on the flux and torque modification principles as summarized in Table 1. It should be noted that the flux can be observed using voltage and current sensors, and the torque is calculated from the motor characteristics by the lookup table shown in Fig. 5.

Table 1: Voltage vector selection table

$T\downarrow\psi\downarrow(00)$	$T\downarrow\psi\uparrow(01)$	$T\uparrow\psi\downarrow(10)$	$T\uparrow\psi\uparrow(11)$
$U(k-3)$	$U(k-1)$	$U(k+3)$	$U(k+1)$

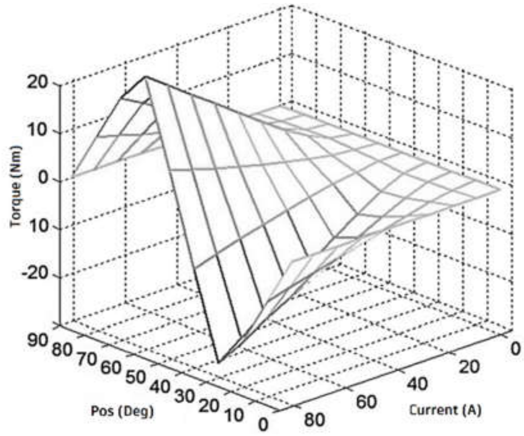
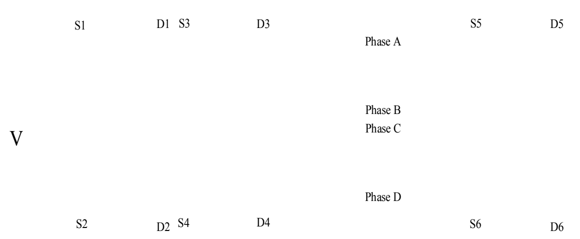


Fig. 5: Position-current-torque characteristics of the SRM

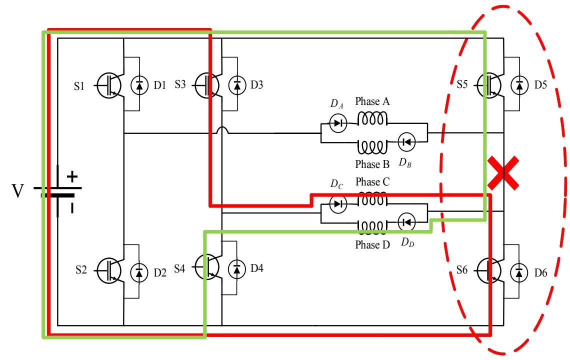
3.2. Implementation of the DTC Method on the Initially Proposed Drive

Using DTC method may reduce the torque ripple of the SRM motor and better control the flux produced by the machine. Hence, in this step, the DTC method is applied to the initially proposed drive. In this study, the torque ripple produced by the proposed drive is effectively minimized. it doubles the value of the proposed strategy. The possibility of implementing such a DTC method on the initially proposed drive is examined in this section. First, in order to find the best solution, the proposed active DTC vectors must be examined to determine whether the initial proposed drive is capable of generating those vectors or not.

By further analyzing the initially proposed drive, it can be noticed that phases A and B cannot be turned on at the same time. As shown in Fig. 6(a), the problem is that in case of simultaneous excitation of these two phases, switches S_5 and S_6 must be turned on simultaneously. Such action causes a short circuit in the third leg of the inverter. Additionally, as illustrated in Fig. 6 (b), this is true for phases C and D.



(a)



(b)

Fig. 6: Illustration of short-circuit in (a) simultaneous excitation of phases A and B, and (b) simultaneous excitation of phases C and D.

The aforementioned short-circuit problem can effectively be solved in this section as it follows. If one looks at Fig.4, he will notice that in all eight generated vectors, phase A never turns on at the same time as phase C. Similarly, phase B never turns on at the same time as phase D. Therefore, in the initially proposed drive, the two phases B and C replace, and the proposed drive circuit is modified as shown in Fig. 7.

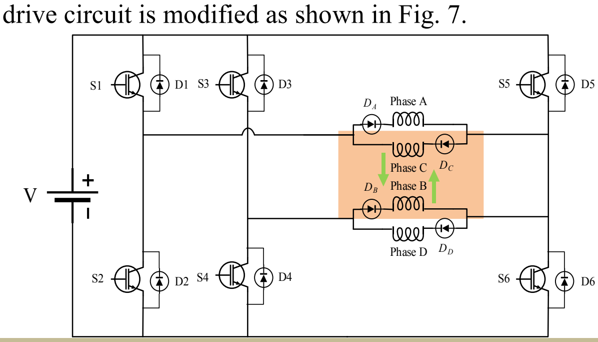


Fig. 7: Phase replacement in the initially proposed drive to avoid short-circuit

After solving the short-circuit problem in the third leg of the proposed converter, which is simply accompanied by the replacement of phases B and C, it is time to examine whether the proposed drive can produce all the eight vectors or not. As an example, the generating modes for vectors U_1 and U_8 are examined in the proposed drive. Fig. 8 illustrates the generation mode of vector U_1.

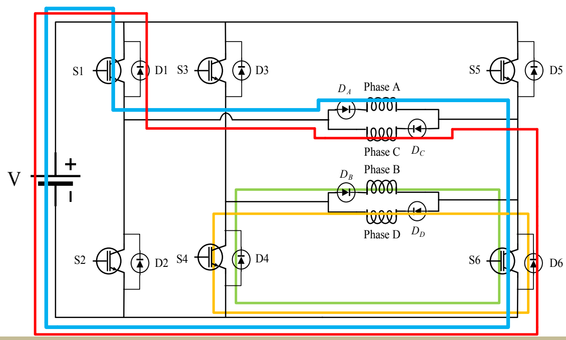


Fig. 8: Generation of vector U_1in the initially proposed drive

Fig. 8 demonstrates that vector U_1 can be obtained by turning on switches S_1, S_4, and S_6 without any short-circuit or particular problem. Fig. 9 illustrates the same assessment for vector U_8.

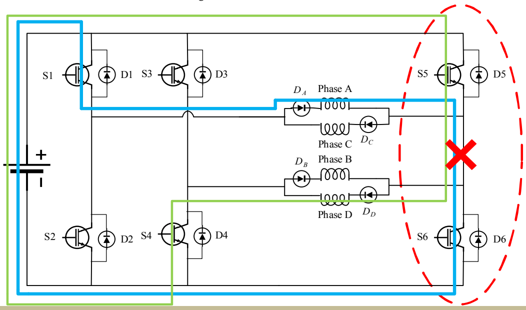


Fig. 9: Generation of vector U_8 in the initially proposed drive

As shown in Fig. 9, it can be noticed that by turning on the switches S_1, S_5 and S_6, vector U_8 is generated. However, the third leg of the inverter is short-circuited. As a result, it is not possible to produce vector U_8 with this initially drive. Thus, it can be generally said that some vectors may be generated with the initial proposed drive, but others may not. Therefore, it is concluded that the initially proposed drive cannot produce all necessary vectors to implement DTC. In fact, by using this proposed drive, DTC control cannot be applied to the SRM. To overcome this problem, some changes have been made to the initial proposed drive so that an additional leg can be added to the initial drive circuit. In the next section, the finally improved structure of the proposed drive, which can produce all of eight necessary vectors, is discussed and examined.

4. Finally proposed Drive Using Standard Inverters with DTC Implementation Capability

In general, as mentioned earlier, some of vectors for DTC could be generated with the drive proposed in the previous section. However, there were some problems generating other vectors with this drive topology. In fact, with the initial drive, direct torque control could not be applied to a four-phase switched reluctance motor. To overcome this problem, changes were made to fix it in such a way that another leg could be added to the initially proposed drive in the previous section. Practically, the improved structure with an additional leg results in two full-bridge inverters, which are illustrated in Fig.10.

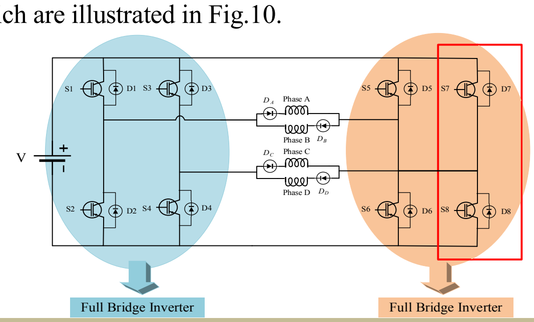


Fig. 10: Final proposed drive for a four-phase switched reluctance motor

Table 2 summarizes the switching strategy for eight modes of the vectors in the finally proposed drive. In general, the first drive topology (Fig.1) cannot produce all the vectors in DTC strategy and can be used in applications that do not require precise control. The second topology (Fig. 10) produces all the vectors in DTC mode and can, thus, be used in precise control.

Table 2: Switching table of the finally proposed drive

Vector	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
U_1	1	0	0	1	0	1	0	1
U_2	1	0	1	0	0	1	0	1
U_3	1	0	1	0	1	0	0	1
U_4	0	1	1	0	1	0	0	1
U_5	0	1	0	1	1	0	0	1
U_6	0	1	0	1	1	0	1	0
U_7	1	0	0	1	1	0	1	0
U_8	1	0	0	1	0	1	1	0

5. Results and Discussion

5.1. Simulation Results of the Conventional Drive

As discussed in the earlier section, many converters have been proposed so far to feed SRM machines with some advantages and disadvantages. One of these converters widely used in SRM machine drives is the asymmetric bridge converter explained earlier. Since the SRM studied in this paper has four phases, a four-phase type of asymmetric bridge converter is going to be considered. This type includes eight switches as well as eight diodes in its structure. The asymmetric bridge converter is selected as the most common converter in the SRM drives and will be the basis for all subsequent comparisons with the proposed drive systems. Table 3 lists some of the common parameters of an SRM drive. Fig. 11 shows the simulation results for the conventional asymmetric bridge converter. It should be noted that in a conventional converter, the switching angles are selected in a way that the motor phases produce less torque ripple.

Table 3: Parameters used in SRM converters

Speed (rpm)	**1500**
Voltage (V)	**400**
Max current (A)	**50**
Stator resistance (Ohm)	**0.05**
Inertia (kg.m.m)	**0.05**
Friction (N.m.s)	**0.02**
Poles	**8/6**

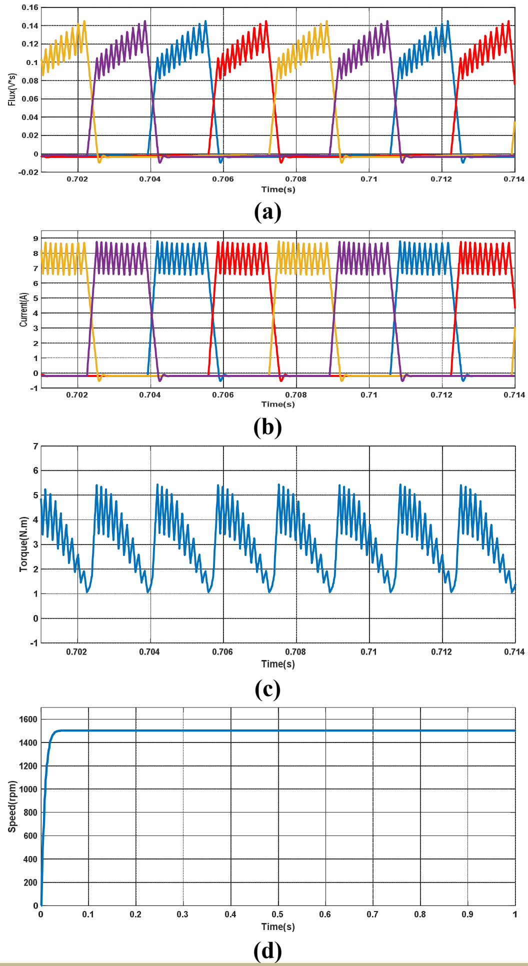


Fig. 11: Waveforms of (a) Magnetic flux, (b) current, (c) torque and (d) speed in the conventional SRM drive

5.2. Simulation Results of the Initially Proposed Drive

In this step, the four-phase SRM is energized by the initially proposed drive. In this case, instead of using a four-phase asymmetric bridge converter, a typical three-phase inverter and four diodes are used as illustrated in Fig. 7. The asymmetric bridge converter uses two diodes and two switches for each phase. Thus, the four-phase type of this converter will have eight diodes and eight switches in its structure. On the contrary, the proposed SRM drive has two diodes as well as two switches on each leg; in total, it includes six switches and six diodes. In this new topology, additional four diodes are also included. Therefore, the initially proposed drive uses a total of six switches and ten diodes in its structure; thus, it has a low number of switches in comparison with the conventional converter.

In the initially proposed drive system, instead of two asymmetric bridge converter switches, two diodes are structurally used in the new drive system. The cost analysis of these two drive systems reveals that using two diodes is cheaper than two switches individually. On the other hand, the use of a three-phase standard inverter is much simpler and cheaper than a particular asymmetric bridge converter. As a result, it is clear that the initially proposed drive system is more beneficial and cost-effective in comparison with the asymmetric bridge converters in terms of cost and control simplicity. Moreover, the initially proposed drive uses a standard inverter in its structure, which is more available as well as good to start and feed SRMs. However, as mentioned in the previous section, the DTC technique cannot be applied to this new drive system. Fig. 12 shows the motor performance waveforms when the SRM is running under the initially proposed drive system. As seen, although the motor speed is effectively controlled, the torque ripple increases; this, in turn, will lead to a low-efficiency drive. It should also be mentioned that in this step, there is no additional effort to decrease the torque ripple further. In the subsequent sub-section, the torque ripple is effectively reduced using the finally proposed drive system.

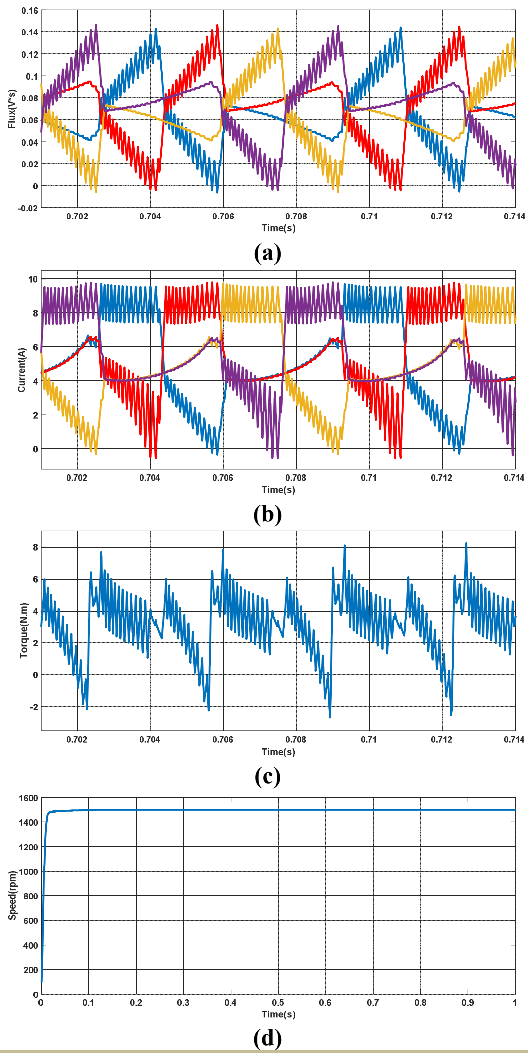
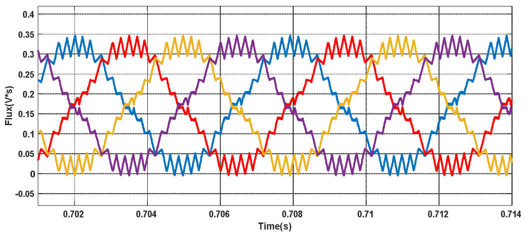


Fig. 12: Waveforms of (a) Magnetic flux, (b) current, (c) torque and (d) speed in the initially proposed SRM drive

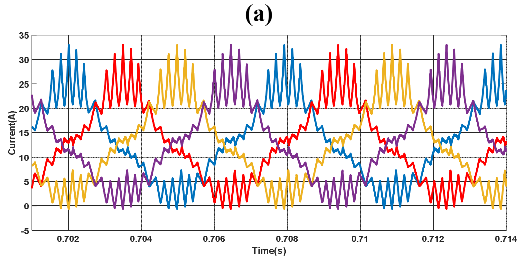
5.3. Simulation Results of the Finally Proposed Drive

As discussed in the previous sections, besides using standard inverters, which will lead to a simple and cost-effective drive system in SRMs, another essential attempt which should befocused on is the reduction of the SRM torque ripple. This can be reached using modern DTC techniques; however, in the initially proposed drive, this technique cannot be applied for reasons mentioned. In brief, it was investigated that by reducing two switches in the initially proposed drive, it could not produce all necessary vectors to implement DTC. For this reason, an improved structure based on standard inverters was proposed in which two full-bridge inverters were used instead of three-phase inverters. It should also be mentioned that the full-bridge inverters, like the three-phase standard inverters in the initially proposed drive, are also much cheaper than a particular SRM converter. Asymmetric bridge converters are the same; that is why they are widely used in different industries. The finally proposed drive system can minimize the torque ripple by accurately applying DTC technique to the SRM drive.

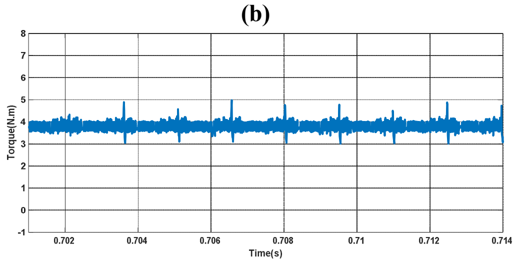
Fig. 13 shows the motor performance waveforms when the SRM is running with DTC technique in the finally proposed drive system.



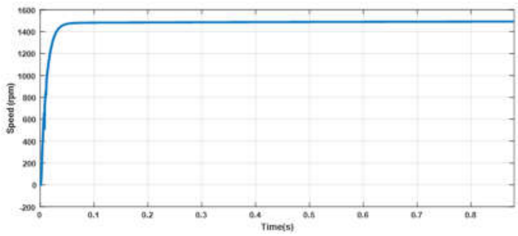
(a)



(b)



(c)



(d)

Fig. 13: Waveforms of (a) Magnetic flux, (b) current, (c) torque and (d) speed in the final proposed SRM drive with the implementation of DTC

As shown in Fig. 13, the motor torque ripple is effectively reduced, and the speed control is successfully carried out. The RMS of phase currents is not considerably changed. Therefore, the copper losses are approximately the same. The flux linkage is increased in comparison with the previous mode. However, this will not lead to extreme saturation and slightly affects the iron losses. Fig. 14 compares the torque diagrams of the three mentioned modes using a conventional converter, a proposed converter, and a proposed converter with DTC. As seen, the proposed converter with DTC produces obviously less torque in comparison with the others. In addition, it shows that a conventional asymmetric bridge converter will lead to a low ripple in comparison with the proposed converter without DTC. It should be mentioned that the proposed converter uses a standard three-phase inverter that makes it easy to drive SRM anywhere. In other words, if asymmetric bridge converters or other special SRM converters were unavailable, it would be possible to use the proposed converter instead. Finally, the implementation of the proposed SRM drive with DTC control method using two typical bridge inverters and the minimum possible torque ripple could be effectively achieved.

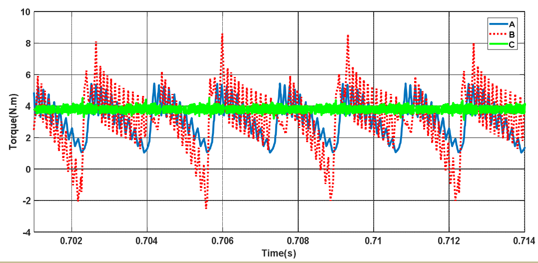
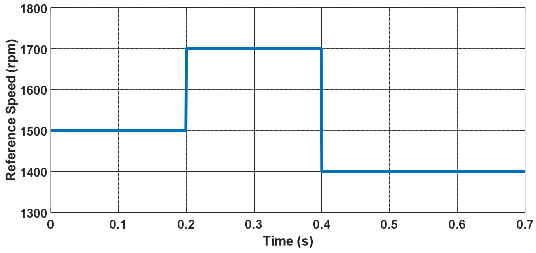
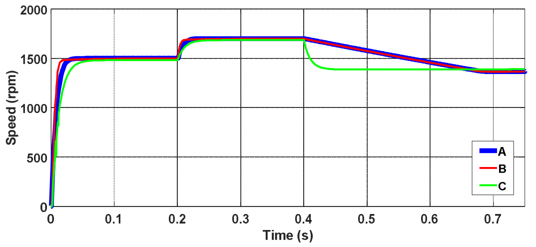


Fig. 14: Comparison of the motor torque using conventional SRM drive(A), proposed SRM drive (B), and proposed SRM drive with DTC.

The drive performance is further examined during reference speed and load step changes. Fig. 15 shows speed responses for different mentioned SRM drives. As seen, the proposed drive with DTC exhibits a good performance especially during speed reduction. A similar analysis using step load change is also included in Fig. 16. Again, the proposed SRM drive with DTC shows an appropriate performance with a low torque ripple.

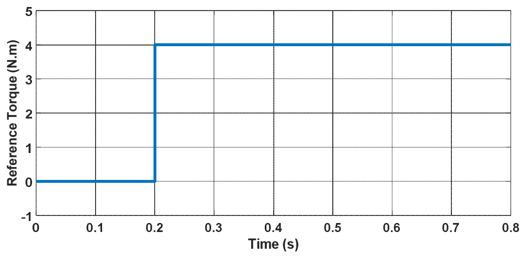


(a)

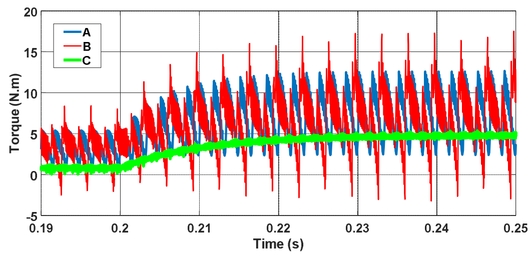


(b)

Fig. 15: Speed reference waveform (a) and drive responses (b): Conventional SRM drive (A), proposed SRM drive (B), and proposed SRM drive with DTC



(a)



(b)

Fig. 16: Load step waveform (a) and drive responses (b): Conventional SRM drive (A), proposed SRM drive (B) and proposed SRM drive with DTC

The parameter variation has no essential effect on the mentioned controls. This is carried out for a 10% variation of stator resistance, and the result is depicted in Fig. 17. The SRMs usually use special converters compared with other electric motor types that use (one or three-phase) standard inverters to drive. The cost of these special converters is higher than the standard inverters. Therefore, this paper uses standard inverters with minimum additional components to drive the motor. In the proposed drive, additional diodes are just inserted in series with the motor phases. The current rating of the diodes is the same as it is for motor phases. The inverse voltage of the diode is less than the DC link voltage. The inverse voltage for the 400V DC link is shown in Fig 18. The use of these additional diodes, besides standard converters, is cost-effective in comparison with utilizing special converters. Additionally, the number of switches in the proposed drive is equal to or less than that of the conventional one as in Table 4.

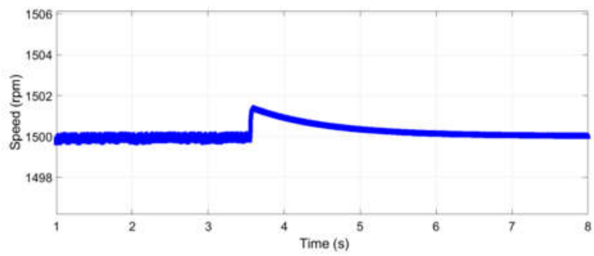


Fig. 17: Speed response to step variation of the stator resistance in the proposed SRM drive

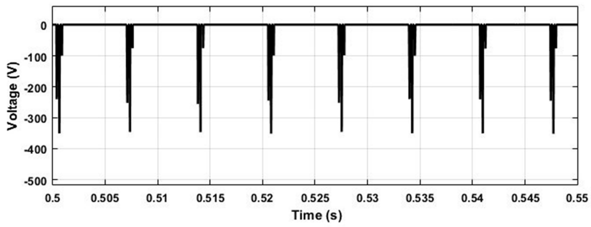
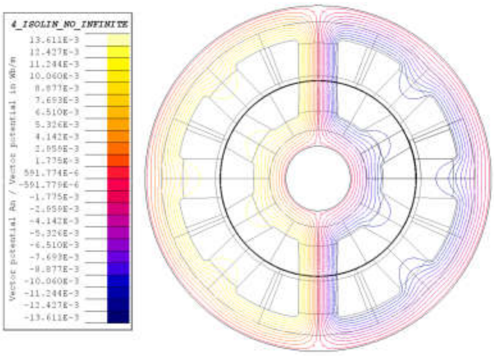


Fig. 18: Inverse voltage waveform of the additional diode for the proposed SRM drive.

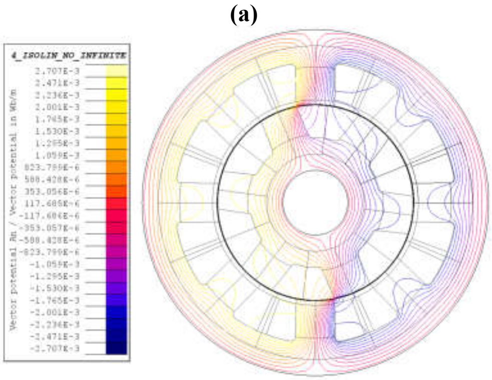
Table 4: Comparison of converter elements

	Number of switches/converter type	Number of diodes
Conventional	**8/special** converter	**8**
Proposed drive	**6**/one (three phase) **standard** converter	**10**
Proposed drive with DTC	**8**/ two (one phase) **standard** converter	**12**

The proposed drive system is further verified by implementing it in the FEM software. Fig. 19 shows the magnetic flux lines of the SRM in the aligned and unaligned positions when the phase A energized. Since the same magnetic flux-current-position and position-current-torque characteristics were used in the SRM model for the previous analysis, it is expected to obtain similar results using a FEM-based model. Fig. 20 confirms the same results for the torque, as an example, using a mathematical model as well as an FEM-based model.

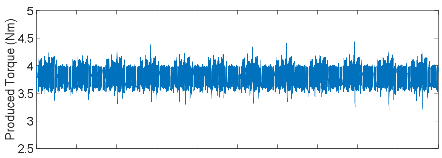


(a)

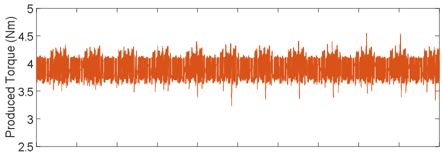


(b)

Fig. 19: The magnetic flux lines of the four-phase SRM in the aligned (a) and unaligned positions using FEM



(a)



(b)

Fig. 20: The produced torque using (a) mathematical and (b) FEM-based model

6. Conclusion

This paper focuses on using standard inverters in SRM drives. The reason lies in the fact that they are more common than other SRM converters, and they are produced in high scales. Thus, they are cheaper, and their use totally reduces the cost of the drive. On the other side, the torque ripple is a primary challenge in SRM drives, and implementation of the converters, using a standard inverters, may negatively affect the torque ripple. In this paper, a new converter based on a standard inverter has been introduced, and its modes of operation have been discussed. In order to reduce the torque ripple in the proposed SRM drive, the DTC control strategy is considered, and the way of implementation in the new SRM drive is thoroughly discussed. The results have shown that a proposed SRM drive with a DTC control strategy reduces the torque ripple by more than 90 percent. More importantly, the proposed SRM drive uses standard inverters which are more accessible with no additional design requirements.

References

[1] Sun, H., Moghaddam A. F., Sergeant, P., and den Bossche, A. V., "*A Novel Driving Method for Switched Reluctance Motor With Standard Full Bridge Inverter*", IEEE Transactions on Energy Conversion, Vol. 35, No. 2, pp. 994-1003, Ju. 2020, doi:10.1109/TEC.2020.2968758.

[2] Feyzi, M. R., Mousavi-Aghdam, S. R., and Ebrahimi, Y., "A comprehensive review on the performance improvement in switched reluctance motor design", In 24th Canadian Conference on Electrical and Computer Engineering (CCECE), May 2011, On, Canada, pp. 348-353, doi:10.1109/CCECE.2011.6030471.

[3] Krishnan, R., "witched reluctance motor drives: modeling, simulation, analysis, design, and applications," CRC press, 2017.

[4] MillerT. J. E., "Switched reluctance motors and their control", Magna physics publishing and Clarendon press, 1993.

[5] LukicS. M., and Emado, A., "Modeling of electric machines for automotive applications using efficiency maps", In Electrical insulation conference and electrical manufacturing and coil winding technology conference Sept. 2003, In, USA, pp. 543-550, doi:10.1109/EICEMC.2003.1247945.

[6] LinY. W., ChouK. F., YehM. J., Wang C., YuS. L., YangC. C., ChangY. C., and LiawC. M., "*Design and control of a switched-reluctance motor-driven cooling fan*", IET power electronics, Vol. 5, No. 9, pp. 1813-1826, 2012, doi:10.1049/iet-pel.2012.0075.

[7] Khanbabaie Gardeshi, H., Torkaman, H., "*Improved Control of Switched Reluctance Motor at High Speeds using Continuous Conduction Mode*", Tabriz Journal of Electrical Engineering, Vol. 47, No.1, pp. 69-79, 2017.

[8] Kyohei, K., Sugimoto, H., Chiba, A., "*Comparing electric motors: An analysis using four standard driving schedules*", IEEE Industry Applications Magazine, Vol. 20, No. 4 pp. 12-20, 2014, doi:10.1109/MIAS.2013.2288380.

[9] Siadatan, A., Shamsabad Farahani, S. S., Afjei, S., "*DSP Circuit Design and Manufacturing for Rotor Position Discovering of Sensorless Motor-Generator Switched Reluctance Motor using Amplitude Modulation in Motor Mode*", Tabriz Journal of Electrical Engineering, Vol. 48, No.2, pp. 699-710, 2018.

[10] ChenjieL., FahimiB., "*Prediction of acoustic noise in switched reluctance motor drives*", IEEE Transactions on Energy Conversion, Vol. 29, No. 1, pp. 250-258, 2013, doi:10.1109/TEC.2013.2291702

[11] Santos, D., LMF., Anthonis, J., Naclerio, F., JC Gyselinck, J., Auweraer, H. V. D., CS GóesL., "*Multiphysics NVH modeling: Simulation of a switched reluctance motor for an electric vehicle*", IEEE Transactions on Industrial Electronics, Vol. 61, No. 1, pp. 469-476, 2013, doi:10.1109/TIE.2013.2247012.

[12] Pere, A., Blanque, B., Martinez, E., Torrent, M., "*A novel type of hybrid reluctance motor drive*", IEEE transactions on industrial electronics, Vol. 61, No. 8, pp. 4337-4345, 2013, doi:10.1109/TIE.2013.2279384.

[13] Giet, V. D., Lange, M. E., Correa, D. A. P., Chabu, I. E., Silvio I. Nabeta, and Hameyer, K., "*Acoustic simulation of a special switched reluctance drive by means of field-circuit coupling and multiphysics simulation*", IEEE Transactions on Industrial Electronics Vol. 57, No. 9, pp. 2946-2953, 2010, doi:10.1109/TIE.2010.2051935.

[14] Hyong-Yeol, Y., Lim, Y., Kim, H., "*Acoustic noise/vibration reduction of a single-phase SRM using skewed stator and rotor*", IEEE Transactions on Industrial Electronics, Vol. 60, No. 10, pp. 4292-4300, 2012, doi:10.1109/TIE.2012.2217715.

[15] Sun, X., Wu, J., Lei, G., Guo, Y., and Zhu, J., "*Torque Ripple Reduction of SRM Drive Using Improved Direct Torque Control With Sliding Mode Controller and Observer*", IEEE Transactions on Industrial Electronics, Vol. 68, No. 10, pp. 9334-9345, Oct. 2021, doi:10.1109/TIE.2020.3020026

[16] Krishnan, R., Materu, P. N., "*Analysis and design of a low-cost converter for switched reluctance motor drives*", IEEE Transactions on Industry Applications, Vol. 29, No. 2, pp. 320-327, 1993, doi:10.1109/28.216539.

[17] Mousavi-Aghdam, S. R., Feyzi, M. R., Ebrahimi,Y., "*A new switched reluctance motor design to reduce torque ripple using finite element fuzzy optimization*", Iranian Journal of Electrical and Electronic Engineering, Vol. 8, No. 1, pp. 91-96, 2012.

[18] Ahmed, M. H., Blasko, V., Lipo, T. A., "*A modified C-dump converter for variable-reluctance machines*", IEEE Transactions on Industry Applications, Vol. 28, No. 5, pp. 1017-1022, 1992, doi:10.1109/28.158824.

[19] Mir, S., Husain, I., Elbuluk, M. E., "*Energy-efficient C-dump converters for switched reluctance motors*", IEEE transactions on power electronics, Vol. 12, No. 5, pp. 912-921, 1997, doi:10.1109/63.623010.

[20] Mousavi-Aghdam, S. R., Moradi, A. and Dolatkhah, A. M., "*Torque ripple reduction of Switched reluctance motor using improved torque sharing functions*", 2017 In Iranian Conference on Electrical Engineering (ICEE), July 2017, Tehran, Iran, pp. 1043-1047, doi:10.1109/IEMDC.2017.8002356.

[21] Dowlatshahi, M., Saghaian-Nejad, S. M., Afshoon, M., Ahn, J. W., "*High efficient torque control of switched reluctance motor taking nonlinear and saturation effects into account*", In4th Annual International Power Electronics, Drive Systems and Technologies Conference, April 2013, Tehran, Iran, pp. 49-54, doi:10.1109/PEDSTC.2013.6506671.

[22] Zare ChavoshiA., GanjiB., "*Online commutation angle control of linear switched reluctance motor with segmental translator*", Tabriz Journal of Electrical Engineering, Vol. 48, No.1, pp. 43-51, 2018.

[23] Dong-Hee, L., Liang, J., Lee, Z., Ahn, J., "*A simple nonlinear logical torque sharing function for low-torque ripple SR drive*", IEEE Transactions on Industrial Electronics, Vol. 56, No. 8, pp. 3021-3028, 2009, doi: 10.1109/TIE.2009.2024661.

[24] Liang, X., Li, G., Ojeda, J., Gabsi, M. and Ren, Z., "*Comparative Study of Classical and Mutually Coupled Switched Reluctance Motors Using Multiphysics Finite-Element Modeling*", IEEE Transactions on Industrial Electronics, Vol. 61, No. 9, pp. 5066-5074, 2014, doi:10.1109/TIE.2013.2282907.

[25] Turker, Ç. G., Kuyumcu, F. E., Tokan, N. T., "*Performance of support vector regression machines on determining the magnetic characteristics of the E-core transverse flux machine*", Turkish Journal of Electrical Engineering & Computer Sciences, Vol. 23, No. 3, pp. 698-708, 2015, doi:10.3906/elk-1301-84.

[26] Wichert, I. T., "Design and construction modifications of switched reluctance machines", Ph.D. Thesis, Warsaw University of Technology, 2008.

[27] Lee, D. Y., Hur, J., Hyun, D. S., "An improved C-dump converter system for switched reluctance motors", InProc. International Conference of Electrical Engineering, 2002, Hanyang, Korea, pp. 1027-1030,

[28] Yoon, Y.,Kim, Y., Song, S., Won, C., "*Control of C-dump converters fed from switched reluctance motors on an automotive application*", Journal of Power Electronics, Vol. 5, No. 2, pp. 120-128, 2005, doi:10.1016/j.epsr.2006.07.005.

[29] Lamchich, M. T., "Torque control" Intechopen, 2011.

[30] Singh, S., and Ganguli, S. G., "Comparative study of various converter topologies of switched reluctance motor drive using P-SPICE", PhD Thesis, Thapar University, 2011.

[31] Vukosavic, S. and Stefanovic, V. R., "*SRM inverter topologies: a comparative evaluation*", IEEE Transactions on Industry Applications, Vol. 27, No. 6, pp. 1034-1047, 1991. doi:10.1109/28.108453.

[32] Mousavi-AghdamS. R., SharifianM. B. B., BanaeiM. R., "*A new method to reduce torque ripple in switched reluctance motor using fuzzy sliding mode*", Iranian journal of fuzzy systems, Vol. 9, No. 197-108, 2012, doi: 10.22111/IJFS.2012.228.

[33] Singh, B., Saxena, R., Pahariya, Y., Chouhan, A. R., "*Converters performance evaluation of switched reluctance motor in Simulink*", International Journal of Industrial Electronics and Control, Vol. 3, No. 2, pp. 89-101, 2011.

[34] Elamin, M., Yasa, Y., Elrayyah, A.and Sozer, Y., "Performance improvement of the delta-connected SRM driven by a standard three phase inverter", IEEE International Electric Machines and Drives Conference (IEMDC), May 2017, FL, USA, pp. 1-7, doi:10.1109/IEMDC.2017.8002356.

[35] Widmer, J. D., Mecrow, B. C., Spargo, C. M., Martin, R. and Celik, T., "Use of a 3 phase full bridge converter to

drive a 6 phase switched reluctance machine", 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012), March, 2012, Bristol, doi:10.1049/cp.2012.0260.

[36] Khan, Y. A., Twinkle, I. K., Kumar, S. and Verma, V., "*Comparative Analysis of Different Converter Topologies for an SRM Drive with Conventional and Vector Control Schemes*", 2020 International Conference on Emerging Frontiers in Electrical and Electronic Technologies, 2020, pp. 1-6, doi:10.1109/ICEFEET49149.2020.9187008.

[37] Dowlatshahi, M., Nejad, S. M. S., Moallem, M. and Ahn, J., "Torque ripple reduction of switched reluctance motors considering copper loss minimization", In IEEEInternational Conference on Industrial Technology (ICIT), Feb 2014, Busan, Korea, pp. 858-865, doi:10.1109/ICIT.2014.6895012.

[38] Hua, C., Xu, P., Ma, Q., Ye, W., "Performance analysis of switched reluctance motor based on Maxwell and Simplorer", Chinese Automation Congress (CAC), Oct. 2017, Jinan, China, pp. 6510-6515, doi:10.1109/CAC.2017.8243950.

[39] Jing, J., Lv, S. and Shi, C. f., "Direct torque PID control of switched reluctance motor based on duty ratio control technique", In IEEE International Conference on Mechatronics and Automation (ICMA), Aug. 2015, Beijing, China, pp. 649-653, doi:10.1109/ICMA.2015.7237561.

[40] Fan, J. and Ahn, J. W., "Research on direct torque control of switched reluctance motor with improved commutation strategy", In IEEE International Conference on Industrial Technology (ICIT), Feb. 2018, Lyon, France, pp. 510-515, doi:10.1109/ICIT.2018.8352229

[41] Yufei, H., Ping, X., and Qishuang, M., "Torque ripple reduction of four-phase SRM based on DTC method", InIEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Oct. 2018, Chongqing, China, pp. 994-997, doi:10.1109/IAEAC.2018.8577728.