Chapter

Switched Reluctance Motor Drives: Fundamental Control Methods

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Abstract

The switched reluctance motor has been gaining interest both at the academic and industrial levels. Its most appreciated characteristics are the nonuse of rare elements and the low construction price. The control of the switched reluctance motor is not as easy as other traditional machines. In the control, it is necessary to reduce the torque ripple as much as possible, which has been the most studied problem in the field. This chapter aims to give the reader a concise but focused knowledge on how the switched reluctance motor can be controlled. Fundamental control methods and their impact in the motor performance are described. A simulation section is presented, where the simulation files are provided for the reader. The simulations are based on the theory described and have the advantage of using a non-linear switched reluctance motor model from a real motor.

Keywords: switched reluctance motor, electric drive, modelling, linear control

1. Introduction

The switched reluctance motor (SRM) is an electrical machine that converts electric power into mechanical power. This electric motor, similarly to conventional motors (induction motor, synchronous motor and others), can operate in the four quadrants: In other words, it can accelerate and decelerate for clockwise and anticlockwise rotor rotations.

SRM control cannot be compared either with the alternated current motor, which is fed with sinusoidal current waveforms or with the direct current motor. In the simplest control, it needs each motor phase (winding) to be magnetized and demagnetized at the right moments of rotor position, so square current waveforms can be used in the simplest control. But as the motor is highly non-linear, the electromagnetic torque does not depend only on the instantaneous current value but also on a non-linear inductance profile, which means that using only square current waveforms will create torque with a high ripple component.

Our aim in this chapter is to describe a variety of fundamental methods to operate the SRM in the four quadrants. Indeed, there are many works published on this subject, [1–5], and due to this reason, we propose a chapter for beginners who wants to really understand the foundations of SRM drives. For a more extensive and systematic exposition of SRM, the reader is referred to the many good books on the subject. For example, in [6] there is a complete description on every subject related to the SRM. In [7] a description about the SRM and a brief description about the controllers are given. Although these works are very complete, they do not give a clear path for the reader to create a SRM drive. So, in this chapter, simple controllers and all fundamental methods to develop a SRM controller and thus contribute to a very steep learning curve in SRM drives are described. And while it is aimed at beginners, we hope that even experts will have something to learn from this chapter.

Linear controllers are presented: voltage impulse, current and torque controllers, respectively. Depending on the required performance and cost, a choice can be made from the cheapest with the lowest performance of impulse control to the most expensive with the best performance of torque control.

As already stated, the motor is highly non-linear, so linearization needs to be performed for control design. The small-signal linearization method which although being very limited is widely used in real systems is described. It will be seen that an ideal current waveform can be calculated to produce constant torque, instead of using a square waveform current. About the power electronic device, a description is given of how the traditional SRM converter works and how it can be controlled to maximize performance.

A simulation environment is also developed in the numerical tool *Simulink/Matlab*®. It is based on the controllers and methods described in the chapter, to which the reader can have access and make his own simulations. This way, one student who works through this text will get an excellent grounding in SRM drives. He or she will actually learn what SRM control is about and how it can be used and will be in an excellent position to go on to more advanced controllers using this material.

In the description of the theory and in the simulation results, the SRM model parameters described in [8] were used.

The chapter is divided into a description of the SRM in *Section 2*, the fundamental linear control methods in *Sections 3*, a study of the SRM model and its linearization in *Section 4*, the current waveform for constant torque in *Section 5*, a description of the traditional SRM converter and its control in *Section 6*, a presentation of numerical results using the tool *Simulink/Matlab*® in *Section 7* and to end, the conclusions and bibliography.

2. Switched reluctance motors

The SRM is constituted by a stator with concentrated windings disposed around polar cores and by a rotor composed by salient poles free of windings or magnets. Normally, each stator phase is composed by a couple of windings diametrically opposed. In **Figure 1** a SRM configuration of 6 stator poles and 4 rotor poles is shown. That is the configuration of reference for this chapter.

When a stator phase is magnetized, a closed magnetic field is generated between the stator, the air gap and the rotor. This magnetic field tends to minimize the reluctance by reducing the air gap which creates a rotor movement. When a stator pole is aligned with a rotor pole, it is said that they are in the position of minimum reluctance, and when they are completely unaligned, it is said they are in the position of maximum reluctance.

This characteristic of the motor makes it possible to create a rotational movement of the rotor by magnetizing and demagnetizing each phase in the right position of the rotor.

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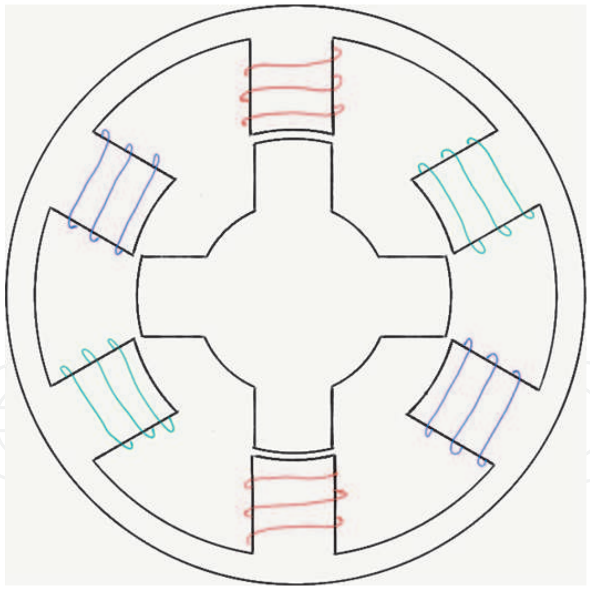

Figure 1.
Switched reluctance motor structure.

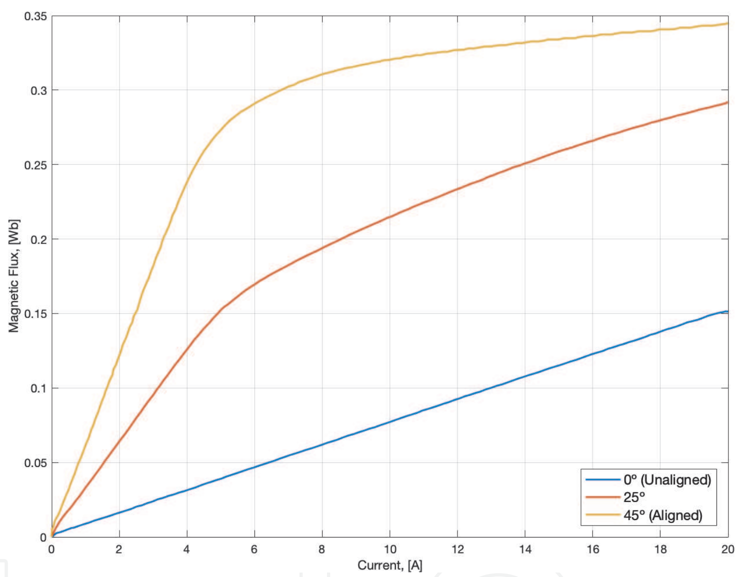

Figure 2.
SRM flux characteristic.

2.1 Torque characteristic

The SRM suffers from high saturation. The inductance profile is non-linear, making the flux characteristic also non-linear. This can be seen in **Figure 2**, where the blue line is the unaligned rotor position and the red line the aligned rotor position. Saturation starts to influence the motor characteristic from about 5 A. It is around this point where the torque ampere ration significantly increases.

The SRM torque characteristic graphic is shown in **Figure 3**. It represents one phase for 90° of the rotor, as the rest of the 360° are just a repetition for the other 3 rotor poles. The blue line represents a low current profile of 5 A, and the red line represents a high current profile of 20 A, which is the maximum motor current. It can be seen that from 0 to 45°, positive torque is produced and from 45 to 90°

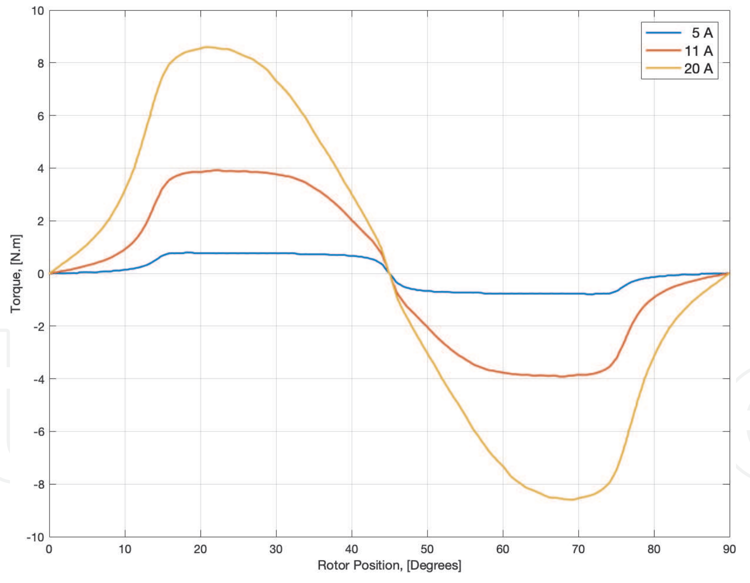

Figure 3.
SRM torque characteristic.

negative torque is produced. It can also be seen that the produced torque is not constant for constant current.

3. Control techniques

Various control schemes have been investigated essentially for torque ripple reduction and the increase of efficiency, for example, in [2, 9]. These can be essentially divided into voltage impulse control, by keeping a constant current or by keeping a constant torque.

3.1 Voltage impulse control

The impulse control is the simplest controller for the SRM. It is used, essentially, for high speed control and for systems that do not require high performance of the drive. Its typical implementation scheme, represented in **Figure 4**, is composed by a speed controller, a phase control method, a block that generates the transistors signals, and an overcurrent protection.

For the speed controller, a linear PI controller is usually used, as in other electric drives with other electrical machines. It receives the speed error and gives a reference voltage signal.

The phase control has the task of triggering each phase and decide how the reference voltage must be applied. For this part, it is essential to have good accuracy

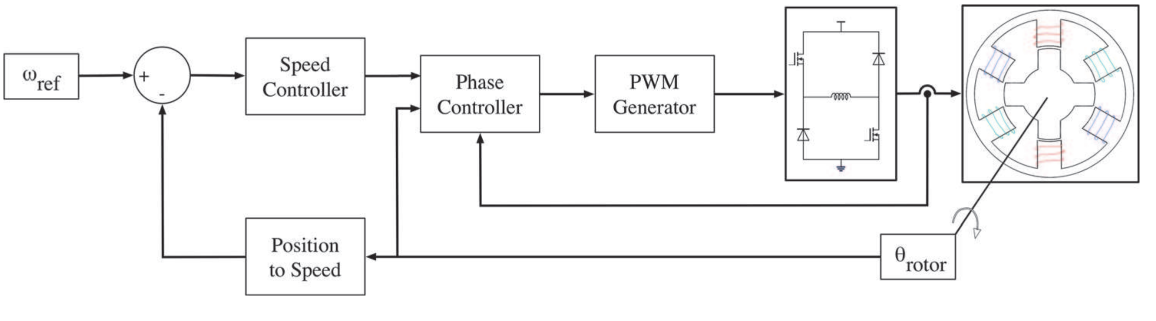

Figure 4.
Speed control loop based on impulse control.

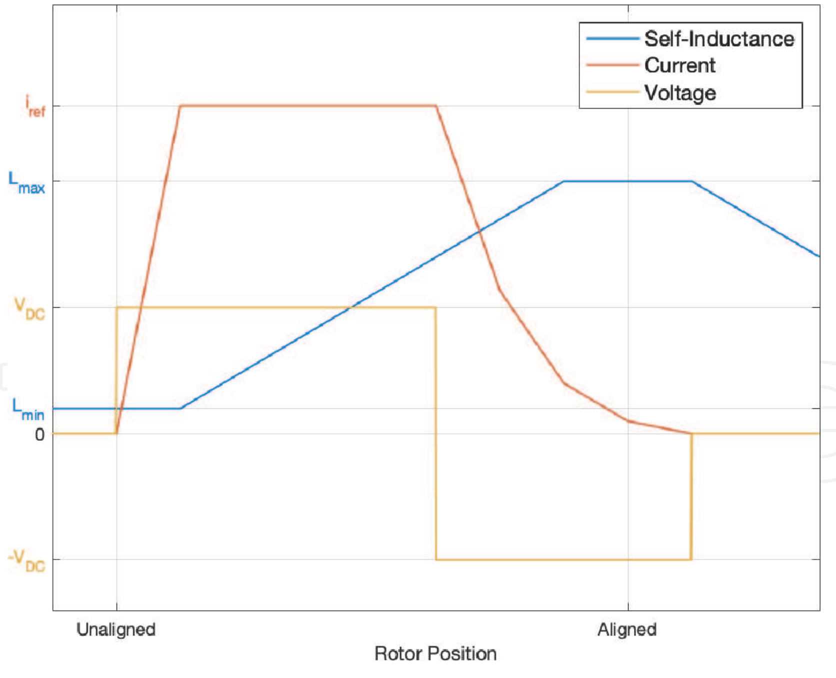

Figure 5.
Impulse control method.

in rotor position measure in order to obtain an effective control. There are various methods for this block, the most complete one being the switching angle, which is demonstrated in **Figure 5**.

This method can be divided into three parts. The first part happens when the inductance is minimum, so the current can grow fast. A voltage is applied for the current to reach the reference value. In the second part, the self-inductance increases, and the current is expected to be kept constant. And in the third part, the negative source voltage is applied, for the current to decrease to zero before it starts producing negative torque.

For very high speeds, advancing the start and end angles of commutation may be necessary, [10]. In this case the magnetizing and demagnetizing times are much shorter, and the back-EMF makes the current dynamic slower.

This controller also needs an overcurrent protection, so some current estimation or current sensor is necessary.

A description of variants of the impulse control can be found in [11] where the effect of advance angle, switching off angle, and the time of the dwell angle are addressed.

3.2 Current control

The voltage is kept constant in the last controller, expecting the current to be constant as well. Due to back-EMF and different inductance values for different rotor positions, this does not happen. So, in order to solve this limitation, a current controller is necessary for each phase.

The configuration of this controller, as shown in **Figure 6**, is in cascade form, where the current is controlled in the inner loop and the speed in the outer loop. There is also a decision block which dictates when each phase must be conducting current or not according to the rotor position.

As seen in **Figure 3**, the torque characteristic does not depend only on the current, which means that keeping the current constant does not make the produced torque constant. In this line of thought, an improvement for this control is

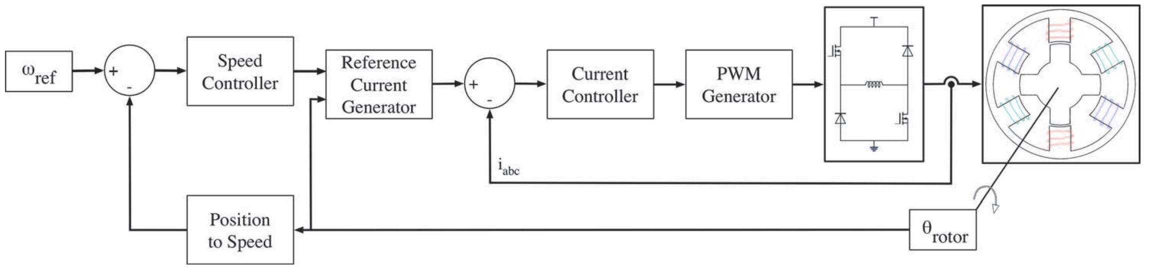

Figure 6.
Block diagram of speed control based on current control.

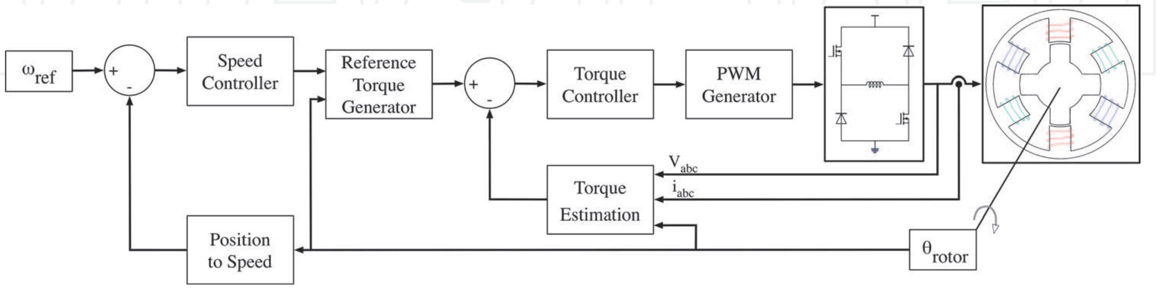

Figure 7.
Torque control diagram.

the use of functions like cosine and exponential to dictate not only when each phase must be conducting but also to give a weight for each rotor position in order to decrease the torque ripple. This subject will be discussed in detail in *Section 5*.

3.3 Torque control

One of the main objectives in a speed controller is to have constant torque with the lowest possible ripple. Measuring the instantaneous torque with a sensor can be too expensive for most applications. The typical solution is to measure currents and voltages in order to estimate the flux and using look-up tables with the motor model, as, for example, in [12, 13]. The torque control diagram is seen in **Figure 7**.

Although the feedback is the torque, a reference generator with the task of dividing the required torque in the different phases is still necessary. If this block is not well designed, and the instants of conduction are wrong or, it does not concern current constraints, the system can become unstable and impossible to control.

4. Linear controller design

Design of linear controllers can be very tricky for a complicated and non-linear model. This is the case of the SRM which is highly non-linear. To overcome this problem, the small-signal method can be used. Although it is a limited method, this solution is frequently applied in practice.

4.1 Model equations

The SRM model can be represented by the electrical equation:

$$V = R_s.i + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{d\theta}\omega \tag{1}$$

where V, R_s, i, L, ω are, respectively, phase voltage, stator resistance, current, self-inductance, and rotor speed and by the mechanical equation:

$$\frac{1}{2} i^2 \frac{dL(\theta)}{d\theta} - T_L = J \frac{d\omega}{dt} + B.\omega \tag{2}$$

where T_L, J, B are, respectively, mechanical load, motor inertia, and viscous friction coefficient.

In these equations the assumptions of non-saturating magnetic structure and steady-state in phase current in order to obtain an equivalent self-inductance that only depends on the rotor position, $L(i,\theta) \rightarrow L(\theta)$, are made. Even so, the model has a continuous dependency with the rotor position and is still highly non-linear.

To resolve the rotor dependency, $L(\theta)$ and $\frac{dL(\theta)}{d\theta}$ can be approximated, with some loss of information, by the self-inductance mean value and by the derivative of the maximum and minimum self-inductance points, respectively.

To resolve the rest of the non-linearities, it is necessary to linearize the model. A common solution is the linearization around an operation point—small-signal linearization. For this, each system state has to be represented by a steady-state value and by a small-signal value as:

$$i = i_o + \delta i \tag{3}$$

$$\omega_r = \omega_{ro} + \delta\omega_r \tag{4}$$

$$V = V_o + \delta V \tag{5}$$

$$T_L = T_{Lo} + \delta T_L \tag{6}$$

where the subscript o is used to represent the steady-state operation point and the δ is used to represent incremental deviations of the state in the vicinity of the steady-state point.

Using the new states defined in Eqs. (3)–(6) in the SRM model equations (1)–(2), the model for small signals is obtained as:

$$\frac{d\delta i}{dt} = -\frac{R_{eq}}{L}\delta i - \frac{\delta_e}{L} + \frac{\delta V}{L} \tag{7}$$

$$\frac{d\delta\omega_r}{dt} = \frac{K_b}{J}\delta i - \frac{B}{J}\delta\omega_r - \frac{\delta T_L}{J} \tag{8}$$

with the constants as:

$$R_{eq} = R_s + \frac{dL}{d\theta}\omega_r \tag{9}$$

$$K_b = \frac{dL}{d\theta} i_o \tag{10}$$

$$\delta_e = \frac{dL}{d\theta} i_o.\delta\omega_r \tag{11}$$

4.2 Laplace model

Applying the Laplace transform to Eqs. (7)–(8), Eqs. (12)–(13) are obtained in the frequency domain and the block diagram shown in **Figure 8**.

$$\delta I(s) = \frac{\delta V(s) - \delta_e}{Ls + R_{eq}} \tag{12}$$

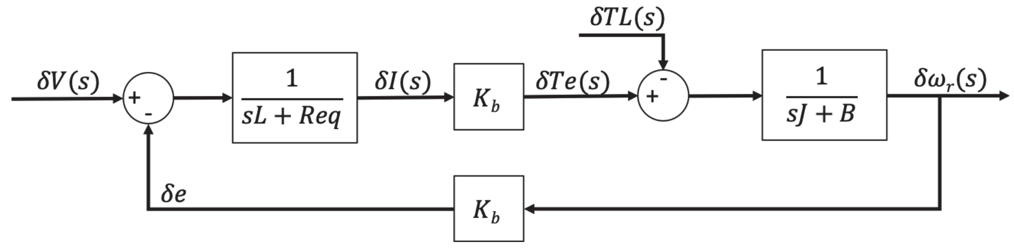

Figure 8.
Linearized SRM model.

$$\delta\omega_r(s) = \frac{K_b.\delta I(s) - \delta T_L(s)}{Js + B} \quad (13)$$

The inputs of the open loop plant diagram are the voltage and load torque variation, and the output is the speed variation.

With the linearized model, it is now easy to design the controllers. Two design methods, using the same linearized model, can be found in [6, 14].

As already stated, the model is a linearization for an operating point, so if the controllers are designed to have fixed gains, a study of the system for other operating points needs to be carried out. Also, it is possible to design adaptive controllers where the gains are a function of the inductance and the operating point. It is expected that more detail will bring a better dynamic for the system.

5. Reference generator

In this section the signal processing block with the function of dividing the output of speed controller between each phase to serve as a reference for the inner controller, whenever there is a current or torque controller, is discussed. The cases are presented for constant current and for constant torque.

As already known, the SRM is not an alternated current motor; the negative current has the same effect as the positive, so the motor is designed to work only with positive currents. Also, the currents have to be commuted in the function of the rotor position for that the rotor to have a constant movement.

The overlapping between phases is explained by the angular measure of a rotor pole, which has $360°/4\,poles = 90°$ for each pole. This means that during a rotor movement of 90°, each phase has to act sequentially. As the motor studied has three phases, this means that each phase is spaced at $90°/3\,phases = 30°$ from the start of the last one. It also means that two phases can be conducting at the same time during 15°.

5.1 Constant current

As already seen, the torque is the result of the squared current times the inductance derivative according to the rotor position, for constant current. This second term is non-linear, so the torque is not a direct calculation of the current. When using constant current, and assuming that current has no dynamic, it will generate the electromagnetic torque represented in **Figures 9** and **10**. In these figures, SRM torque characteristics for the reference motor are shown. In **Figure 9** it is shown the calculations for a medium value of current, specifically 11 A, and in **Figure 10** for a high value of current, specifically 20 A.

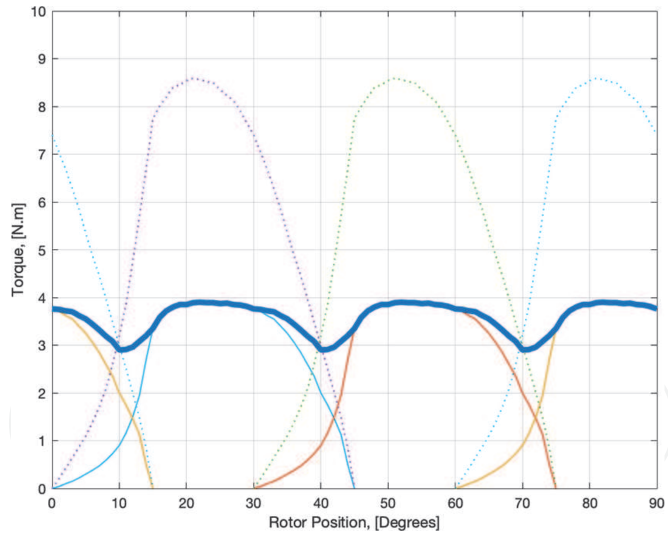

Figure 9.
Torque for medium current value.

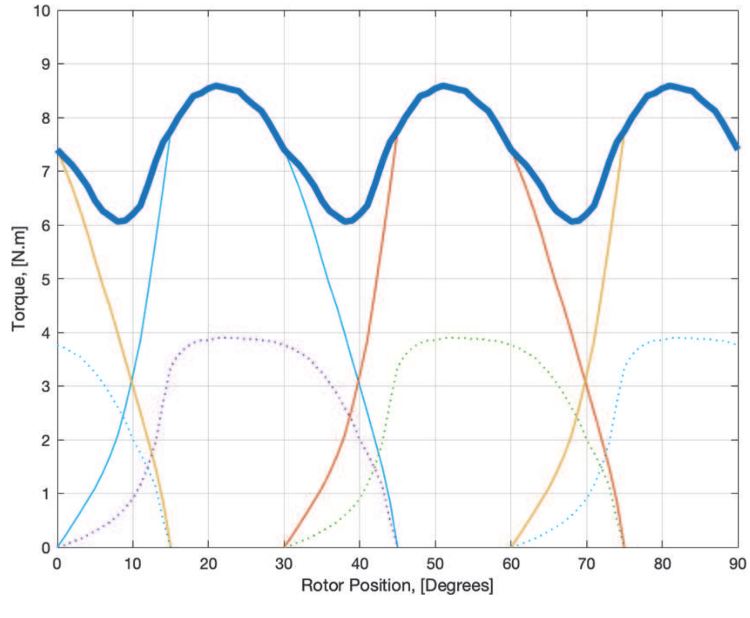

Figure 10.
Torque for maximum current value.

Although the motor has twice the current in the phase transitions, because it has two phases conducting with the same current value, for example, between 30 and 45°, it does not have enough torque as it does when only one phase is conducting, for example, between 15 and 30°.

The SRMs are not all similar; in some of them, this example can be the opposite, where in the phase transitions more electromagnetic torque is produced than when only one phase is conducting, so this study has to be done for each SRM.

5.2 Constant torque

For the SRM characteristic used as the example, it is then necessary to have different values of current for each rotor position to have constant torque.

In this section, the current waveforms which are necessary to have constant torque at medium and high values of electromagnetic torque are generated, as shown in **Figures 11** and **12**.

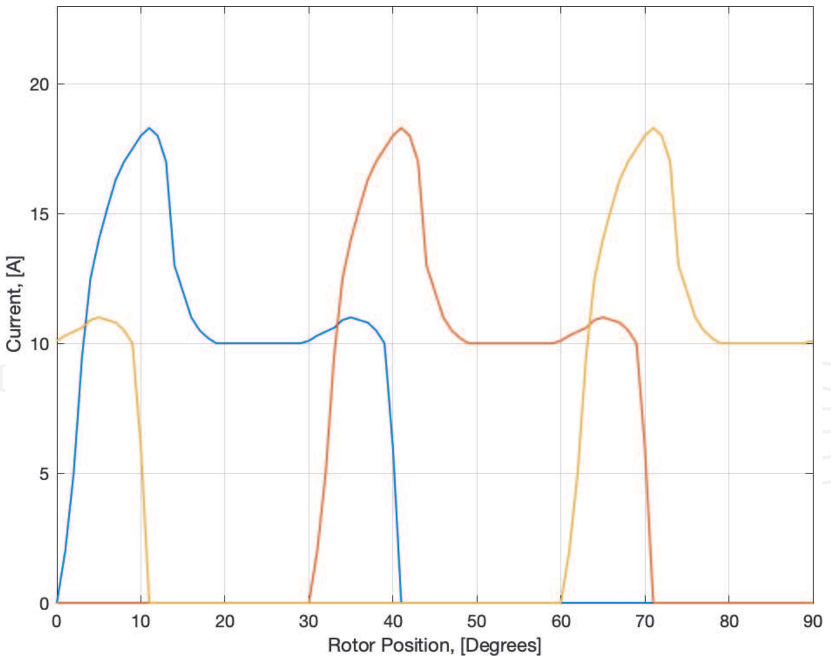

Figure 11.
Current for medium torque value.

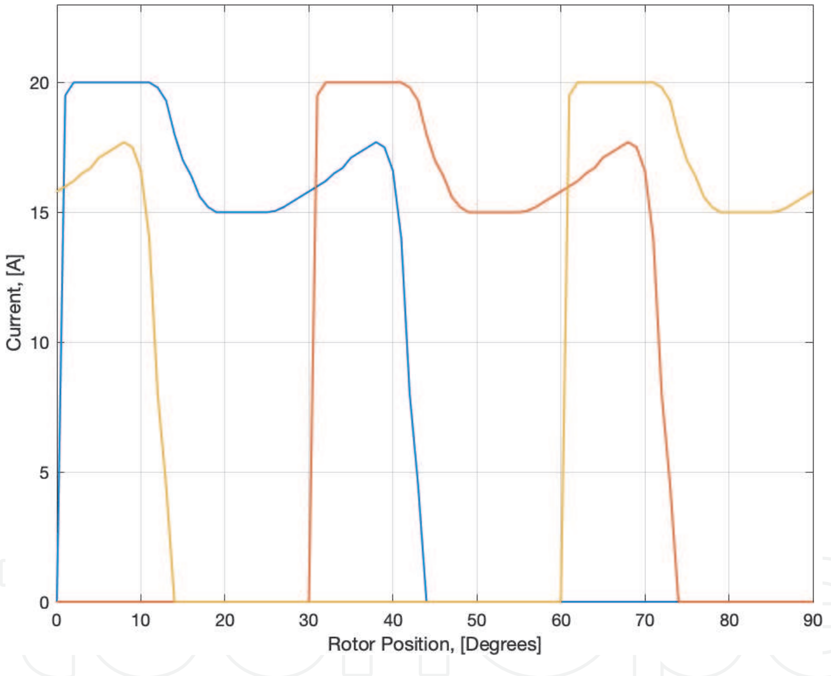

Figure 12.
Current for high torque value.

These waveforms were generated in order to produce constant torque but also to have the minimum necessary current when the phase is demagnetizing.

In both figures the waveforms have similarities. When the phase is magnetizing, it requires much more current than when only one phase is conducting. In **Figure 12** it is seen that current hits its maximum value, so the phase that is demagnetizing has to compensate the torque demand.

The current waveform profile has the name of torque sharing functions in literature, and in most cases it is generated by the use of sine or exponential waves with the rotor position as input, as seen, for example, in [11, 15, 16].

Another solution is the use of look-up tables which are much easier to change and give the right values in the right vector position.

5.3 Current dynamic constraints

In the last two sections, it was assumed that the current had no dynamic and the current controllers were ideal. That, of course, is not true, and from the inductance profile (**Figure 13**), it can be seen that its dynamic changes with the rotor position and with the current itself. The minimum inductance, when the current has a faster dynamic, happens when the phase is magnetized. And the maximum inductance, when the dynamic is slower, happens when the phase is demagnetized.

In **Figures 11** and **12**, it can be seen that the transitions can be very fast, and the current may not be able to follow the reference precisely. The fast-current transitions happen in the phase magnetization and in the phase demagnetization. In the magnetization, the current can start earlier, because as seen in the torque characteristic (**Figure 3**) around rotor position 0°, no significant torque is produced, and this is where the inductance is minimum. The problem is in the demagnetization, where the produced torque is significant, so the current must be of zero amperes or very low in the transition or it will produce a significant negative torque.

Another constraint that influences the current dynamic is the back-EMF. The back-EMF can be represented by a voltage that increases with increase in speed. This means that at high speeds the equivalent voltage applied to the phase is less than the source voltage, decreasing the current dynamic. Solutions can be applied by anticipating the trigger moments or by diminishing the range of the trigging moments.

5.4 Deaccelerating and speed inverting

The last sections were only described for one quadrant, which corresponds to positive speed and accelerating. The case of deaccelerating is a little different. It is necessary to produce torque with the opposite direction of the speed. So instead of conducting current from 0 to 45°, it must conduct current from 45 to 90°.

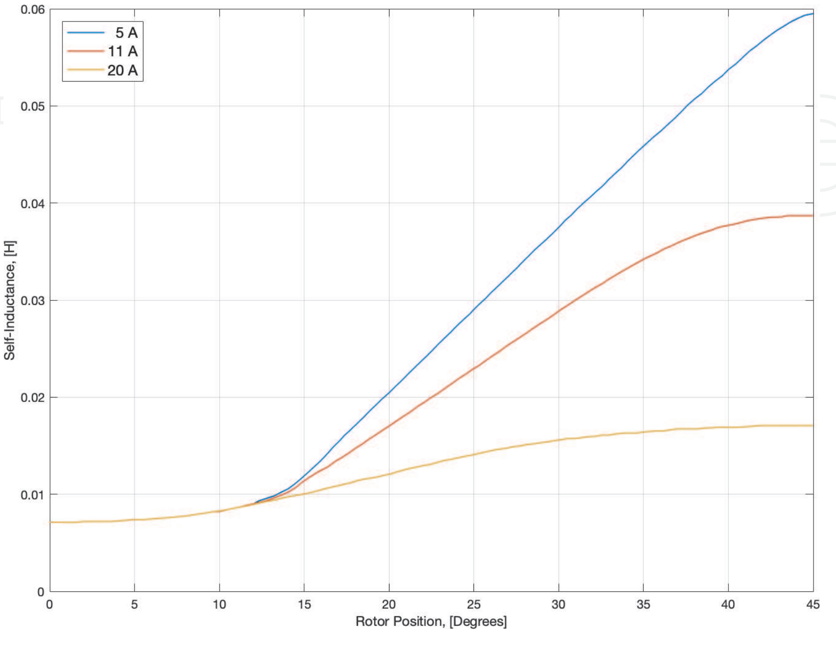

Figure 13.
Self-inductance profile.

In the case of deaccelerating, the magnetization happens in the zone of maximum inductance, making the task of designing waveforms to keep constant torque much harder.

The case for negative speeds is very similar to positive speeds. In positive speeds the rotor angle increases from 0 to 90°, while for negative speeds, it is the opposite, and the rotor angle decreases from 90 to 0°. Thus, to accelerate negatively, the current must be applied from 90 to 45°, and to deaccelerate negatively, the current must be applied from 45 to 0°.

6. Asymmetric bridge converter

One advantage of common electric motors, like the induction motor, is the possibility to plug it to the AC electric socket, and it can run at a certain power. In the SRM this is not possible; it requires a controller and a converter.

The most used converter for the SRM is the asymmetric bridge converter (**Figure 14**). It is composed by two diodes and two transistors for each phase. Its most appreciated advantages are the phase independent control, the possibility of generating three levels of voltage, and the fact that it regenerates current for the voltage source. Other converter configurations are found in [6, 17, 18].

6.1 Converter states

As said before, this converter can apply three voltage levels to the motor, $V_{\{DC\}}$, $0V$, and $-V_{\{DC\}}$. These converter states are seen in **Figure 14**. The $V_{\{DC\}}$ voltage level is applied when both transistors are conducting. The $-V_{\{DC\}}$ voltage level is applied when both transistors are not conducting, and still there is current in the winding, so the current goes by the diodes. And the $0V$ voltage level is applied when only one transistor is conducting, where it is represented by a freewheeling of the top or bottom mesh.

As the SRM only needs to work with positive currents, the converter cannot allow a negative current. The asymmetric bridge meets this objective because the current in the winding always has the same direction.

6.2 Converter control

For the control, both transistors can have the same control signal or different ones. When using the same signal, it is only possible to apply two voltage levels

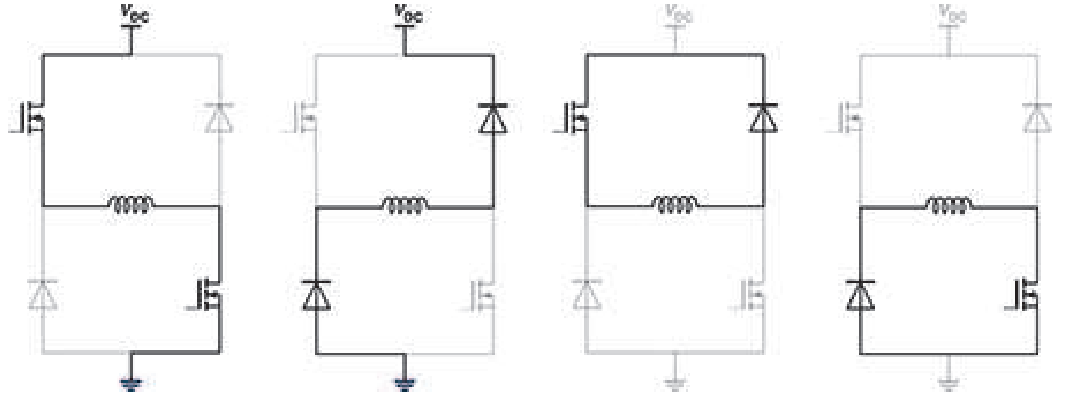

Figure 14.
Asymmetric converter states.

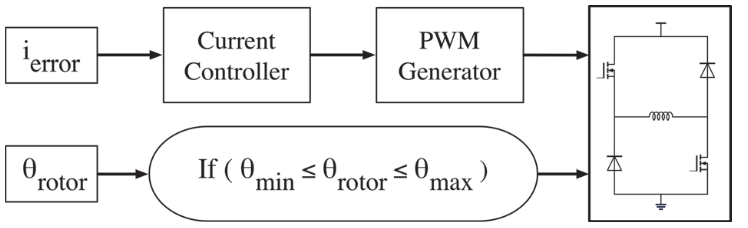

Figure 15.
Technique for generation of two signal of converter command.

when conducting, $V_{\{DC\}}$ and $-V_{\{DC\}}$. In this case, the converter's full capability cannot be used.

When using two signals, it is possible to use the three voltage levels at any time. Various methods can be used. A simple one is represented in **Figure 15** where the converter receives two signals for each transistor.

In this method the first signal is the result of the current controller and the PWM generator. The second signal is the trigger of defined values of rotor position. For example, if applying current between 0 and 45° is desired, the second signal will be active during 0 and a little less than the 45°, specifically when it is necessary for the current to decrease, for example, around 40°. So, in this method, the converter applies $V_{\{DC\}}$ and $0V$ from the beginning until the desired moment of demagnetization where $-V_{\{DC\}}$ is applied and $0V$ until the current returns to zero amperes. Although it limits the number of states in different zones, the method is simple and effective.

7. Numerical simulations

To demonstrate the fundamental control of the switched reluctance motor, a numeric simulation environment was developed in *Simulink/Matlab®* (version R2018a), available in the link: https://bit.ly/2KfPUsG . To open the application, the user has to type "Hello" in the *Matlab* command window. A window appears, as in **Figure 16**, and it is then possible to choose to see the SRM model parameters and flux characteristic or to open the simulation. The SRM is a non-linear model based on a real motor described in [8]; the main parameters are presented in **Table 1**.

The simulation is in a closed-loop speed control with a direct control of the current. The current waveform method for constant torque was applied, and the asymmetric bridge converter was used with the control described in *Section 6.2*.

Some simulations are shown. First the steady-state operation of the motor is analyzed, and then the transient response showing the four quadrants of operation. Controller gains are presented in **Table 2**.

7.1 Steady-state condition

In the first set, a torque load of 3 N m is applied, and two reference speeds of 750 rpm and 1250 rpm, respectively, are shown in **Figure 17**.

The currents have the same waveform as described in *Section 5.2*, where in the magnetization higher current values are required than the rest of the phase. Looking for results at 750 rpm speed reference, this method keeps the torque in a ripple less than 2 N m. For the 1250 rpm speed reference, the speed is higher so more current is necessary, and the time for magnetizing and demagnetizing is less. Because of that, the current cannot be as fast as the current reference, which means that during the

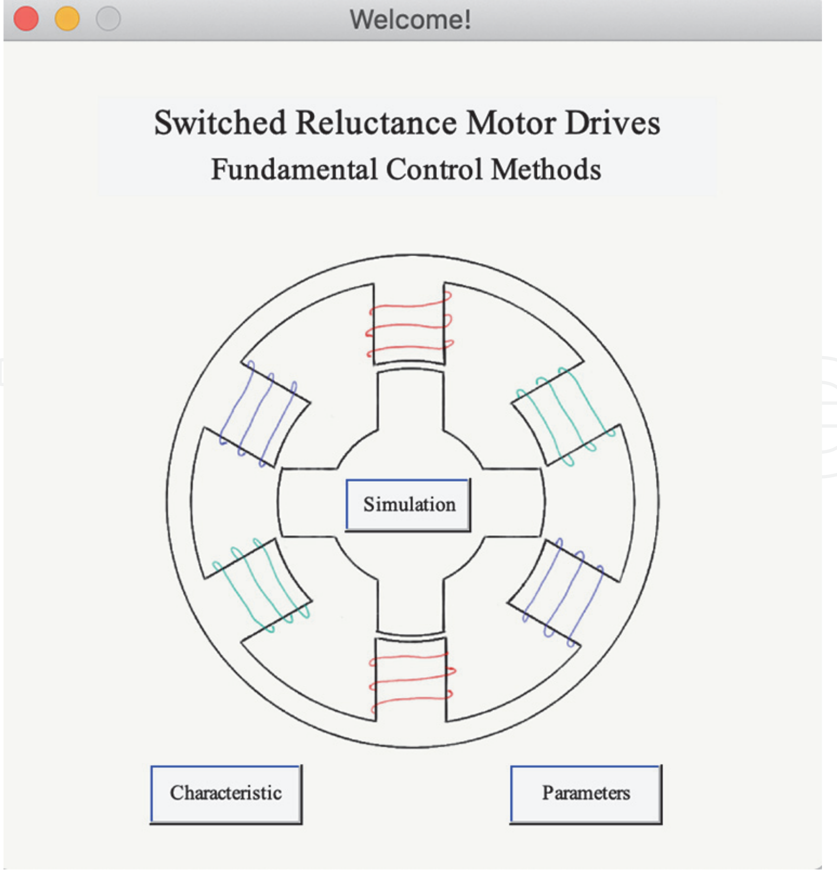

Figure 16.
Initial window for the simulation environment.

Stator poles	6
Rotor poles	4
Voltage	150 V
Stator resistance	1.3 Ω
Inertial value	0.0013 $Kg\ m^2$
Friction coefficient	0.0183 $N\ \ m/(rad/s)$
Minimum inductance	8e-3 H
Maximum inductance	60e-3 H

Table 1.
SMR model parameters.

Current proportional gain
20
Current integrative gain
1100
Speed proportional gain
0.22
Speed integrative gain
5.50

Table 2.
Controllers gains.

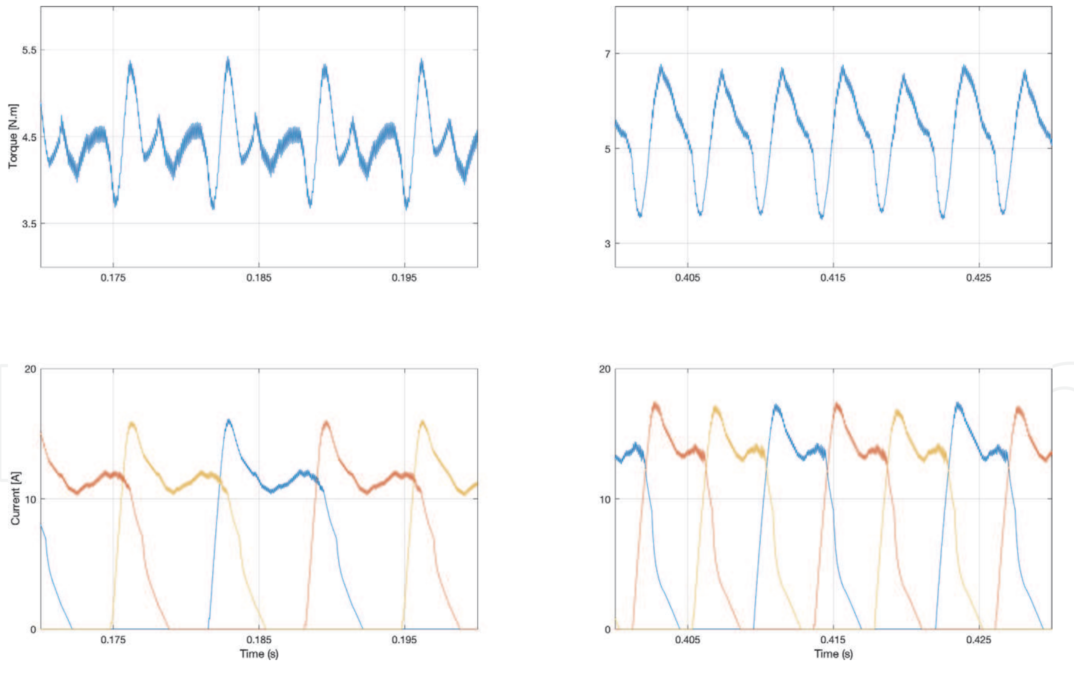

Figure 17.
Steady-state condition for same load and different speeds.

phase transition it is not possible to have enough current to keep the torque as constant as in the operation at lower speed.

In a second set of simulations, shown in **Figure 18**, the speed reference is kept constant at 1000 rpm, and a load torque is applied of 2 and 4 N m, respectively.

For the 2 N m load torque simulation, the response torque has a ripple of less than 1.5 N m. For the 4 N m load, it is necessary to have more current in the phase transition due to the SRM torque characteristic, so during this period, the torque has a low value.

7.2 Transient condition

For the transient response of the motor, all four quadrants of operation are simulated, accelerating, and deaccelerating for positive and negative speed. A reference speed is given as 1000 rpm from 0 to 0.5 s, and −1000 rpm from 0.5 to 1 s. The load torque is of 2 N m from 0 to 0.25 s and 0.75 to 1 s and of −2 N m from 0.25 to 0.75 s. Results are shown in **Figure 19**.

Firstly, the controller applies the maximum current so the motor can quickly reach 1000 rpm. The torque has some ripple during the acceleration phase, but when the speed reaches the set point, the ripple decreases. The speed response to the step has a minimum of overshoot.

At 0.25 s the load torque signal is changed, so the load is helping the rotor to move. The speed controller sees this as a perturbation and tries to compensate, which takes no longer than 0.05 s to recover the reference speed. This situation is similar at 0.75 s where the difference is in the signals of speed and load.

At time 0.5 s the reference speed is changed from 1000 to −1000 rpm. The motor has to break, stop, and accelerate negatively. This process happens with no problem. It is possible to see that the sequence of current phases is changed from orange, yellow, and blue to blue, yellow, and orange.

7.3 Discussion

In general, with the developed controller and with the use of the described fundamental control methods, the results of the numerical simulations are very

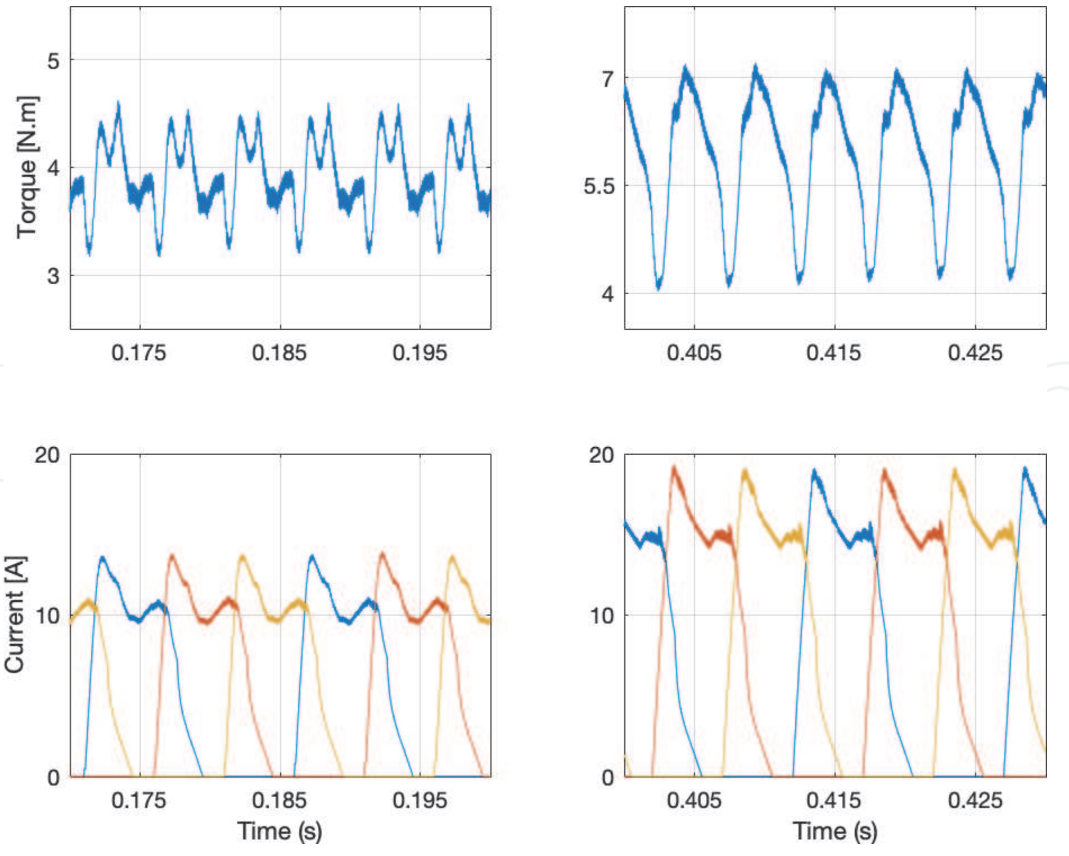

Figure 18.
Steady-state condition for same speed and different loads.

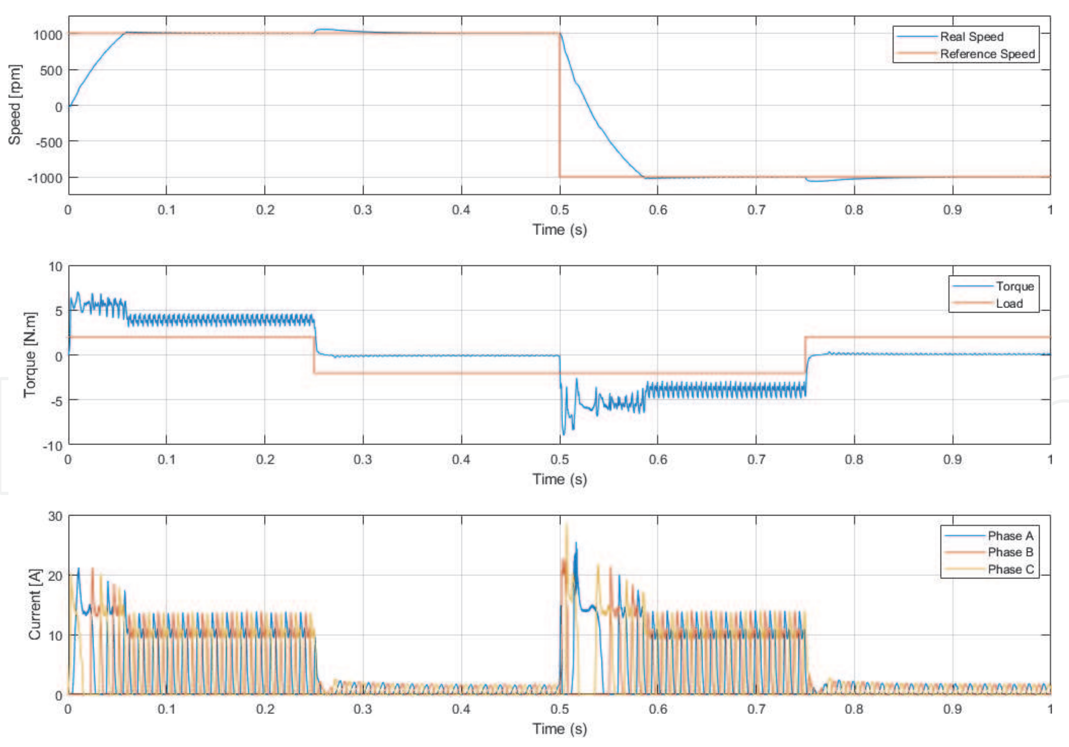

Figure 19.
Operation in the four quadrants.

satisfactory. However, there is a margin for improvement and design of a more robust controllers and methods.

As seen in *Section 7.1*, the required current waveform for always having the best performance changes essentially with speed and load. For high speeds, it is necessary to anticipate the current magnetization and demagnetization, and with high loads, it is necessary to have more current in the phase transitions. For improvement, a series of optimal control problems could be solved with a posterior extrapolation of results in order to have the ideal waveform for any operation point.

Current controller performance can be optimized too. As seen the inductance value is non-linear, changing with rotor position and current itself. An improvement could be the use of adaptive controllers that change its gains, at least, with the rotor position.

Other works, such as [13], are recommended to readers with further interest in direct torque control. For this type of electric drives, the feedback variable is the torque, so a torque estimation is necessary. There's also additional reading material if the reader wants to go more in depth. For example, in [19] the sliding mode technique to control the current is used, and in [20] an adaptive control methodology for the speed control is used.

8. Conclusions

The control of the SRM may not be as easy as conventional electric motors. Torque ripple, which is one of the main problems, may and must be reduced by the controller.

Different types of controllers can be used—the fundamental ones are voltage impulse, current, and torque controllers. Impulse control is essentially used for high speeds, while current and torque controllers are used for high performance.

As the produced torque does not depend only on the current but also on the non-linear derivative of the inductance, a constant current control is not sufficient for high performance. Reference current waveforms, or torque waveforms, have to be calculated for the response to have the minimum ripple torque component possible. Also, current dynamic has to be considered in the controller design. The inductance changes along the rotor position and so does the current dynamic. The back-EMF also has an effect in the current dynamic, especially at high speeds.

Numerical simulations of a real SRM model were performed. Steady-state results of the reference operating point and on a speed and load change were analyzed. Moving away from the used operating point to design the controller changes the response, as expected.

The dynamic behaviour was also simulated. It contemplates all four quadrants of operation. The speed response follows the reference speed with good accuracy. The load changes provoke perturbations on speed, which are compensated very quickly by the controller.

Finally, we hope that seeing the simulation files will help the reader to feel a concrete experimentation.

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References

[1] Xue XD, Cheng KWE, Ho SL. Optimization and evaluation of torque-sharing functions for torque ripple minimization in switched reluctance motor drives. IEEE Transactions on Power Electronics. 2009;**24**(9): 2076-2090

[2] Vujičić VP. Minimization of torque ripple and copper losses in switched reluctance drive. IEEE Transactions on Power Electronics. 2012;**27**(1):388-399

[3] Ye J, Bilgin B, Emadi A. An extended-speed low-ripple torque control of switched reluctance motor drives. IEEE Transactions on Power Electronics. 2015;**30**(3):1457-1470

[4] Cheng H, Chen H, Yang Z. Average torque control of switched reluctance machine drives for electric vehicles. IET Electric Power Applications. 2015;**9**(7): 459-468

[5] Mikail R, Husain I, Sozer Y, Islam MS, Sebastian T. Torque-ripple minimization of switched reluctance machines through current profiling. IEEE Transactions on Industry Applications. 2013;**49**(3):1258-1267

[6] Krishnan R. Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications. Boca Raton: CRC Press; 2001. p. 398

[7] Boldea I, Nasar SA. Electric Drives. Boca Raton: CRC Press; 2005. p. 544

[8] Soares F, Branco PJC. Simulation of a 6/4 switched reluctance motor based on Matlab/Simulink environment. IEEE Transactions on Aerospace and Electronic Systems. 2001;**37**(3): 989-1009

[9] de Doncker R, Pulle DWJ, Veltman A. Advanced electrical drives: Analysis, modeling, control. Power System. 2011;**52**:1-443

[10] Kim J, Krishnan R. High efficiency single-pulse controlled switched reluctance motor drive for high speed (48k RPM) application: Analysis, design, and experimental verification. In: Conference Record – IAS Annual Meeting (IEEE Industry Applications Society). 2008

[11] Ahn J-W. In: Lamchich MT, editor. Switched Reluctance Motor, Torque Control. IntechOpen; 2011. Available from: https://www.intechopen.com/books/torque-control/switched-reluctance-motor

[12] Inderka RB, De Doncker RW, Krehenbrink M. On-line estimation of instantaneous torque in switched reluctance machine control. In: IEEE International Symposium on Industrial Electronics. 2000. pp. 385-389

[13] Nakao N, Akatsu K. Torque control of a switched reluctance motor by using torque estimation and excitation angle control. In: 2012 IEEE Energy Conversion Congress and Exposition, ECCE 2012. 2012. pp. 4314-4321

[14] Pereira M, Araújo RE. Analysis and Design of a Speed Controller for switched reluctance motor drive. U. Porto Journal of Engineering. 2019;**5**(1): 46-58

[15] Ye J, Bilgin B, Emadi A. An offline torque sharing function for torque ripple reduction in switched reluctance motor drives. IEEE Transactions on Energy Conversion. 2015;**30**(2):726-735

[16] Dowlatshahi M, Nejad SMS, Ahn JW. Torque ripple minimization of switched reluctance motor using modified torque sharing function. In: 2013 21st Iranian Conference on Electrical Engineering, ICEE 2013. 2013

[17] Skvarenina TL. The Power Electronics Handbook. Boca Raton: CRC Press; 2002

[18] Pittermann M, Fort J, Diesl J, Pavlicek V. Converters for switched reluctance motor - topology comparison. In: Proceedings of the 2018 18th International Conference on Mechatronics - Mechatronika, ME 2018. 2019. pp. 1-8

[19] Ye J, Malysz P, Emadi A. A fixed-switching-frequency integral sliding mode current controller for switched reluctance motor drives. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2015;**3**(2):381-394

[20] Namazi MM, Rashidi A, Koofigar H, Saghaiannejad SM, Ahn JW. Adaptive control of switched reluctance motor drives under variable torque applications. Journal of Electrical Engineering and Technology. 2017; **12**(1):134-144