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Performance Analysis of Switched Reluctance Motor by Using Closed Loop Current Control Technique

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ABSTRACT

This paper presents the performance analysis of an 6/4 3-phase switched reluctance motor in terms of current, flux, torque and speed. When the speed of the motor is low the current rises quickly. If the speed is large the increase in current is low. In low-speed region, the current can be controlled by using chop/hysteresis current control mode. In this mode a voltage of +Vdc and -Vdc is applied in such way the current is limited to a band. The bands can design around the reference value of current. The upper and lower bands can be designed based on the reference current. After the base speed we have to maintain current, current can't increase quickly because speed becomes large, so in this region instead of keeping current constant the power is to be considered constant. When the speed is large this mode is not preferable. So still we have to maintain the power current has to build up, so we switch little earlier that angle is called advance angle. Angle by which voltage application is advanced that angle is the advance angle. The advance angle control can be used in such way that the current increase will happen in the lower inductance region only. The advancing of angle can be increased up to certain angles only i.e up to the lower value of inductance minimum point. The simulation has been carried out for 6/4 3-phase switched reluctance motor using MATLAB/Simulink by applying closed loop current control technique. The detailed control of SRM for different speed modes has been carried out and the analysis of results demonstrated.

Keywords: Switched reluctance motor; aligned inductance; chop mode; electromyography

INTRODUCTION

The Switched Reluctance Motor (SRM) has salient poles, the poles carry concentric windings, and the coils on the opposite poles are connected in series to form the stator phases. The rotor contains no windings or permanent magnets, no copper losses, no cooling is required. It is built up of steel laminations, the laminations are stacked to the shaft. Due to this mechanical simplicity, the cost of the SRM is low. Attracts many industries to use this motor. The stator and rotor cores of the SRM are manufactured with laminations. For any m number of phase motor, the poles on stator Ns are 2mq and Nr number of poles on the rotor, q is pair of stator poles per phase. Frequently used configurations for single pair of stator poles are 6/4 for three-phase and 8/6 for four-phase SRMs. The configurations for high q value are 12/8 or 18/12 used either for low-speed high torque or high-speed stator generator for aircraft systems (Rana et al. 2021; Fan et al. 2020; Chintala et al. 2016). In general, the pole angles of the stator and rotor are almost the same to avoid zero torque zones.

The operation of SRM depends on the variation of phase inductance. Inductance of stator phases is depending on relative positions of the rotor teeth with stator poles. Stator and rotor poles align to minimize the reluctance, so the inductance is maximum (Reddy et al. 2015; Rana et al.

2019). The phase inductance increases remain constant decrease remains constant and arises cyclically, this variation depends on the amount of overlap of the rotor teeth with stator poles of the concerned phase. The current in the phase should be forced in the winding when the rotor teeth is just entering the stator pole of that phase. It is essential to know the position of rotor for switching (Raley et al. 2017; Lokeshwar et al. 2022; Zhang et al. 2019). The energized phase should be switched off when the inductance of that phase is decreasing.

To produce torque SRM should be designed in such a way that the stator winding inductance vary with the position of rotor teeth, double saliency of the motor satisfies this requirement. The inductance of the stator varies with rotor position such that the inductance is maximum if the rotor axis is aligned with magnetic axis of that phase and minimum if the two axis are perpendicular (Deng et al. 2017).

High efficiency, good performance in terms of torque to inertia ratio, maximum operating speed, and simple construction. It is available in various sizes with different speed ranges, due to these advantages SRM as an attractive solution for variable speed applications (Lokeshwar et al. 2017; Maksoud et al. 2020; T. Ishikawa et al. 2014).

SRM drive is an alternative for conventional DC series drive, and variable speed induction motor drive. The performance of SRM depends on the control system which is to be used. Rapid development if power electronics and digital controllers have made the implementation of semiconductor switching circuits and controllers easy and economical. The control of input is very essential to get desired performance. Next chapters discuss the characteristics of SRM, modes of operation of SRM, current control techniques applied to SRM, simulation results for the application of control technique to SRM.

CHARACTERISTICS OF SRM

The mechanism of electromechanical energy conversion is investigated. The stator phase is excited at the unaligned position that is where the stator pole and rotor teeth have the maximum air gap length. The magnetization of the exciting pole will magnetically polarize the closest rotor teeth and produce a force of attraction. The tangential component of this force produces an electromagnetic torque in the direction which reduces the air gap length between the stator pole and rotor teeth (Reddy et al. 2017; Ch et al. 2021). As the rotor teeth approach the aligned position i.e where the stator pole and rotor teeth have the minimum air gap length, the tangential component of attractive force decreases and becomes zero.

The phase current may be switched off before the rotor teeth occupies the align position. The flux linkages vs phase current characteristics is shown in the Figure 1. The shaded portion represents electromechanical energy developed. The region R corresponds to the energy return to the supply. This area is less than the stored energy as a part of it is used by the motor during free-wheeling period (F.L.M dos Santos et al. 2014; Kumar et al. 2014). The shaded portion W is depending on the variation of current with rotor angle control parameters, speed and motor design.

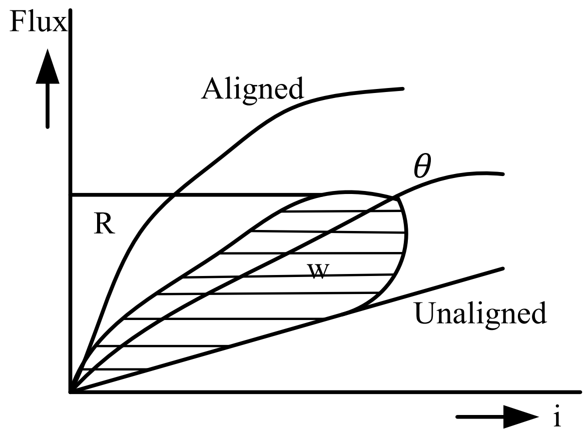


FIGURE 1. Flux linkages vs phase current characteristics

In SRM the torque is produced by the variation of reluctance or permeance or airgap. In an inductor/coil the stored energy is E= ½ Li^2. The torque is the derivative of energy with respect to the position. If any variation of energy with respect to the position we will get torque. Torque $T = \frac{i^2}{2}\frac{dL}{d\theta}$, so the torque in SRM is proportional to i^2 and $\frac{dL}{d\theta}$. It means there is an inductance variation with respect to the position of the rotor i.e . Torque does not depend on the direction of the current.

The developed torque can be increased by different ways i.e aligned inductance should be as large as possible, this can be achieved by reducing the aligned air gap length. Next is the unaligned inductance should be as small as possible for the air gap length should be maximum at the unaligned position. Operate the magnetic circuit at highly saturated conditions. With this, the developed torque can be increased (X. Zhao et al. 2020).

The positive value of $\frac{dL}{d\theta}$ corresponds to motoring action and the negative value corresponds to generating action. The torque is depending on the square of current then it is independent on the direction of current. , Torque can be increased by increasing the current, it can be controlled by T_{on}, T_{off} and I_{ref}. In low-speed region the motor will be controlled by T_{on}, T_{off} and I_{ref} , in high-speed region it can be controlled by T_{on} by keeping T_{off} as constant. The flux linkage, current and torque waveforms with respect to rotor position is shown in Figure 2.

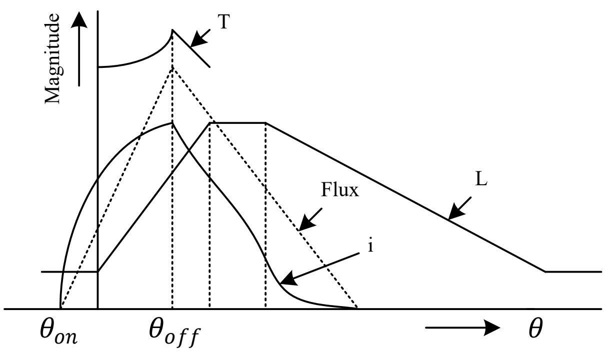


FIGURE 2. SRM Characteristics

MODES OF OPERATION OF SRM

The SRM can be operated in low, medium, and high-speed modes. The current waveforms of these three modes of operation are shown in Figure 3. When the speed is low the current rises quickly. If speed is large the increase in current is low. Therefore, we can plot the variation of current with respect to speed. Therefore, in low speed region the current can be controlled by using chop mode. In this mode we apply +Vdc and -Vdc in such way current is limited to a band. The bands can design around reference value of current. The upper and lower bands can be designed based on the reference current. The voltage can be switched such that the current should be within the band. If the rate of raise is +ve we can apply +Vdc, if the rate raise is -Ve we can apply -Vdc. Therefore, we alternatively switch between +Vdc and -Vdc the current is within the limit, we are chopping the applied voltage. It is called chop mode. The applied voltage and current wave forms shown in the Figure 4.

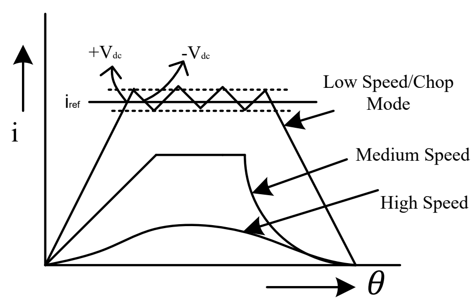


FIGURE 3. Modes of operation

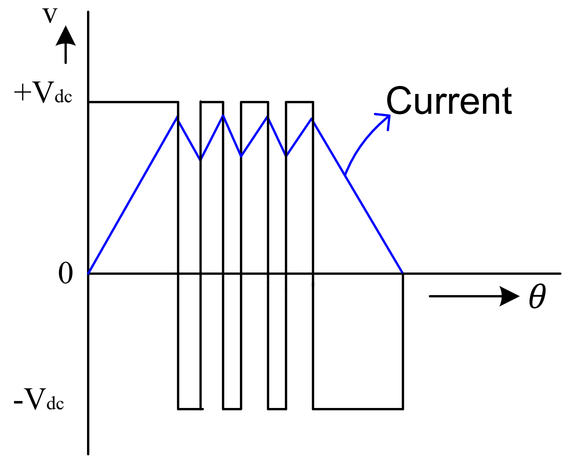


FIGURE 4. Applied voltage and current

Advance angle control: After the base speed we have to maintain current, current can't increase quickly because speed become large, so in this region instead of keeping current constant the power is to be considered constant. Therefore, this mode is constant power mode. This can be achieved by controlling θ. (i and T are not kept constant, but P=Tw is kept constant)

$$P = Tw = k \frac{V_{dc}}{wL} \theta \frac{V_{dc}}{L} \theta \qquad (1)$$

Here θ is the advance angle. Therefore, with the increase of speed(w) the θ can be increased then the power can be constant.

This mode goes up to some speed. Once we increase the it reaches to maximum value. The θ can't be increased further. In this angle can be controlled such that power remains constant. When θ reaches to maximum value, θ kept constant. P= $k \frac{V_{dc}^2}{wL^2} \theta$ = Tw is not constant because is constant w is increasing. So $Tw^2 = k \frac{V_{dc}^2}{wL^2} \theta$ is to be kept constant.

Advance angle control: When the speed is minimum the current increases quickly. Therfore, we have to operate in chop mode. In chop mode, current has to be controlled in such a way it remains with in a band. Before falling the inductance, current is brought down to zero. When the speed is large this mode is not preferable. Therefore, we still have to maintain the power current has to build up, so we switch little earlier that angle is called advance angle. Angle by which voltage application is advanced that angle is advance angle. The advance angle control can be used such way that current increase will happen in lower inductance region only. The advancing of angle can be increased up to certain angles only i.e up to the lower value of inductance minimum point. The Figure 5 shows the characteristics of SRM for different modes of operation.

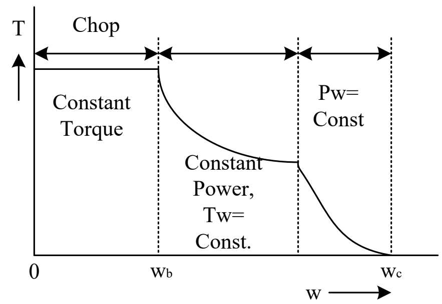


FIGURE 5. Characteristics of SRM for different modes of operation

CURRENT CONTROL TECHNIQUE

The inductance (L) profile with respect to the rotor position ( ) obtained as follows

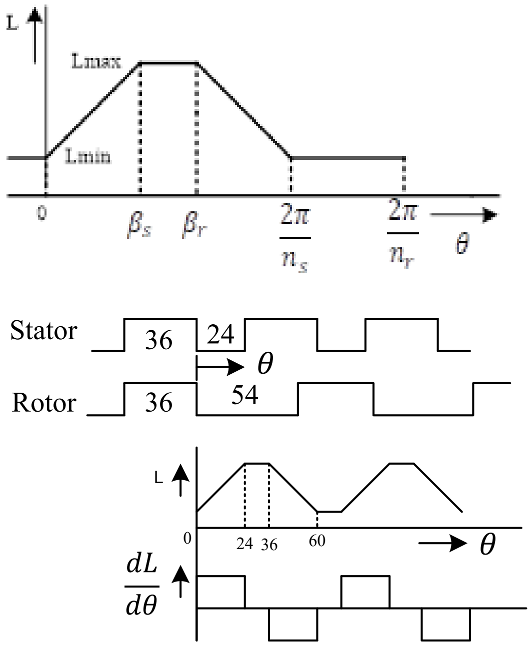


FIGURE 6. Inductance Profile

The inductance starts raises from minimum value when the rotor starts occupying stator i.e θ is zero and the inductance reaches to maximum value if the rotor occupies complete stator pole pitch ($0<\theta<\beta_s$ the inductance raises from L_{min} to L_{max}). For $\beta_s<\theta<\beta_r$ the inductance remains constant this angle $\beta_r - \beta_s$ is called dwell angle. For $\beta_r<\theta<\frac{2\pi}{N_s}$ the inductance starts decreasing and reaches L_{min} at $\theta=\frac{2\pi}{N_s}$ For $\frac{2\pi}{N_s}<\theta<\frac{2\pi}{N_r}$ the inductance remains constant at L_{min}. is the dwell angle. Here N_s and N_r are stator and rotor poles respectively. The variation of inductance with rotor position is show in above Figure 6.

Consider 6/4 SRM. 6-stator poles and 4-rotor teeth. Stator pole pitch = $360^0/6 = 60^0$. Rotor pole pitch= $360^0/4 = 90^0$. Each phase on the stator has two windings. A 6-pole machine consists of 3-phases. 40% of pole pitch is for tooth and 60% is for the slot. Stator pole pitch is 60^0. Tooth angle is 60^0*0.4 is 24^0, so the rotor pole will occupy an angle of 24^0. Stator slot angle is 36^0. Rotor tooth angle is 90^0*0.4 is 36^0 and Rotor slot angle is 54^0.

When the rotor moves, the inductance of every phase will undergo variation. Therefore, to find out the torque we should have to find out variation of inductance with respect to rotor position.

The variation of inductance with respect to rotor position comes under the stator is shown in Figure 4. The inductance can be taken along y-axis and rotor position can be taken along x-axis. At $\theta = 0^0$, at this position the inductance is minimum. As the rotor moves the θ increases, air gap reduces, the inductance increases. This increase of inductance will continue up to θ reaches to stator tooth angle(24^0). Both stator tooth and rotor tooth will overlap for an angle i.e rotor tooth angle – stator tooth angle (36-24= 8^0). In this overlapping period the inductance is constant. After this position of rotor the overlap will reduces, air gap increase and inductance will reduce. So to find the torque we need to find change of inductance with respect to rotor position.

When we inject current results into torque production. Current can be injected only during positive change of inductance to produce positive torque. This can be achieved by applying voltage for a suitable time.

If any voltage is applied to a phase, then the corresponding voltage equation is

$$V = iR + N\frac{\partial\varphi}{\partial t} \quad (2)$$

By neglecting resistance drop $V \cong N\frac{\partial\varphi}{\partial t} = V_{dc}$

$$\varphi = \int \frac{V_{DC}}{N} dt = \int \frac{V_{DC}}{Nw} d(wt) = \int \frac{V_{DC}}{Nw} d(\theta) \quad (3)$$

For a steady state condition the speed is constant, so we can write the above equation as

$$\varphi = \frac{V_{DC}}{Nw}\int d(\theta) = \frac{V_{DC}}{Nw}\theta \quad (4)$$

From the above equation we can say, if we apply the voltage the flux will increase linearly with θ.

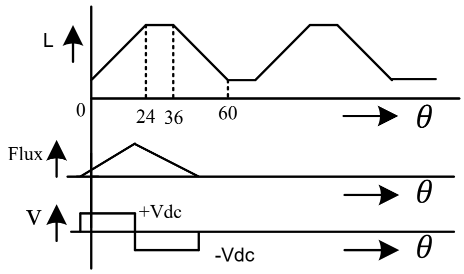


FIGURE 7. Flux and Applied Voltage

We can apply +Vdc and -Vdc through the winding to control the current. By controlling the current, torque can be controlled. To get positive torque current can be injected in the winding during positive change of inductance region. So we can control the current such that it exists only during positive change of inductance. This is achieved by switching the voltage in the winding. With the electronic switch the voltage is to be applied to the winding and current flows through the winding. When the switch is on the voltage across the winding is +Vdc, the current is continuous when the switch is off alTherefore, then the current will flow through the alternative path through diode then voltage across the winding is -Vdc. The flux and applied voltage waveforms are shown in Figure 7.

Current can be obtained from the flux.

$$L = \frac{N\emptyset}{i} \qquad i = \frac{N\emptyset}{L}$$
$$i = \frac{N\,V_{dc}}{NwL}\theta = \frac{V_{dc}}{wL}\theta \qquad (5)$$

The above equation gives the value of current when we apply voltage. Here w is the speed of the rotor. Current is a function of speed, inductance, applied voltage and . So current is proportional to Vdc and θ.

When we apply voltage initially, the current increases linearly. At this position the inductance is minimum then current will increase quickly and reach high value. If the inductance increases the current rise will be decreased.

The initial rate of rice of current is $\frac{di}{dt} = \frac{V_{dc}}{L_{min}}$

To reduces the currents and make it to zero, a negative voltage to be applied. The flux is going to fall because flux is proportional to Vdc.

SIMULATION RESULTS

In this simulation a 6/4 switched reluctance motor is considered. Closed loop current control technique is preferred to control the speed and torque of SRM. The position sensor has three inputs, these are turn on, turn off angles and third input is speed or position of the rotor. In position sensor the position (w rad/sec) of the rotor is converted into degrees. The modulus output of the position is compared with turn on and turn off angles. If the position of the rotor is between turn on and turn off angles then rotor position to be changed, the output of AND gate is one, otherwise the AND gate output is zero, the rotor does not rotate.

The output of the position sensor (1 or 0) is multiplied with reference current and the result is subtracted from the actual current of the motor. The difference of current is given to the hysteresis band. If the difference of the current is above or below the threshold value, then the hysteresis band generates signals. These signals are given to converter as gate signals for the switching devices.

At low speeds the self emf of stator winding is small and hence the current must be limited. For this hysteresis type or voltage pulse width modulation control is used. Here the current is maintained almost constant.

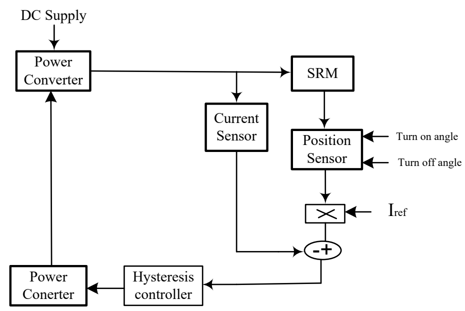


FIGURE 8. Closed loop control of SRM

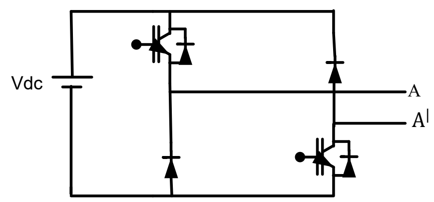
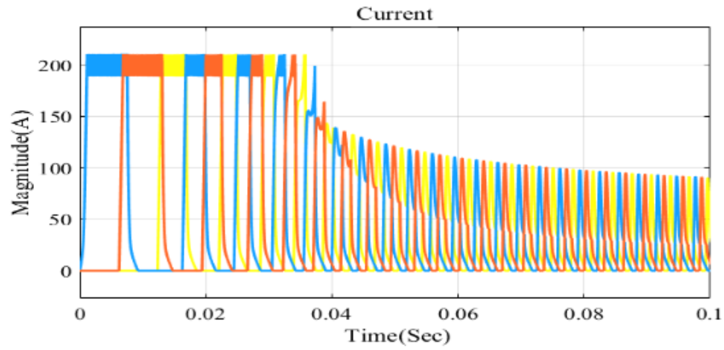
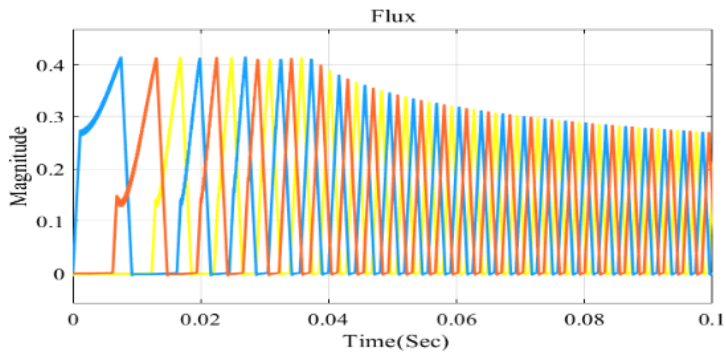


FIGURE 9. Power converter for every phase

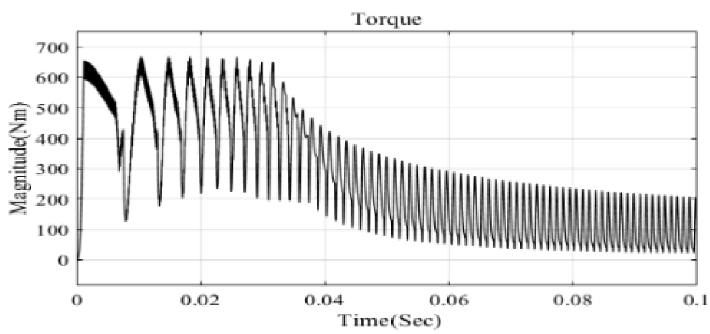
Each phase of SRM should be excited independently. An excited phase should be demagnetized before the SRM entry into generating mode. Free wheeling should be achieved during chopping period. The magnetization energy should be fed back to the source for using it in the subsequent conducting zone. Therefore, every phase is excited through a single switching device. The block diagram for closed loop control and power converter circuits are shown in Figures 8 and 9.



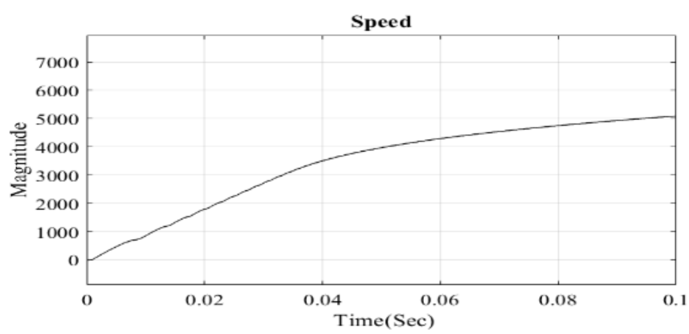
(a)



(b)



(C)



(d)

FIGURE 10. SRM waveforms of a) Input current, b) Developed flux, c) Output torque, and d) Output speed.

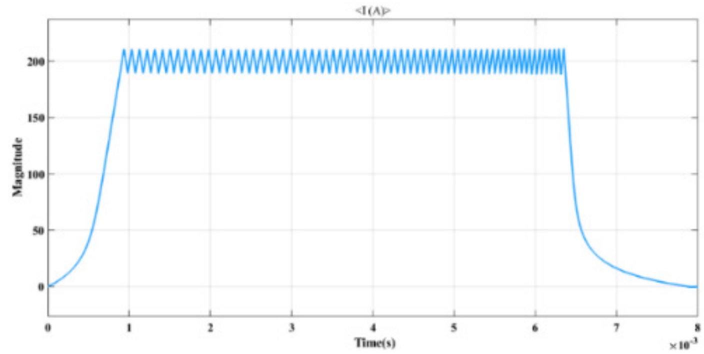
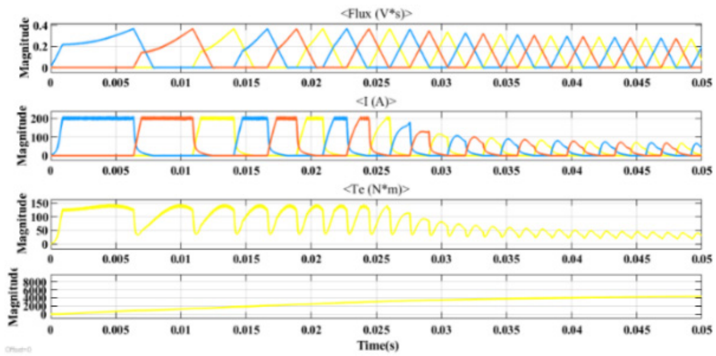
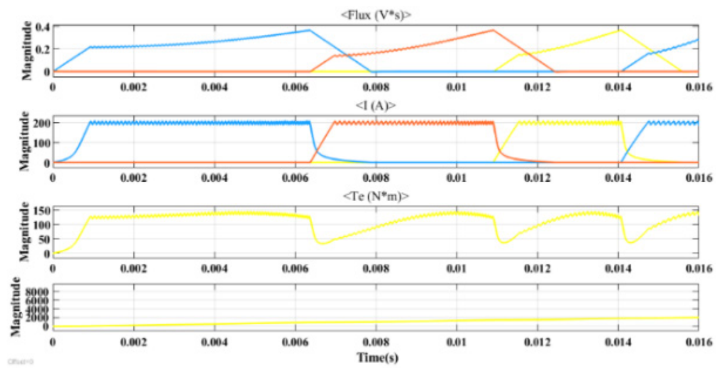


FIGURE 11. Enlarged waveform of input current



(a)



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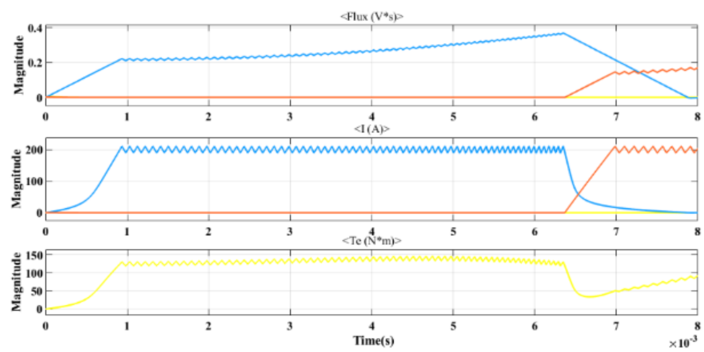

(C)

FIGURE 12. Simulation results with closed loop current control of actual currents all the phases, fluxes of all the phases, total torque and speed a) actual b) enlarged c) more enlarged.

It is observed from the Figures 10, 11 and 12 when the speed is low the current rises quickly. If speed is large the increase in current is low. In low-speed region the current is controlled by using chop mode or hysteresis current control mode. In this mode current is limited to a band. The bands are designed around reference value of current. The upper and lower bands are designed based on the reference current. The variation of current with respect to speed is shown in figure 11. During low speed (for the speed w is less than base speed), current is maintained constant, maintained with in two bands by switching the input voltage alternatively between +Vdc and -Vdc. This is also known as constant torque mode. Before falling the inductance, current is brought down to zero. When the speed is large this mode is not preferable. So still we have to maintain the power current has to build up, so we switch little earlier that angle is called advance angle. Angle by which voltage application is advanced that angle is advance angle.

TABLE 1. Summary of simulation Results

	Low Speed Region	High Speed Region
Change of current	Raises quickly	Raise is low
Method of Control	Chop or Hysteresis control mode	Advance angle control

The advance angle control can be used such way that current increase will happen in lower inductance region only. The advancing of angle can be increased up to certain angles only i.e up to the lower value of inductance minimum point.

It is observed from the simulation results that after the base speed the current can't increase quickly because speed become large, so in this region instead of keeping current constant the power is also constant. Therefore, this mode is constant power mode. The summary of simulation results is shown in Table 1.

CONCLUSION

The simulation of SRM has been done by applying closed loop hysteresis current control technique. In low-speed region the current is controlled by using chop mode or hysteresis current control mode. In this mode current is limited to a band. The bands are designed around reference value of current. The upper and lower bands are designed based on the reference current. During low speed (for the speed w is less than base speed), current is constant, and it is maintained with in two bands. When the speed is large this mode is not preferable. So still to maintain the power current has to build up, so switch little earlier that angle is called advance angle. Angle by which voltage application is advanced that angle is advance angle. The advance angle control can be used such way that current increase will happen in lower inductance region only. The advancing of angle can be increased up to certain angles only i.e up to the lower value of inductance minimum point. And it is observed from the simulation results that the ripples present in the torque is also low.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Rana, Ashwani Kumar, and AV Ravi Teja. A mathematical torque ripple minimization technique based on a nonlinear modulating factor for switched reluctance motor drives. *IEEE Transactions on Industrial Electronics* 69(2): 1356-1366.

Fan, Jiayi, and Yong Keun Lee. 2020. Design consideration to achieve wide-speed-range operation in a switched reluctance motor. *Canadian Journal of Electrical and Computer Engineering* 43(4): 290-294.

Chintala, Lokeshwar Reddy, Satish Kumar Peddapelli, and Sushama Malaji. 2016. Improvement in performance of cascaded multilevel inverter using triangular and trapezoidal triangular multi carrier svpwm. *Advances in Electrical and Electronic Engineering* 14(5): 562-570.

Niguchi, Noboru, et al. 2020. Proposal of a new coil arrangement for a four-phase switched reluctance motor. *IEEE Transactions on Magnetics* 57(2): 1-6.

Reddy, Ch Lokeshwar, P. Satish Kumar, M. Sushama, and NNV Surendra Babu. 2015. A five level cascaded H-bridge multilevel STATCOM. In *2015 IEEE Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics (PrimeAsia)*, pp. 36-41. IEEE, 2015.

Rana, Ashwani Kumar, and AV Ravi Teja. 2019. Torque ripple minimization with maximum utilization of inductance profile in 6/4 3-phase switched reluctance motor drives. IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society. Vol. 1. IEEE, 2019.

Ralev, Iliya, et al. 2017. Impact of smooth torque control on the efficiency of a high-speed automotive switched reluctance drive. *IEEE Transactions on Industry Applications* 53(6): 5509-5517.

Lokeshwar Reddy, Ch, and G. Sree Lakshmi. 2022. Design of cascaded multilevel inverter-based STATCOM for reactive power control with different novel PWM algorithms. In *Advances in Electrical and Computer Technologies*, pp. 1033-1053. Springer, Singapore, 2022.

Zhang, Xing, et al. 2019. A switched reluctance motor torque ripple reduction strategy with deadbeat current control and active thermal management. *IEEE Transactions on Vehicular Technology* 69(1): 317-327.

Deng, Xu, et al. 2017. Design and development of low torque ripple variable-speed drive system with six-phase switched reluctance motors. *IEEE Transactions on Energy Conversion* 33(1): 420-429.

Lokeshwar Reddy, C., P. Satish Kumar, and M. Sushama. 2017. Design and performance analysis of 7-level diode clamped multilevel inverter using modified space vector pulse width modulation techniques. *International Journal of Engineering* 30(11): 1762-1770.

Maksoud, Hady Abdel. 2020. Torque ripple minimization of a switched reluctance motor using a torque sharing function based on the overlap control technique. J*ournal of Engineering, Technology & Applied Science Research* 10(2): 5371-5376.

T. Ishikawa, Y. Hashimoto and N. Kurita. 2014. Optimum Design of a Switched Reluctance Motor Fed by Asymmetric Bridge Converter Using Experimental Design Method. in IEEE Transactions on Magnetics, vol. 50, no. 2, pp. 781-784, Feb. 2014, Art no. 7019304, doi: 10.1109/TMAG.2013.2285584.

Reddy, Ch Lokeshwar, P. Satish Kumar, and M. Sushama. 2017. Performance comparison of star connected cascaded STATCOM using different PWM techniques. *International Journal of Power Electronics and Drive Systems* 8(3): 1303.

Ch, Lokeshwar Reddy. 2021. Analysis of THD for Multilevel Inverters with Novel Pulse Width Modulation Techniques. In *2021 IEEE International Conference on Intelligent Systems, Smart and Green Technologies (ICISSGT)*, pp. 150-155. IEEE, 2021.

E. Bostanci, M. Moallem, A. Parsapour and B. Fahimi. 2017. Opportunities and challenges of switched reluctance motor drives for electric propulsion: A comparative study. *IEEE Transactions on Transportation Electrification* 3(1): 58-75. doi: 10.1109/TTE.2017.2649883.

Reddy, Ch Lokeshwar, P. Satish Kumar, and M. Sushama. 2018. Implementation and performance analysis of cascaded multilevel inverter using modified SVPWM techniques. *International Journal of Power Electronics* 9(3): 250-273.

F. L. M. dos Santos, J. Anthonis, F. Naclerio, J. J. C. Gyselinck, H. Van der Auweraer and L. C. S. Góes. 2014. Multiphysics NVH Modeling: Simulation of a switched reluctance motor for an electric vehicle. *IEEE Transactions on Industrial Electronics* 61(1): 469-476. doi: 10.1109/TIE.2013.2247012.

Kumar, P. Satish, K. Ramakrishna, Ch Lokeshwar Reddy, and G. Sridhar. 2014. Minimization of switching losses in cascaded multilevel inverters using efficient sequential switching hybrid-modulation techniques. *International Journal of Electrical and Computer Engineering* 8(3): 583-588.

X. Zhao. 2020. Emerging hybrid reluctance motor drives for electric propulsion. 2020 8th International Conference on Power Electronics Systems and Applications (PESA), 2020, pp. 1-4, doi: 10.1109/PESA50370.2020.9343997.