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Hysteresis Current Control of Switched Reluctance Motor in Aircraft Applications

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Article Info	ABSTRACT
	The switched reluctance motor (SRM) drives have been widely used in aircraft applications due to the motor advantages like high speed operation, simple construction, no windings on rotor. But high torque ripples and acoustic noise are main disadvantages. The current hysteresis chopping control is one of the important control methods for SRM drives. These disadvantages can be limited using the hysteresis or chopping current control. This control strategy makes the torque of SRM maintained within a set of hysteresis bands by applying suitable source voltage. This paper introduces two hysteresis control modes; hard chopping and soft chopping mode. The SRM drive system is modeled in Simulink model using MATLAB/SIMULINK software package.

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1. INTRODUCTION

One of the most applications of SRM in aircraft is using the SRM coupled with DC generator through high speed gear box to drive the generator. This DC generator may be interfaced with a three-phase 115V lines through a four-quadrant drive to be used in another aircraft application. The SRM is operated as a source of torque, and the DC generator regulates the system speed. The SRM is driven by its converter synchronized by the control and the resolver on the motor's shaft. This electric drive system has been recognized to provide benefits in system efficiency, weight and size, and flexibility in speed control of SRM. Figure 1 shows the basic components of the motor drive system. These components are 3-ph 6/4 SRM, asymmetric DC-DC IGBT converter, gear box, DC machine works as generator and also the electronic control that contain comparator, and the current controller.

The DC-DC converter and SRM are explained in details in [1]. The standard voltages of the converter used in aircraft are: 270, 350 and 540V [2]. The SRM parameters are mentioned in Appendix (A). The comparator regulates the motor performance via comparing the measured rotor position θ, switching turn-on angle θ_{on}, and switching turn-off angle θ_{off} [3]-[5]. The comparator can be implemented experimentally using a programmed computer connected to a controller that follows the commands of the simulated program in this computer [6]. Rotor position sensor is an integral part of SRM control system mounted on the rotor to determine turn-on and turn-off angles to excite and commutate the phase windings. Usually, optical encoders, resolver, or hall-effect sensors mounted on the shaft are used to obtain rotor position information [3]-[4], [7]. The SRM and the DC generator speeds are never the same, so, a gear box system is used between the motor and the generator's rotor to protect it from an excessive wear and tear. The

gear system helps the generator's rotor to run at the generator's rated speed [5], [6]. This gearbox is essential to ensure that the generator speed is constant irrespective of the SRM speed and aircraft status [2].
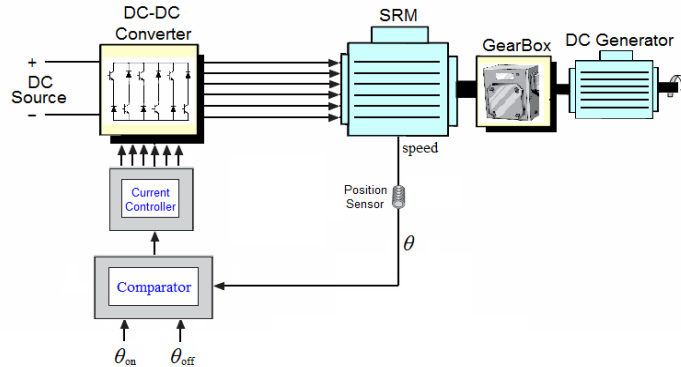

Figure 1. The SRM drive system in aircraft application

2. PRINCIPLE OF HYSTERESIS CURRENT CONTROL

Hysteresis/chopping current control is a control strategy used with SRM for controlling the phase's currents to be within a band around a reference value [8]. This strategy is preferable over wide speed range for SRM operation because the desired current can be easily reached. The control strategy based on turning on the switches of the converter when the phase current is lower than a lower band limit, and turning off these switches when the current is above an upper band limit [9], [10]. The lower limit and the upper limit can be obtained according to the control requirements and the switching frequency of the power converter of SRM [4].

The hysteresis control implemented through using two modes; soft and hard chopping which are illustrated in Figure 2(a), 2(b) [14]. The soft chopping and hard chopping that can be easily used with the asymmetric bridge converter. Figure 2c shows the asymmetric converter has two switches per phase and the hysteresis band. It achieves all forms of control, including hard and soft chopping [11]. In chopping control of Fig. 2c; the phase current is controlled between two levels (i.e., the upper limit and the lower limit) equal to $i_{ref,j} \pm \Delta i/2$, where $i_{ref,j}$ is the reference current of each phase and $\Delta i/2$ is the hysteresis band that has an acceptable range around the reference current [4].

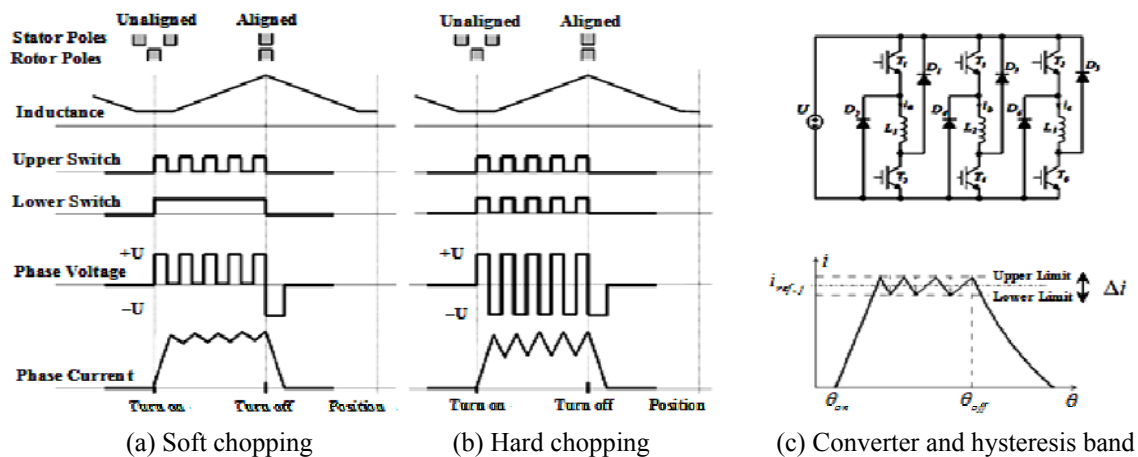(a) Soft chopping   (b) Hard chopping   (c) Converter and hysteresis band

Figure 2. SRM drive using soft chopping and hard chopping control

This hysteresis current control is achieved with a closed-loop control by one of the two modes of a chopping action; hard chopping mode or soft chopping mode.

     a)   In soft chopping mode: Figure 2(a), the phase voltage is switched between (zero) and (+U) value. For phase of inductance L_1, the lower switch T_2 is left on during phase conducting period

and the upper switch T_1 is chopped according to the pulsed signal. It allows not only control of the current but also minimize the ripple current. Also, it produces lower acoustic noise and less electromagnetic interference (EMI). Therefore, soft switching is often preferred for motoring operation [12].

b)   In hard chopping mode: Figure 2b, the phase voltage is switched between (–U) and (+U) value. For phase inductance L_1, both switches T_1 and T_2 are switching on during the conducting period. So, (+U) voltage is applied to conducting phase when T_1 and T_2 are on, and (–U) voltage is applied when T_1 and T_2 are off before the phase current drops to zero. It has large value of current ripples. It can be applied in braking operation [13].

3.   HARD CHOPPING CONTROL OF CURRENT AT NO-LOAD

The Simulink block control diagram when hysteresis current control (hard chopping) is used for three phases 6/4 SRM at no load is shown in Figure 3. The data required for this motor in the following block control diagram is mentioned in Appendix (A). The most significant parameter in this drive system of the hysteresis controller is the hysteresis band which is desired to be as small as possible in order to reduce the current ripple. Also, selecting the proper switching strategy, dwell angle, voltage source, and switching angles will improve the overall efficiency of the drive system. The main idea of current control is to produce a total torque as steady as possible in non linear operation; as if the motor operates in linear mode of operation. This linearity of torque depends on choosing switching angles to make the current of the phases at commutation producing a total current nearly as dc current in order to maximize the motor total torque. So, the used switching angles are turn-on angle, θ_{on} =45º, and turn-off angle, θ_{off} =80º.
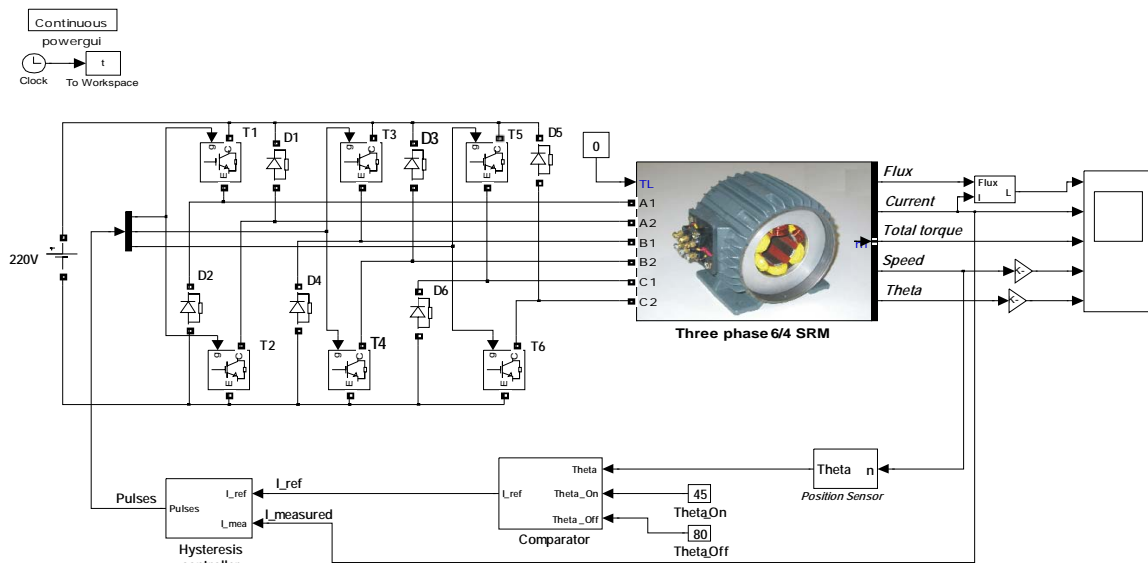

Figure 3. Simulink model using hard chopping control for 3-ph 6/4 SRM at no-load

3.1. Hard Chopping Control with Source Voltage of 220V

The phase's inductances, voltages and currents against rotor position at no load using hard chopping control are shown in Figure 4, where the rated converter voltage is 220V, but this voltage will be increased with loaded motor to increase the gradient of motor phase's currents producing flat-topped total current. The hard chopping mode is more suitable for braking operation to hold on the load torque and to provide motor operation at zero speed. The motor characteristics: inductance, phase voltage, phase current, torque, and speed will be obtained at using the DC source voltage values 220, 350 and 540V. The last two values of the source voltage are used in aircraft applications.

Motor total torque versus rotor position using hard chopping at no-load with source voltage of 220V is shown in Figure 5. The torque ripple is small; also, the torque becomes more stable. The motor speed reaches its steady state after a number of revolutions less than seven complete revolutions of the rotor; as shown in Figure 6. Motor phase current versus phase flux-linkage is shown in Figure 7. Hard chopping

control makes the envelope area in this Figure 7 as maximum as possible, that means, motor total torque not decreased as rotor position changes.
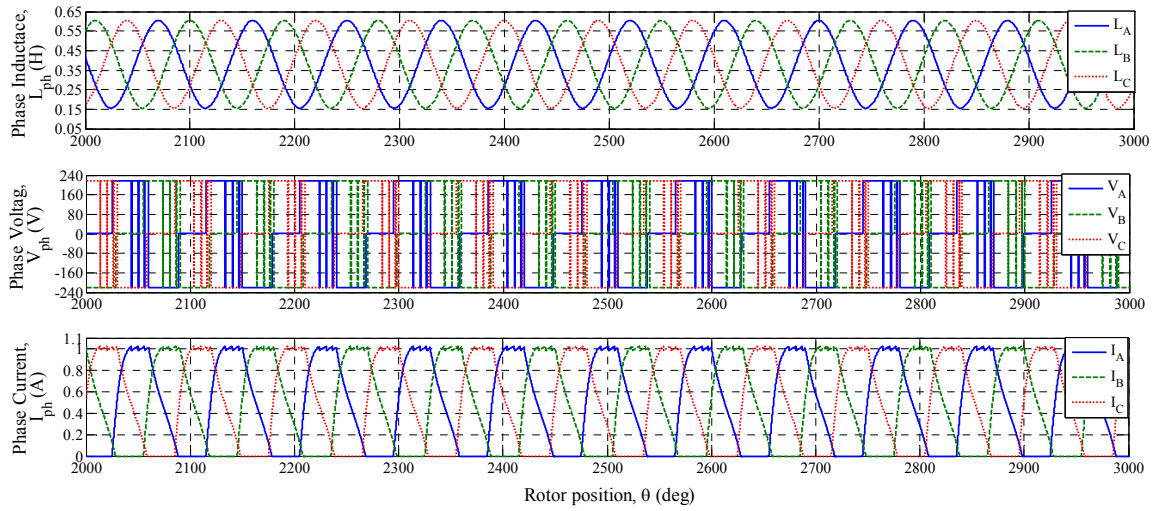

Figure 4. Instantaneous phases inductances, voltages, and currents versus rotor position using hard chopping control at U_{dc} =220V
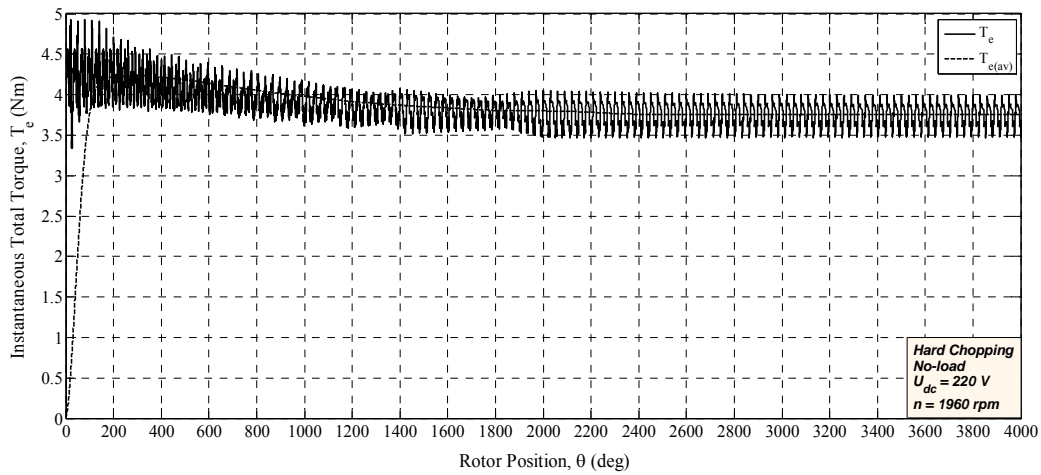

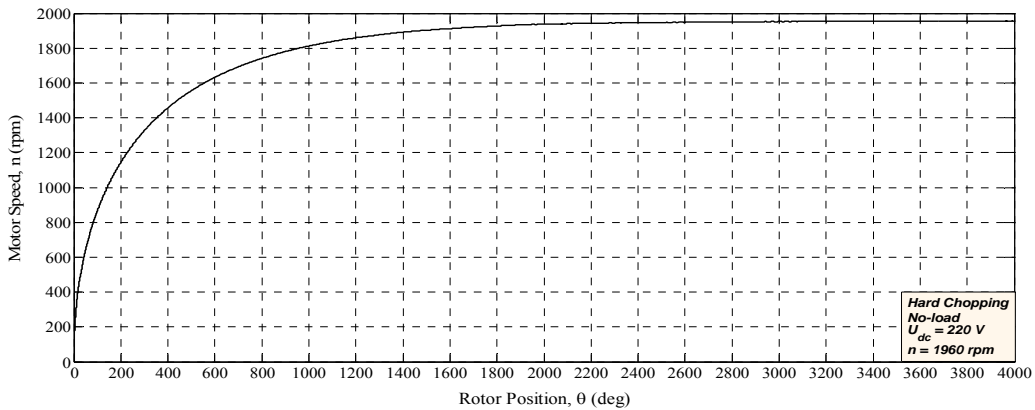Figure 5. Instantaneous total torque versus rotor position using hard chopping control at U_{dc} =220V

Figure 6. Motor speed versus rotor position using hard chopping control at U_{dc} =220V
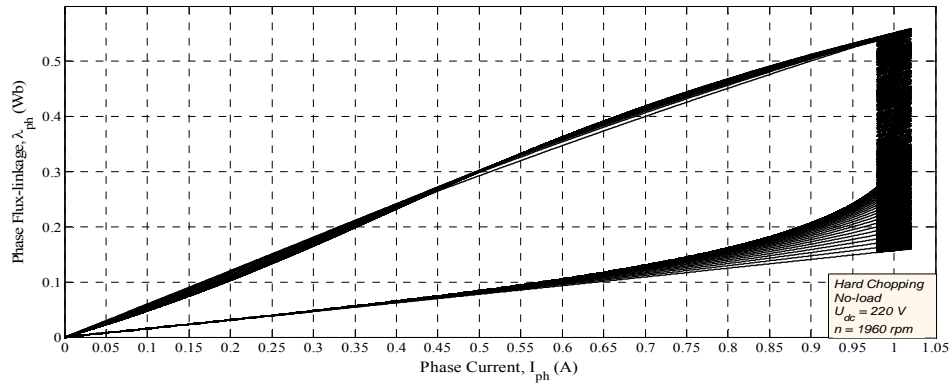
Figure 7. Phase flux-linkage versus phase current using hard chopping control at U_{dc} =220V

3.2. Hard Chopping Control with Source Voltage of 350V

The simulation is repeated in this section under the same conditions as before while allowing the phase currents to overlap at applied higher value of source voltage 350V. Motor characteristics; phase inductance, phase voltage, and phase current versus rotor position are shown in Figure 8. Increasing value of the source voltage will result in an increase of the gradient of the phase current. The motor total torque versus rotor position is shown in Figure 9. It is noticed that the total torque reaches to steady state faster than the case when the source voltage is 220V. But the total torque has larger ripple.
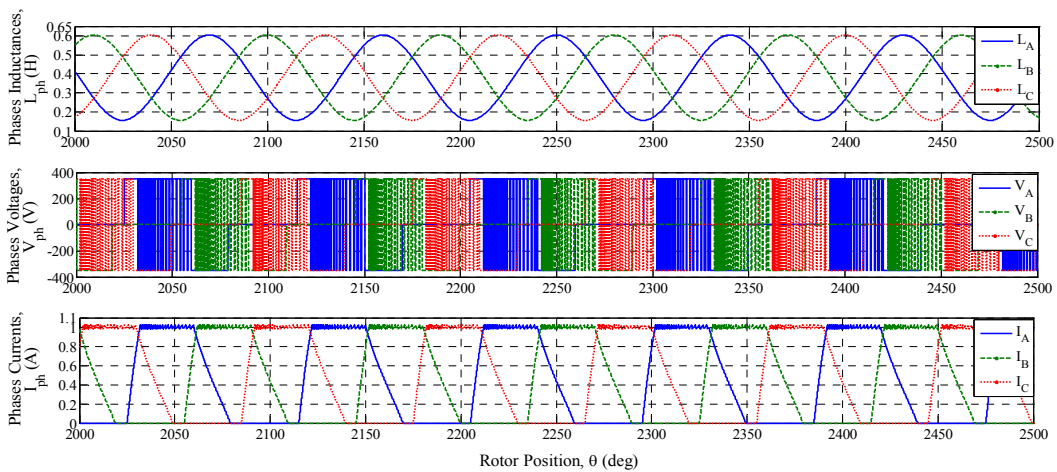

Figure 8. Instantaneous phases inductances, voltages, and currents versus rotor position using hard chopping control at U_{dc} =350V
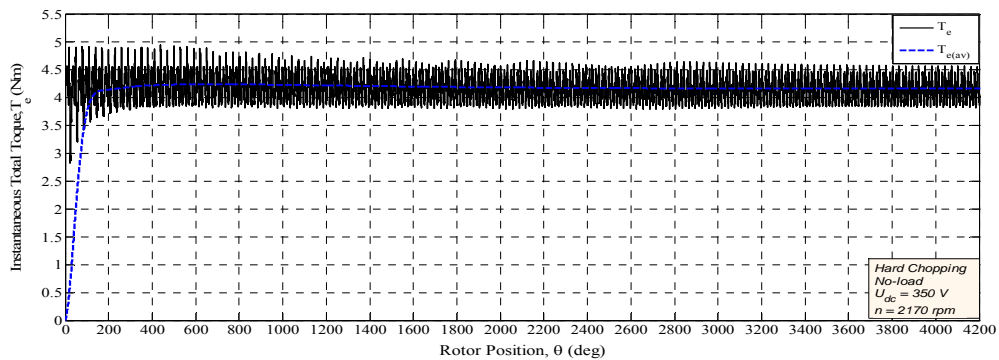

Figure 9. Instantaneous total torque versus rotor position using hard chopping control at U_{dc} =350V

From Figure 10, the motor speed reaches its steady state after about eleven revolutions. The steady state value of speed becomes 2170 rpm that increases further with increasing the supply voltage. The phase flux-linkage versus the phase current at 350V is shown in Figure 11. In this case when the supply voltage equals 350V, the envelope area is larger than that case when the supply voltage is equal to 220V.
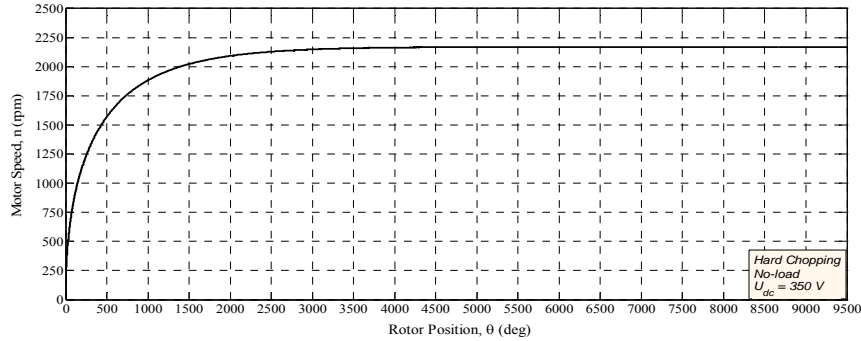

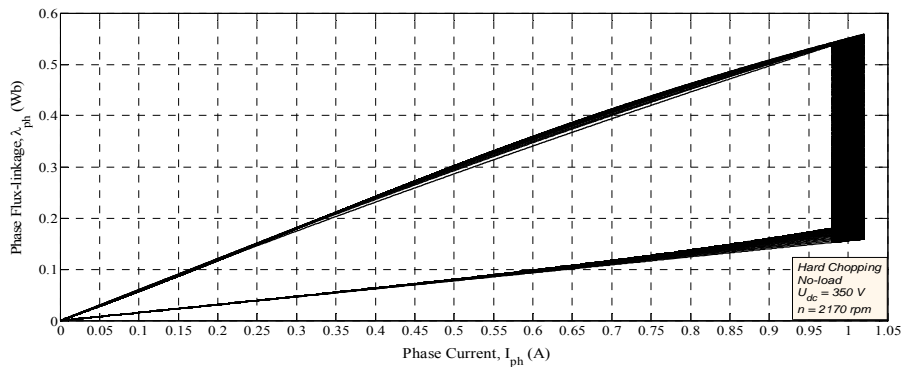Figure 10. Motor speed versus rotor position using hard chopping control at U_{dc} =350V

Figure 11. Phase flux-linkage versus phase current using hard chopping control at U_{dc} =350V

3.3. Hard Chopping Control with Source Voltage of 540V

The simulation for obtain machine characteristics is repeated at applied higher value of source voltage 540V. Motor characteristics; phase inductance, phase voltage, and phase current versus rotor position are shown in Figure 12. Increasing value of the source voltage will result in further increase in the gradient of the phase current.
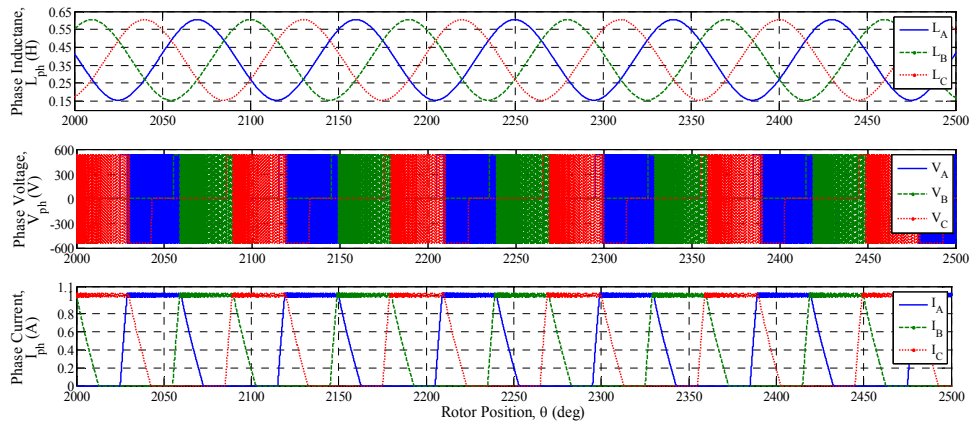

Figure 12. Instantaneous phases inductances, voltages, and currents versus rotor position using hard chopping control at U_{dc} =540V

The motor total torque versus rotor position is shown in Figure 13, where the steady state reaches faster than the two cases of applying 220V and 350V but with larger ripples. The motor speed reaches its steady state value of 2220 rpm after fifteen revolutions as shown Figure 14. The steady state speed becomes 2220 rpm that increases further with increasing supply voltage. The phase flux-linkage versus phase current at 540V is shown in Figure 15.
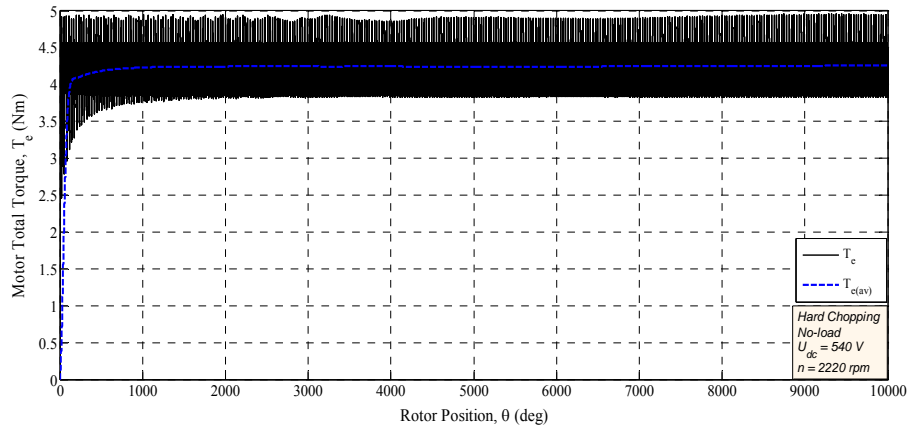

Figure 13. Instantaneous total torque versus rotor position using hard chopping control at U_{dc} =540V

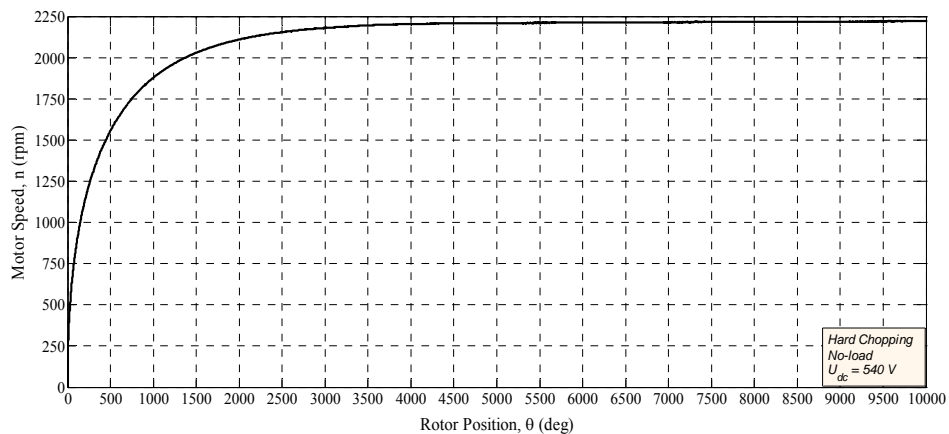

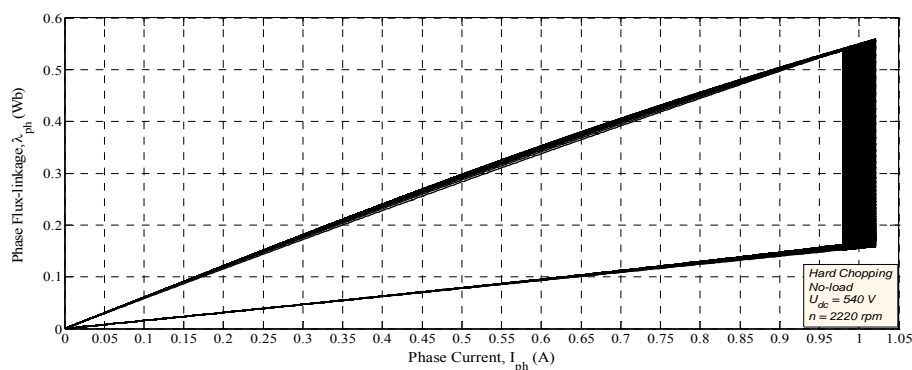Figure 14. Motor speed versus rotor position using hard chopping control at U_{dc} =540V

Figure 15. Phase flux-linkage versus phase current using hard chopping control at U_{dc} =540V

4. SOFT CHOPPING CONTROL OF CURRENT AT NO-LOAD

The Simulink block control diagram when using hysteresis current control (soft chopping) for three phases 6/4 SRM at no load is shown in Figure 16. The data required for this motor in the following block control diagram is obtained from Appendix (A). In soft chopping mode for asymmetric bridge, the lower switches are left on during phases conducting periods and the upper switches are chopped according to the pulsed signal in order to allows not only control of the current but also minimize the current ripples. Also, it produces less acoustic noise and less electromagnetic interference (EMI). The hysteresis band is desired to be as small as possible to reduce current ripples. Also, selecting the proper switching strategy, dwell angle, voltage source, and switching angles will improve the overall efficiency of the drive system. The switching angles are chosen such that the source current and total torque becomes has less ripple values. So, the switching used angle are turn-on angle, θ_{on} =45º, and turn-off angle, θ_{off} =80º.
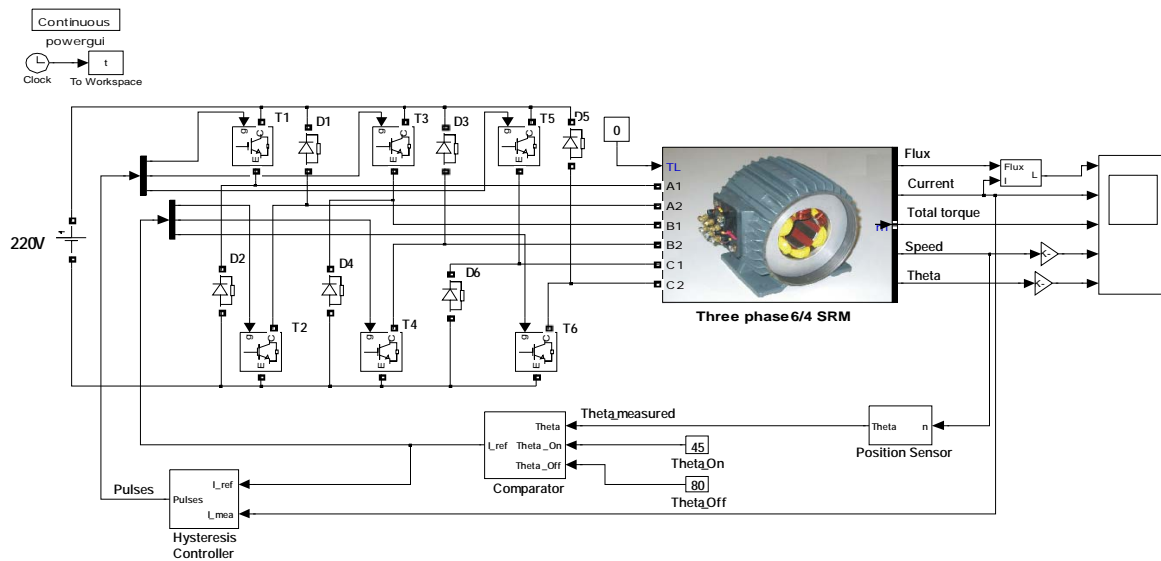

Figure 16. Simulink model using soft chopping control for 3-ph 6/4 SRM at no-load

4.1. Soft Chopping Control with Source Voltage of 220V

The machine characteristics; phases inductances, voltages and currents against rotor position using soft chopping control are shown in Figure 17, where the rated converter voltage is 220V, but this voltage will be increased with loaded motor to increase the gradient of motor phases currents to produce flat-topped total current. The soft chopping mode is more suitable for motoring operation. The motor characteristics will be obtained at source voltage of 220, 350 and 540V.
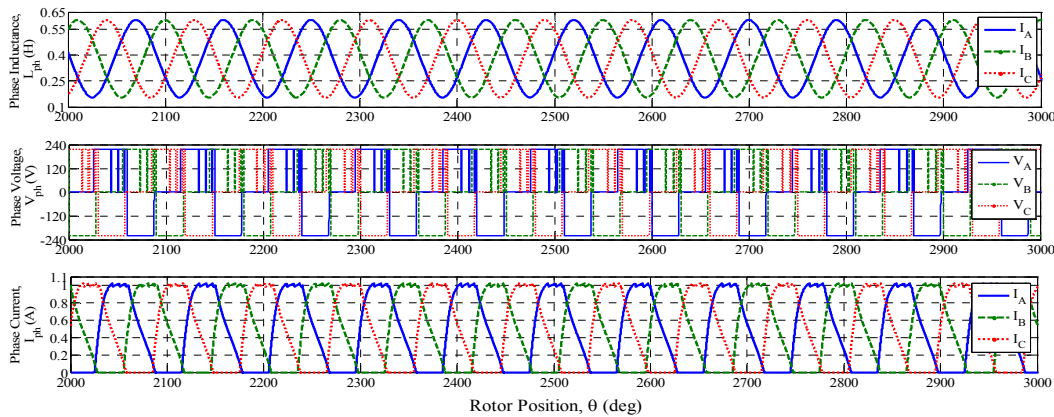

Figure 17. Instantaneous phases inductances, voltages, and currents versus rotor position using soft chopping control at U_{dc} =220V

The motor total torque versus rotor position using soft chopping at no-load with source voltage of 220V is shown in Figure 18. The torque ripple is smaller than that the case when hard chopping control is used at 220V. The motor speed reaches its steady state after about eight revolutions of the rotor as shown in Figure 19. The phase flux-linkage versus phase current is shown in Figure 20. The envelope area becomes larger than using hard chopping at 220V.
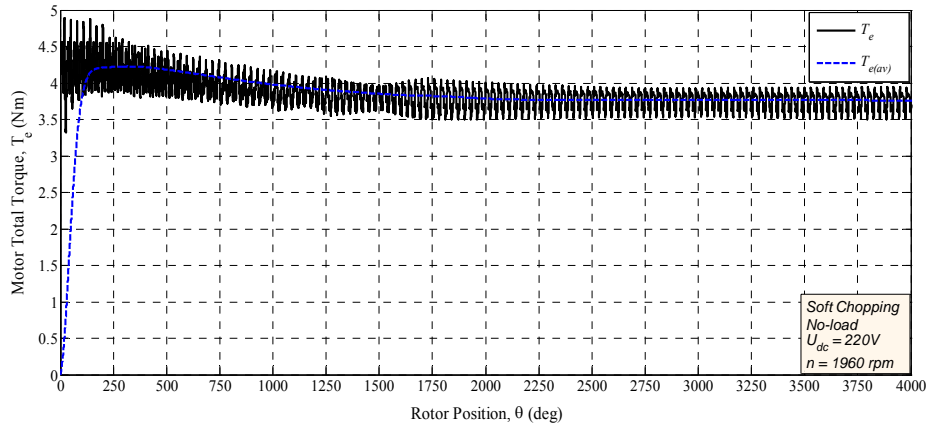

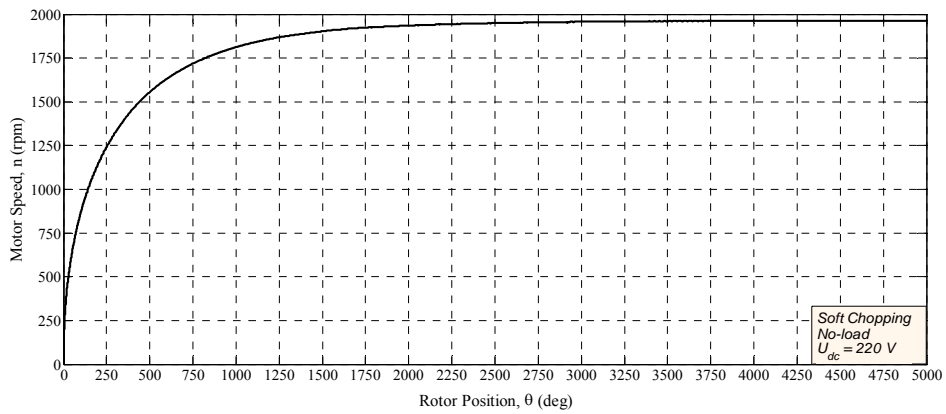Figure 18. Instantaneous total torque versus rotor position using soft chopping control at U_{dc} =220V

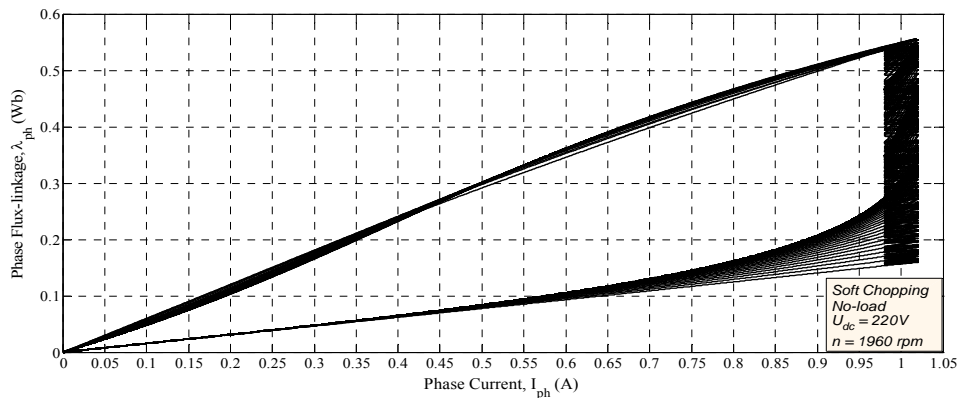Figure 19. Motor speed versus rotor position using soft chopping control at U_{dc} =220V

Figure 20. Phase flux-linkage versus phase current using soft chopping control at Udc =220V

4.2. Soft Chopping Control with Source Voltage of 350V

The simulation is repeated at applied source voltage 350V. Motor characteristics; phases inductances, phases voltages, and phases currents versus rotor position are shown in Figure 21. By increasing the value of source voltage will results in increasing of the gradient of the phase current. The motor total torque versus rotor position is shown in Figure 22, where the steady state of the total torque reaches faster than apply 220V, but it has larger ripple value.
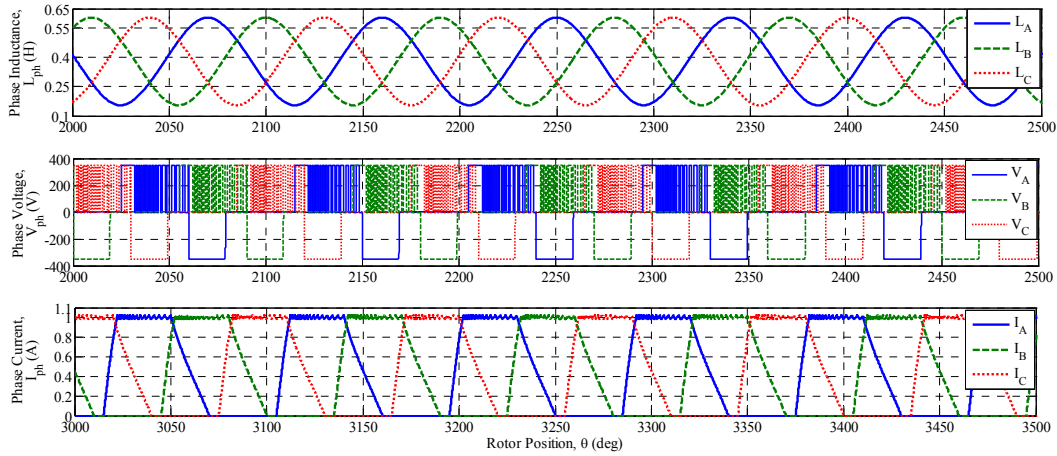

Figure 21. Instantaneous phases inductances, voltages, and currents versus rotor position using soft chopping control at U_{dc} =350V
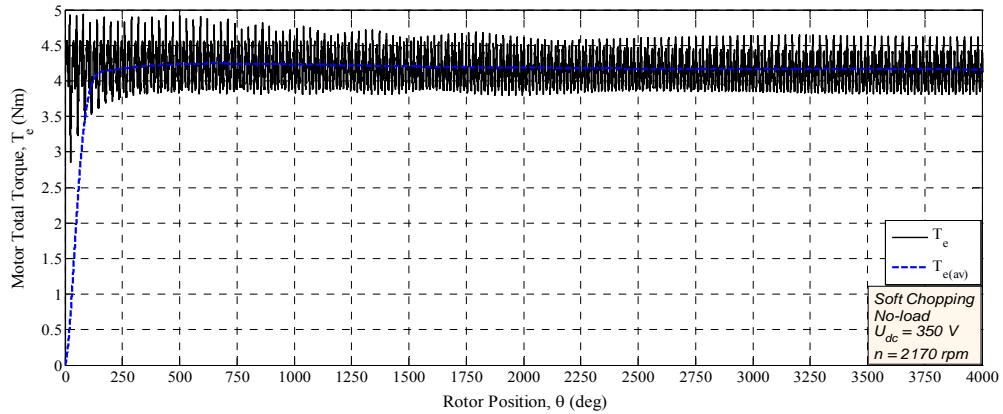

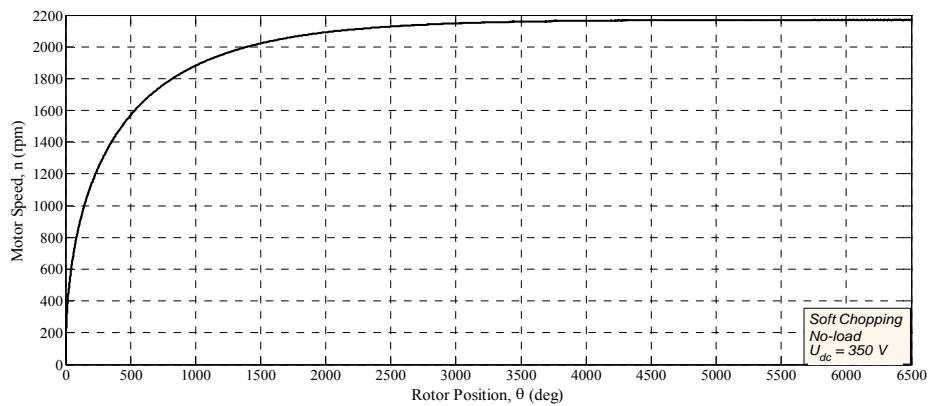Figure 22. Instantaneous total torque versus rotor position using soft chopping control at U_{dc} =350V

Figure 23. Motor speed versus rotor position using soft chopping control at U_{dc} =350V

As shown in Figure 23, the motor speed reaches its steady state after eleven revolutions. The steady state speed becomes 2170 rpm that increases further with increasing supply voltage. The phase flux-linkage versus phase current is shown in Figure 24.
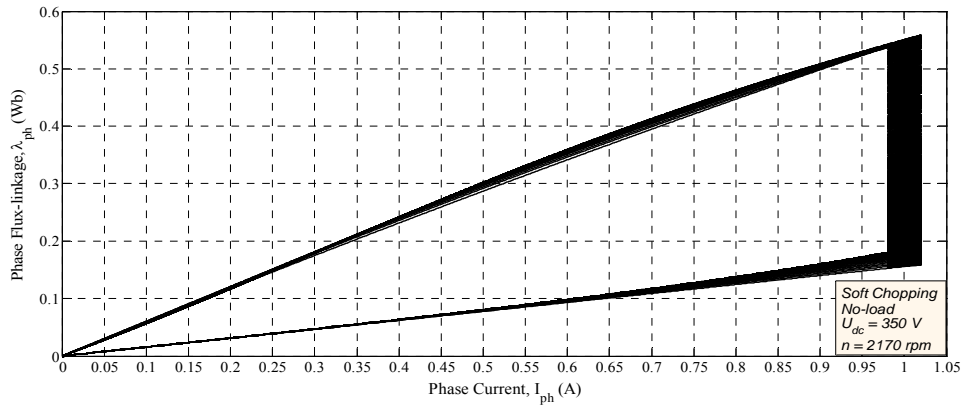

Figure 24. Phase flux-linkage versus phase current using soft chopping control at U_{dc} =350V

4.3. Soft Chopping Control with Source Voltage of 540V

The simulation is repeated at voltage 540V. Motor characteristics; phase inductance, phase voltage, and phase current versus rotor position are shown in Figure 25 producing further increase in the gradient of the current.
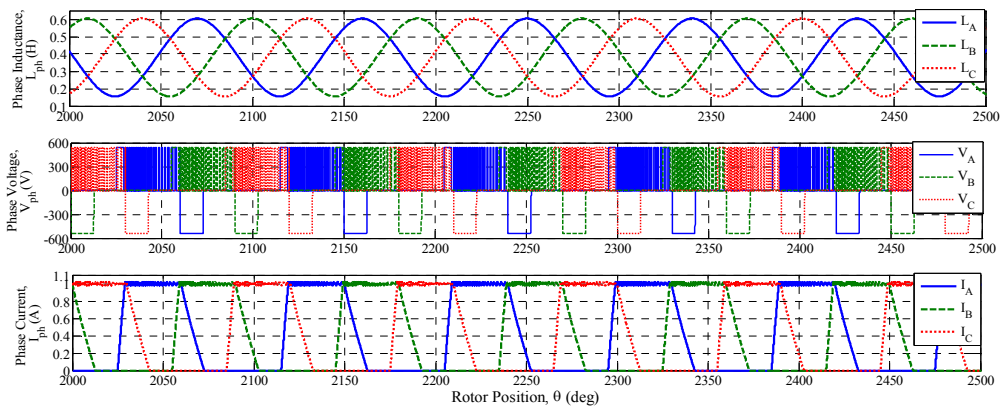

Figure 25. Instantaneous phases inductances, voltages, and currents versus rotor position using soft chopping control at U_{dc} =540V
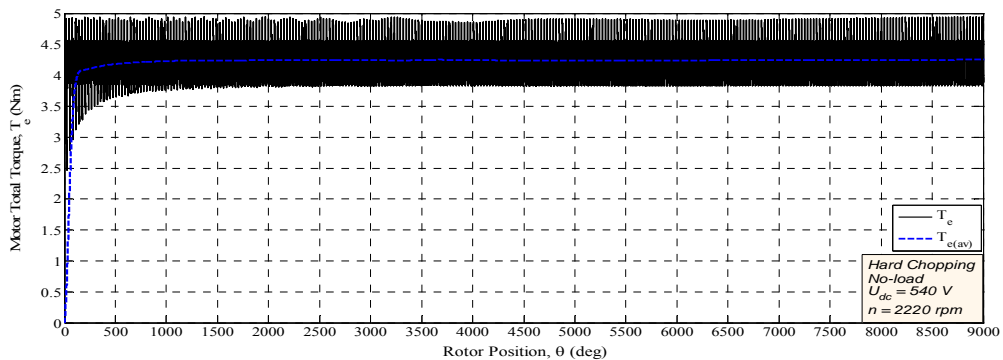

Figure 26. Instantaneous total torque versus rotor position using soft chopping control at U_{dc} =540V

The motor total torque versus rotor position is shown in Figure 26, where the total torque reaches to steady state faster than apply: 220V or 350V, but it has larger ripple value. From Figure 27, the motor speed reaches its steady state after fourteen revolutions. The steady state speed becomes 2220 rpm that increases further with increasing supply voltage. The phase flux-linkage versus phase current with source voltage 540V is shown in Figure 28.
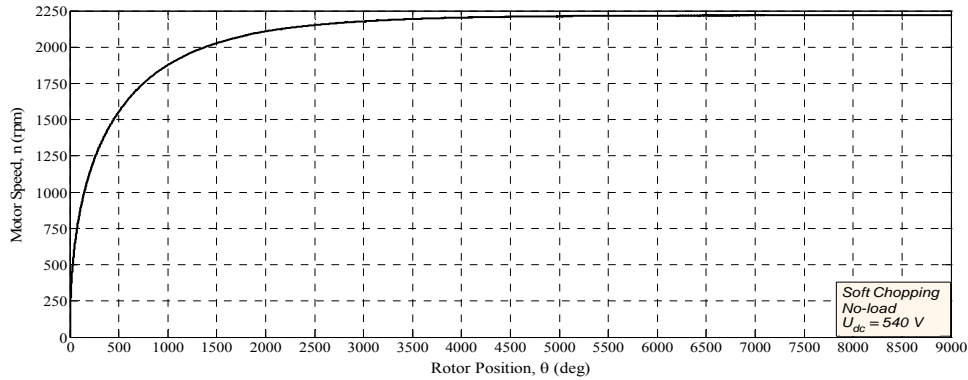

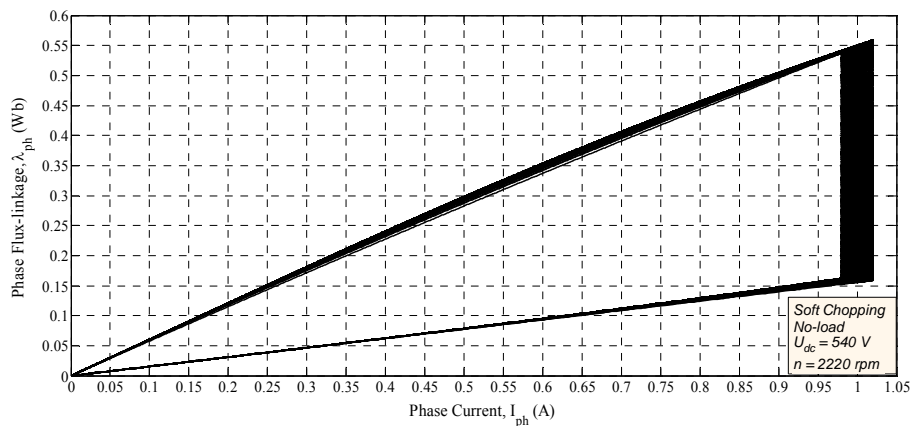Figure 27. Motor speed versus rotor position using soft chopping control at U_{dc} =540V

Figure 28. Phase flux-linkage versus phase current versus using soft chopping control at U_{dc} =540V

5.   AVERAGE MOTOR CHARACTERISTICS AT NO-LOAD

To compare the operations of asymmetric bridge converter at using hard or soft chopping, the average characteristics is presented. In this section; average source current, average total torque, average total torque per ampere, and motor speed versus rotor position is introduced with different source voltage by using turn-on switching angle equals 45° and turn-off switching angle equals 80°. The main idea for using these switching angles are that to produce average characteristics with less ripples for producing more precise operation of less acoustic noise.

We must note that the different values of used voltages in comparison are the voltages that can be used in aircraft applications with SRM converter.

5.1. Average Characteristics with Hard Chopping

Hard chopping control with θ_{on}= 45° and θ_{off}= 80° by applying different source voltages 220, 350, 540V is used in this section to obtain average characteristics of SRM as function of rotor position. The average source current versus rotor position is shown in Figure 29; the average source current is decreased due to the increasing of switching frequency with increasing the source voltage.
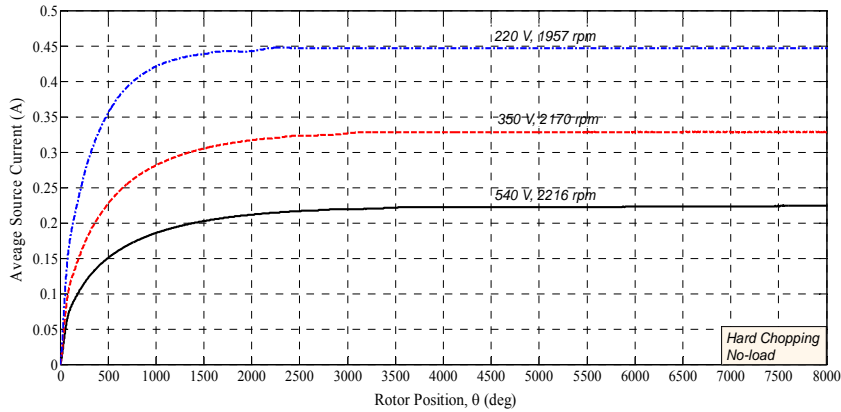
Figure 29. Average source current versus rotor position for hard chopping at no-load at different source voltage values

The average total torque versus rotor position with different source voltage that used in aircraft applications is shown in Figure 30. The average total torque decreases with decreasing the source voltage. With low voltage, the total torque reaches steady state faster. But, for most precise operation of SRM, the average total torque per ampere is the most powerful characteristic than the average total torque. The average total torque per ampere versus rotor position is presented in Figure 31. The torque per ampere increases as the voltage source increases. As shown in Figure 32, the motor speed increases as the voltage source increases.
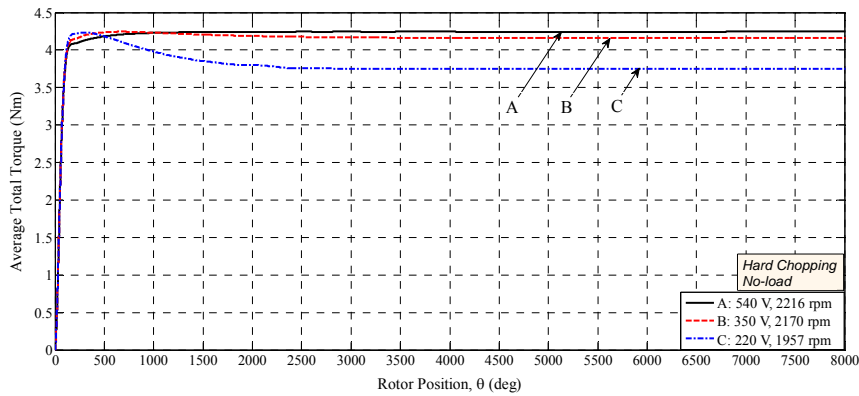

Figure 30. Average total torque versus rotor position for hard chopping at no-load for different source voltage
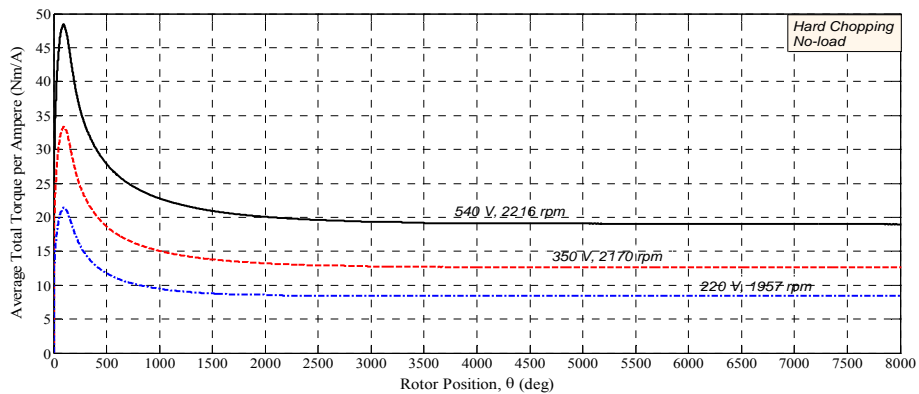

Figure 31. Average total torque per ampere versus rotor position for hard chopping at no-load for different source voltage

Figure 32. Motor speed versus rotor position for hard chopping at no-load for different source voltage

5.2. Average Characteristics with Soft Chopping

The average source current versus rotor position at using soft chopping with different applied source voltage is shown in Figure 33. The current is decreased with increasing the source voltage depending on the switching frequency that increases with increasing the source voltage. The average total torque versus rotor position when the soft chopping is used with different source voltage is shown in Figure 34. As the voltage source increases, the total torque increases. Also, the average total torque per ampere and motor speed increase versus rotor position increases with increasing the source voltage as shown in Figure 35 & Figure 36 respectively.

Figure 33. Average source current versus rotor position for soft chopping at no-load for different source voltage values

Figure 34. Average total torque versus rotor position for soft chopping at no-load for different source voltage

Figure 35. Average total torque per ampere versus rotor position for soft chopping at no-load for different source voltage
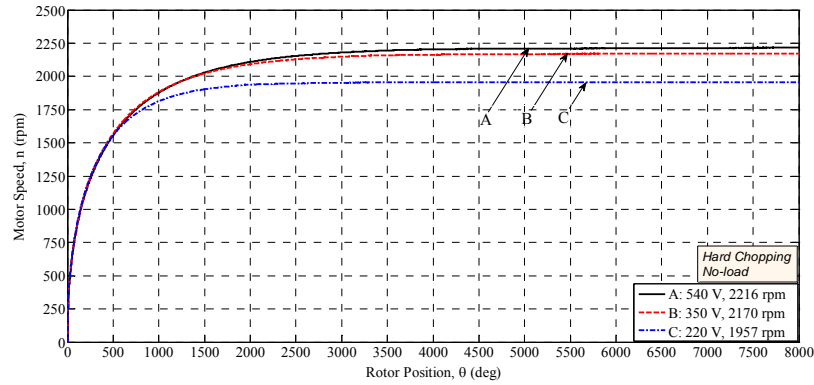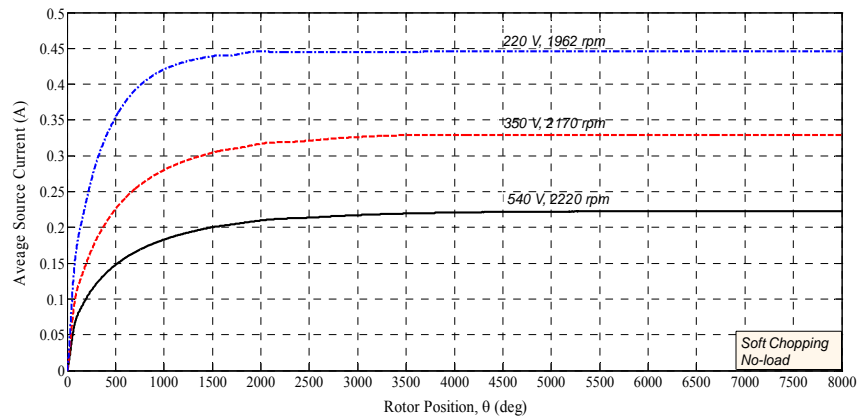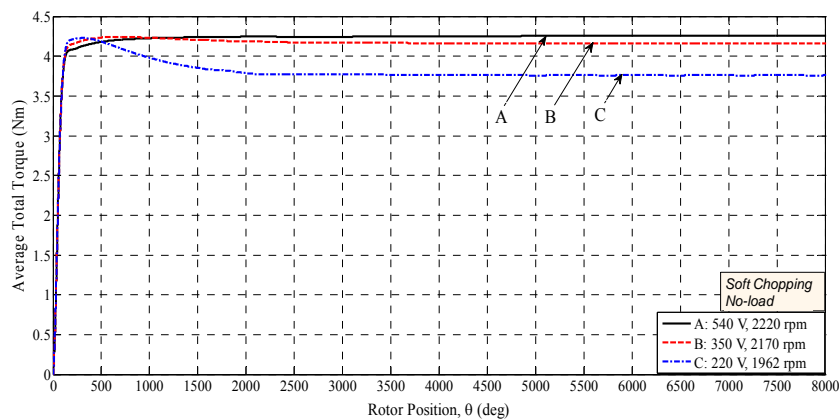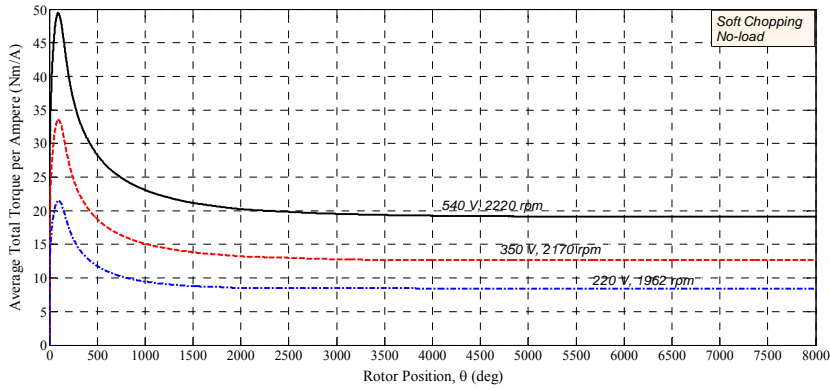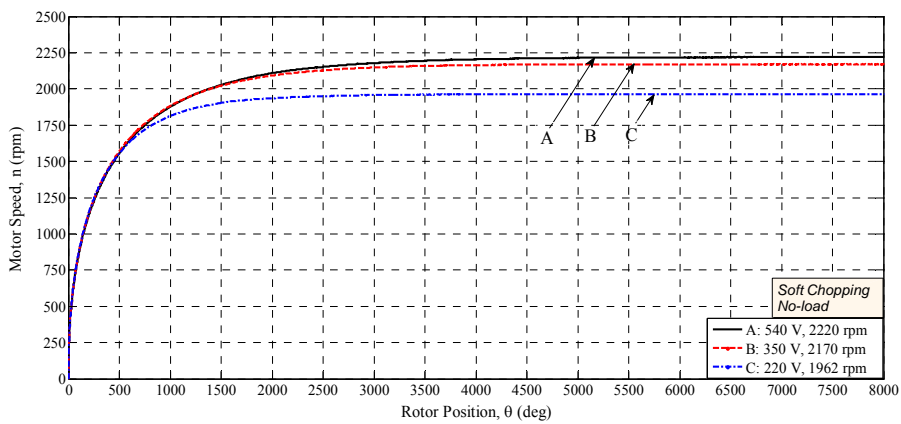

Figure 36. Motor speed versus rotor position for soft chopping at no-load for different source voltage

5.3. Comparison between Average Characteristics for Soft and Hard Chopping

Table 1 shows the comparison between motor characteristics at different source voltage; where, U_{dc}, I_s, T_e, T_e/I_s and n are the DC source voltage, average source current, average total torque, average total torque per ampere, and motor speed respectively.

Table 1. Steady state values of motor characteristics at different source voltages

Ch/s U_{dc} (V)	Soft Chopping				Hard Chopping			
	I_s (A)	T_e (Nm)	T_e/I_s (Nm/A)	n (rpm)	I_s (A)	T_e (Nm)	T_e/I_s (Nm/A)	n (rpm)
540	0.2229	4.255	19.09	2220	0.2239	4.25	18.98	2216
350	0.3294	4.16	12.629	2170	0.3284	4.159	12.66	2170
220	0.4457	3.759	8.434	1962	0.4463	3.75	8.4	1957

6.   CONCLUSION

The investigation in this paper indicates that the control parameters and outputs under the current hysteresis chopping control can affect in SRM drives. The current hysteresis chopping control is one of the important control methods for SRM drives. It is often used during speed operation of SRM drives. At steady state operation, for motor parameters comparison at different source voltage with constant switching angles; then:

a) The average source current is inversely proportional to increase of source voltage.
b) The average total torque is directly proportional to increase of source voltage.

    c)   The average total torque per ampere is directly proportional to increase of source voltage.

    d)   The motor speed is directly proportional to increase of source voltage.

The hysteresis control cannot be implemented without closed loop control. There is no limitation of high switching frequency without using additional circuitry to the drive system, but if faster switching devices are used to limit the high switching losses and noise, the cost of the control system will be much increased. Also, the chopping strategy allows a very precise current control because the hysteresis band is a design parameter, but acoustic and electromagnetic noise is difficult to be filtered because the high switching frequency of converter switches.

APPENDIX A: MOTOR PARAMETERS

The parameters of the three phase 6/4 poles SRM are:

Number of motor phases	$: K = 3$	Inertia constant	$: J = 0.0013 \text{ Kg.m}^2$
Number of stator poles	$: N_S = 6$	Viscous friction coefficient	$: B = 0.0183 \text{ N.m.Sec}^2$
Number of rotor poles	$: N_R = 4$	Rated speed	$: n_r = 1000 \text{ rpm}$
Stator pole arc (mech. deg.)	$: \beta_S = 40°$	Rated phase current	$: I_r = 3 \text{ A}$
Rotor pole arc (mech. deg.)	$: \beta_R = 45°$	Rated torque	$: T_o = 1 \text{ Nm}$
DC voltage rating	$: U_{dc} = 220 \text{ V}$	Number of turns per phase	$: N_{ph} = 600$
Stator phase resistance	$: R = 17 \, \Omega$	Winding wire diameter	$: d = 0.5 \text{ mm}$
Aligned inductance	$: L_{al} = 0.605 \text{ H}$	Rotor pole arc (mech. deg.)	$: \theta_r = 30°$
Unaligned inductance	$: L_{ul} = 0.155 \text{ H}$		

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