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Control Strategy for a Direct Torque Control of a Switched Reluctance Motor

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***Abstract*—The Switched Reluctance Motor is an old member of the electric machine family. It receives the significant response from industries in the last decade because of its simple structure, ruggedness, high reliability, inexpensive manufacturing capability and high torque to-mass ratio. The Switched Reluctance Motor consists a salient pole stator with concentrated coil and salient pole rotor, which have no conductors and magnets. The motor's doubly salient structure makes its magnetic characteristics highly nonlinear. This work briefly describes the constructional features, principle of operation and mathematical model of Switched Reluctance Motor. However the application of SRM has been limited because of their large torque ripple, which produces noise and vibration in the motor. In order to solve these problems, a Direct Torque control (DTC) technique is used in order to control the torque of the Switched Reluctance Motor. By using this method we can well regulate the torque output of the motor with in hysteresis band.**

Keywords*— *Control, direct torque control, torque ripple, torque splitting, electric motors, switched reluctance motors.

I. INTRODUCTION

The functionality of Switched Reluctance Motor is already known for more than 150 years, but only some vast improvements of the power electronics drive technologies have made a great success of adjustable speed drives with Switched Reluctance Motor. Due to enormous demand for variable speed drives and development of power semiconductors the conventional reluctance machine has been come into picture and is known as Switched Reluctance Machine. The name "Switched Reluctance", first used by one of the authors of [1], describes the two features of the machine configuration (a) switched,(b) reluctance. Switched word comes into picture because this machine can be operated in a continuous switching mode. Secondly reluctance word comes into picture because in this case both stator and rotor consist of variable reluctance magnetic circuits or we can say that it have doubly salient structure. A SRM has salient poles on both stator and rotor. Each stator pole has a simple concentrated winding, where the rotor does not contain any kind of winding or permanent magnet [2]-[4]. It is made up of soft magnetic material that is laminated steel. Two diametrically opposite windings are connected together in order to form the motor phases. During the rotor rotation a circuit with a single controlled switch is sufficient to supply an unidirectional current for each phase. For forward motoring operation the stator phase winding must be excited when the rate of change of phase inductance is positive. Otherwise the machine will develop breaking torque or no torque at all. As SRM has simple, rugged construction, low manufacturing cost, fault tolerance capability and high efficiency the SRM drive is getting more and more recognisation among the electric drives. It also have some disadvantages that it requires an electronic control and shaft position sensor and double salient structure causes noise and torque ripple. SRMs are typically designed in order to achieve a good utilization in terms of converter rating.

II. SWITCHED RELUCTANCE MOTOR CONFIGURATION

Switched Reluctance Motor can be made up of laminated stator and rotor cores with Ns =2mq poles on the stator and Nr poles on rotor. Where m is number of phases and each phase made up of concentrated windings placed on 2q stator poles. Switched reluctance motor is having salient pole stator with concentrated winding and salient pole rotor with no winding or permanent magnet. As both stator and rotor have salient pole structure, hence we can say that switched reluctance motor is having doubly salient structure which is single excited with different number of stator and rotor poles. It is constructed in such a manner that in no way the rotor poles in a position where the torque due to current in any phase is zero. The common stator/rotor pole configuration are 6/4,8/6,10/8. In stator the coils on two diametrically opposite poles are connected in series in order to form single phase. So, 6/4 stator/rotor pole configuration means that represent the 3-phase configuration of switched reluctance motor drive. Similarly 8/6 and 10/8 stator/rotor pole configuration represents the 4 and 5 phase configuration of switched reluctance motor drive.

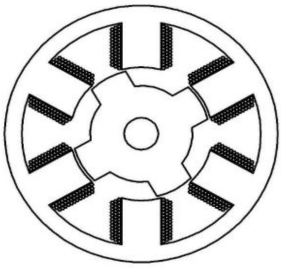

Fig.1 Switched reluctance motor configuration.

A. Principle of operation: An electromagnetic system in order to form stable equilibrium position gives rise to minimum magnetic reluctance is the main principle of operation of switched reluctance motor. When the two diametrically opposite poles are excited, the nearest rotor poles are attracted towards each other, in order to produce torque. When the two rotor poles gets aligned with the stator pole then it gets de energise and the adjacent stator pole gets energise to attract another pair of rotor poles. According to this principle switched reluctance motor gets run. When both the stator and rotor poles gets aligned with each other than that position is known as aligned position. The phase inductance during the aligned position reaches its maximum value known as La as the reluctance reaches its minimum value. The phase inductance decreases gradually as the rotor poles move away from its aligned position. When the rotor poles get completely unaligned or misaligned from stator poles then the phase inductance at that moment reaches its minimum value known as Lu. Reluctance in this case reaches its maximum value.

III. DRAFT OF A DIRECT TORQUE CONTROL

To achieve a constant total torque, the phase currents should be functions of the operation point. The advantage of the DTC is that it is not necessary to determine the current waveforms in advance. Rather the torque is controlled directly. In this section a control strategy is developed to determine the phase torques based on the operation point.

Torque splitting In the overlapping region it is theoretically possible to describe the reference total torque T_{ref} as an arbitrary summation of reference phase torques $T_{ref.ph}$. The only additional condition is that a constant total torque should be achieved over an electrical period. Figure 5 shows an example of linear torque splitting, where the control region and commutation region are defined.

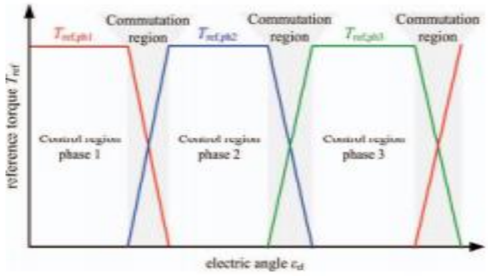

Fig.2 Linear torque splitting for the reference phase torque.

Since only one phase generates the total torque in the control region, the phase torque should be kept constant. The commutation region begins with switching on the successive phase. Because of the linear torque splitting, both reference phase torques cross each other in the middle of the commutation region. Each of the phase torque should generate half of the total torque. The end of the commutation is defined as the point where the current of the previous phase becomes definitely zero. Varieties of functions can be used for torque splitting [6], [7] and [8]. The only additional condition is that the sum of these functions should be constant. Moreover, it should be ensured that the required current dynamic can be achieved. The torque function can be static or dynamic. For the SRM the torque function should be dynamic because of two reasons. First of all a high current dynamic is necessary for the SRM, because of the pulsated current waveform. However, the essential voltage reserve to apply this current is limited at high speed. That means the speed of the motor affects the torque behavior. The second reason is the dependency of the phase torques to the degree of saturation as mentioned in section 2. In the following section a control strategy will be developed to determine the dynamic torque splitting as a function of speed and degree of saturation.

B. Direct Torque Control The scheme of the DTC is indicated in figure 3.

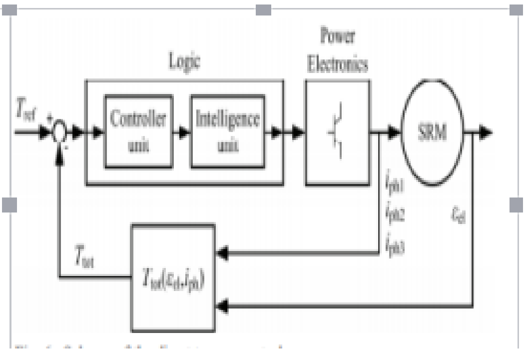

Fig.3 Scheme of the direct torque control.

A look up table $T_{tot}(\dot{I}_{el}, i_{ph})$ based on the Finite Element Method (FEM) is used to determine the total torque. The main part of the control system is the Logic. It is divided into intelligence and control unit. The control unit contains a three point controller which detects the deviation of the torque from its referenced value. The intelligent unit determines how the phase torques should react based on this torque deviation. This will be developed in order to generate an operating point dependent torque splitting.

IV. CONTROL UNIT

The scheme of the control unit is indicated in figure 7 and 8 [5]. The three point controller responds to the torque derivation drastically. This means the power electronics can switch between three states for the regulation voltage V_{reg}. State (1) connects the phase to the positive dc-link voltage V_{dc}. State (0) indicates the freewheeling and state (-1) connects the phase to the negative dc-link voltage. Moreover, only one phase should be controlled via the three point controller. This phase is defined as “active phase”. In the case of torque generation through an inactive phase, its value T_{ph} inactive should be subtracted from the reference total torque T_{ref} and the resulted T_{ref} active is controlled via the active phase.

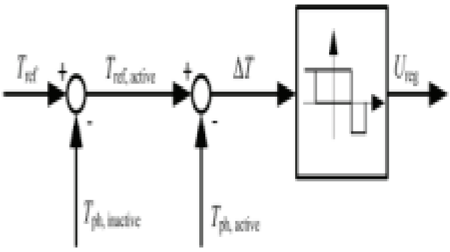

Fig.4 Scheme of the control unit.

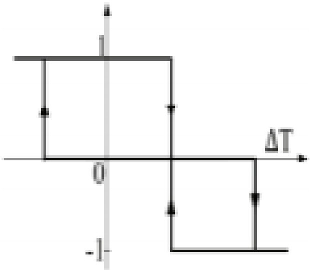

Fig.5 Control unit three point controller.

V. SIMULATION RESULTS

To clarify the control strategy the results of the simulation are illustrated in figure 9. The Simulation is carried out for a motor with 1000 rpm and 16 Nm. The courses of phase 1, phase 2 and phase 3 are indicated restrictively in red, blue. In the control region, only phase 1 generates torque. This phase is controlled with the three point controller which switches between supply (1) and freewheel (0). Phases 2 and 3 are turned off and have no current, which is indicated with X in table 3. The commutation region from phase 1 to phase 2 begins with switching on of phase 2 at angle $\dot{I}_{on}$. The maximum achievable voltage is applied to phase 2 in order to achieve the maximum current gradient. The rest of the total torque Ttot is still actively controlled via phase 1. Therefore, the torque splitting is realized in a manner that phase 2 generates its maximum torque based on the operating point. From the point of torque intersection of phase 1 and 2, phase 1 is switched off and phase 2 is controlled actively via the three phase controller. Thus, this point is known as commutation angle $\dot{I}_{com}$. The control region of phase 2 begins when the current in phase 1 becomes zero. The switch-on angle $\dot{I}_{on}$ has not been defined yet and it results to a new degree of freedom which will be described in the next section.

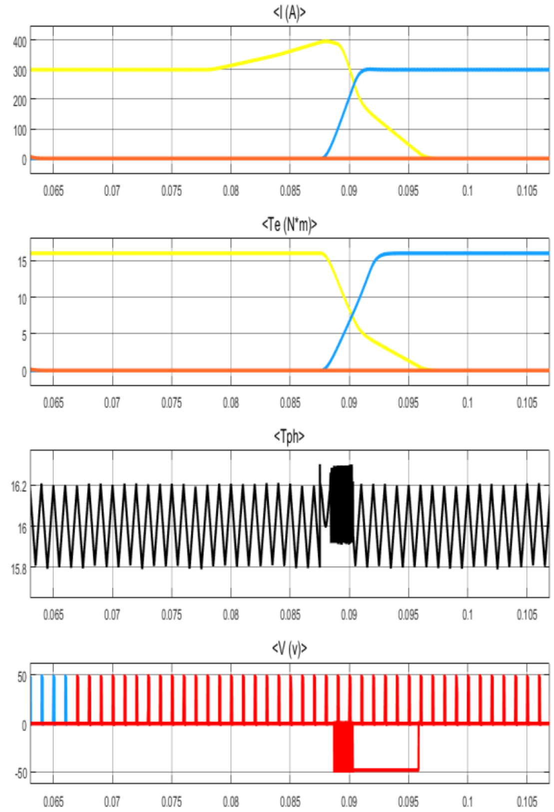

Fig.6 Simulation results of phase current, phase torque, total torque and regulation voltage with DTC and developed control strategy.

VI. ANALYSIS OF THE SWITCH-ON ANGLE

The switch-off time of the phase currents are determined by the commutation angle. This angle is detected using the intersection point of the phase torques in the commutation region. The switch-on angle is not yet determined and represents a new degree of freedom for the control. In the first part of the following section, the influence of the switch on angle on the torque behavior is analyzed using the control strategy of section 2. Considering the results of this analysis a suggestion for speed and torque dependent determination of the switch-on angle is given. Finally the results are discussed.

A. Influence of the switch-on angle Figure 10 shows the current, torque, differential inductance and induced voltage behaviors of one phase for different switch-on angles varied from 150° to 200°. The results are obtained for a motor with 3000 rpm and a reference total torque of 16 Nm.

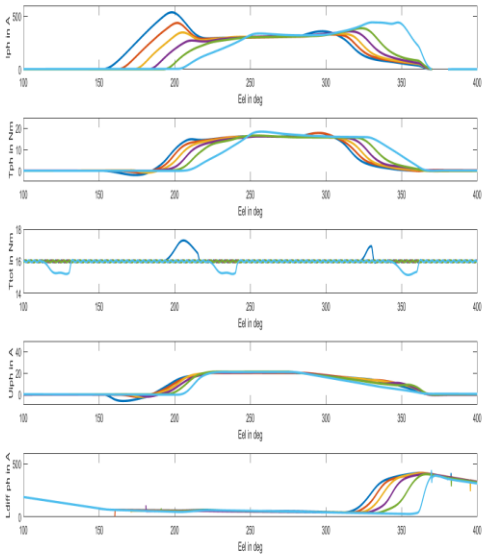

Fig.7 Simulation results for different switch-on angle at a speed of 3000 rpm and a reference torque of 16 Nm.

1) Phase current behavior As seen in figure 10, the phase current has the same dynamic for different switch-on angles. This is because of the approximately same differential inductances at the different switching on regions and low induced voltages referring to equation (2). It also can be observed that the current drop-out shows a kink. This happens because the motor leaves the saturation and consequently the differential inductance increases.

2) Phase and total torques behaviors if the phase current is switched on too early, it results in a current overshoot. The reason is that the phase current is switched on at angles in which the phase generates no or only a small positive phase torque. And because of the control strategy the maximum achievable voltage is applied to the successive switched on phase until the intersection point is achieved. The current overshoot results in a total torque overshoot if the following phase current drop-out is not fast enough at angles with high phase torque generation. The late switch-on leads also to a current overshoot in the switching off process as shown in figure 10. The active phase should be controlled for a relatively long time, even at regions where its torque generation capability decreases. This creates a negative phase torque, because there is not enough time for the current drop-out. If the previous phase and the successive phase cannot generate the reference torque, it results a total torque undershoot.

Results of optimized switch angle Figure 12 shows the phase current, phase and total torque for different speeds at a reference total torque of 16 Nm. The switching angle is calculated based on the described method.

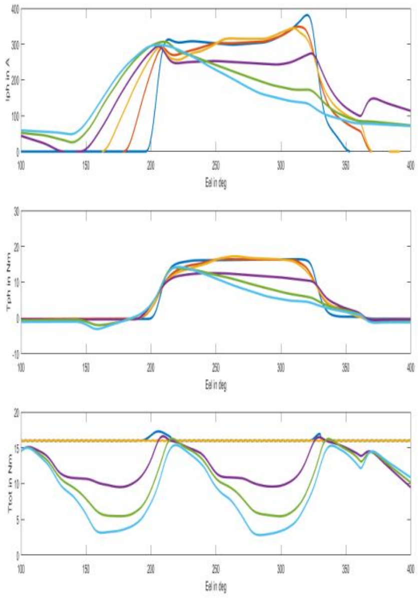

Fig.8 Simulation results for optimized switch-on angle at different speeds and a reference torque of 16 Nm.

1) Switching on behavior It is obvious from figure 12 that at higher speed the phase current should be switched-on early to reach a phase current of 300 A at the commutation angle. The commutation angle emerges from the control strategy and it has a value about 205° for different speeds. At the beginning it is possible to generate a reference torque of 16 Nm, because the phase has always enough current there.

2) Switching off behavior According to figure 10, at low speed in the BSR a compromise has to be found between the current overshoot at switch-on and switch-off region. According to figure 12, the described switch-on angle calculations from the previous part result to a current overshoot in the switch-off region. However, this is beneficial, because according to figure 12 at higher speed the current overshoot disappears in the switch off region, whereas it would be still present in the switch-on region. Figure 12 shows also that at a speed of 7000 rpm and higher, the phase current is not more controlled. It is switched on and off just once in every electrical period. Moreover, it can be observed that it is impossible to keep the phase current constant over 7000 rpm. The consequence is a phase and total torque undershoot. The current characteristics at 7000 rpm can be categorized in SPR and at 9000 rpm and 11000 rpm in CCR. In CCR it is not possible to fully remove the phase current before it is switched-on again, although the phase current is now much lower in the switch-off region. It is because of the fact that the requirement on the change of the current (di/dĬel) does not depend on the speed, but according to the equation (5) by increasing the speed a higher current dynamic (di/dt) is

$$\frac{di}{dt} = 2\pi n \frac{1}{N_R} \frac{di}{d\varepsilon_{el}}$$

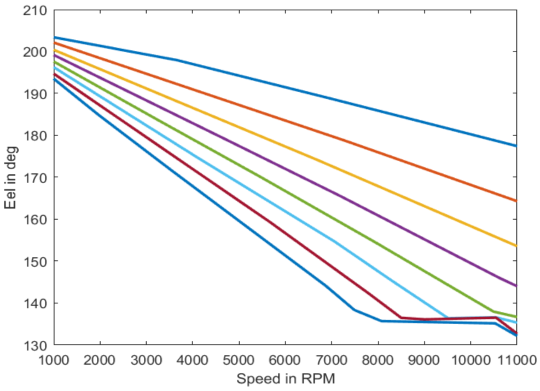

Fig.9 Relation between switch-on angle dependency on speed and reference total torque.

For the speeds in the BSR and SPR the switch-on angle reduces linearly. From the CCR however, there is a kink, so that the switch-on angle remains constant for increasing speed. This can be described as follows. In the CCR the phase current cannot be removed. Moreover, the rest current increases at higher speed, so that the switch-on angle has not be reduced.

VII. TORQUE-SPEED CHARACTERISTICS

With the help of the torque and power diagrams it should be investigated which operating regions can be controlled using the introduced control strategy. Figure 14 shows the average torque against the speed for different reference torques. The regions BSR, SPR and CCR are calculated by simulations. Moreover, the maximum applicable mechanical power P_{mech} is pictured.

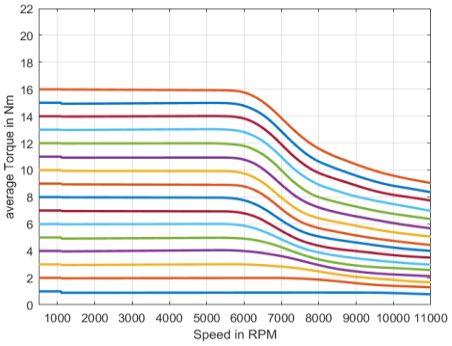

Fig. 10. Torque and power diagram

The voltage limit VI$_{ph}$ = V$_{dc}$,) which is also the boundary between BSR and SPR is achieved with the torque break. The rectangular current waveforms can only be applied in this region. The characteristic of this boundary becomes more vertical for higher torques. This behavior shows a constant induced phase voltage, even in different operating points, where different torques and phase currents are applied. The simulation results have shown that the changing of the magnetic flux Ö over electric angle İ$_{el}$ in saturation stays constant and therefore it results in the same induced phase voltage according to equations

$$\frac{\partial \Psi(\varepsilon_{out})}{\partial \varepsilon_{out}} = i\frac{\partial L(\varepsilon_{out})}{\partial \varepsilon_{out}} = \text{const.}$$

For lower torques in non-saturated regions the torque break occurs at higher speeds. In non-saturated regions this can be described with the following equation:

$$\frac{\partial L(\varepsilon_{out})}{\partial \varepsilon_{out}} = \text{const.}$$

An advantage of the control strategy is that the SRM can be controlled at high speeds in the SPR and CCR, where the block currents cannot be controlled any more. The reason is that the voltage limit (Vi,$_{ph}$ = V$_{dc}$,) is already achieved. However, the operation points can be applied because the average of the phase voltage V$_{ph}$ is still lower than the dc-link voltage. The global voltage limit can be described as: ph cd u u = (8) The control strategy ensures that at the beginning of the switch-on process the reference phase currents and torques can be realized also for higher speeds in the SPR and CCR (figure 12). But in the control region the induced phase voltage becomes even higher than the dc-link voltage. This leads to a decrease of the phase current, phase and total torque. This results into an average total torque, which is lower than the reference torque. Figure 14 shows a linear power increase in the BSR. The power can be kept constant in a range between 9 kW and 10 kW in the SPR and CCR.

VIII. CONCLUSION

An operating point dependent torque splitting is achieved using the developed control strategy, so that the SRM can operate in an extended speed range. A constant total torque generation is achieved in the BSR, where the phase current waveforms are applied depending on the operation point. Moreover, a relatively high average torque can be achieved in SPR and CCR. This can be realized with an operating point dependent determination of the switch-on angle. Hence in the beginning of the switch-on process the reference phase currents and torques are always achieved in higher speeds, too. The calculation of the switch-on angle is carried out predictively and therefore no look up table is needed. In the commutation region the maximum available voltage is applied to the successive phase, so that the phase reaches its maximum torque dynamic for the speed dependent commutation. The switch-off event of the phases occurs in the commutation region at the point when both phases generate the same torque. Therefore it is warranted that at the point when the active phase is changed, the successive phase has an adequate torque generation capability.

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