CHAPTER 1

INTRODUCTION

The recent developments in power electronics converters have made the converters effective tools for machine drives. The converters that are serving as interfacing blocks between the voltage sources and the machines can be designed to have any number of phases, therefore, the number of the phase of the machines are not limited to three any more. This fact has allowed the industries to utilize the advantages of multi-phase machines. Compared to the regular three phase-machines, the multi-phase machines have inherent advantages such as high reliability, lower constructing cost, lower torque pulsations, higher fault tolerance, high torque-to-inertia ratio, higher efficiency, higher power density and power splitting capability.

These advantages have made the multi-phase machine the most attractive option for the applications that need high reliability, such as safety-critical, electric aircraft, electrical and hybrid vehicles, electric ship propulsion and high power generation. The higher reliability of a multi-phase machine is mostly due to the higher number of phases. In the case of the three phase machine, when one phase is lost, the currents of the two remaining phases are not independent, therefore, it is not possible to control them without extra hardware, such as neutral point connection. But in the multi-phase machines, after losing one or more phases, there is still enough number of stator phases to perform independent current control on them and develop a rotating field inside the machine without additional hardware.

In all the applications of the multiphase machines (drive system or energy generations), it is essential to know the exact position of the rotor flux linkage to perform effective drive on them. The exact position and the rotor speed are needed for two goals. The first goal is the fast dynamic torque development. Most of the controllers are based on the field oriented technique, in this technique the exact position of the rotor magnetic flux linkage is essential for the current regulators to be able to regulate the stator currents.

The second goal is to calculate the rotor speed (based on the rotor position) to develop the feedback for the speed controller loop. The goal of the speed controller is to develop dynamic stiffness for the system to be able to follow the desired speed reference and load requirements. The essential speed feedback can be calculated using the position of the rotor that is generated by the position measurement or the position estimation.

The mechanical sensors or Hall Effect sensors can be used for measuring the rotor position. But they increase the price of the drive significantly, which leads to the need for sensorless position estimation methods. In sensorless position estimation methods, the machine itself is used as a position sensor and the position is extracted from the voltages and currents applied to the machine. Using these methods, the precise drive can be implemented without any extra sensor.

The computer simulation is one of the simplest methods to study the electrical machines behavior. The simulations are performed based on the models of the machines. The models project different levels of accuracy in projecting the machine characteristics. For conventional analysis such as: steady state and transient machine characteristics, the classical qd model based on the general theory of the machine can project precise results. This modelling method is based on the following approximations:

- Stator and rotor windings are sinusoidally distributed and their turn functions are equal to the fundamental component of their Fourier series
- Air-gap length varies sinusoidally

- The magnetic flux linkage of the rotor permanent magnets varies sinusoidally with respect to the rotor circumferential angle.

Based on the above approximations, the inductance matrix is only composed of sinusoidal terms and can be transformed into a constant matrix in the synchronous reference frame using Parks transformation. Although this method shows a good accuracy for modelling the machine behavior, but it lacks projecting some higher frequency characteristics of the machine.

In some studies, such as high frequency injections and torque pulsations, an accurate model is needed to project more details of the machine behavior. This model could be generated using fundamental geometry of the machine with limited simplifying assumptions. This model is able to project more details about the interaction between rotor saliency and stator currents. It also can project the higher components of the flux linkage and the electromagnetic torque. Such model is capable of projecting the resulting current components, due to the high frequency voltage injection.

The main objective of this dissertation is to develop a position estimation method that can be used for estimating the rotor position without imposing extra torque pulsations to the machine. The torque pulsations are mostly due to the interaction between the high frequency signals that are injected to the machine stator for position estimation purpose and the rotor of the machine. The high frequency torque pulsations in the regular methods can cause acoustic noise and damages to the mechanical parts of the machine. In this dissertation, to remove the torque pulsations, the high frequency signals are injected in non-torque producing channels of the machine in which they cannot generate any torque pulsations.

To perform simulation for high frequency and low frequency behavior of the machines, using conventional software’s such as MATLAB/Simulink, accurate models are needed to be developed. The in this dissertation the needed models are developed using a well-known method called coupled modeling that was presented in [81].

For the case of multiphase machines, due to the couplings between the different sets of three phase windings, designing the drive can be complicated which results in complicated equations that are not easy to handle and implement. To avoid the complexities of design and implementation, a new reference frame is needed in which the machine equations can shrink to decoupled and simple ones. In this dissertation a new decouple transformation is proposed for triple-star IPM machines (symmetrical and asymmetrical connections). Using the new transformation matrix, the machines models can be transformed to the decoupled reference frame and to remove the coupling terms between the three phase sets. Using the decoupled transformation matrix, the machine controller can be designed and implemented without facing the complexities raised by coupling terms.

1.1 Coupled Modelling

In this dissertation, after a literature review, coupled models of the nine-phase IPM machines are presented in chapter 3. The machines that are modeled in this chapter are:

- Nine-Phase Single-Star IPM Machine.
- Nine-Phase Symmetrical Triple-Star IPM machine.
- Nine-Phase Asymmetrical Triple-Star IPM machine.

The models in chapter 3 are full order models, in which the basic geometry of the machines such as windings, airgap lengths and permanent magnet flux linkages are used to generate the models of the machines. Therefore, the models are accurate enough to predict the high frequency behavior of the machines. The developed models for the machines are also simulated using MATLAB/Simulink and the simulation results are presented in chapter 3.

1.2 Modelling Using Fourier Series

The symmetrical and asymmetrical triple-star machines are modelled using the Fourier series of the machine parameters in chapter 4. In this modelling method, unlike the full order one, the machine parameters are generated from the Fourier series of the turn functions of the stator phases and airgap function. After obtaining the Fourier series of the inductances by neglecting the higher harmonics, they can be used to run the machine model in MATLAB /Simulink. The machine models are simulated and the simulation results are presented. After that the models of the machine are decoupled using proposed decoupling matrixes. The new transformations to the decoupled reference frame are also presented in this chapter. The decoupled models can be used for designing the drive of the machines without facing the complexities raised by the couplings between different machines windings.

In the chapter 4 the average model of a double-star six-phase IPM machine is also presented. Like the nine phase cases, using the Fourier series of the machine parameters, the Fourier series of the stator inductances are generated and after transforming them to the rotor reference frame they are used in the model of the machine. Finally, the machine model is decoupled to remove the coupling terms between the machine windings. The new transformations and decoupling matrixes are presented in this chapter.

1.3 Controller Design for Single-Star Nine-Phase IPM

In chapter 5 a controller is designed for the single-star nine-phase IPM machine. The design starts from modelling the nine-phase converter. After modelling the converter, the machine drive is designed using the main component of the machine circuits. The designed drive uses minimum copper loss strategy in which the reference currents of the machine axis are generated such that the machine supplies the load torque with minimum copper loss.

The current controllers are also designed using the dynamic equations of the stator voltages in the rotor reference frame. To be able to perform an accurate drive, the rotor position is also needed. The rotor position is obtained from the high frequency injection in which a voltage set with low magnitudes and high frequency (compared to the main voltage) are injected in the stator phases. The rotor position is extracted from the high frequency currents that are modulated by the rotor saliency. The high frequency analyses and the signal processing method of the position estimation are presented in this chapter as well.

The position observer is also designed using the mechanical model of the machine. The designed drive and the observer are simulated with the full order model of the machine and the simulation is run for several conditions. Finally, the drive and the observer are discretized and implemented using a DSP-FPGA controller and experimental results are presented.

1.4 Controller Design for Symmetrical Triple-Star Nine-Phase IPM

In chapter 6, a sensorless controller is designed for a symmetrical triple-star nine-phase IPM machine. The chapter starts with modelling the nine-phase converter with three isolated star points. After modeling the converter, the controller is designed for the average model. The complexities of such controller will be shown in the designed drive. Then using the decouple model of the machine a controller is designed based on the minimum copper loss strategy. The converter has six controllers to control the currents of two torque producing channels and four none-torque producing channels.

The essential signal processing method for position estimation is also presented in this chapter. Then the controller and the position estimator are simulated along with the full order model of the machine and the simulation results are presented for several speed profiles. Finally, the controller is discretized and implemented using a DSP-FPGA controller and the experimental results are presented.

The major contributions of this work are:

- The injection of a high frequency voltage signals into non-torque producing circuit of the machine in which the rotor angle can be estimated without generating any extra high frequency torque ripple.
- The requirement of only one low pass filter in the angle estimation.
- The Full order models of the nine-phase machine are developed for different stator connections (single-star, symmetrical triple-star and asymmetrical triple-star). These models can be used for performing accurate, MATLAB/Simulink, simulations. The MATLAB simulations can project an accurate behavior of the machine under different operating conditions, including high frequency injections.
- The decoupled model of the triple-star nine-phase machine and corresponding transformation matrix to the new reference frame (decoupled reference frame) are also presented in this work. The decoupled models which are derived from the average model of the machine can be used for designing the machine controllers without facing the complexities that are raised with the coupling inductances between different sets of the three phase machines.

CHAPTER 2

LITERATURE REVIEW

2.1 Position Estimation

2.1.1Position Sensors

To implement a precise vector control of an IPM machine, the position of the rotor flux linkage of the machine should be accurately known [1]. The first solutions that are presented for this problem are Hall Effect, mechanical sensors, resolvers and encoders. In the first method there are at least three Hall Effect sensors installed in the stator of the machine. The Hall Effect sensor basically operates based on the effect of a magnetic field applied orthogonally to a metal plate, while the metal plate carries a constant current [2].

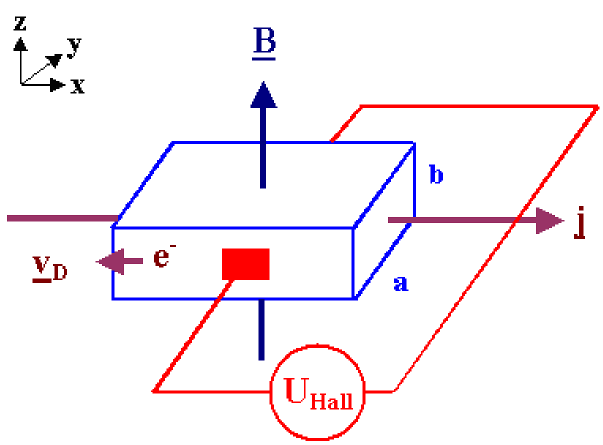

Figure 2.1: The Hall Effect sensor.

According to the Figure 2.1 when the magnetic field (B) is applied to the plate, the perpendicular voltage, over the same metal (U_{Hall}) changes with the variation in strength of the applied magnetic field. The equation (2.1) presents the induced voltage due to the Hall Effect.

$$U_{Hall} = \frac{iB}{q_0 N d} \tag{2.1}$$

Where 'i' is the current (A), 'B' is the applied magnet field (T), 'q_0' is the charge of an electron (1.6×10^{-19} (C)), 'N' is the carrier density (carriers/cm3) and 'd' is the thickness of the conductor (m). The three voltages coming from the three Hall Effect sensors installed in the machine stator can generate a three phase voltage set and the position can be extracted from them [2].

The second type of the position sensors are encoders. In the encoders, the position can be sensed using a certain encoded pattern or track on the rotor and decoded to the position. The encoders can be mechanical, optical or magnetic. In the mechanical method, a brush senses a conductive track placed on the rotor. A drawback with this method is that, the brushes are noisy and wear out.

To avoid the problems of the brushes, it is possible to use light to sense the track. The light can be emitted from a light emitting diode (LED) and pass or be reflected from the rotor track and be sensed by a light diode (LD). Even though this method doesn't suffer from the problems of the brushes, but the dust can cover the LED/LD and affect their performance [2].

Instead of the conductive track, a magnetic track can also be used and the magnetic pulses can be sensed using Hall Effect sensors. These sensors cannot be affected by dust, but external magnetic fields can disturb the position sensing procedure.

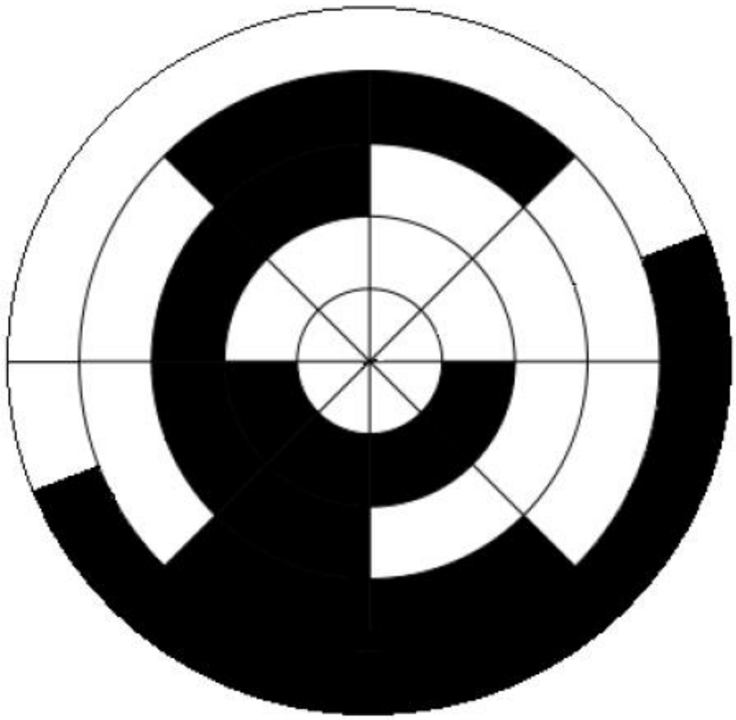

Figure 2.2: The sensor track.

The overall limitation of encoders is their accuracy. The accuracy of these sensors is limited to the number of the bits they have on their track. A typical track is shown in Figure 2.2. The patterns can be seen on the disc and the resolution of that is presented in equation (2.2).

$$\mathrm{Re}\,solution = \frac{360}{2^N} \tag{2.2}$$

Where: 'N' is the number of the bits on the disc.

Resolvers are also widely used as position sensors. The resolver is a durable position transducer, that is designed for harsh operating environments. Basically, is a small electric motor and operates as a rotary transformer. It is composed of a rotating armature and two stationary windings which are placed at right angles to one another [2].

The winding of the rotor is supplied with a high-frequency sinusoidal carrier signal as presented in equation (2.3).

$$V_r = ASin(\omega_c t),\ \omega_c = 2\pi f \tag{2.3}$$

Where 'A' is the magnitude of the high frequency voltage and 'f' is the frequency of the signal applied to the rotor. The typical frequency and voltage are 4(KHz) and 10 (V) respectively. The rotation of the rotor with the speed of 'ω_r' induces the voltages of the equation (2.4) in the stator windings.

$$\begin{aligned} V_a &= \alpha ASin(\theta_r)Sin(\omega_c t) \\ V_b &= \alpha ACos(\theta_r)Sin(\omega_c t) \end{aligned} \tag{2.4}$$

Where: 'α' is the turn ratio between the rotor and stator windings. The angle 'θ_r' can be extracted from the stator voltages using signal processing methods such as phase lock loops.

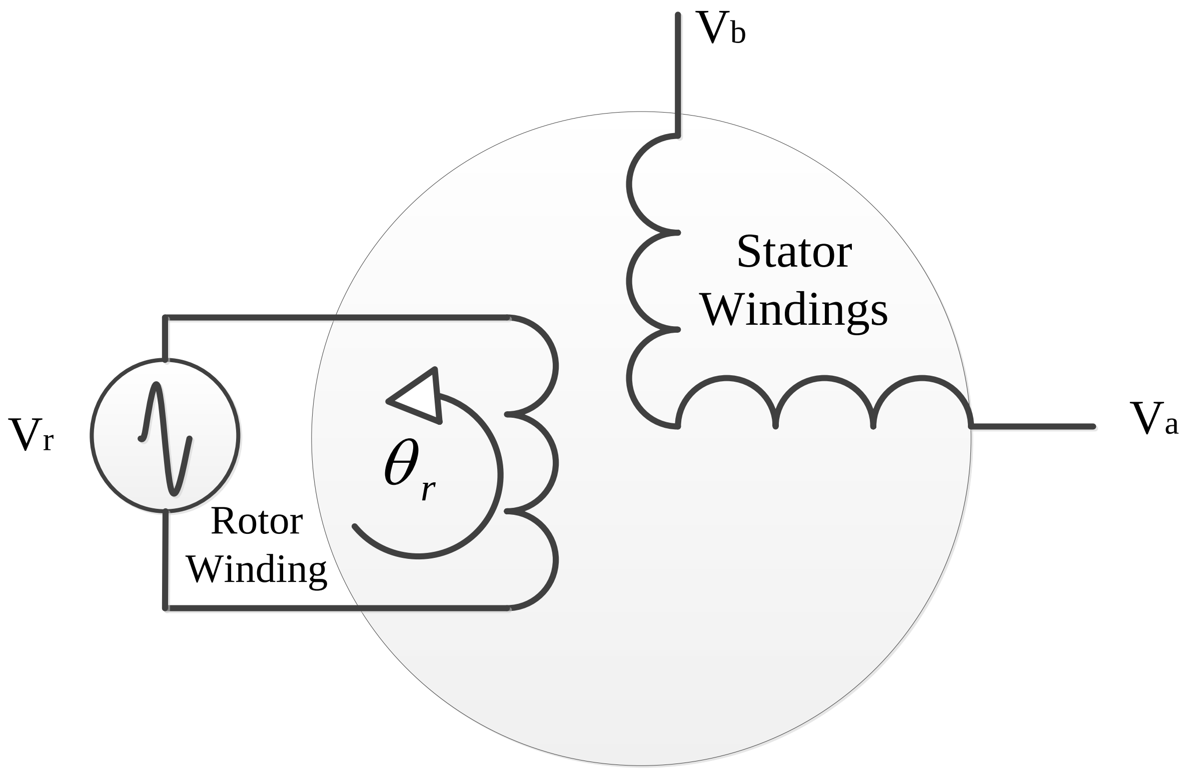

Figure 2.3: The resolver diagram.

2.1.2 Sensorless Position Estimation Using Machine Model

The mechanical sensors and extra components, required for position estimation, increase the price and complexity of the drive, motivating the development of several sensorless methods. The sensorless methods are classified into two major groups.

- Medium and high speed observers
- Zero and low speed observers

The first group of estimators utilizes the back EMF voltages and input currents of the machine to estimate the rotor position and rotor speed. The observers in all these methods are operating on the basic equations of the machine ether in rotor or stationary reference frames. These estimators do not need any extra excitation such as high frequency signal, which is the major feature of these methods that makes them suitable for estimating the machine position and speed without imposing extra loss or torque pulsations due to the high frequency signals [3- 27]. In the back EMF method, the estimator uses the commanded or measured stator voltage and deducts the voltage drop of the stator leakage impedance using the measured input current to get the back EMF voltage in the synchronous reference frame. Finally, a closed loop estimator, estimates the flux linkages of q and d axis of the machine and using a speed adoption, that operates based on the error of the estimated flux and calculated values, (calculated by multiplying the saved values of inductances in the controller and the measured currents) the speed of the machine can be estimated. These methods are highly dependent on the accuracy of the machine parameters. Therefore, these methods are sensitive to inaccurate parameters [3-4]. Due to the saturation, the machine parameters such as, inductances can vary with the operating point of the machine. There are some papers that proposed online parameter estimations to make these methods, robust [4-5]. In these papers, there are different estimators that adapt the machine inductances and their outputs (machine inductances and permanent magnet flux linkage) are used for the main estimator.

Some papers, use the difference between the stator flux and instantaneous load angle of the machine. In this method the position of the stator flux linkage is calculated using the command voltages of the stator in the stationary reference frame and the load angle is calculated using a closed loop estimator that operates on the torque equation. Finally, the rotor position is obtained from the difference of the stator flux linkage position and estimated load angle. In this procedure the exact value of the rotor speed, needed for the estimation, is calculated by a closed-loop state observer [7-12].

Some other presented methods use the induced voltage due to the saliency of the machine on the switching signals of sliding mode control [13-20]. Basically the current ripples due to the PWM signals can be modulated by the saliency of the machine. Therefore, the currents carry some information about the rotor position which can be extracted by signal processing. These methods enjoy the robustness of the sliding control such as non-sensitivity to the measurement noise. These methods also do not need any extra high frequency signal injection and they therefore, do not impose extra copper loss or torque pulsations due to the high frequency signals. In these methods the q and d inductances of the machine in the stationary reference frame are calculated and using their ratio the rotor position is estimated.

Since the mentioned methods use the fundamental signals of machine, they are not useful in low speed ranges of the machine because in the lower speed ranges, the input voltages are small and the signal to noise ratio is poor. Also, these methods need precise parameters of the machine such as, stator resistance, leakage inductance, stator inductance and magnitude of the permanent magnet flux linkage. Any error in the machine parameters can result in error in the output of the position and speed estimators [21]. To solve this problem, the exact values of the machine parameters need to be computed. Several methods have been presented to identify the precise values of the machine parameters. Some of these methods compute the machine parameters at the stand still using measurement signals [22, 23]. In these methods, before running the machine, some signals are injected into the machine and the machine parameters are extracted using the currents and the voltage values. Even though these methods can generate accurate values for the machine parameters at stand still but they can lose their accuracy at the higher speeds, when the magnetic saturation changes the machine inductances. Hence these methods cannot be used for high performance drives. Some investigators [24, 25] use the measurement signals to measure the machine parameters at specified load conditions and use them for the whole range of the operation. Also these methods are not always accurate because the machine parameters will not remain the same when operating conditions change.

The solution for this problem is to estimate the parameters online (during machine operation). In this method, for each operating condition the machine parameters are computed [26, 27]. In reference [26] the outputs of the position and speed estimators are used for the parameter identification. Therefore, the accuracy of the computed parameters is dependent on the accuracy of the position estimator. In reference [27] the stator resistance is identified independently, but the inductances still depend on the output of the position estimator.

2.1.3 Sensorless Position Estimation Using High Frequency Injection

The second group of observers is the set that uses extra high frequency signal (current or voltage) injection to estimate the rotor position. The high frequency currents due to the high frequency voltage injections can be modulated with the machine saliency, therefore they include some components related to the rotor position which can be extracted using filters and heterodyning process. In the case of the high frequency current injection, high frequency sinusoidal currents are injected to machine stator. The induced high frequency voltages, due to the high frequency currents, carry some information about the saliency of the rotor. The induced voltages can be measured from the stator terminal and the position can be extracted from them. These methods enjoy the capability of position and speed observing in zero and low rotor speeds.

2.1.4 Sensorless Position Estimation Using Transient Excitation Based Method

The observers can be classified based on the type of the high frequency signal they use. The first group is transient excitation based method, which uses the derivations of the stator currents due to the PWM signals [28-38]. Generally, applying PWM voltages to the machine stator, results into currents in two components. The fundamental component due to the main component of the voltage and the high frequency component due to the changes of the voltage sets due to the PWM signals. It has been proved that, the derivatives of the high frequency components contain some information about the machine saliency which can be used for position estimation [28]. In this method the general form of the high frequency components due to the PWM signals is investigated and using the current form, the proper signal processing method is presented. The signal processing method relies on phase lock loops or observers to extract the position of the rotor from the signals. This method does not need any extra signal injection therefore, it does not result in extra loss and torque pulsations.

In reference [28-31], the inductances of the machine in q and d axis are calculated from the $\frac{di}{dt}$ of the currents due to the PWM signals and from them the position of the minimum value of the stator inductance is calculated which shows the position of the rotor flux linkage of permanent magnets. This method shows some sensitivity to the changings of the inductances due to the magnetic saturation and cross saturation effects. Authors of [31] present an adaptive method to compensate the saturation effect. This method uses a second estimator to estimate the magnitudes of the inductances in each moment to be used in the position estimation loop. Even though the method projects a good accuracy, it has a complicated observer that makes the method hard to implement and tune.

Some other methods use the induced back EMF of the machine due to the PWM signals [31, 32]. In these papers the back EMF voltage of the machine due to the high frequency components of the stator currents for each phase are extracted and from the phase angle of the back EMF voltages, the rotor position is computed. These methods can also be used for surface mounted permanent magnet (SMPM) machines as well. In the SMPM case, slight saturation of the rotor iron due to the flux linkage of the permanent magnet in one axis can operate as saliency and modulate the high frequency currents. This method also can lose its accuracy by changes of the machine parameters.

The next method is called INFORM (Indirect Flux Detection by Online Reactance Measurement). In this method, the currents produced by the space phasor voltages can be used to estimate the position. The currents can be measured from one, two or all machine phases [33-35]. In [35] the currents due to the space phasor voltages are calculated from the DC link current. In this method the high frequency currents are extracted by removing the stator offset current. The offset currents are basically the fundamental components of the phase currents generated by the fundamental frequency of the PWM signals. This method is suitable for low and medium performance machines. It is claimed that the best feature of this method is the capability to estimate the position of the rotor by measuring the DC link current. By measuring the DC link current, the method can be implemented with just one current sensor and it enjoys the simpler filtering process to extract the high frequency signals. Even though in most applications the three phase currents are needed for the controller feedback which means that measuring the DC link current requires one more extra current sensor to implement the controller.

2.1.5 Sensorless Position Estimation Using Rotational Voltage High Frequency Injection

The next method is the rotational voltage high frequency injection. In this method a proper high frequency voltage is injected to the machine stator windings to let the resulting currents to be modulated with the machine saliency. Using some methods such as, the magnitude peak tracking [36], PLL [37] or Luenberger observe, the rotor position can be extracted. This method is applicable for a wide range of the rotor speed including zero. The drawback of this method is the need of an extra voltage injection, which increases the machine loss and torque pulsations. This method enjoys the non-sensitivity to the machine parameters and rotor speed which results in capability to perform the estimation in the zero and low rotor velocity where the back EMF voltage is low. The first studies have been done in [38-41]. The papers [38, 39] use a three phase high frequency sinusoidal voltage injection to extract the rotor flux position of induction machine. This method relies on the small saliency in the induction machine caused by the magnetic saturation due to the rotor flux linkage to modulate the high frequency current. The saliency results in a high frequency component with the angle equal to the second harmonic of the machine saliency which can be extracted to estimate the rotor position.

The same method is applied to a permanent magnet machine with inherent rotor saliency as reported in [40]. This method relies on the sinusoidal profile of the changing inductances in the stationary reference frame which introduces some complexity in rotor position estimation. The complexity is mostly caused by the coupling terms between the q and d axis equations. In this method, the q and d axis inductances of the stationary reference frame are estimated using the high frequency currents and using their magnitudes, the profile of the stator inductance is obtained. Using the obtained inductance profile, the rotor position can be extracted. This method also can lose its accuracy by changes of the inductances magnitude by magnetic saturations. Also cross saturation can cause some inaccuracies in the results of the position estimation.

To decrease the complexity [41] uses the same procedure in the rotor reference frame. Since in the rotor reference frame the d and q axis voltages are decoupled, the number of the functions needed to be used for rotor position estimation decrease which results in a simpler estimation process and implementation.

Beside torque pulsations, the high frequency signal injection can cause another problem by saturating and decreasing the differential inductances of the stator in rotor reference frame [42, 43]. Decrease in the q or d axis inductances can result in lower signal to noise ratio and consequently signal loss. Also the method suffers from the effect of the cross-saturation which can cause errors in the output of the position estimator [44, 45]. The error caused by the cross-saturation is not constant and it depends on the motor operation point, therefore this error is not easy to compensate [46]. Many strategies have been presented in the references [47-55] to compensate the cross-saturation error. In these references, the parasitic saturation is measured to provide accurate information about the position of the cross-saturation. Then by using decoupling method the effect of the cross-saturation is compensated.

Authors of [53] use a nonlinear adaptive decoupling scheme based on a structured neural network to compensate the effects of the cross-saturation. Moreover, the effect of the rotor geometry on the position estimation has been studied in paper [51] using Finite Element Method Magnetics (FEMM). The geometry of the rotor includes the different angles, width, heights and position of the permanent magnets inside the rotor iron. Based on the effect of the rotor geometry and saturation in position estimation, papers [54, 55] have presented some proper machine design methods to decrease the cross saturation effect. In these papers it suggested that by changing the saliency shape to curved channels and bury the magnets with the same shapes into the channels, the cross saturation effect can be decreased. But since the design is not optimum from the torque producing point of view, these methods have the drawback of decreasing the maximum possible torque of the machine by going far from the optimal torque generation design.

2.1.6 Sensorless Position Estimation Using Hybrid Methods

As it was mentioned before, the high frequency signal injection produces an extra loss and torque pulsations, while the methods based on the induced back EMF voltage which is not applicable in the low rotor velocities do not impose extra loss and torque pulsations. Therefore, it is possible to combine the two methods for the whole range of the rotor speed. While the machine is at the stand still or low rotor speed, the drive can use the high frequency injection method. After the machine reaches the higher speeds the controller can stop high frequency injection and use the position estimation which uses induced back EMF. Many studies have been done on hybrid method [57-58].

Reference [58] uses an adaptive full order observer combined with the high frequency injection method. In this method the high frequency observer uses a modified method which decreases the steady state estimation error and also the stable regions of the observer gains are presented. In this method, the controller uses the high frequency injection at the low rotor speeds and at the higher speeds the controller switches to the back EMF method. Since the back EMF and high frequency rotor position estimation methods do not generate exactly the same outputs, switching from one rotor position estimation scheme to the other one introduces transients that can cause rotor vibrations for a short time.

Instead of switching between the modes there is a smooth transient from the high frequency injection to the back EMF reported in [59-60]. During the transient from low to high speeds, there are two variable weighting coefficients for the outputs of the estimators that enable the final estimated position to be a combination of the two observes output. By increasing the speed, the weighting coefficient of the position, estimated by high frequency injection, decreases and the weighting coefficient of the position, estimated by the back EMF, increases finally at high speeds, the high frequency injection will be disabled and its coefficient goes to zero.

The high frequency injection can also be combined with an adaptive reduced order observer as presented in [61]. In the low speed range, the position is estimated using high frequency signal injection and the method simply changes to the adaptive observer at a specified speed which can cause some oscillations in the rotor speed. The oscillations are due to the fact that the adaptive observer cannot generate a zero error in an open loop operation. It simply means that when the controller is operating on the estimated position from the high frequency injection, the adaptive observer is open loop which implies that, there will be errors in the output of this observer. At the moment the controller starts operating based on the adaptive observer output, the observer switches to the closed loop scheme and the error goes to zero after a while. The required time for the observer reach the zero error can cause oscillations in rotor speed. To solve this problem both of the observers, high frequency signal injection and adaptive outputs have to be used together in at least a narrow speed range to enable smoother transients between the observers.

Some recent references use a hybrid method in which the error of the back EMF estimator passes through a high pass filter and the error of the high frequency injection passes through a low pass filter. Therefore, in low rotor speeds, when the rotor position error has a low frequency, the error from high frequency injection passes through the filter and the position of the rotor is estimated using the high frequency signal injection method. At the higher rotor speeds, when the error has high frequency, the error from back EMF can pass through the filter and the position is calculated using the back EMF method [62, 63].

Other reported hybrid methods use the adaptive observer with the high frequency signal injection with some weighting factors. In this method there are weighting factors for each of the high frequency injection output and adaptive estimator output. The final position used for the drive is the sum of the outputs of the two methods. At low speeds, the weighting coefficient of the adaptive is zero and at higher speeds, the weighting factor of the high frequency injection goes to zero. At medium speeds both of the coefficients have non-zero values which means a smooth transition from high frequency injection to the adaptive observer [64, 65].

Reference [66] uses the same method as [64] with an extra coefficient for adaptive estimator which remains non-zero in all the machine operation speeds. By this technique the adaptive observer stays operative in all the speed ranges including low rotor speeds and improves the performance of the drive. In this method since the adaptive observer is in operation during all the speed ranges, it has a very low error when the controller switches to the adaptive observer. Therefore, the transients of switching between the two methods are negligible.

The authors of papers [68-71] present a new adaptive flux observer to be implemented in the rotor reference frame to estimate the rotor speed and position along with the high frequency injection that is integrated with the adaptive observer at low and zero speeds [72]. The adaptive observer is using the output of the position observer to estimate the flux linkages of the machine. The estimation error is zero when the d axis flux linkage is aligned with the rotor flux linkage. Therefore, the observer uses two different errors to observe the machine flux linkages. One is based on the error signal from the high frequency signal injection. The other is from the current estimation error to compensate the effect of the stator resistance and stator inductances variation. The torque and flux linkage are then regulated via direct torque and flux control (DTFC) and indirect space vector modulation (ISVM).

2.2 Stability of the Observers

While designing the sensorless controller, the stability of the observer needs to be guaranteed. There are many studies on the stability of the observers and the possible sources of their instability. If the transient speed between back EMF and high frequency injection methods is not correctly selected, switching between the signal injection and the back EMF method can make the observer unstable. Authors of [67], [73] show the design rules for selecting the transient region. They also recommend the proper parameter selection for the observers based on the root Locus method. In these papers the roots of the characteristic polynomials of the both methods are determined with respect to the rotor speed and observer parameters. Then, based on them the switching rotor speed is selected at a proper speed, where both of the observers are stable. Based on the same method they suggest the proper values for the observer gains to guarantee the stability of them in their operating regions. Even though, the papers present an effective method to guarantee the stability of the observers, but they use many simplifying assumptions and linearized equations to determine the stability which introduces some inaccuracy in the results.

The Lyapunov theory is used in [74-75] to investigate the stability of the position and speed observer. In these papers the observer is using the machine model to observe the flux linkages and it adopts the rotor speed and position using two different methods. The adaptation methods are sliding-mode and fuzzy-logic adaptation mechanisms. The sliding mode adaptation mechanism is derived based on the Lyapunov theory to guarantee the stability of the observer. In this method the rotor speed error is used to generate a sliding surface. The sliding surface is used to generate the Lyapunov function. Checking the sign of the derivation of the Lyapunov function can guarantee the limited error between the estimated and the reference speed which basically means the observer is stable.

Authors of [72] also use Lyapunov theory to investigate the stability of the observer that is operating on the induced back EMF of the machine. In this paper the Lyapunov function is defined based on the errors of the q and d axis currents and the rotor speed. Finally, by checking the Lyapunov function, the stability of the observer is investigated.

The authors of the paper [76] use the root Locus method to investigate the stability of the observer that is based on the high frequency injection. In this paper the small signal model of the observer is derived based on the dynamic equations of the machine and based on that the stability of the observer is investigated for different operation regions. Similarly, [77] uses linearization method to present the transfer functions of the observer output with respect to the rotor speed. By plotting the bode diagrams of the observer transfer functions, the stability of them are investigated and also their robustness against the high frequency disturbances, such as EMI noise made by PWM signals are guaranteed by selecting a proper bandwidth for the transfer functions.

2.3 Machine Modelling

As it was mentioned before, due to the attractive features of the multiphase machines such as high fault tolerance, power segmentation, low torque pulsations and lower cost of insulation, these machines are becoming one of the most preferred types of machines in the industry for high power applications [83]. They are widely used in applications such as, high power generators, ultra-high speed elevators and drives [88]. Therefore, many studies have been done on the modelling of these machines to generate accurate models to study the behavior of them [81-104]. The regular models of the machines use the fundamental component which does not consider some of the details of the machine behavior. To have a precise model the machine needs to be modeled with limited simplifying assumptions motivating some methods that consider the basic geometry of the machine [83, 84].

2.3.1 Machine Modelling Using Winding Function Theory

The Winding Function Theory (WFTh) was first presented of [78]. Unlike the conventional d-q model, this theory can consider all of the winding magneto motive force (mmf) space harmonics in modelling of small air-gap machines. Based on the Winding Function Theory, the authors in [79] presented a coupled circuit model of the squirrel cage induction machine (IM) with no restrictions as to the space distribution of the stator windings and rotor bars, considering all of the winding mmf harmonics. After that, the WFTh has been widely used in the modelling and analysis of faulty IM windings, such as short circuits, open connections in the stator windings, as well as broken rotor bars and cracked end rings [80-82].

In reference [84] the investigators started with the winding function of the machine, then using Fourier series, the fundamental part of that is extracted. Finally using the fundamental components of the winding function, the stator inductances are calculated and using them and the fundamental part of the permanent magnet flux linkage the machine is modeled. In this method, the higher order components of the winding function and permanent magnet flux linkage are neglected. Therefore, the model generates a pure DC electromagnetic torque.

To include the torque due to the higher components of the winding function the same procedure can be applied to the higher components of the winding functions [86, 87]. In [87] the third, fifth and seventh components of the winding function and permanent magnet flux linkage are also considered and the corresponding inductances are generated. Then the torque due to them are generated and added to the torque due to the main component.

The magnet materials and also the influence of the stator windings on the machine performance are investigated and reported in [87]. Three models are presented in [89]. The first model has a concentrated permanent magnet with distributed windings, the second one has concentrated winding with open slot and the third one has concentrated non overlapping winding with semi-closed slots. In this paper the effect of the stator slot shape is considered in the modeling.

Papers [90-91] use a modified winding function theory to model the windings of the stator and rotor. This modified method presents a more precise winding distribution with eccentricity between the stator and rotor. The modified winding function basically considers the saliency or non-symmetries of the machine rotor while generating the inductances and turn functions of the machine. Therefore, this paper takes into account more details about the air gap function and presents more accurate results for machine inductances. The developed model can be used for the simulation of the machine to obtain the frequency spectrum of the stator current in salient pole machines.

The papers [92] to [96] use the winding function of the machine for modeling. Reference [92] presents phase-dominated model of synchronous machine. In this model, the exact distribution of the windings and rotor shape are considered. Also the magnetic saturation, due to the machine operation, is considered which also includes the cross saturation. Moreover, reference [94] presents and extends the theory of the non-uniform air gap. The effect of the saliency is considered in this paper; therefore, the stator inductances are related to the rotor position. This extended air gap theory also can be used to obtain a modified winding function that reflects the effect of the non-uniform air gap presented in [95]. The reference [96] uses the same procedure and presents a numerical solution for calculating the stator inductances based on the winding functions of the stator phases. In this paper the rotor saliency is modeled using a permeance function. The permieance function, with respect to the rotor angle, is obtained using a numerical method that is based on finite-element analysis.

The authors of the [97] use the winding function theory to model a brushless DC motor (BLDC). In this paper the full order model of a BLDC motor is generated and its characteristics are analyzed for different drive strategies and short winding fault.

An accurate procedure is used to allow precise computation of the inductances of the multiphase machine as a function of the rotor position in [98-100]. In this method the inductances are functions of the rotor position and they are generated by solving three magneto static models. Each of the three models is generated based on the suitable simplification of the actual machine cross-sectional geometry. This method can be used for some limited kinds of the machines which have the same number of the saliency as the number of poles.

2.3.2 Machine Modelling Using Winding Function Theory Including Armature Reaction Model

A direct method for modelling the machine is used in [101-102]. This method uses the armature reaction analysis to model the machine. The proposed model is derived based on the winding function theory and the rotor magnetic field is used to model the pole-cap effect (the effect of the embedded magnet in the rotor). The proposed model can be used to predict the armature reaction field under different types of stator MMF, such as the different orientation of the excitation current as well as various MMF wavelengths. This method also does not have simplifying assumption for air gap and winding functions. The method is almost accurate, but it is limited to some ranges of the machine operation modes.

Laplacian-Poisson equation is used in papers [103]- [109] to get the armature reaction field distribution. The authors of [103] use an analytical solution for the prediction of the armature reaction of the magnetic field in stator slots. This method can be used to analyze slotted surface mounted permanent magnet radial flux synchronous machines in both cases of internal and external rotor radial-field machines. The expression of the magnetic is developed for the both slots regions and magnetic air gap region, which can generate accurate calculation results for the effect of slotting on the air gap magnetic field.

A new model for armature reaction magnetic field of IPM machine is presented in [104]. This model considers pole-cap effect. In this model the stator windings are modeled using their basic geometry without any simplifying assumptions while the rotor magnetic motive force is derived from the pole-cap effect. Using this model, the armature reaction can be predicted under different machine operation modes.

Some analytical solutions of armature reaction of the magnetic motive force of slotless brushless machine with surface and internal magnets are presented in [105]. This paper assumes that, the rotor and stator iron have infinite permeability and the analytical solutions for the windings, air gap and magnet regions have been obtained. In [106-108] an analytical method to model a very high speed slotless permanent magnet motor is presented. This model can also be used for optimal design of these types of machines. This model includes the magnetic fields, the mechanical stress of the rotor and the different losses, including the electromagnetic and windage power loss. The friction function for the bearings is also modelled in [107].

An analytical finite-element is used in [108-109] to model the machine. These papers, use the model to study the behavior of the machine under the third harmonic and zero sequence current injections. In these papers the finite element method is used to show the effect of the third and zero sequence current injection on the behavior of the flux linkage of the machine which is too complicated to be measured. This method can represent almost the actual behavior of the machine, but it is not still suitable for dynamic simulation using conventional software's such as MATLAB/Simulink.

Laplacian/quasi–Poissonian field equations are used in [110-114] to model the permanent magnet field of the machine. Authors in [110] use the Laplacian/quasi–Poissonian field equations in polar coordinates in the air gap to model the waveform of the magnetic field for each instant. This wave form model is added to the machine model generated by means of an analytical method based on machine geometry and materials. Using this method one can avoid the long finite element analysis (FEA) calculations while some effects like cogging torque, machine torque ripples and back-EMF can still be predicted.

The authors of [111] also use the same method as [110] in a general form. In this method the field wave form is generated using two-dimensional models in polar coordinates by solving the governing Laplacian field equations for the airgap and quasi-Poissonian field equations for magnet regions without any assumption regarding the relative recoil permeability of the magnets. Then the wave form is added to the model that is generated from the machine geometry. This general model can be used for both internal and surface mounted permanent magnet machines with the slotted or slotless stators.

The authors of [112] present a general analytical model to compute the magnetic field distribution in surface mounted permanent magnet motors. The model can be used for any machine with any pole/slot combinations including fractional slot machines with distributed and concentrated windings. This model also considers the armature reaction magnetic field and the mutual inductance between the slots. In this paper also the Laplace's and Poisson's equations are used for analytical analysis. The authors in [113] use the same method to model a surface permanent magnet machine. In this paper, the armature reaction is generated using Maxwell’s equation. In paper [114], the effect of the armature reaction on the slots and the airgap is expanded to the three phase windings of the stator. In this paper an analytical method is presented for calculating the open-circuit magnetic field distribution of a brushless DC machine and its effect on the airgap flux linkage, stator slots and the stator windings.

In reference [115], the armature reaction of magnetic field in slotted surface mounted permanent magnet radial flux synchronous machines is predicted using an analytical solution. This method is suitable for the case of internal and external rotor radial-field machines. The magnetic field expressions are developed in both slots regions and magnetic airgap region leading to an exact calculation of the effects of slotting on the airgap magnetic quantities. The self and mutual inductances are also generated using the same method resulting in precise model.

2.4 Multiple-Star Machines

By increasing the application of the multiphase machines in the industry, a new configuration of the multi-phase machine has been emerging during the last decades. The new configuration is called multiple-star machine which is basically a multiphase machine with two or three isolated star points and insulated sets of three phase windings. The multiple star machines offer a good compromise between the complexity and benefits of the multi-phase machines. Moreover, the multiple-star machines have higher reliability compared to the single-star machines. The higher reliability is due to the electrical insulation between the different sets of three phase windings [116-117].

The earliest work on the application of the double star machine was presented in [118]. The authors in this paper are proposing the use of a double-star generator to decrease the current rating of the circuit breakers. In this paper, since the output power of the generator is divided between two sets of the three-phase windings, the maximum current rating of the circuit breakers is divided by two. Even though the new topology needs six circuit breakers, but it still offers more transient stability (in faulty conditions) compared to the conventional three phase generator. For the same reason the double-star machines were used to limit the current ratings of the switches of the converters [119, 120]. Another attractive application for the double-star machine that is presented in [121-122], is the ability to supply DC and AC loads simultaneously. In some applications, such as aircrafts and ships there are both DC and AC loads to be supplied by the generator. In conventional three phase generators, when both DC and AC loads are supplied by the same stator windings, the harmonic currents derived by the rectifier can affect the voltage wave forms of the generator and consequently affect the AC loads. To remedy this problem, extra filters are needed to be installed to remove the harmonic contents of the rectifier. By using the double-star machine, the DC and AC loads can be connected to the different winding sets without significant effect on each other.

The next step in the development of the multiple-star machines was asymmetrical connection. In this new connection the spatial phase shift between two sets of three-phase machine is 30 electrical degrees instead of 60 degrees [121-123]. [122] proves that the torque characteristic of a multiphase machine, with asymmetrical connection, is noticeably better than symmetrical one. Also, the authors of this paper proved that, by supplying the two three-phase sets displaced by 30 degrees with two sets of three-phase inverters instead of one set of sex-phase inverter, the pulsating torque component have smaller magnitude and higher frequencies.

One of the most attractive applications of the multiple-star machines is full power converter for offshore wind turbine applications [124]. Due to some limitations of the offshore turbines, such as limitations in footprint, higher maintenance cost and weight of the offshore structures, they need to be designed highly reliable, light and efficient. Instead of the doubly fed generators with two sets of the converters operating on their rotor and stator, a full power converter that operates on the stator can offer a higher reliability and lower maintenance. Similar to the doubly fed generator, the full power converter does not need a gearbox, which makes it more cost efficient and removes some of the mechanical maintenance.

Authors of papers [125-126] used the full power converter to control triple-star nine-phase machines in the wind power application. Authors of [125] use three sets of the three phase converters to control a triple-star nine-phase permanent magnet synchronous generator. The goal of the paper is to increase the reliability of the generator by insulating the converters. In [126] triple-star nine-phase machine is connected through three isolated AC/DC converter to a DC grid. The AC/DC converters are boost type and, due to the insulation between the machine sets, they can operate independently.

The authors of the [127] use a triple-star nine phase machine connected to a three phase grid through an AC/DC/AC converter. The machine side converter is composed of three sets of three phase inverters that are operating on different sets of three phase windings. All the inverters share a single DC link and the generated power is sent to the grid using a three phase converter. By using the tripl-star machine, the machine side insulation transformers can be removed, which significantly decreases the overall cost of the system.

2.5 Control of the Multi-Star Machines

The multiple-star machines have been successfully used in the different application such as ultra-high speed elevators, tractions, propulsion, wind turbine and high power turbo compressors [128-133]. To improve the performance of the multiple-star machines a good controller is essential. The control design for the multi-star machines is complicated due to the magnetic coupling between the different sets of the three phase machines and unbalanced currents and harmonics in machine windings [134-137]. Therefore, new modelling methods have been presented to remove the complexity of these machines controller.

Various controllers have been presented to improve the performance of these machines. The first controller is using multiple d-q models. In this method each set of the three phase machines is modelled separately in the rotor reference frame, then for each machine, there is an independent controller that operates on it [139-140]. In this method there are some couplings between the dynamic equations of the machine sets. The couplings can bring many complexities in drive design [141].

To remove the complexities of the controller design, many strategies have been presented in the literature. The first method is called vector space decomposition (VSD) method [134, 142]. In this method the voltages of the machine are decomposed to three sequences in the stationary reference frame, then the controllers are designed for each sequence separately. This method separates the electromechanical and nanoelectromechanical energy conversion variables of the machine into two-dimensional reference frame. Therefore, each of the sequences has two orthogonal reference frames that are decoupled from each other and can be controlled separately. Due to the decoupling between the reference frames the machine model and the controller are simplified. This method has a drawback of having imbalance currents in the machine phases. The imbalance currents are coming from the error of the currents in the non-torque producing axis. In the ideal case the non-torque producing axis should have zero current to let the machine phases get balanced currents. In reality, when the controller has some errors or noises in these axis, then the resulting current causes imbalance phase currents.

The DTC (Direct Torque Control) is another method used for removing the complexities of the designing drive for multi-star machines. In this method (presented in [143-144]) the hysteric control is used to regulate the machine currents without dealing with the complexities of the couplings in the model of the machine. In this method, the current regulators are not designed based on the machine model. Therefore, the design procedure does not deal with the complexities due the coupling terms. This method also enjoys the robustness of the hysteric control method.

This method has the drawback of harmonic distortions (low and high frequency) which is the basic drawback of the hysteric control strategy.

One effective method to overcome the complexities of the couplings in the machine model is to use the diagonalized model of the machine for designing the controller [144]. In this modelling method the machine model is transformed to a new reference frame in which the couplings between the different sets do not exist. After transforming the machine model to the new reference frame the model which is decoupled can be used for designing the drive. However, this is an effective method to remove the complexities of the machine drive, it suffers from having a more complicated transformation matrix. The objective of model diagonalization is to convert the square matrix of the machine inductances into a diagonal matrix that has the same fundamental properties of the original one. In this new matrix, the non-diagonal terms are absorbed by the diagonal terms. The diagonal terms of the matrix are simply the eigenvalues of the original matrix. Also the eigenvectors of the matrix generate a new set of axis corresponding to the eigenvalues and the new transformation matrix is generated by the eigenvectors [145].

The authors of [146-147] also use the diagonalization method to remove the non-diagonal terms of the inductance matrix of the machine stator. The machine that is studied in this paper is a six-phase double star induction machine with arbitrary displacement between three phase winding sets. In this paper a general model of the double-star machine with arbitrary phase shift between three phase winding sets is generated and the general transformation matrix is also proposed to get the diagonalized inductance matrix. The model is derived in the stationary reference frame and three sets of two-dimensional decoupled sequences are obtained.

The authors of papers [148-149] are also using the same method to derive the decoupled qd model for a double-star six phase PM machine. In these papers the rotor based harmonics are also considered in the modelling. The harmonics of the magnetic flux linkage of the rotor are generated and transformed to the decoupled reference frame. Therefore, the model considers more details of the machine structure and the result is more general in terms of the rotor flux linkage. These papers do not consider the saliency effect of the rotor, therefore, their method cannot be used for the PM machines with embedded magnets.

The authors of [150] used the same procedure to study the mutual leakage inductances of the six-phase induction machine with 30-degrees phase shift between the sets. In this paper, the inductance matrix is transformed to the stationary reference frame and by decoupling them, the leakage inductances are derived in the stationary reference frame. In this paper, it is shown that the harmonic currents of the multiphase machine are highly dependent on the coil pitch of the machine. The paper also investigates the effect of the slot shape on the machine harmonics and suggests proper coil pitch and special slot shape design to reduce the harmonic currents in the stator of the machine.

The Authors of [151] present a generalized lumped parameter qd model for a n phase synchronous machine, in this model considering the rotor saliency, there are several axis for all harmonic of the stator circuit. The model is generated for a wound rotor high power synchronous machine and the control strategy is based on the independent control of harmonics in the synchronous reference frame. The model provides a tool to inject the average command voltage for each harmonic. Therefor the harmonics can be controlled independently using the injected voltages.