CHAPTER 10

CONCLUSIONS and FUTURE WORKS

10.1 Conclusions

This thesis deals with various aspects of the single five-phase and two five-phase motors series-connected drive systems, fed using a single current-controlled pulse width modulated voltage source inverter. Modelling and control of a five-phase induction machine is reviewed first. It can be seen from the developed model that only two stator current components are responsible for torque and rotor flux production while other components are non flux/torque producing. These additional degrees of freedom are further utilized to connect in series the other machine in such a way that the flux/torque producing current components of one machine become non flux/torque producing currents for the other machine and vice versa. This is enabled by an appropriate phase transposition of the phases of the stator windings. The vector control then enables independent flux and torque control of each machine in two-motor drive system, as well as an independent control of two machines with respect to each other.

The potential application area for this drive configuration has been identified, where it may offer considerable saving in the installed inverter power when compared to the standard solution with two three-phase motors and two three-phase VSIs. The area includes processes where the two motors are required to operate in the constant power mode, with opposing requirements on rotational speeds and torques. Such a situation arises in winders. In winder applications one machine typically operates at low speed (low voltage) with high torque (high current) while the other machine operates at high speed (high voltage) with low torque (low current). Thus the situation may be such that the total stator copper losses remain less than or equal to the rated value, hence avoiding the need for de-rating of the machines. The total losses compared to the conventional three-phase two-motor drive, would still be higher. However, the rating of the five-phase VSI may be kept approximately equal to the rating of just one three-phase VSI, thus enabling saving in the installed power.

A complete mathematical model of the five-phase voltage source inverter has been reviewed. The model is developed on the basis of space vector representation and the results obtained are verified using the available literature on modelling of five-phase inverters.
Current control schemes for three-phase inverters are reviewed and speed and current controllers are designed for the single five-phase motor drive. The current control is exercised upon the phase currents of the drive. Performance of a vector controlled single five-phase induction motor drive, obtainable with hysteresis current control and ramp-comparison control methods, is evaluated and illustrated for a number of operating conditions on the basis of simulation results. Full decoupling of rotor flux control and torque control was realised by both current control techniques under the condition of a sufficient voltage reserve. Dynamics, achievable with a five-phase vector controlled induction machine, are identical to those obtainable with a three-phase induction machine. Steady state analysis of stator voltages and currents under no-load conditions is performed as well.

A novel mathematical model for two-motor five-phase series-connected drive is reviewed. The model is at first constructed in phase variable form. Clark's transformation in power invariant form is then applied to develop a set of decoupled equations. Application of appropriate rotational transformations leads to corresponding models in stationary and arbitrary reference frames. Vector control scheme is explained next for the two-motor drive system. The simulation is done for various transients using a single current-controlled PWM voltage source inverter with hysteresis current control in stationary reference frame. Simulations were performed using novel d-q model in stationary reference frame, in order to validate the modelling procedure. A completely independent control of two machines is observed from the simulation results.

The major shortcoming of the five-phase two-motor drive system is the increase in the stator winding losses due to flow of flux/torque producing current of both machines through stator windings of both machines. As x-y components of current do not flow in the rotor the rotor copper losses are not affected. The higher losses mean lower efficiency of individual machines and will lead to reduction of efficiency of the overall drive system, compared to an equivalent three-phase drive system. This drawback is significant in the five-phase two-motor drive system since both machines are affected. This shortcoming of the five-phase two-motor drive prevents its application in general-purpose drives.

Sensorless vector control of five-phase induction motor and two five-phase induction motors is further investigated. Information about speed is required by the vector controller due to its dependence on co-ordinate transformation. Speed estimator is necessary for speed mode of operation. Criteria for selection of speed estimator are also independent of the operation of the vector controller.
Various rotor speeds and slip frequency estimators are obtained by considering the voltage equations of the five-phase induction machine. The schemes explained in the thesis use the monitored stator voltages and currents or the monitored stator currents and reconstructed stator voltages. In general, the accuracy of open-loop estimators depends greatly on the accuracy of the machine parameters used. At low rotor speed, the accuracy of the open-loop estimator is reduced, and in particular, parameter deviations from their actual values have great influence on the steady-state and transient performance of the drive system which uses an open-loop estimator. Furthermore, high accuracy is achieved if the stator the stator flux is obtained by a scheme which avoids the use of pure integrators.

The MRAS based speed estimation is also investigated in the thesis. The model reference approach makes use of two independent machine models of different structure to estimate the same state variable on the basis of different sets of inputs variables. The estimator that does not involve the quantity to be estimated (here, the rotor speed) is considered as a reference model. The other estimator, which involves the estimated quantity, is regarded as an adjustable (adaptive) model. The error between the outputs of the two estimators is used to drive a suitable adaptive mechanism that generates the estimated rotor speed for the adjustable model. When the estimated rotor speed in the adjustable model attains the correct value, the difference between the output of the reference model and the output of the adjustable model becomes zero. The estimated rotor speed is then equal to the actual rotor speed, under ideal conditions. The most frequently used scheme has rotor flux space vectors at the output of the reference and the adjustable model. However, other solutions are possible as well. Four rotor speed observers using the Model Reference Adaptive System have been described in the thesis. The outputs of the two models may be rotor flux space vectors, back e.m.f., reactive power and artificial intelligence assisted. The appropriate adaptation mechanism can be derived by using Popov’s criterion of hyperstability. This results in a stable and quick response system, where the differences between the state-variables of the reference model and adaptive model are manipulated into a speed tuning signal, which is then an input into a PI-type of controller, which outputs the estimated rotor speed. Artificial Intelligence assisted MRAS speed estimators do not contain any mathematical adaptive model, and the adaptation mechanism is incorporated into the tuning of the appropriate artificial Intelligence based network (which can be a neural network, a fuzzy-neural network, a wavelet network, etc.).

The attainable performance are examined by simulation and compared. It is shown that the dynamic behaviour, obtainable with the indirect vector control, is the same as it
would have been had a three-phase machine been used. Rotor flux and torque control are fully
decoupled, enabling the fastest possible accelerations and decelerations with the given torque
limit. The comparison of results for different MRAC schemes shows that the performance
obtained with ANN assisted MRAC technique are much better than other schemes.

The artificial intelligence based speed estimation has been explained in the thesis. It is
possible to perform the simulations and also implementations of estimators, controller, etc. (in
real time) by using artificial-intelligence (AI)-based techniques e.g. artificial intelligence
networks (ANN), fuzzy-logic systems, fuzzy-neural networks, neural-wavelet networks, etc.,
which do not require a mathematical model of the machine and drives system. Such a system
is not restricted by the many assumptions used in conventional electrical machine and linear
control theories. It can also yield the results more quickly than by using the conventional
approach.

The artificial neural networks (ANN) can be used for different types of artificial-
intelligence-based speed and position estimators. It is believed that this type of approach will
find increasing application in the future. This is mainly due to the fact that the development
time of such an estimator is short and the estimator can be made robust to parameter
variations and noise. Furthermore, in contrast to all conventional schemes, it can avoid the
direct use of a speed-dependent mathematical model of the machine. The ANN schemes
presented is a part of a Model Reference Adaptive System (MRAS). In this system, the ANN
takes the role of the adaptive model.

The conventional schemes require the use of a mathematical model for the adaptive
model. However, greater accuracy and robustness can be achieved if this mathematical model
is not used at all and instead, an artificial-intelligence-based non-linear adaptive model is
employed. It is then also possible to eliminate the need for the separate PI controller, since
this can be, integrated into the tuning mechanism of the appropriate artificial-intelligence
based model.

The thesis also describes the speed estimator performance under fault conditions. The
induction motor parameters are affected by variations in the temperature and the saturations
levels of the machine. Incorrect settings of parameters of the motor are instrumented in the
controller. The estimators will show poor performance in terms of steady-state error and
transient oscillations of rotor flux and torque. As a result, parameter sensitivity has been
treated as a secondary matter in a vector controlled induction motor drives system. The
tracking capability of an estimator is one of the important factors. The performance of
an estimator is evaluated in terms of convergence of the estimated rotor speed to the actual

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rotor speed. An estimator is said to have good tracking capability if the estimated value can track the actual value at high and even at close to zero speed. Using the same parameters in the induction motor and of the speed estimator, the tracking performance of the estimator can be examined by changing the motor parameters. The thesis describes the speed estimator performance under parameter \((R_s, R_r, L_s, L_r, \text{and} J)\) variation and fault (single phasing) condition.

Various types of speed observers are explained in the thesis, which can be used in high-performance induction machine drives. These include a full-order (fourth-order) adaptive state observer (Luenberger observer) which is constructed by using the equations of the induction machine in the stationary reference frame by adding an error compensator. In the full-order adaptive state observer the rotor speed is considered as a parameter, but in the EKF and ELO the rotor speed is considered as a state variable. It is shown that when the appropriate observers are used in high-performance speed sensorless torque controlled induction motor drive (vector controlled drives, direct controlled drives), stable operation can be obtained over a wide speed range, including very low speeds. This chapter presents a detailed study of a full order Luenberger observer and extended Kalman filter based sensorless control of a five-phase induction motor drive and then comparison between the performances of an adaptive flux observer and those of an extended Kalman filter-based algorithm, used to estimate the rotor flux components, and so the rotor speed. Simulation results have shown the superior performances of Kalman filter with respect to adaptive observer.

Sensorless operation of a vector controlled three-phase induction machine drive is broadly discussed in the literature, but the same is not correct for multi-phase induction machine. Only few application of sensorless operation of multi-phase machine is presented in the literature. The difficulties associated with the position sensor in ‘more-electric’ aircraft fuel pump fault tolerant drive is highlighted in literature.

Although several schemes are available for sensorless operation of a vector controlled drive, but the simplest is the open-loop scheme because of ease of their realization. An attempt is made in the thesis to extend the different sensorless techniques of a three-phase machines and five-phase machines to series-connected two-motor five-phase drive system.

The analysis is here limited to Open-Loop, MRAS, ELO and EKF-based sensorless control of a series-connected two-motor five-phase drive system, with current control in the stationary reference frame. Phase currents are controlled using hysteresis current control.
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A simulation test is performed for speed mode of operation, for a number of operating conditions, and the results are presented in this chapter of the thesis.

The thesis is also devoted to the experimental proof of dynamic control of five-phase induction machine, supplied from five-phase VSI and controlled using indirect rotor flux oriented control scheme. The chapter at first describes the experimental rig. This is followed by detailed presentation of experimental results. The variable frequency supply for five-phase machine drive is obtained from five-phase inverter, which is configured as a five-phase current controlled VSI. The first stage of experimental testing is related to five-phase induction motor drive configuration. The five-phase induction machine is tested first for the Volt per Hertz (V/f) open-loop and then closed loop control. Finally, dynamic performance of a sensorless controlled five-phase induction machine under indirect vector control condition is investigated. The transients investigated are acceleration, deceleration, reversing and loading/unloading for all type of control. The dynamic performances of three-phase induction motor are also investigated for the purpose of comparison with five-phase motor performance.

By comparing the work described in this thesis with the research objectives listed in section 1.5 it can be concluded that all the set goals have been achieved successfully.

10.2 Future works

This thesis explores the feasibility of independent control of five-phase and five-phase two-motor drive systems, fed from a single five-phase current regulated PWM voltage source inverter in sensorless mode. Since both drive structures are novel, it is believed that there is plenty of scope for further research. Some possible directions are the following:

- Investigation of the feasibility of using parallel connection of multi-phase machines, with supply coming again from one VSI.
- An evaluation of the overall efficiency of the multi-motor drive systems for specific applications.
- Investigation into fault tolerant properties of single and five-phase two-motor drive systems.
- Experimental verification of sensorless control of multi-phase multi-motor system.
- The analysis can be performed for torque controlled multi-phase motor systems.

In the thesis, the problem of pure integration, related to DC drift and initial value, has been ignored, although pure integrators have been used in stator flux estimator and speed estimator. Further work with alternatives for pure integrators being used in flux and speed estimators should be done in the future. Alternative stator flux estimators, which are less
sensitive to accuracy of the measured voltage and current, and variation of stator resistance, should be utilised in the direct torque controller for future research. Compensation for detuning of stator flux and torque estimation due to the variation of stator resistance with temperature should also be researched. Novel modifications for the classical switching table to provide high quality of flux response at low speed and torque response at high speed should also be designed.

In the future, it is expected that computational power and memory will get still cheaper leading to realization of more powerful control techniques. It will be possible to make a totally automatic control system which will derive a mathematical model of the plant by providing some test signals at the input, or obviate the need for a plant model by using an intelligent control technique like ANNs. It will be possible to identify the required parameters, decide on the control strategy and self-commission the drive. For induction motor drives, it will be possible to have an accurate estimate of the speed without using a speed sensor. Motion control will also have to deal with nonlinear systems, and this would require further maturity of base technologies like nonlinear adaptive control theory, fuzzy logic and ANNs.

One may find many references in the literature regarding the study of the speed sensorless estimation techniques. However most of the study performed by the previous researchers only focuses on a particular type of control structure such as direct field oriented control. Therefore, a various structure of induction motor drive controls should be taken into consideration when working with speed sensorless estimation such that the results are robust for all type of controls.

The ANN techniques presented in this thesis can be implemented experimentally in future and the results can be compared with the theoretical simulation results. Some more ANN based MRAS least square schemes can be investigated. The number of inputs and number of layers of ANNs selected for speed estimation can be further increased. This would of course increase the complexity of adaptation mechanism. The study must utilize standard/common criteria for comparison to obtain justified results. Adaptation mechanism tuning constitutes parts of the problem related to estimator implementation. Its level of difficulty varies with estimators and requires a lot of time to determine the appropriate values for the gains. Therefore, a study on the tuning of the adaptation mechanism using different type of controller such as PID, Fuzzy and Fuzzy-PI etc can be carried out in conjunction with the above suggestion. This effort will help to solve the difficulty in tuning the adaptation mechanism for MRAS based speed sensorless estimation.