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Design Optimization Control of Scalar Controlled Drives a Review

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***Abstract* – This paper presents a review of the developments in the field of efficiency optimization of scalar controlled drives through optimal control and design techniques. Optimal control covers both the broad approaches namely, loss model control (LMC) and search control (SC). Optimal design covers the design modifications of materials and construction in order to optimize efficiency of the motor.**

***Keywords* – Loss Model Control, Search Control Optimal Control**.

I. Introduction

Induction motor is a high efficiency electrical machine when working closed to its rated torque and speed. However, at light loads, no balance in between copper and iron losses, results considerable reduction in the efficiency. The part load efficiency and power factor can be improved by making the motor excitation adjustment in accordance with load and speed. To implement the above goal, the induction motor should either be fed through an inverter or redesigned with optimization algorithms.

The optimization of induction motor design with AI and NIA has received considerable attention recently. The design optimization of a three-phase induction motor can be formulated as a general non-linear programming and the standard non-linear programming (NLP) techniques can be used to solve it. But this techniques are computationally very expensive and inefficiency whereas NIA is competent tool to solve NLP. Extensive work has also been done on inverter-fed induction motor design in order to realize torque ripples and harmonic currents. Some of the design optimization results are available in [1]-[23].

In optimal control, there are two main approaches to improve the induction motor efficiency at light loads, namely loss model controller (LMC) [24]-[65], search controller (SC) [66]-[80] for minimum power input. References [81] – [83] described both LMC and SC, [84] – [89] described other controls of IM efficiency optimization and [90] – [95] described soft starting to improve motor performance. LMC determines the optimal air gap flux through the motor loss model. In case of SC, it measures the input power of the drive and searches for optimum flux or excitation current.

This paper describes the various types of optimization techniques including soft computing to induction motor efficiency optimization in section II, Optimum design of induction motor is given in section III, the review of loss model controller and search controller applied to IM efficiency optimization are given in section IV and V respectively and this paper concludes in section VI.

II. Optimization Techniques

Optimum design of induction motor is a non-linear multi dimension problem whereas optimal control is a single or two dimension problems. Therefore the role of optimization techniques is more important in design than control of IM to get global optimum.

A. Conventional Optimization Techniques

Statistical method [1], Monto Corlo [2], Sequential Unconstraint Minimization Technique (SUMT) [11], [12], modified Hook Jeeves [3], Han Powel method [4], modified Han Powel method [5] are the few methods which applied successfully in IM design in the past.

B. AI Based Optimization Techniques

There are many types of AI controllers applied to IM optimization through control as well as design and are available in the literature [35], [36], [63], [77] – [80]. Some controllers use Fuzzy [653], [77]-[80], ANN [35], [36]. Fast convergence can be achieved by these controllers.

C. NIA Based Optimization Techniques

Nature Inspired Algorithms (NIA) are relatively a newer addition to class of population based stochastic search techniques based on the self organising collective processes in nature and human artefacts. Some popular NIA are Genetic Algorithms (GA)[61], [62], [18].

Particle Swarm Optimization (PSO) [48]-[51], [23], Evolutionary Algorithm [98], Simulated Annealing (SA) [19], [22], and Evolution Strategy [21], etc. NIA seem promising because of their social – cooperative approach and because of their ability to adapt themselves in the continuously changing environment.

III. Design Optimization of Induction Motor

A. Conventional Algorithms

In Ref [6], Hook Jeeves search method used to find optimal design sheet of IM. Efficiency, efficiency-cost and cost are considered as objective functions. Authors analyzed the effects of supply voltage variation in the motor performance and concluded that higher efficiency can be obtained by increasing the voltage. Service condition has been considered in [7] before taking the design optimization of IM. From the author's conclusion of above paper, the pump load systems, the following modifications are helped to consume minimum energy,

(i) Stator core length increase up to 130%,

(ii) Number of stator winding turns decrease up to10%.

Hydraulic pump in aerospace applications have been considered in [8] for design optimization. Supply frequency, environment, inrush current are considered as constraints in addition with normal constraints. Two level optimization carried out in [9], one was material cost and other was operating cost. A global optimization approach has been introduced in [10]. Here error is taken as objective function (for efficiency maximization, calculate efficiency in each step and find error (100-efficiency)). If error is more, large step size was used for adjusting variables.

Sequential unconstraint minimization technique (SUMT) was successfully applied to optimize IM in [11], [12]. Torque pulsation has been considered in [11] as an additional constraint for a inverter fed IM design. Authors suggested that the flux and higher order harmonic currents are as low as possible to have least pulsation. Reactance should be maintained at least 4 times greater than normal machine. Stack length and stator and rotor current densities to be decreased. Also to have a least pulsation, select stator core depth greater, rotor slot depth deeper and larger stator bore dia.

In Ref [13], constraint Rosenbrock method (Hill Algorithm) used to optimize the motor. Material cost has considered as an objective function and concluded that higher value of current densities required for getting optimum value. Six to four pole machines are to be selected for adjustable speed applications even 3600 rpm speed required, suggested in [14].

Sequential quadratic programming (SQP) for non-linear constraint optimization technique was successfully implemented to IM design in [15]. In this paper, authors have included practical considerations to reduce the computation time. The following are the practical considerations [15],

Effects of different starting vectors

Here the starting values of variables are taking their lower limit, upper limit and intermediate values. Then the analysis was carried out in the objective function value iteration by iteration. The values of the variables available in the literature have also considered for analysis. Out of four combination of variables, the upper limit value of variation offered poor results at starting but good results at final iteration.

Effect of different step size

Authors have observed that the step size for increasing variable values is too small (less than 10^{-3}) or too big (greater than 0.1) deteriorates the result in 30 kW IM and recommended to set the value 0.005 as step size to get good results.

Effect of constraints

There was no distinct difference between different sets of constraints considered, said the authors.

Effect of changing objective function

Authors considered various types of objection function like efficiency, power factor, torque and observed that efficiency slightly affected when torque was considered as an objective function.

Change of variables and performance parameters with iteration:

Authors set the entire variables to upper limits and analyzed the performance related parameters with iteration. From the observation, efficiency and power factor were almost same from second iteration onwards.

Stator copper losses and core losses including harmonic losses are reduced by optimal selection of stator slot design in [16]. Authors used finite element method (FEM) to design the same and reduced core and winding losses by 2.22%. IM efficiency has been improved in [17] by modifying production technological process and is called as no tooling cost (NTC). It does not require a complete redesign of laminations. Authors modified the following in a totally enclosed fan cooled standard IM, (i) the rotor with copper bar included in the slot before the aluminium die cast of the cage, (ii) increase of the core axial length, (iii) Annealing of the stator core. Authors finally concluded that the production cost for higher efficiency motors in considerably reduced by NTC.

IV. Optimal Control of Induction Motor Through Loss Model

Optimum control of IM is essential one because it is not possible to optimize the motor efficiency for every operating point by optimizing machine design. In many applications of constant speed operation, induction motor operate under partial load for prolong periods, such as spinning drive in textile industry [24], mine hoist load, drill presses and wood saw. In these applications, induction motor should operate at reduced flux causes a balance in between iron losses and copper losses results efficiency improvement. A simplest method to improve efficiency of induction motor operates at light load is to keep the motor connection in star results reduced power consumption. When the motor run in star mode, the voltage applied to stator phase winding is reduced by the factor 3 . Since the torque developed in the motor is directly proportional to square of the voltage, the developed torque in star mode is also reduced by the factor

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3. Therefore, the motor can be operated in star mode up to 0.33 p.u loads.

In this case the developed torque of the motor should be measured and find sufficient to drive the control system and also measure the temperature to be normal. Even though this method is not suitable for wide range of partial loads still it is working with many textile industries in India. Here no switching losses due to the absence of power electronic controllers.

The role of loss model controller is to measure the speed and stator current and determines optimal air gap flux through the loss model of the motor. The inner part of the control algorithm may be in scalar [25] - [45] or vector [46] – [65]. In scalar control technique, variables are controlled in magnitude only whereas in vector control, variables are controlled in magnitude and phase. The complex induction motor can be modeled as DC motor by performing simple transformation in the vector control scheme.

One advantage of loss model controller is that no delay in calculation of optimal flux and drive performances but time delay occurs in case of search control due to the search.

Artificial intelligence controllers like ANN, fuzzy, PSO, GA can also be used for finding optimal flux level with minimum time. The exact values of machine parameters including their variations due to core losses and main inductance flux saturation are required in this approach. Fig. 1 [24] shows the different part of losses in the induction motor. Many researchers have been reported several strategies using different variables to minimize losses in IM. Some algorithms use slip speed [24], [29], [30], rotor flux [54], [55], excitation current [52], voltage [31]. The general block diagram of energy optimal control using PSO and fuzzy logic is shown in Fig. 2. Here fuzzy logic is used to maintain good stability of the drive during flux change at optimal control.

A. Scalar Controlled Drives

The behavior of an ac induction motor drive is described by three independent variables- the speed, the terminal voltage, the terminal frequency- and the parameters of the motor and its power supply [25]. At any operating point characterized by the speed and torque, an optimal flux (in other words, ratio of voltage and frequency) can be found that meets the requirement of the operating point and minimizes the overall losses. Losses of the IM are represented by resistances in the equivalent circuit shown in Fig. 3 [26]. The stray load losses are represented by the equivalent resistance r_{str} in the stator side. As in Fig. 3, the power losses in the resistances depends on stator current and should be measured it to calculate optimal air gap flux as well as to avoid over current flow in the motor [27].

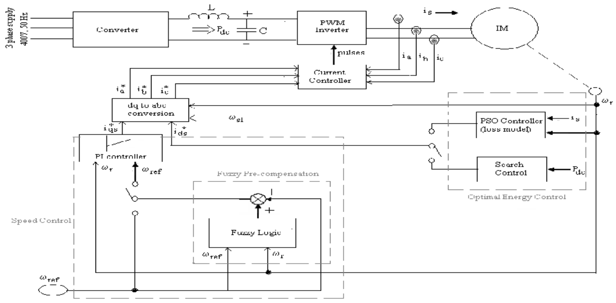


Fig.2. Block diagram of optimal energy and speed control using PSO and fuzzy logic

B. Conventional Controllers

In Ref. [27], a loss model controller with detailed analysis for minimizing the losses in scalar controlled induction motor is presented and suggested that the air gap flux is always kept greater than 0.3 pu independently on LMC command. This is because of very low flux creates more motor currents and disturb torque and finally losses will be more. Authors of the above paper concluded that rated flux operation essential during transient (starting) to maintain good dynamics. The detailed study on efficiency optimization of scalar controlled IM is available in [28].

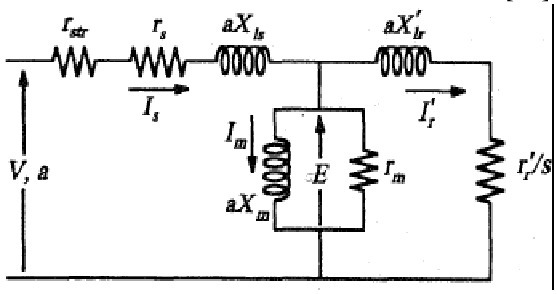


Fig.3. Per unit induction motor equivalent circuit

The procedure described in [29] is based on optimal slip control of current source inverter fed induction motor. First, the optimal slip is searched by trial and error with the help of loss model and the results are tabulated microprocessor memory. Then the motor is operated at optimal efficiency by simply tracking the optimal slip given in the table. The span of the optimal slip with respect to torque is high in case of lower speed rated motors and is shown in Fig. 4[29]. Optimization was carried out successfully at centrifugal pump drives and is available in [30].

The variables, input voltage and frequency are considered to optimize the motor efficiency in [31]. Authors achieved 10-15% of efficiency improvement in a 2 hp induction motor at 0.4 pu load. Core saturation, source harmonics and skin effects are included in their research.

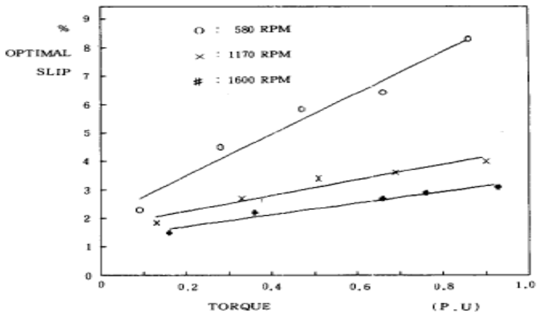
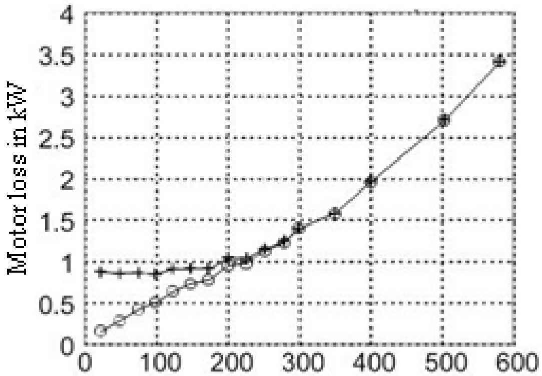
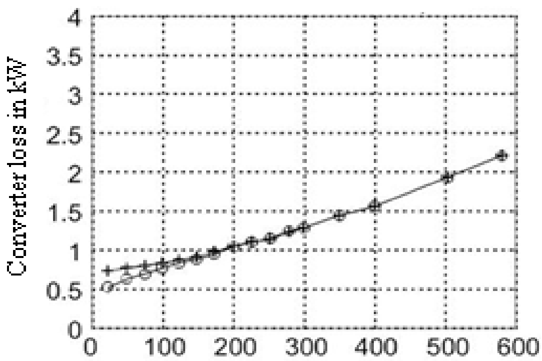


Fig.4. Optimal slip versus torque at various speed

It should be noted that the flux level can be adjusted to get maximum efficiency without considering inverter losses in small drives less than 10 kW; but the effect of inverter losses in medium size (10-1000 kW) drives is significant [32]. Authors concluded from the experiments that no critical issues in the drive operation when the converter losses are neglected but the robustness will decrease when disturbance occurs. As an example, Fig. 5 [32] shows the converter, drive and motor losses versus load torque in 90 kW drive and demonstrates that a reduction in converter losses by flux reduction at very low speed. More studies on efficiency optimization of scalar controlled IM was carried out in [33]-[43].





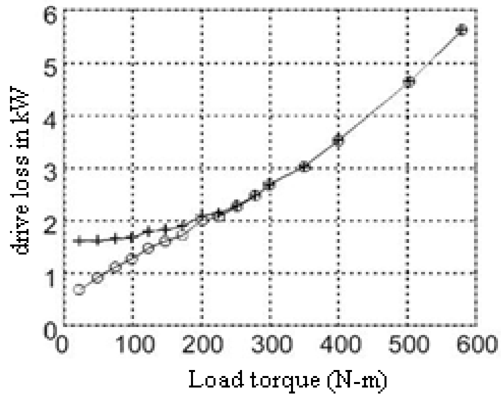


Fig.5. Converter, drive and motor losses in 90 kW motor at 900 rpm speed.

V. Optimal Control of Induction Motor Through Search Control

Search control (SC) does not require the knowledge of the motor loss model for implementing optimization controllers. This controller measures the input power of the machine drive regularly at fixed interval and searches optimal flux value which results in minimum power input or stator current for the given values of speed and torque. Torque ripple always presents in SC due to the oscillations in the air gap flux.

IM efficiency optimization through search control was successfully carried out in [65]-[79]. The advantages of SC control in induction motor efficiency optimization are as follows [71],

- If the power input is measured on the source side of the rectifier, the minimization is not restricted to the motors but affects the entire system and thus reduces the total amount of energy consumed.
- Since the source voltage and current waveforms have a much smaller harmonic content than the corresponding motor waveforms, the power measurement is more accurate and easier to obtain Insensitive to parameter variation in the motor due to thermal and core saturation effects

In Ref [72], authors described the problems arised when the input power is considered instead of stator current as the controlled variable to optimize the efficiency of IM. When stator current used as variable, its minimum can be more easily detected than the input power. Stator current leads more loss reduction and less torque ripple due to the absence of oscillation in the air gap flux. Fig. 9 [73] shows the loss minimization process in the 1 hp drive when both the controlled variables are considered and it revealed that power input to the drive is smaller in stator current minimization than the power input minimization.

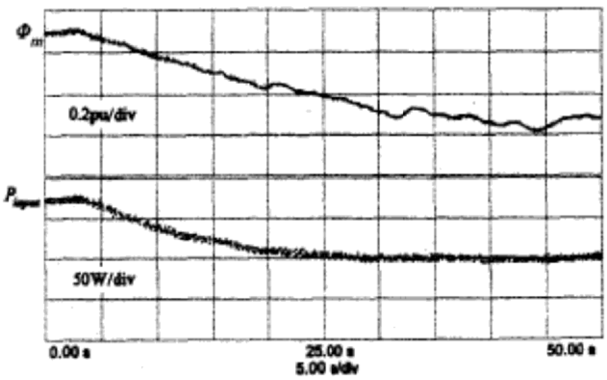
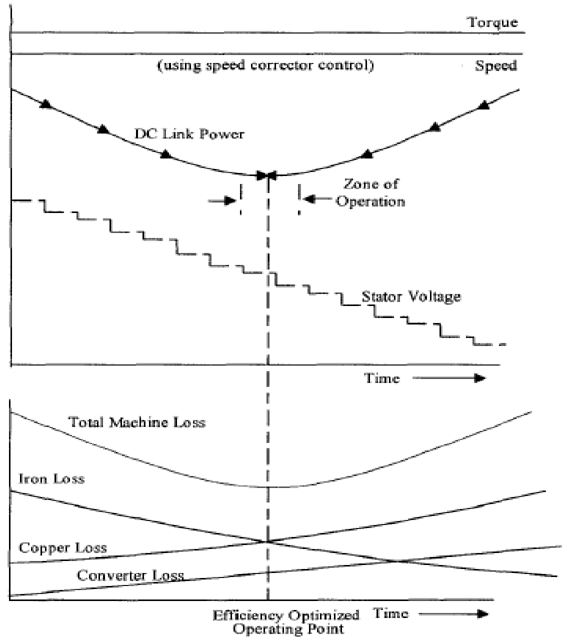


Fig.9. Loss minimization on process in the 1-hp drive when the controlled variable IS (a) the input power and (b) the stator current

Minimum power input to the drive is achieved by adjusting inverter input frequency in [73]. Authors have shown a significant efficiency improvement than v/f control and concluded that large energy saving potentials available in pump and fan drives. In Ref [74], voltage adjustment was carried out according to losses for minimum power input and the second controller changed the frequency to correct rotor speed losses caused by voltage drops. The third controller produced an initial commanded frequency which compensates the variation in slip with changing load and speed. Fig. 10 [74] shows the voltage perturbation optimization control.



A. Both LMC and Search Control

In Ref [81]-[83], both LMC and SC are used to analyze induction motor efficiency optimization. The developed controller in [81] ensures to retain good features of both the LMC and SC, while eliminating their major drawbacks. Authors used input power in order to identify on-line the loss function parameters and optimize flux value. Therefore slow convergence (drawback of SC) and parameter variation (drawback of LMC) were eliminated. Hybridization of LMC and search control was performed in [82] and achieved good results with rough knowledge of parameters.

LMC compared with SC in [83] and concluded that the LMC is more appropriate in FOC because optimal flux can be imposed in a short time where as search control vary the flux continuously which produce more oscillation in the torque.

VI. Conclusion

Efficiency optimization is very much essential not only to electrical systems, it require all the systems to get beneficial in terms of money and also reduction in global warming. This paper presented a review of the developments in the field of efficiency optimization of three-phase induction motor through optimal control and design techniques. Optimal control covered both the broad approaches namely, loss model control and search control. Optimal design covers the design modifications of materials and construction in order to optimize efficiency of the motor.. Experimental and simulation examples on efficiency optimization were illustrated.

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