A Comprehensive Review of Loss Minimization Techniques of Induction Motor

Miss. Renuka Rameshvar Pardhi[1], **Prof. Kalpesh M. Mahajan**[2]
[2]Assistant Professor, Dept of Electrcal
[1, 2] K.C.E. Society's College of Engineering and Management, Jalgaon1(MH) India

Abstract- *This research examines and compares the various methods for reducing induction motor power loss. It distinguishes a subset of loss minimization approaches. Convergence rates, parameter dependence, and convergence errors varies amongst techniques. Offline techniques are discussed, as well as real-time techniques. Model-based, physics-based, and hybrid real-time loss minimization strategies are the three types. It is discussed the sensitivity of real-time loss minimization approaches to motor settings. Strategies can be chosen based on application-specific needs, and hybrid loss reduction techniques balance partial parameter independence and quick convergence for the greatest overall performance.*

Keywords- Induction Motor Losses, Loss minimization, real time loss minimization.

I. INTRODUCTION

Concerns about the environment, rising energy demand, and limited resources have pushed electrical engineers to increase efficiency in all parts of their work. Motors consume more than half of all electrical energy produced worldwide, mostly induction motors [1], [2], which account for over 60% of the industrial electrical load [3]. Induction machine power loss mitigation has been studied for over 30 years. There are potential for development given the wide range of applications and heavy use. An electric ship's induction-motor propulsion system, for example, accounts for 70%–90% of the electrical load [4], [5]. Any small increase in efficiency would result in enormous global energy savings.

Existing loss minimization techniques (LMTs) are divided into three categories and are chosen based on the application or drive type. The drive determines the accessible optimization variables, while the application is linked to the desired convergence speed, parameter sensitivity, and convergence error. [6] discussed the LMT classifications. Offline and online (or real-time) types are broadly defined. By redesigning the motor or establishing its operating point based on specified values, offline procedures often produce minimal power losses.

There are two subcategories of offline techniques: 1) factory-set methods that set a "optimal" motor drive command set based on expected operating conditions; and 2) structural methods using electromagnetic studies. Offline approaches can't modify losses while the motor is running. Feedback and information regarding motor parameters are used in real-time procedures to alter motor orders and minimise losses in operation. The flux, voltage, current, torque, and speed must all be controlled in these LMTs. Model-based online techniques rely on motor parameters and power-loss models; physics-based online techniques rely on feedback and search for the lowest-loss operating point; and hybrid online techniques rely on both motor parameters and feedback. Fig. 1 shows a typical inductionmotor drive operated with a control-based real-time LMT.Fig. 2 summarizes these categories.

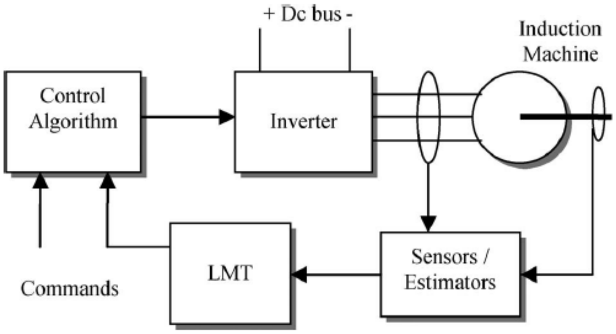


Figure 1: Induction motor under loss minimization technique

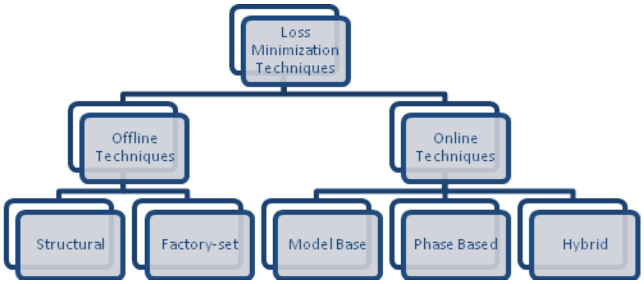


Figure 2: Loss minimization approach classification Reference

[7] splits these approaches into "methods based on [an] induction motor loss model" and "methods based on [the]

least [power loss] search controllers." These are similar to model- and physics-based LMTs, but [7] does not take into account search-based approaches that require parameter information. LMTs are defined as "basic state control," such as power factor control, "model-based control," and "search control," according to [8].

LMTs are compared in this evaluation based on their speed of convergence to the optimum, their reliance on motor parameters, and their accuracy. LMTs are methods that minimise input power given a defined output power.

II. OFFLINE LOSS MINIMIZATION TECHNIQUES

Analyses of power loss are required to ensure that an LMT is accurate. The waveforms of currents and voltages, as well as the motor construction, are frequently used in these evaluations. The switching patterns that govern power electronics have an impact on motor losses. The majority of published material links switching patterns to motor structure in order to accomplish two goals: 1) power loss analysis and estimate, and 2) loss minimization utilising structural LMTs.
[11] uses multi slice finite element analysis (FEA) to investigate power losses in an induction motor with square-wave and sinusoidal pulse width modulation (SPWM) inputs. The switching technique is linked to copper and eddy-current losses in [11].In [12], space-vector pulse width modulation and discontinuous pulse width modulation are used in a similar way. In [13], the fundamental and harmonic losses under SPWM are analysed using motor geometry. The results are contrasted to experimental measurements that identified harmonic losses as rotor and stator but not copper, eddy-current, or hysteresis losses. As in [13], the work provided in [14] and [15] uses FEA and extends it to harmonic analysis.

Experiments on motor and drive efficiency can be carried out without the need for FEA's costly simulations. In [16], a constant volts-per-hertz (V/f) drive was used to regulate an induction motor at three distinct switching frequencies, with input and output power measurements. This method calculates the combined motor and drive efficiency, however it is unable to precisely identify losses. Another experimental solution is provided in [17], which uses SPWM to vary the line frequency up to 60 Hz. The voltage and current waveforms of the stator, as well as the torque and speed, were all measured.The power and efficiency of the input and output were calculated. On a 1-hp induction motor, the results suggest that a 35–40-Hz input was best for a 5.1-N • m load torque. Structural offline LMTs are another method for analysing and reducing power losses. [18] and [19] are two examples.

Fei et al. employ two methods to find the best motor configuration for minimising losses in [18]. The first uses the Han–Powell approach, whereas the second uses a boundary search along active constraints. [18] contains descriptions as well as results. Another method used in [19] is to vary a number of geometric parameters, like as stator and rotor diameters, and estimate losses in each geometry to find the best design.

[20] compares multiple analysis approaches, including the boundary element method, the Schwarz–Christoffel method, and FEA, in a recent study on motor design.

III. MODEL BASED LOSS MINIMIZATION TECHNIQUES

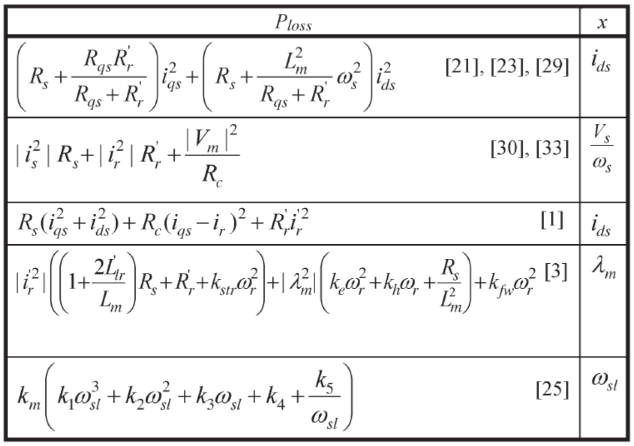
In the literature, there are model-based techniques that use different power-loss models and control methodologies. Their dependence on motor specifications and specific power-loss equations is a common feature. LMTs based on models are defined as follows:

Definition 1: To achieve minimum-loss operation, a model-based LMT relies on motor characteristics and a power-loss or input power model. It does not involve closed-loop power estimation or measurement, but it may make use of additional feedback.

Under parameter modifications, the dependence on motor parameters causes departures from ideal operation. Some LMTs rely on motor parameters acquired from offline motor testing, which are believed to be constant [1], [3], [21]–[26].

The LMT in [1] uses a steady-state motor model to manage the magnetising current in a vector drive to achieve minimal loss. The power-loss model accounts for iron and copper losses, although it is reliant on stator resistance (Rs). In [25], the suggested LMT uses field oriented control (FOC) to manage the slip frequency (sl). [25] usesRs, rotor resistance (R r), stator inductance (Ls), rotor inductance (L r), magnetising inductance (Lm), and core resistance to calculate core and copper losses (Rc).

Table 1:Power Loss Function and Minimization Variables



P_{loss}	x
$\left(R_s+\frac{R_{qs}R_r^{'}}{R_{qs}+R_r^{'}}\right)i_{qs}^2+\left(R_s+\frac{L_m^2}{R_{qs}+R_r^{'}}\omega_s^2\right)i_{ds}^2$ [21], [23], [29]	i_{ds}
$\lvert i_s^2\rvert R_s+\lvert i_r^2\rvert R_r^{'}+\frac{\lvert V_m\rvert^2}{R_c}$ [30], [33]	$\frac{V_s}{\omega_s}$
$R_s(i_{qs}^2+i_{ds}^2)+R_c(i_{qs}-i_r)^2+R_r^{'}i_r^{'2}$ [1]	i_{ds}
$\lvert i_r^{'2}\rvert\left(\left(1+\frac{2L_{lr}^{'}}{L_m}\right)R_s+R_r^{'}+k_{str}\omega_r^2\right)+\lvert\lambda_m^2\rvert\left(k_e\omega_r^2+k_h\omega_r+\frac{R_s}{L_m^2}\right)+k_{fw}\omega_r^2$ [3]	λ_m
$k_m\left(k_1\omega_{sl}^3+k_2\omega_{sl}^2+k_3\omega_{sl}+k_4+\frac{k_5}{\omega_{sl}}\right)$ [25]	ω_{sl}

The optimal input is calculated using a linearized induction motor model. [25] does not compare the proposed LMT versus non-optimal operation, but simulations demonstrate that the "theoretical" optimal sl for a 1.5-hp induction motor is tracked.

Seleme et al. [26] investigate a steady-state model-based LMT with a linearized motor model and sl as the control variable. Except for Ls. Kioskeridis and Margaris [3], who alter the magnetising flux to produce minimal power loss, this method is dependent on all motor parameters. When compared to traditional V/f operation, the proposed LMT results in a considerable reduction in required stator voltage from 220 to 85 V at light load on a 1-hp motor.Rs, R r, and Lm all play a role in this lowering. [21] describes another FOC-based LMT. The stator current is the control variable, and iron and copper losses are taken into account. The LMT is dependent on Rc, which is split between the rotor and stator, in addition to Rs, R r, and Lm. Variations in R r are critical, according to sensitivity analysis in [21], but they result in a 2% reduction of power. The proposed solution in [23] relies on Rs, which is split into Rq and Rd, and employs the stator current as the control variable. This LMT is used to improve the efficiency of a 500-N linear motor's FOC drive, which improves from 5% to 50% at light load.

[24] presents an LMT that additionally uses stator current as a control variable. Despite the fact that the stator voltage and current are significantly lower than the nominal values, the power factor declines for light loads. At light load, the input power is reduced, and the efficiency of a 1-hp motor is improved by more than 50%.

Several references, such as [31], look at loss minimization in relation to rotor flux. [32] derives an analytical and experimentally confirmed relative convex relationship between input power and rotor flux. [22] proposes an approach based on optimum control theory. The system's Hamiltonian is discovered, and optimal control is achieved using optimal time and losses.This application is mathematically verified, but no results are provided. A lookup table is another strategy utilised in model-based LMTs. [27] provides an example in which optimal operating locations for various loading scenarios are derived via offline calculations. Under V/f-control, the load is evaluated, and the optimal slip frequency is established. Because it employs feedback and changes the slip frequency, this technique could be mislabeled as physics-based, although the procedure provided here uses a lookup table rather than perturbations. In [33], the best V/f ratio is determined using a lookup table based on motor characteristics and dynamic equations.

Model-based LMT convergence times are affected by motor size, application, and implementation. [1], [21], [24], [26], [27], and [33] exhibit convergence periods of 300 ms–5 s for 1–3 hp motors. Under rare circumstances, efficiency gains of up to 70 points have been achieved.

The dependence on motor parameters and ratings, as well as the connectivity to a steady-state model of the motor from which losses are computed, are common aspects of model-based LMTs. The majority of model-based LMTs are designed for steady-state applications where the motor operating points rarely change; as a result, parameter estimates are rarely altered. They are also appropriate for dynamic applications, such as EVs and HEVs, that require a very fast update of the control variable.

IV. PHYSICS BASED LOSS MINIMIZATION TECHNIQUES

LMTs based on physics do not rely on motor models or parameters. To lower a cost function like as power loss, the LMT drives the control input.

2nd Definition: Regardless of the motor ratings or characteristics, a physics-based LMT uses electromechanical or mathematical concepts to drive the control input in the direction of least power loss.

A control variable is perturbed in some physics-based LMTs to determine minimum power loss or input power. In optimization applications like maximum power supply from photovoltaic arrays, perturb and observe (P&O) techniques are commonly used. The technique used in [35], for example, perturbs the V/f ratio until minimal power losses are attained.
To operate with lower flux, the controller starts with the rated voltage and frequency, then reduces the voltage and increases

the frequency. For a 10-hp motor, efficiency increased by 12 points at light loads.

[36] presents a similar P&O technique with the magnetising flux as the input variable. Figure 3 depicts the standard P&O method. The LMT perturbs the dc link voltage and the motor frequency to control the voltage and speed, respectively, in another P&O technique presented in [37]. The result is a changeable V/f ratio that provides the drive with the best possible input power.At light loads, efficiency rose by eight points, according to [37]. The flux command in a FOC drive is used as the control variable by P&O, as shown in [38]. In [39], three LMTs were discussed. One is based on physics, while the other two are hybrid. The physics-based method alters the motor's frequency until the reference rotor speed is reached. After that, the voltage is changed to minimise the input power. When the speed changes, the procedure is repeated.

In [40], fuzzy logic is used to determine the optimal direct-axis stator current (ids), which reduces the input power (Pin). Derivative estimates (ΔPin/Δids) are used to create membership functions.This establishes a link between changing ids and the result in Pin, and directs the ids command to the lowest possible power. Pin was lowered by 50% during transients, compared to rated flux operation, according to controller simulations. In [41], a neural fuzzy combination varies the stator voltage to minimise Pin using fuzzy logic.

Back propagation is used to update the membership functions of this controller, and the neural network is trained by altering the input power. At low speeds, efficiency increased by 27 points.However, because the trials are conducted with a 0.25-hp motor and quick speed fluctuations, the time scale is unclear. After a speed step, it takes about 0.5 seconds to attain optimum power. This happens quickly, and it's due to the motor's low rated power and inertia. For machine ratings between 1.5 and 10 hp, convergence durations for these techniques [3], [35], [37],–[40] range from 5 s to 6 min, which is slower than model-based LMTs.

V. HYBRID LOSS MINIMIZATION TECHNIQUES

It is essential to consider hybrid techniques with features ofboth model- and physics-based methods.

Definition 3: Hybrid procedures start with a motor or system model to find the least amount of power loss, then employ electromechanical principles and mathematical properties to reach optimality.

As shown in [42], several strategies categorised as model- or physics-based are actually hybrid. Ripple correlation control (RCC) [32], [43], [44] as a physics-based LMT was investigated in [6]. RCC, on the other hand, necessitates the estimation of rotor flux, which is dependent on motor characteristics. RCC is discussed in depth in [43] and [44]. For extremum-seeking control, the method makes use of power electronics' intrinsic ripple. RCC should be able to dynamically minimise Pin utilising instantaneous power and flux data, according to [32]. The convergence to the optimum is faster when the frequency of the ripple is higher.

Although RCC has been theoretically proved to operate with induction motors, the ripple that is inherent in a motor drive may not have the required qualities. RCC application methods are being researched. RCC is discussed as a sample hybrid technique in this research. The LMT described in [42] evaluates Pin using the motor model, comparing the past value of Pin to the current value to determine sl.

[45] uses a perturbation method that changes the rotor flow while determining the rotor resistance in real time. In less than 1 second, a Fibonacci search algorithm uses this estimate to discover the ideal rotor flux.Using the optimal slip value and the speed command, two hybrid approaches provided in [39] evaluate the optimal stator frequency and apply a voltage to produce minimum power. The power factor can also be used as an optimization criterion. By adjusting for the optimum power factor, a hybrid technique introduced in [2] uses fuzzy logic to search around a model-based optimal point. The motor model is used to calculate an optimal, and fuzzy logic is used to adjust for the optimum power factor using speed feedback.

VI. COMPARATIVE ANALYSIS

Because most physics-based LMTs must wait to analyse steady-state power losses or input power to update their control variable, many physics-based techniques are slower than model-based techniques. Oscillations around the optimal point plague P&O methods. As the controller approaches the optimum point, the perturbation step can be varied to lessen this effect. The key benefits of physics-based LMTs are their parameter independence and ease of implementation.

Model-based LMTs converge to the optimum within a specified tolerance of the optimum without causing steady-state system performance to suffer. The fundamental disadvantage is that they are reliant on motor characteristics. This necessitates adjustment and diminishes accuracy in fluctuating settings.RCC and other hybrid LMTs require fewer motor parameters and converge quickly. As a result, hybrid LMTs combine the best features of model- and physics-based LMTs, such as shorter convergence times for physics-based LMTs and less parameter dependence for model-based LMTs. The intricacy of implementation could be a disadvantage.

Digital signal processors, on the other hand, are widespread in motor drives and are capable of handling complex processes. The settling time and improvements induced by some of the LMTs accessible in the literature are summarised in Table II. Table III summarises the characteristics of real-time LMT categories. There is no standard format for reporting LMT findings.While the major focus is on power loss reduction and energy savings, there are publications on efficiency improvement, stator voltage reduction, and other topics in the literature. Table II shows that, with the exception of low motor power ratings and hence low inertia, physics-based procedures are slower than model-based techniques. Overall, any LMT can boost performance significantly, although hybrid LMTs outperform physics-based and some model-based LMTs.

Table II: Comparison of real time loss minimization techniques

Technique	Parameter Sensitivity	Fast Convergence	Convergence to Optimum	Example
Model Based	High	Yes	Not guaranteed	$\partial P_{loss}(x)/\partial x = 0$
Physics Based	None	Not guaranteed	No	P&O
Hybrid	Medium	Yes	Yes	RCC

VII. CONCLUSION

Real-time LMT comparisons and comments were given. Model-based, physics-based, and hybrid LMTs were identified. Overviews of offline and online LMTs, as well as dynamic and steady-state induction motor applications, were presented, as well as a study of the three online LMT categories. A model-based LMT reduced losses in a simulated HEV by 22.7 percent throughout the FUDS cycle. Hybrid LMTs have parametric advantages and are promising for loss minimization in induction machines, according to simulations of the three real-time LMT categories. The simulations for model- and physics-based methodologies were confirmed by experimental results.

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