Control of Induction Motor Drive by Optimizing Efficiency: A Review

Bhavana Tiwari[1], Babli Dewangan[2]

[1]RCET Bhilai, (CG), India,
er.bhavanatiwari@gmail.com

[2]RCET Bhilai, (CG), India,
tulsibaib@gmail.com

Abstract - ***Induction motors are factotum of industry, but*** **low efficiency of motors waste a lot of energy which result in increment of operational cost. Induction motors** ***is reliable, robust, low price, and perfect power/mass ratio due to which it is replacing all other motors in industry, so even a small increase in efficiency can have major impact on the total electrical energy consumptions. Estimation implies that efficiency improvement could reduce worldwide electricity demand by great amount, hence a considerable positive impact on global environment. This paper presents a review of the developments in the field of efficiency optimization of three-phase induction motor through optimal control, which covers both the approaches namely, loss model control (LMC) and search control (SC). The use of Artificial Intelligence (AI) techniques such as artificial neural network (ANN), fuzzy logic, expert systems and nature inspired algorithms (NIA), Genetic algorithm and differential evolution in optimization are also comprise in this paper.***

(**Keywords**: Induction motor, neural network control, efficiency optimization, loss model control, search control)

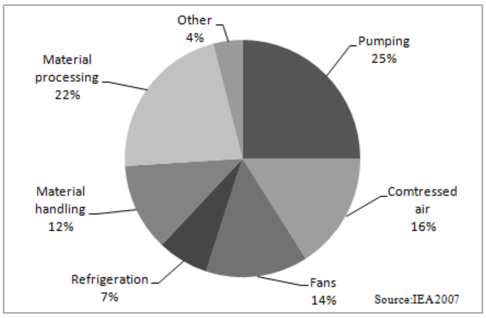
1. Introduction

Electricity is mostly generated from conventional resources such as oil, natural gas and coal. In 1970's, energy crisis cause increased in distributional costs of energy. Impact of greenhouse gases on world climate are among the key forces that encourage efforts and progress for electrical energy efficiency or its saving (Bose, 2000). Worldwide, approximately around 70% of total electrical energy is consumed by electric motor (Sen *et al.*, 1996). In U.S., motors consume over 1700 billion kWh per year. Each year, 140 million new motors are sold. Energy consumption is done by motor in which 90% motors are three-phase induction motors among the total motor in power range from 0.75 kW to 750 kW. Induction motors are featured by their excellent power/mass ratio, cost efficient and effortless maintenance (since no mechanical commutator is present). A breakdown of the electricity consumption by end-use is given in Table 1. Estimation of growth rate of motor load in industrial sector is about 1.5 % and for tertiary sector 2.2 % (Callcut *et al.*, 1997). While observing statistical data, squirrel cage induction motors, with 52 kW capacity or less, are major consumers of electricity. Since installation of new unit increasing, so even a small improvement in efficiency can have major impact on total consumption of electrical energy. Increment of single percent in motor efficiency would save over $1 billion per year in energy costs, since combustion of coal deduce by 6-10 million tons (5.4-9.1 million tons) and emission of carbon dioxide into atmosphere is reduced by approximately 15-20 million tons (13.6-18.1 million tons). Estimation implies that efficiency improvement could reduce worldwide electricity demand around 7 percent (IEA 2008). Poor efficiency of motors wastes a lot of energy which result in increment of operational cost. Electric Power Research Institute observe that over 60% of industrial motors are operating below 60% of their rated load capacity (Fernando and Anibal, 2008). In other word, 40% of industrial motors waste about 15% of electrical energy. Although, motors are efficient, idling or cyclic but consume more power than required even when they are not working (Ramdan and Ahmed, 2012). It is predicted that if all countries start to adopt best Minimum Energy Performance Standards (MEPS) for motors used in industry then we can save up-to 325 terawatt hours of annual electrical energy by year 2035. Such amount of energy saving would reduce CO_2 emission by 206 million tons. Therefore, it is prime requirement to concentrate on efficiency due to economic and environmental reasons.

Table 1: Electricity consumption by end-use

Type of Load	Industrial Sector	Tertiary Sector
Motors	69%	36%
Lighting	6%	30%
Other	25%	34%

Figure 1 (a), reflects share of each category of motor system in total electricity consumption in the US. Although figures vary slightly country by country, general pattern is compatible to most countries. Pumping, compressed air and fan systems are some of most electricity-consuming motor system. Furthermore, material handling and processing consume a great deal of electricity.



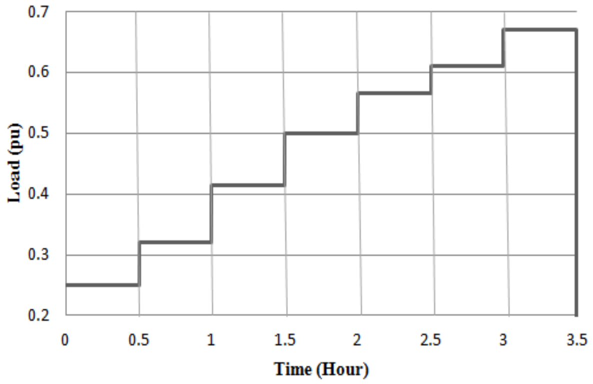


Figure 1: (a) Share of different motor system, (b) Load diagram of typical textile mill

Pump systems are categories as highest share for consumption of electricity. They represent about one quarter of total electricity consumption of all industrial motor systems in US. In Europe, they account for about 20 percent of industrial electricity demand. Share of pumps in petrochemical (51 percent), pulp and paper (28 percent) and chemicals industry (18 percent), while in many industries pumps consume about 10 percent of total electricity consumption. Refrigeration also accounts for a high share of electricity consumption in food industry to ensure quality and to comply with hygienic standards and even in chemicals industry, which usually needs very low temperature cooling for liquefaction of gases. Material handling and processing differ strongly on account of electricity consumption. For example, in paper industry there are mostly rolls and conveyors consume more energy, while cement industry mills demand less electricity. Fans are mostly used as air exchanger in air-conditioning, ventilation or heating system, but they are also installed for other processes like material handling, cleaning, drying or painting. Fans account for about 9.5 to 17.5 percent of industrial sectors' total electricity consumption with highest share of 17.5 percent in pulp and paper industry. In developed country (like USA), on Energy Information Administration (EIA) survey, it is estimate that energy used to operate HVAC can be use twice in a typical commercial building. In Malaysia, electrical consumption for cooling system refer to previous works on energy audit and ASEAN USAID survey observed that energy consumed for cooling building is about 68% of total electrical energy consumptions. In cooling systems such as air conditioning system or refrigerator-freezers system, electric motors are used for inlet fan drive, outlet blower and compressor. In air conditioning system, electrical energy is consumed mainly by compressor motor drive which is about 80%. On above mentioned example, it is clear that induction motors spends most of its time running at low loading. Also in Marine Vehicles and Traction system, light running conditions persist for longer period, so by using optimal control of VFD we have a great chance of energy saving.

2. Optimal Efficiency Operation

Technique to minimize motor loss by adjusting motor flux level according to motor load is called energy optimal control, also known as efficiency optimization control or loss minimization control or optimal efficiency operation. Optimal operating point is achieved when sum of induction motor losses components is minimum. Induction motors have a high efficiency at rated speed and torque. However, at light loads, iron losses increase dramatically, reducing considerably efficiency. At light loads flux at rated value causes excessive core loss, since it is more than necessary for development of required torque. Induction motor losses are usually split into five components: stator copper losses, rotor copper losses, iron losses, mechanical losses and stray losses. A study of copper and core losses components reveals that their trends conflict. When core losses increase, copper losses tends to decrease. Electromagnetic torque of induction motor can be approximated by:

$$T_e = k_{te} I_m I_r$$

Where

T_e: electromagnetic torque
I_m: magnetizing current
I_r: rotor current
K_{te}: constant

From Equation (1), electromagnetic torque of the induction motor can be generated by the numbers of combinations of magnetizing and torque producing rotor current. It is thus possible to obtain same torque with different combination of flux and current value. For every load and speed condition, there exists a magnetizing current where motor losses are minimal. So, it is well known that, for a given load torque, there exists different combinations of input voltage and frequency to yield this operation. Their efficiencies are different, however, for that given load torque there is an air-gap flux density at which the total losses are minimized, with a slight loss in speed accuracy. Hence, electrical losses minimization process ultimately comes down to selection of appropriate air-gap flux density of operation. In vector control scheme, same can be interpreted as at a particular value of stator current, optimal efficiency can be achieved. Challenge to engineers, however, is to be able to predict appropriate flux values at any operating points over complete torque and speed range which will minimize machines losses, hence maximizing efficiency. At same time it is also important to ascertain that rotor speed of motor is still stable. In addition, nonlinearities of induction motor characteristic and varying of motor variable parameters due to temperature variations and magnetic saturation need to be considered when designing a robust efficient optimization control. Various methods are there for loss minimization and efficiency improvement. An Extensive literature survey is produced in next section.

3. Methods of Efficiency Improvement

All optimal control schemes are divided into three categories which are, Simple State Control, Loss Model Control and Search Control. Many authors recognize only two types (SC and LMC) since SSC can be viewed as a simpler form of LMC. Simple State Control is first strategy which is based on control of one specific variables or predefined relation in drive. This variable must be measured or estimated and its value is used in feedback control of drive, with aim of running motor by predefined reference value. Slip frequency or power factor displacement are most often used variables in this control strategy. Which one to chose depends on which measurement signals are available? Power factor control is simple, i.e., it does not require speed or load information, and it has a relatively fast adaptation, it is a good choice for industrial drives. But the generation of optimal power factor commands remains restrictive and tedious. So trial and error methods are often used. On other hand, rotor slip frequency control requires both speed and load information. This strategy is simple, but gives good results only for a narrow set of operation conditions. Also, it is sensitive to parameter changes in drive due to temperature changes and magnetic circuit saturation. In overall, these methods only yield suboptimal operation since parameter variations due to temperature changes and saturation effects are not taken into consideration.

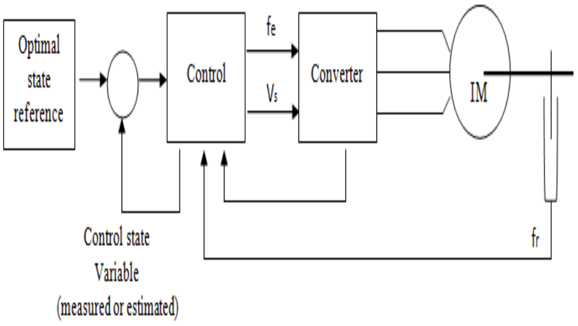


Figure 2: Control diagram for the simple state control method

Loss Model Control is second strategy, a drive loss model is used for optimal drive. It consists of computing losses by using machine model and selecting flux level that minimizes these losses. Role of loss model controller is to measure speed and stator current and determines optimal air gap flux through loss model of motor. Inner part of control algorithm may be in scalar or vector. Feedback controller directs motor to work at its minimum loss point, where losses of both direct axis and quadrature axis are balanced. This approach is fast because optimal control is calculated directly from loss model. Convergence times depend on motor size, application, and implementation. For 1-3-hp motors, convergence times of 300 ms-5s are shown in various literatures. Efficiency improvements up to 70 points are recorded under certain conditions. Parameter estimation has been studied and implemented with model-based LMTs to get a more accurate motor model. But, power loss modeling and calculation of optimal operating conditions can be very complex. This strategy is also sensitive to parameter variations in the drive.

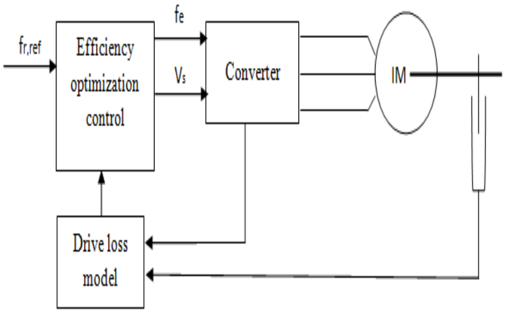


Figure 3: Block diagram for the model based control method

Search Control Method is third technique, in which, on-line procedure for efficiency optimization is carried. On-line efficiency optimization control on basis of search, where stator or rotor flux is decremented in steps until measured input power settles down to lowest value is very attractive. Search strategy methods have an important advantage compared to other strategies. It is completely insensitive to parameter changes while effects of parameter variations caused by temperature and saturation are very expressed in two other strategy. Besides all good characteristics of search strategy methods, there is an outstanding problem in its use. When load is low and optimal operating point is found, flux is so low that motor is very sensitive to load perturbations. At minimum loss point the relation between flux and input power is almost flat. So to avoid oscillatory behavior input power must be accurately measured in control. Also, flux convergence to its optimal value sometimes can be to slow, and flux never reaches value of minimal losses then in small steps oscillates around it. Difficulties in tuning algorithm for a given application and need for precise load information are also there. For these reasons, this is not a good method in industrial drives.

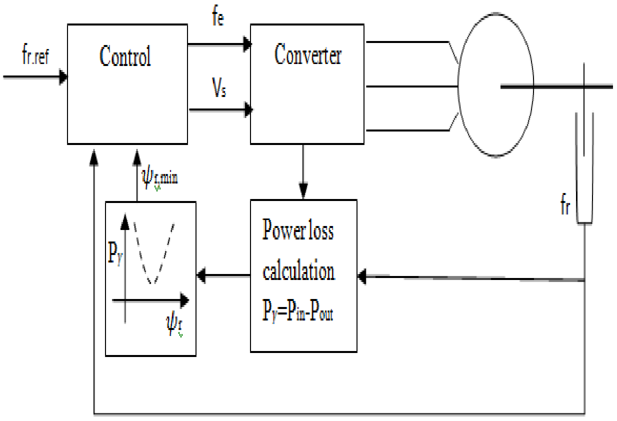


Figure 4: Block diagram of search control method

There are hybrid methods which combine good characteristics of two optimization strategies SC and LMC and it was enhanced attention as interesting solution for efficiency optimization of controlled electrical drives. Use of Artificial Intelligence (AI) techniques such as artificial neural network (ANN), fuzzy logic, expert systems and nature inspired algorithms (NIA), Genetic algorithm and differential evolution in optimization have significant utility in flux optimization. There are many types of AI controllers applied to IM optimization through control as well as design and are available in the various literatures. Some controllers use Fuzzy ANN. Fast convergence can be achieved by these controllers. Nature Inspired Algorithms (NIA) are relatively a newer addition to class of population based stochastic search techniques based on self-organizing collective processes in nature and human artifacts. Some popular NIA are Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Evolutionary Algorithm, Simulated Annealing (SA), and Evolution Strategy, etc. NIA seem promising because of their social – cooperative approach and because of their ability to adapt themselves in continuously changing environment.

4. Simple State Control

A constant-optimal slip control is proposed for increasing efficiency at light loads, based on an intuitive adaptation of well known Maximum Torque per Ampere (MTA) algorithm, ensuring a constant-optimal slip. MTA strategy imposes a constant optimal slip control equal to the inverse of rotor time constant. An experimental evaluation has been accomplished on a 1.5 Hp induction motor drive to measure losses minimization and verify the dynamic performance of proposed method [3]. Authors of [4] dealt with power factor tracking in a field-oriented scheme for induction motor drive leading to efficiency optimization. Simulation results illustrated that the efficiency is optimized in the light load region. They are also noticed that efficiencies, with and without optimization algorithm, are identical for rated loads.

5. Loss Model Control

Many works have been reported using various strategies using different variables to minimize losses in IM. Few use slip speed, excitation current, rotor flux, voltage etc, others use lookup tables derived offline, or estimate the parameters on line and then use them to achieve minimum losses. Authors in [5] have derived optimal value voltage and frequency based on loss model. Under specific speed and torque, without harmonic frequency effect consideration, the optimum voltage and slip frequency to achieve the minimum power losses are obtained,

Most model-based LMTs are suitable for steady-state applications where the motor operating points; thus, parameter estimates rarely change. They are also suitable for dynamic applications that require very fast update of control variable, e.g., EVs and HEVs. Artificial intelligence controllers like ANN, fuzzy, PSO, GA can also be used for finding optimal flux level with the minimum time.

6. Search Control

Input power is a parabolic function of flux that has strictly positive second derivative with regime-dependent minimum that can be found by various search procedures [14]. It was concluded [68] that loss function is concave and it means that there is a value of flux that will generate minimum power losses. The losses minimization condition with respect to air-gap flux of induction motor can be determined by sensitivity power losses equation equal to zero.

7. Hybrid Methods

A perturb and observe technique is presented in [46], where input variable is magnetizing flux. The basic P&O algorithm is proposed in [47] where LMT perturbs dc link voltage and the motor frequency to control the voltage and speed, respectively. The result is a variable V/f ratio that achieves optimum input power to the drive. Three LMTs were discussed in [48]. One is physics – based while two are hybrid. Physics-based techniques vary the frequency of motor until the reference rotor speed is achieved. Voltage is then varied to reduce input power. This procedure is repeated as the speed changes. It is suggested that in order to maintain maximum efficiency, induction motor should operate at a constant slip [68]. The function of efficiency in terms of slip frequency is derived after substantial algebraic expression is given by:

$$\omega_{sl,opt} = \frac{1 - \sqrt{1 - 4(T_e)^2 d}}{2T_e c}$$

The slip frequency that result maximum efficiency is determined by:

$$i_{s,opt} = \sqrt{T_e}\,\frac{\sqrt{X_{rr}}}{X_m}\,\sqrt{\frac{1}{\tau_r \omega_{sl,opt}} + \tau_r \omega_{sl,opt}}$$

Another approach [68], the optimum torque current (I_d) for maximizing the efficiency is determined by differentiating the power losses function with respect to the torque current (I_d) and equaling this to zero. Optimal torque current (I_d) for maximum efficiency is given by,

$$I_{d,opt} = I_q \sqrt{\frac{R_s(R_c + R_r) + R_c R_r}{R_s(R_c + R_r) + M_d^2 \omega^2}}$$

One another approach [68], proposed loss minimizing control scheme for induction motors in the vector control. With this neglecting saturation and L_d is d-axis inductance, the optimal torque current (I_d) to achieve the minimum losses is given by:

$$I_{d,opt} = I_q \sqrt{\frac{R_s(R_c + R_r) + L_d^2 \omega^2}{R_s R_c + L_d^2 \omega^2}}$$

The procedure described in [76] is based on the optimal slip control of current source inverter fed induction motor. Optimal operating points for different loading conditions are taken from off-line calculations. The load is estimated, and optimal slip frequency is set under V/f – control. First, the optimal slip is searched by trial and error with this help of loss model and the results are tabulated in microprocessor memory. Then the motor is operated at the 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 the case of lower speed rated motors. The Optimization was carried out successfully at centrifugal pump drives. Similar lookup table is also used in [39] where as the optimal V/f ratio is selected based on motor parameters and dynamic equations.

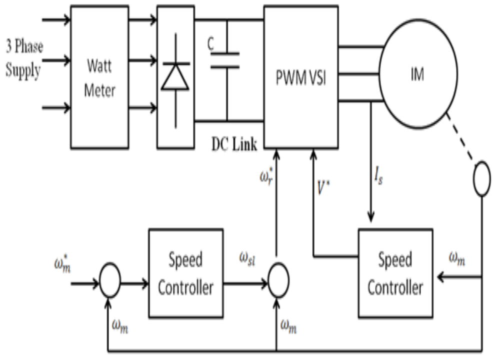


Figure 5: Block diagram of the LMC of the Induction Motor Drive

Author of [20-23, 32] have utilized good features of both the mode of control. Both the steady-state and dynamic performance are taken conscientiousness. Fast convergence time is also achieved. Authors of [20] have decided minimum loss operating point from a functional approximation of the motor and the power converter losses, in the form of a suitably defined the loss function. The loss function parameters are obtained online from input power measurement and a dedicated identification routine acting in confluence with the common drive control functions. Proposed controller is coded into a conventional low-cost 16-bit DSP and verified on a 2.2-kW induction motor drive prototype. In [21, 22] authors, the first estimate is from the loss model approach and the subsequent adjustment of the flux is through the search technique. To avoid the torque pulsations, I_{ds} is fed through a filter. This filter offers a critically damped second-order response and reaches 99% of the reference value in about 0.2 second. During EOC the filter avoids any abrupt change of motor flux. The EOC is activated every 0.3s only after the dc-link power settles down corresponding to the change in the I_{dsref}. [51] authors have suggested that three control schemes: (i) MBC with a low pass filter (ii) torque producing current (iqs) injection in the output of speed controller (iii) Variable Structure Speed Controller (VSSC) for improving dynamic performance. Authors of [23] have proposed the dynamic space-vector model for loss-minimizing. Based on this corresponding steady-state loss function, a method is proposed for solving the loss-minimizing flux reference at each sampling period. In order to improve dynamic operation of the drive, a proportional flux controller is applied.

Smooth variations instead step change in control variable to minimize the input power of IM was proposed in [17]. Flux producing current (i_{ds}) was considered as a variable. The torque producing current (i_{qs}) also adjusted in accordance with ids to avoid deterioration in the torque. From the experience of the authors, a 7.5 hp motor took 7 seconds for completing minimization program and the minimization process depends on the motor time constant, and concluded that minimum losses are reached when d axis power losses is equal to q axis power losses. In Ref [77], the loss minimization algorithm (LMA) has been simplified with a voltage dependant source and loss resistance. Authors considered current and voltage constraints when searching the optimal flux level and suggested that the model without leakage reactance yield a higher loss than the actual value.

Two hybrid techniques presented in [48] evaluate the optimal stator frequency using the optimal slip value and the speed command and apply a voltage to achieve the minimum power. One also includes power factor as an optimization criterion. A hybrid scheme presented in [38] uses fuzzy logic to search around a model – based optimal point by correcting for optimum power factor. An optimum is first calculated using the motor model, and then the fuzzy logic uses speed feedback to compensate for the optimum power factor.

8. Modern Tools of Optimal Control

In [24-25] authors have used a neural network (NN) to improve the efficiency. A complex loss model in d-q frame of the motor, including magnetic and thermal deviations of its parameters, and it is used to estimate losses. Based on this model, the neural network is trained to estimate optimum rotor flux. Inputs to the NN are torque, speed and rotor resistance of the IM and the output is rotor flux, are considered [24]. They used the Levenberg-Marquardt learning algorithm, neural network was trained with an off-line scheme. The neural controller consists of the three layers, three neurons in the input layer and the output layer is the current flux reference. Input of proposed controller consists of electromagnetic torque, rotor resistor and speed of the motor.

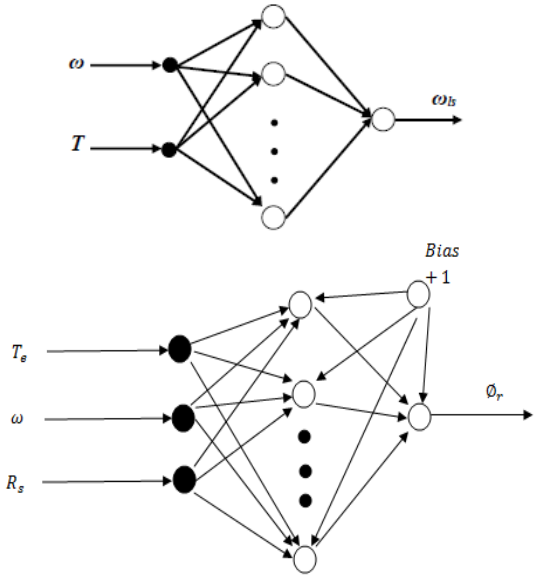


Figure 6: Various neural network-based efficiency optimization control scheme

In [25] an ANN controller is synthesized and trained offline to determine optimal flux level that attains maximum drive efficiency. In [68] authors used a neural network to search in vector control induction motor drive system. Based on steady state induction motor model, the motor power losses are calculated as a training data. The back propagation learning algorithm is employed to train neural network controller in different operating point. There is proposed neural control model has one input layer, two hidden layer and one output layer. The input layer consists of speed and load torque as a reference signals. The output layer has only one neuron for magnetizing current. The first hidden layer has ten neurons and the second hidden layer has five neurons. Authors of [26-28] have utilized fuzzy logic in optimal searching, since power electronic systems and drives have complex non-linear structure with the parameter uncertainty, fuzzy logic is quite suitable for power electronics and motion control. Fast convergence is reported.

Loss minimization during the transient state by adjusting flux level using fuzzy logic proposed in [78]. Voltage was considered as a controlling variable in [79]. For both steady-state and transient state, fuzzy logic used to optimize the motor efficiency in [80]. In Ref [81], fuzzy logic was used to decrement flux up to the drives settled down minimum the input power. But the speed or torque command change, the efficiency optimization using fuzzy abandoned and rated flux was established to get the best transient performance. Feed forward torque compensator used to reduce the torque pulsation.

In [26-27] when the drive system is in a steady-state condition, the efficiency-optimization is enabled and the fuzzy search controller begins to search optimal flux. When the load torque or the command speed suddenly changes, the rated flux operation is established. The low-frequency pulsating torque due to decrementation of rotor flux is compensated in a feed-forward manner in [27].

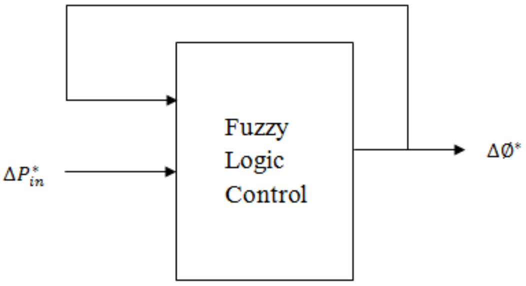
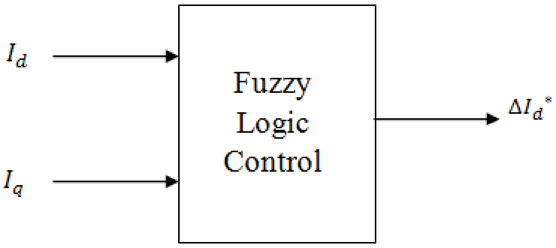
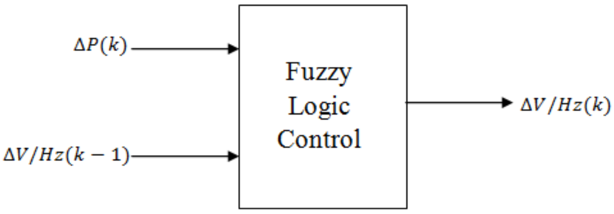


Figure 7: Proposed fuzzy-logic scheme in [27]

Authors of [28] propose one step change of voltage, irrespective of the load change. But they have suggested avoiding too large reduction in voltage since its result in larger slip which will lead to poor efficiency, high rotor heating and even pulling out and motoring stalling. In [68] authors have proposed the search controller in the scalar control model by adaptively obtaining stator voltage per hertz ratio use fuzzy logic controller. Input of the fuzzy logic controller is change of input power and volt per hertz ratio. The output is new change of volt per hertz ratio. Another authors proposed the search controller in the scalar control model by adaptively reducing the stator voltage reference with use of a fuzzy logic controller. The torque pulsation problem is overcome with the help of feed-forward pulsating torque compensation. Input of the fuzzy logic controller is stator voltage and input power and the output is voltage reference compensator.





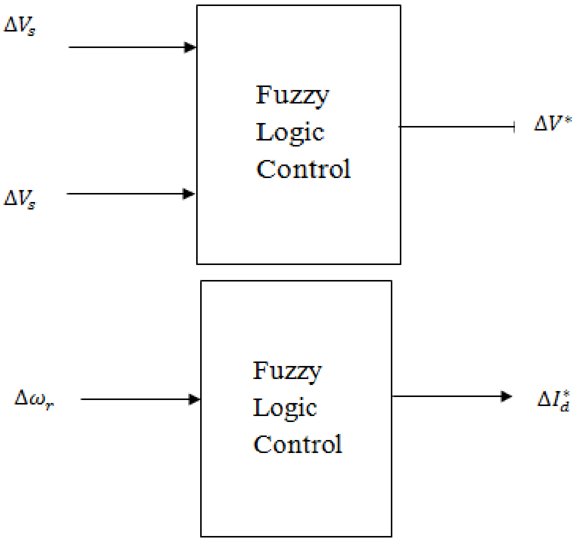


Figure 8: Various fuzzy-logic control scheme

Few other authors compare the different flux optimization algorithms to improve the efficiency at steady state in a vector controlled induction motor drive. In this paper conventional numeric search algorithm such a Rosenbrock, proportional, gradient, Fibonacci method and intelligent search fuzzy logic control is reviewed. The fuzzy logic control employed 14 rule based, with the error speed signal as an input. In [53], authors use hybrid fuzzy-fuzzy controller (HFFC) scheme to gain control over the speed of an induction motor's variable speed drive (VSD). In order to overcome drawback of the field oriented control (FOC) method, the principle of HFFC is based on set of rules to control speed of a rotor by utilizing fuzzy frequency controller during the accelerate decelerate stage. Alternatively, a fuzzy stator current magnitude controller is used during the steady-state stage.

Authors of [29-30] have implemented ANN for the loss minimization. In [29] controller is designed to generate signal voltage and frequency references simultaneously. This technique allows for control of both the speed and the efficiency. In order to achieve a robust BPEOC from variation of the motor parameters, an on-line learning algorithm is employed. Authors of [30] propose a neuro-controller which adjusts slip angular frequency adaptively for minimum loss operation based on the measured input power. A Neuro-Fuzzy-Based On-Line Efficiency Optimization is proposed in [31]. Authors of [32] have proposed search based on the "Rosenbrock" method, which determines flux level that results in the minimum input power. Once this optimal flux level has been found, this information is utilized to update rule base of a fuzzy controller that plays the role of an implicit mathematical model of the system. Initially, for any the load condition, the rule base yields the rated flux value. As the optimum points associated with the usual operating conditions (given by the required speeds and load torques) are identified by SC, the rule base is progressively updated such that the fuzzy controller learns to model the optimal operating conditions for the entire torque–speed plane. As the machine parameters are subject to change during operation, the SC is kept active to track possible minor deviation of optimum point, thus ensuring true optimal efficiency operation. Authors of [33-35] have utilized all possible methods and mechanisms for the performance improvement. All possible modern tools like PSO, ANN, Fuzzy etc are used for determining optimal operating point. In [33] the Fuzzy Pre-Compensated Proportional Integral (FPPI) is used to improve motor's dynamic performances during the activation of optimal energy control. In [34, 35] utilizes ANN and PSO together. In these papers, four strategies for the induction motor speed control are proposed. Those four strategies are based on PSO and called Maximum Efficiency Strategy, Minimum Stator Current Strategy, Maximum Power Factor Strategy, and Maximum Weighted Cost Strategy. They are having simple structure and straightforward maximization of the induction motor efficiency and its operating cost for a given load torque.

[43] As we discussed earlier, the effect of motor parameter variations has been focused in and GA is used to search motor parameter to avoid error in loss model. Genetic algorithms to estimate the motor parameters and then vary the V/f ratio to reach minimum power loss. Then optimum voltage and frequency arranged as table for energy saving controller. For light loads on a 1.5 – hp motor, results presented in show loss reduction of more than 75% compared to the nominal operation. In Ref. [28], authors used the off-line NN to find optimal voltage values to the best efficiency of the IM in a short time and also only two step changes in the voltages required irrespective of load to settle in the desired speed or torque. The PSO is used to adjust proportional –integral- differential controller gains in and get less torque and speed ripples in the drive. Many authors used differential evolution to find optimal slip speed from loss model of the induction motor.

A hybrid technique, GA-PSO based vector control of the induction motor for loss minimization as well as torque control is presented in [72]. The PSO as used for mutation process of GA so that the learning efficiency of GA was improved. Floating point of GA is applied in [73] for minimizing IM losses through flux adjustment. Basic GA is used in [74] to identify rotor time constant from error between motor and commanded stator currents, which helped on-line adjustment of slip angular speed. Optimum flux producing current and corresponding efficiency are focused in [75] by using the neural network. Change in core loss resistance due to flux and frequency have taken into account. The variation in iron loss resistance can be found. Where, R_{mb} is value of R_m at rated frequency and flux.

$$R_m = R_{mb} \left({}^{f}/_{f_{rated}} \right)^{1.1} \left({}^{\emptyset}/_{\emptyset_{rated}} \right)^{2}$$

9. Conclusion

Efficiency optimization in system is such parameter which is essential not only to electrical systems, but provide benefit in terms of money and also reduce global warming. This paper delivers a review of the development in the field of efficiency optimization of the three-phase induction motor through optimal control. Review on various real-time optimal control methods was presented. OCM were categorized as simple state control, loss model control, search control, hybrid methods etc. Overviews of off-line and on-line OCM and dynamic and steady-state performances of induction were considered. The use of Artificial Intelligence (AI) techniques such as artificial neural network (ANN), fuzzy logic, expert systems and nature inspired algorithms (NIA), Genetic algorithm and differential evolution in optimization are also included in this paper.

Acknowledgement:

The authors acknowledge the help from *P. K. Choudhary* during the progress of this work.

References:

1. Review of Methods for Real-Time Loss Minimization in Induction Machines, Ali M. Bazzi, Philip T. Krein, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 46, NO. 6, NOVEMBER/DECEMBER 2010
2. The Next Generation Motor: Designing a new approach to improve the energy efficiency of NEMA Premium motors, JUERGEN F. FUCHSLOCH, WILLIAM R. FINLEY, REINHARD W. WALTER, 2008 IEEE
3. Efficiency Optimization Techniques via Constant Optimal Slip Control of Induction Motor Drives, M. Cacciato, A. Consoli, G. Scarcella, G. Scelba, A. Testa, SPEEDAM 2006 IEEE
4. An Efficiency-Optimization Controller for Induction Motor Drives, M.E.H. Benbouzid, N.S. Nait Said, Power Engineering Review, 1998 IEEE
5. Optimal Efficiency Analysis of Induction Motors Fed by Variable-Voltage and Variable-Frequency Source , Sen Chen, Sheng - Nian Yeh, IEEE TRANSACTIONS ON ENERGY CONVERSION, Vol. 7, No. 3, 1992.
6. Fast Efficiency Maximizerf For Adjustable Speed Induction Motor Drive, G.O. Garcia , J.C. Mendes Luis, R.M. Stephan e E.H. Watanabe, 1992 IEEE
7. Model-Based Loss Minimization for DC and AC Vector Controlled Motors Including Core Saturation, Fidel FemBndez-Bernal, Aurelio Garcia-Cerrada, Roberto Faure, 1999 IEEE
8. New Online Loss-Minimization-Based Control of an Induction Motor Drive, M. Nasir Uddin, and Sang Woo Nam, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 23, NO. 2, MARCH 2008
9. Efficiency Optimizing Control of Induction Motor Using Natural Variables, Gan Dong, Olorunfemi Ojo, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 53, NO. 6, DECEMBER 2006
10. Loss-Minimizing Flux Level Control of Induction Motor Drives, Zengcai Qu, Mikaela Ranta, Marko Hinkkanen, and Jorma Luomi, 2011 IEEE
11. Loss Minimization of Induction Machines, in Dynamic Operation, Jean-Francois Stumper, Alexander Dotlinger, and Ralph Kennel, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 28, NO. 3, SEPTEMBER 2013
12. Efficiency-Optimized Control of Medium-Size Induction Motor Drives, Flemming Abrahamsen, Frede Blaabjerg, John K. Pedersen, and Paul B. Thoegersen, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 37, NO. 6, NOVEMBER/DECEMBER 2001

13. Towards a global control strategy for induction motor: Speed regulation, flux optimization and power factor correction, A. El Fadili, F. Giri, A. El Magri, R. Lajouad, F.Z. Chaoui, Electrical Power and Energy Systems 43 (2012) 230–244, Science Direct
14. Loss Minimization in Scalar-Controlled Induction Motor Drives with Search Controllers, Iordanis Kioskeridis and Nikos Margaris, IEEE Transactions on Power Electronics, Vol 11, No. 2, March 1996
15. A Fast Flux Search Controller for DTC-Based Induction Motor Drives, Shahriyar Kaboli, Mohammad Reza Zolghadri, and Esmaeel Vahdati-Khajeh, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 54, NO. 5, OCTOBER 2007
16. Efficiency Maximization of Induction Motor Drives for Electric Vehicles Based on Actual Measurement of Input Power, Cao-Minh Ta, Chandan Chakraborty, Yoichi Hori, IECON’O 2001 IEEE
17. On-Line Efficiency Optimization of a Variable Frequency Induction Motor Drive, DANIEL S. KIRSCHEN, DONALD W. NOVOTNY, THOMAS A. LIPO, SENIOR MEMBER, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. IA-21. NO. 4. MAY/JUNE 1985
18. Design of an Efficiency Optimization Controller for Inverter-fed AC Induction Motors, John G Cleland, Vance E. McCormick, and M. Wayne Turner 1995 IEEE
19. Alternative Energy Vehicles Drive System: Control, Flux and Torque Estimation, and Efficiency Optimization , Habib-ur Rehman and Longya Xu, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 60, NO. 8, OCTOBER 2011
20. Robust DSP-Based Efficiency Optimization of a Variable Speed Induction Motor Drive , Slobodan N. Vukosavic, Emil Levi, Senior, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 50, NO. 3, JUNE 2003
21. Fast Efficiency Optimization Techniques for the Indirect Vector-Controlled Induction Motor Drives, Chandan Chakraborty, Yoichi Hori, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 39, NO. 4, JULY/AUGUST 2003
22. Fast Search Controllers for Efficiency Maximization of Induction Motor Drives Based on DC Link Power Measurement, Chandan Chakraborty, Minh C. Ta, Toshiyuki Uchida and Yoichi Hori, 2002 IEEE
23. Loss-Minimizing Flux Level Control of Induction Motor Drives, Zengcai Qu, Mikaela Ranta, Marko Hinkkanen, Jorma Luomi, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 48, NO. 3, MAY/JUNE 2012
24. Neural network flux optimization using a model of losses in induction motor drives, Bogdan Pryymak, Juan M. Moreno-Eguilaz, Juan Peracaula, Mathematics and Computers in Simulation 71 (2006) 290–298, Science Direct
25. ANN-Based Optimal Energy Control of Induction Motor Drive in Pumping Applications, Osama S. Ebrahim, Mohamed A. Badr, Ali S. Elgendy, Praveen K. Jain, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 25, NO. 3, SEPTEMBER 2010
26. Efficiency Optimization Of Induction Machines Based On Fuzzy Search Controller , JIE LI, YAN-RU ZHONG, 2005 IEEE
27. Fuzzy Logic Based On-Line Efficiency Optimization Control of an Indirect Vector-Controlled Induction Motor Drive, Gilbert C. D. Sousa, Bimal K. Bose, and John G. Cleland, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 42, NO. 2, APRIL 1995
28. Fuzzy Logic Approach for Energy Eficient Voltage Controlled Induction Motor Drive, K.Sundareswaran and S.Palani. IEEE 1999
29. Efficiency Optimization of Variable Speed Induction Motor Drive Using Online Backpropagation, A. H. M. Yatim, Senior Member, IEEE, and W. M. Utomo, 2006 IEEE
30. On-Line Efficiency Optimization Control of a Slip Angular Frequency Controlled Induction Motor Drive Using Neural Networks, Ick Choy, Soon H. Kwon, J. Y. Choi, J. W. Kim K. B. Kim, 1996 IEEE
    A Neuro-Fuzzy-Based On-Line Efficiency Optimization Control of a Stator Flux-Oriented Direct Vector-Controlled Induction Motor Drive, Bimal K Bose, Nitin R Patel, Kaushik Rajashekara, IEEE Transactions on Industrial Electronics, Vol 44, No 2, April 1997
31. Adaptive Fuzzy Controller for Efficiency Optimization of Induction Motors , Durval de Almeida Souza, Wilson C. P. de Aragao Filho, and Gilberto Costa Drumond Sousa, Member, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 54, NO. 4, AUGUST 2007
32. Optimal Energy Control of Induction Motor by Hybridization of Loss Model Controller Based on Particle Swarm Optimization and Search Controller, T.R. Chelliah, J.G. Yadav, S.P. Srivastava, Pramod Agarwal, 2009 IEEE
33. Optimal Operation of Induction Motors Using Artificial Neural Network Based on Particle Swarm Optimization PSO, Radwan H. A. Hamid Amr M. A. Amin Refaat S. Ahmed Adel A. A. El-Gammal, 2006 IEEE
34. New Technique for Maximum Efficiency and Minimum Operating Cost of Induction Motors based on Particle Swarm Optmization, Radwan H. A. Hamid Amr M. A. Amin Refaat S. Ahmed Adel A. A. El-Gammal, 2006 IEEE
35. Implementation of Fuzzy Control to Improve Energy Efficiency of Variable Speed Bulk Material Transportation, Leposava B. Risti´c, Member, IEEE, and Borislav I. Jefteni, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 59, NO. 7, JULY 2012
36. Optimal regulation of electric drives with constant load torque, C. M. Vega, J. R. Arribas, and D. Ramirez, IEEE Trans. Ind. Electron., vol. 53, no. 6, pp. 1762–1769, Dec. 2006

37. S. M. Yang, "Loss-minimization control of vector-controlled induction motor drives," *J. Chin. Inst. Eng.*, vol. 26, no. 1, pp. 37–45, 2003.
38. I. Kioskeridis and N. Margaris, "Loss minimization in induction motor adjustable-speed drives," *IEEE Trans. Ind. Electron.*, vol. 43, no. 1, pp. 226–231, Feb. 1996.
39. L. Kawecki and T. Niewlerowicz, "Bi-criterial optimization in induction motors speed control taking into consideration the electromagnetic transients," in *Proc. IEEE Int. Symp. Ind. Electron.*, 1996, vol. 2, pp. 935–939.
40. J. Liu, L. Fei, S. Hu, and T. Q. Zheng, "Optimal efficiency control of linear induction motor for linear metro," in *Proc. IEEE Power Electron. Spec. Conf.*, 2008, pp. 673–677.
41. G. Mino-Aguilar, J. M. Moreno-Eguilaz, B. Pryymak, and J. Peracaula, "An induction motor drive including a self-tuning loss-model based efficiency controller," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2008, pp. 1119–1125.
42. S. Sujitjorn and K. L. Areerak, "Numerical approach to loss minimization in an induction motor," in *Proc. Applied Energy Conf.*, 2004, vol. 79, pp. 87–96.
43. E. Poirier, M. Ghribi, and A. Kaddouri, "Loss minimization control of induction motor drives based on genetic algorithms," in *Proc. IEEE Int. Elect. Mach. Drives Conf.*, 2001, pp. 475–478.
44. A. M. Bazzi and P. T. Krein, "Input power minimization of an induction motor operating from an electronic drive under ripple correlation control," in *Proc. IEEE Power Electron. Spec. Conf.*, 2008, pp. 4675–4681.
45. I. Kioskeridis and N. Margaris, "Loss minimization in scalar-controlled induction motor drives with search controllers," *IEEE Trans. Power Electron.*, vol. 11, no. 2, pp. 213–220, Mar. 1996.
46. P. Famouri and J. J. Cathey, "Loss minimization control of an induction motor drive," *IEEE Trans. Ind. Appl.*, vol. 27, no. 1, pp. 32–37, Jan./Feb. 1991.
47. T. Ohnishi, H. Miyazaki, and H. Okitsu, "High efficiency drive of an induction motor by means of V/F ratio control," in *Proc. IEEE Annu. Conf. Ind. Electron. Soc.*, 1988, vol. 3, pp. 780–785.
48. L. Ramesh, S. P. Chowdhury, S. Chowdhury, A. K. Saha, and Y. H. Song, "Efficiency optimization of induction motor using a fuzzy logic based optimum flux search controller," in *Proc. Int. Conf. Power Electron. Drives Energy Syst.*, 2006, pp. 1–6.
49. A. H. B. M. Yatim and W. M. Utomo, "Neuro-fuzzy on-line optimal energy control for variable speed compressor motor drive system," in *Proc. Int. Conf. Power Electron. Drives Syst.*, 2005, vol. 1, pp. 776–780.
50. Adaptive control schemes for improving dynamic performance of efficiency-optimized induction motor drives, Navneet Kumar, Thanga Raj Chelliah, S.P. Srivastava. 2014 Science Direct
51. Direct torque control implementation with losses minimization of induction motor for electric vehicle applications with high operating life of the battery, Farid Tazerart, Zahra Mokrani, Djamila Rekioua, Toufik Rekioua, 2015, Science Direct
52. Efficiency improvement of induction motor variable speed drive using a hybrid fuzzy-fuzzy controller, Muawia A. Magzoub, Nordin B. Saad, Rosdiazli B. Ibrahim, 2015, Science Direct.
53. Modeling and Simulating of the Induction Motor in Electric Vehicle Applications, Yan Liu, 2015 IEEE.
54. Investigation and analysis of high performance green energy induction motor drive with intelligent estimator, A. Chitra, S. Himavathi, 2015 Science Direct.
55. Improved Direct Torque Control for Induction Motor with Fuzzy-PI controllers, Chengli Zhu, Yanzhong Wang and Liangwei Hou, International Conference on Logistics Engineering, Management and Computer Science (LEMCS 2015).
56. *Energy Optimal Control of Induction Motor Drives, F. ABRAHAMSEN, Aalborg, Denmark, CHAPTER 6*
57. *New Trends in Efficiency Optimization of Induction Motor Drives, Branko Blanusa, University of Banja Luka, Faculty of Electrical Engineering, Bosnia and Herzegovina, Chapter 18*
58. *Swarm Intelligence Applications in Electric Machines, Amr M. Amin and Omar T. Hegazy, Power and Electrical Machines Department, Faculty of Engineering – Helwan University, Egypt, www.intechopen.com, Chapter 2*
59. *Artificial Neural Network Applications in Power Electronics and Electrical Drives, Chapter 36, B. Karanayil, M.F. Rehman, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*
60. *Mathematical Optimization Techniques, S.A. Soliman and A.H. Mantawy, Modern Optimization Techniques with Applications in Electric Power Systems, Energy Systems, Chapter 2, DOI 10.1007/978-1-4614-1752-1_2, Springer Science Business Media, LLC 2012*
61. *Electric Motor Drives: Modeling, Analysis & Control, R.Krishnan, Verginia Tech, Blacksburgs, VA, Prentice Hall, New Jersy 07458*
62. *Modern Power Electronics and AC Drives, Bimal K. Bose, Prentice Hall PTR, New Jersy 07458*
63. *Engineering Optimization: Theory and Practice, Fourth Edition Singiresu S. Rao, Copyright © 2009 by John Wiley & Sons, Inc.*
64. *Particle Swarm Optimization, Maurice Clerc, ISTE Ltd 6 Fitzroy Square London W1T 5DX UK USA, www.iste.co.uk*
65. *SENSORLESS AND EFFICIENCY OPTIMIZED INDUCTION MACHINE CONTROL WITH ASSOCIATED CONVERTER PWM MODULATION SCHEMES, Gan Dong, December 2005*
66. *ENERGY EFFICIENCY OPTIMIZATION OF INDUCTION MOTORS, Yassine Yakhelef, Digipaino 2010, Boumerdes University, 2007*
67. *TO DEVELOP AN EFFICIENT VARIABLE SPEED COMPRESSOR MOTOR SYSTEM, ABDUL HALIM MOHD YATIM, RESEARCH VOTE NO: 74535, Universiti Teknologi Malaysia, 2007*
68. *INDUCTION MOTOR DRIVE ENERGY EFFICIENCY – SIMULATION AND ANALYSIS, Lassi Aarniovuori, Acta Universitatis*

Lappeenrantaensis, Digipaino 2010, ISBN 978-952-214-962-6, ISBN 978-952-214-963-3 (PDF), ISSN 1456-4491

69. *Induction motors fed by PWM frequency inverters*
70. *Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries, UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, Vienna, 2011*
71. D. H. Kim, "GA-PSO besed vector control of indirect three phase induction motor, " Applied Soft Computing, to be published, DOI:10.1016/j.asoc.2006.04.001.
72. Eric Poirer, Mohsen Ghribi and A. Kaddouri, "Loss minimization control of induction motor drives based on genetic algorithm, " IEEE Conf. Proc. Electrical machines and Drives, IEMDC, 2001, pp. 475-478.
73. L.R. Valdenebro, E. Bim, "A Genetic algorithm approach for adaptive field oriented control of induction motor drives, " IEEE Conf. Proc., Electrical machines and drives, IEMD, WA, USA, 1999, pp. 643-645.
74. E. S. Abdin et al., "Efficiency optimization of a vector controlled induction motor drive using an artificial neural network, " Proc. Of IEEE conf. IECON, 2003, pp. 2543-2548.
75. S. K. Sul, M. H. Park, "A novel technique for optimal efficiency control of a current-source inverter-fed induction motor, " IEEE Trans. Power. Elect. Vol. 3, no. 2, 1988, pp. 192-199.
76. S. Lim, K. Nam., "Loss minimization control scheme for induction motors, " IEE proc. Electr. Power appli., Vol. 151, No. 4, 2004, pp. 385-397.
77. J. M. Eguilaz, et al., "Induction motor optimum flux search algorithms with transient state loss minimization using fuzzy logic based supervisor, " IEEE Conf. Proc. 1997, pp. 1302-1308.
78. K. Sundareswaran, S. Palani, "Fuzzy logic approach for energy efficient voltage controlled induction motor drive, " IEEE Power Electronics and Drives Conf. Proc. PEDS 1999, pp. 552-554.
79. G. C. D. Sousa, B. K. Bose, J. G. Cleland, "Fuzzy logic based on-line efficiency optimization control of an indirect vector controlled induction motor drive, " IEEE Trans. Ind. Elec. Vol. 42, No. 2, 1995, pp. 192-198.
80. J. Moreno, et al., "Fuzzy logic based improvements in efficiency optimization of induction motor drives, " Proc. Of IEEE Fuzzy Systems, 1997, pp. 219-224.

Author Profile

Bhavana Tiwari received the B.E. in Electrical & Electronics Engineering from SSITM, JUNWANI, CSVTU, (C.G), and pursuing M.E. in Power Electronics from RCET, Bhilai, CSVTU (C.G.) India. Her research interests include power electronics and vector & optimal control of machine drives. She has rewarded with fellowship on Rashtriya avishkar abhiyan from AICTE. She is student member IEEE.

Babli Dewangan received the B.E. in Electrical & Electronics Engineering from SSITM, JUNWANI, CSVTU, (C.G), and pursuing M.E. in Power Electronics from RCET, Bhilai, CSVTU (C.G.) India. Her research interests include power electronics and vector & optimal control of machine drives. She has rewarded with fellowship on Rashtriya avishkar abhiyan from AICTE. She is student member IEEE.