IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 2 Issue 12, December 2015.
www.ijiset.com

ISSN 2348 – 7968

Efficiency Optimization of Induction Motor Drive: A Review

V. K. Gupta[1], B. Tiwari[2], B. Dewangan[3]

M.E Student, RCET Bhilai, India

[1]vijayguptadgn@gmail.com
[2]er.bhavanatiwari@gmail.com
[3]tulsibaib@gmail.com

Abstract

Induction motors are workhorse of all industries due to its power/mass quantitative relation, dependability, low worth and nearly maintenance free operation in its life cycle. However motors with low efficiency waste a lot of energy that will increase its operational cost. As a result of high energy consumption and the very large number of installed units, even a small increase in efficiency improvement can have major impact on the entire energy consumptions. It is estimated that a full implementation of efficiency improvement choices may cut back worldwide electricity demand by large amount, hence a substantial positive impact on world environment. This paper presents a review of the developments within the field of efficiency improvement of three-phase induction motor through optimal control. Optimal control covers both the broad approaches specifically, loss model control (LMC) and search control (SC). The utilization of Artificial Intelligence techniques such as artificial neural network, fuzzy logic, expert systems and nature inspired algorithms; Genetic algorithm and differential evolution in optimization are also reviewed in this paper.

Keywords - Variable Speed Drive; Induction Motor; HVAC; Efficiency Optimization

1. Introduction

Most of the electricity these days is generated from non-renewable or fuel resources like oil, fossil fuel and coal. Throughout the energy crisis in seventies, that cause increasing energy prices and therefore the impact of greenhouse gases on world climate are among the key forces that encourage efforts and progress for energy saving. Worldwide, around 70% of total electricity is consumed by electric motor and nearly 90 % of this consumption is done with ac three-phase induction motors in the power range from 0.75 kW to 750 kW. Additionally, the expansion rate of the motor load within the industrial sector is estimated to be 1.5 % and for the tertiary sector 2.2 %. As per the statistical data available the squirrel cage induction motors up to 52 kW capacities are the major consumers of electricity. Because of high energy consumption and the very large number of installed units, even a small increase in efficiency improvement can have major impact on the total electrical energy consumptions.

In every 1% improvement in motor efficiency might lead to savings of over $1 billion per annum in energy prices, 6-10 million tons (5.4-9.1 million tons) less per annum of combusted coal and close to 15-20million tons (13.6-18.1 million tons) less greenhouse emission into the atmosphere. It is calculated that a full implementation of efficiency improvement choices might scale back worldwide electricity demand up to 7 percent. Motors with low efficiency waste plenty of energy that will increase its operational price. Studies conducted by the Electric Power Research Institute reveal that over 60% of industrial motors are operating below 60% of their rated load capacity. In different word, 40% of commercial motors have endlessly wasting the electrical energy for about 15%.

Although, the motors are generally economical, idling, cyclic, gently loaded or outsized motors consume a lot of power than needed even when they are not working. It is estimated that if all countries begin to adopt best Minimum Energy Performance Standards (MEPS) for all motors employed in operation, then by the year 2035 we are able to save up-to 325 terawatt hours of annual electrical energy hence, reduction of CO_2 by 206 million tons. Thus it is of prime importance to focus on efficiency due to economic and environmental reasons. Fig. 1.1 (a) and Table 1, reflects the share of every motor system in the total electricity consumption of all motor systems in the US.

Table 1: **ELECTRICITY CONSUMPTION BY END-USE**

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

Though the Fig. vary slightly by country, the pattern is comparable to most countries. Pumping, compressed gas and fan systems are some of the foremost electricity-consuming motor systems. Moreover, material handling and process consume a good amount of electricity. Energy Information Administration (EIA) survey, it is estimated that the energy consumed in HVAC applications can represent over half the full electricity use in a typical commercial building.

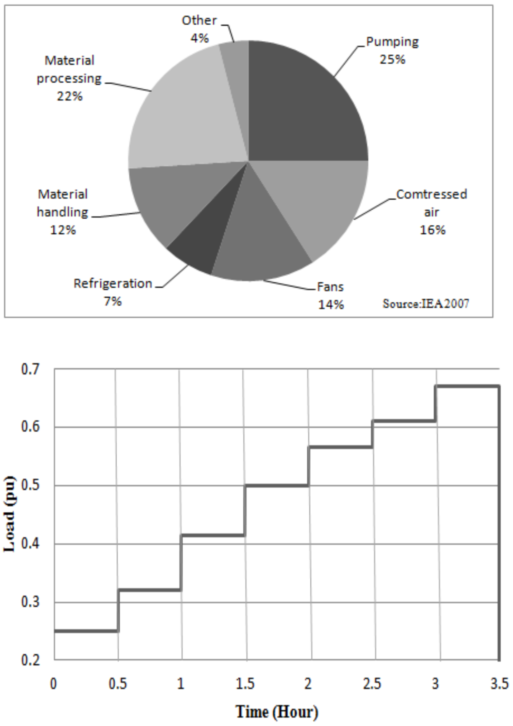

Fig. 1: (a) Share of different motor system, (b) Load diagram of typical textile mill

Pump systems account for the best share of industrial electricity consumption. They represent about one quarter of total electricity consumption of all motor systems in industry in the US. In Europe, they account for about 20% of industrial electricity demand. The use of pumps is highest in the petrochemical 51%, the pulp and paper 28% and the chemicals industry 18%, while the share of pumps of total electricity consumption is well below 10% in many other industries. Refrigeration accounts for a high share of electricity use in the food industry to ensure quality, lifetime and to comply with hygienic standards as well as in the chemicals industry, which mostly needs very low temperature cooling for the liquefaction of gases. Material handling and material processing differ strongly between industries and processes. For example, in the paper industry they are mostly rolls and conveyors, while in the cement industry mills account for a substantial amount of electricity consumption. Fansare mostly used in heating, ventilation and air-conditioning systems to provide the necessary air exchange, but they are also applied in other processes like material handling and cleaning, drying or painting. Fans account for about 9.5 to 17.5 percent of the industrial sectors' total electricity consumption with the highest share of 17.5 percent in the pulp and paper industry. In developed country such as the USA, based on Energy Information Administration (EIA) survey, it is estimate that the energy used to operate the HVAC can represent over half of the total electrical energy use in a typical commercial building. In Malaysia electrical consumption for cooling system, refer to previous works on energy audit and surveys of official building by ASEAN USAID was reported that the energy consumed to cooling the building is about 68% of the total electrical energy consumptions. In cooling systems such as air conditioning or refrigerator-freezers system, electric motors are used for inlet fan drive, outlet blower and compressor. The main consumption of electric energy in air conditioning is consumed by the compressor motor drive which is about 80%. One important thing is also noted, most of the time induction motors utilized in different application as mentioned above, spends considerable time running at low loading. In Marine Vehicles and in Traction also, the light running conditions persist for long period of time, so we have a great chance of energy saving by optimal control of VFD. From the other side there are many applications where, like electrical vehicles, electric energy has to be consumed in the best possible way and use of induction motors in such application requires an energy optimized control strategy.

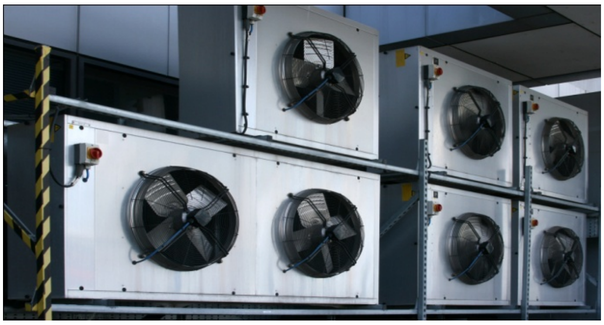

Fig. 2 (a,b): Typical HVAC Systems, (c,d) Typical Mining Application

2. Variable Speed Induction Motor Drive

Variable speed electrical drives have facilitated the revolution of industrial automation leading to better quality and higher productivity in various industries and home appliances. Recent advancements in power electronic, microelectronic and micro computing technologies have made it possible to implement variable speed induction motor in many applications. The system efficiency can be increased from 15 to 27% by the introduction of variable –speed drive operation in place of constant –speed operation, can lead to annual energy savings of up to 50%, when compared with fixed speed systems.

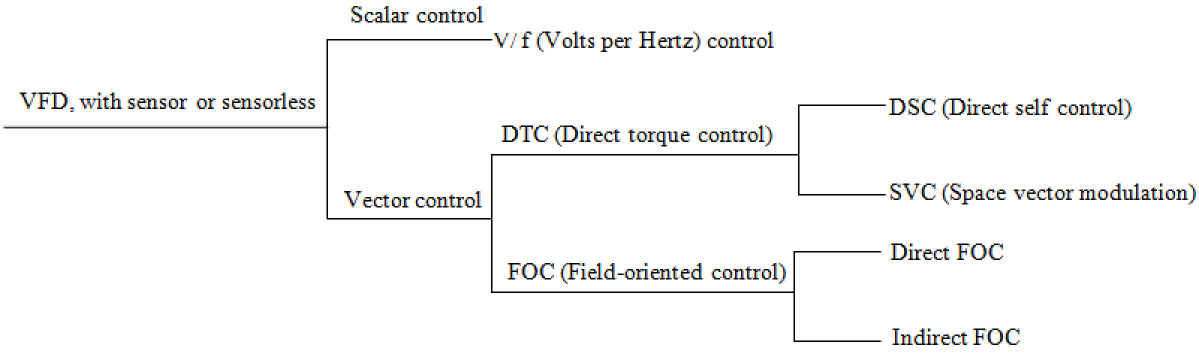

Fig. 3: Various VFD Control Platforms

With variable voltage variable frequency operation, any combination of voltage and frequency can be used to supply the motor, with the condition that operation should remain within the limits of rated voltage and frequency. Many methods are there. The scalar control is based on the steady–state model of motor is due to magnitude variation of the control variable only. The stator voltage can be used to control the flux, and frequency or slip can be adjusted to control the torque. Different schemes for scalar control are used, such as: constant V/f ratio, constant slip, and constant air-gap flux control. One of the most popular control techniques is by varying frequency and voltage by maintaining their ratio constant, popularly known as V/f control. The developed torque by an induction motor is directly proportional to the ratio of the applied voltage and supply frequency. By changing the voltage and the frequency and by keeping constant ratio between them the torque developed can be made constant in entire speed range. This allows us to keep the torque of the motor nearly independent on the motor velocity. It is simple to implement and cost effective and used when the motor load is approximately independent on motor speed or if load dependence on speed is known in advance. In addition, this method has advantage like low starting current, but suffer a drawback due the inherent coupling effect (both torque and flux are function of stator voltage or current and frequency) give sluggish response and system is easily prone to instability. To improve the performance a close loop mode can be implemented. However, it is expensive and destroys the mechanical robustness of the drive system.

Performance analysis of scalar-controlled drives shows that scalar control can produce adequate performance in variable speed drives, where the precision control is not required. These limitations of scalar control can be overcome by implementing vector (field oriented) control.

Vector control was introduced in 1972 to realize the characteristics of separately-excited DC motor in induction motor drives by decoupling the control of torque and flux in the motor. Vector control is widely used in drive systems requiring high dynamic and static performance. The principle of vector control is to control independently the two Park components of the motor current, responsible for producing the torque and flux respectively. In that way, the IM drive operates like a separately-excited DC motor drive (where the torque and the flux are controlled by two independent orthogonal variables: the armature and field currents, respectively). Vector control schemes are classified according to how the field angle is acquired. If the field angle is calculated by using stator voltage and currents or hall sensors or flux sensing winding, then it is known as direct vector control DVC. The field angle can also be obtained by using rotor position measurement and partial estimation with only machine parameters, but not any other variables, such as voltages or currents. Using this field angle leads to a class of control schemes, known as indirect vector control IVC. Undoubtedly, vector control and the corresponding feedback signal processing, particularly for modern sensor less vector control, are complex and the use of powerful microcomputer or DSP is mandatory or hardware with very high computational capability is essential.

3. Optimal Effcieicny Operation

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

$$T_e = k_{te} I_m I_r \text{ ----------------------------------- (1)}$$

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

From Equation (1), the 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 the same torque with different combination of flux and current value. For every load and speed condition, there exists a magnetizing current where the motor losses are minimal. So, it is well known that, for a given load torque, there exists many 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 is minimized, with a slight loss in speed accuracy. Hence, electrical losses minimization process ultimately comes down to the selection of the appropriate air-gap flux density of operation. In vector control scheme, the same can be interpreted as at a particular value of stator current, optimal efficiency can be achieved. The challenge to engineers, however, is to be able to predict the appropriate flux values at any operating points over the complete torque and speed range which will minimize the machines losses, hence maximizing the efficiency. At the same time it is also important to ascertain that the rotor speed of the motor is still stable. In addition, the nonlinearities of the induction motor characteristic and the varying of the motor variable parameters due to the 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.

4. Method of Efficiency Imtprovenet

All the 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 the first strategy which is based on the control of one specific variables or predefined relation in the drive. This variable must be measured or estimated and its value is used in the feedback control of the drive, with the aim of running the motor by predefined reference value. Slip frequency or power factor displacement are the 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 the other hand, the 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 the 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.

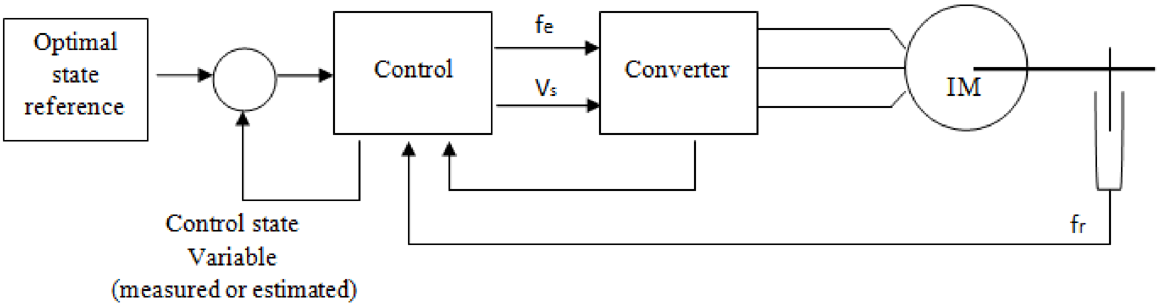

Fig. 4: Control diagram for the simple state control method

Loss Model Control is the second strategy, a drive loss model is used for optimal drive. It consists of computing the losses by using the machine model and selecting the flux level that minimizes these losses. 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 or vector. The feedback controller directs the motor to work at its minimum loss point, where the losses of both direct axis and quadrature axis are balanced. This approach is fast because the optimal control is calculated directly from the 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 the optimal operating conditions can be very complex. This strategy is also sensitive to parameter variations in the drive.

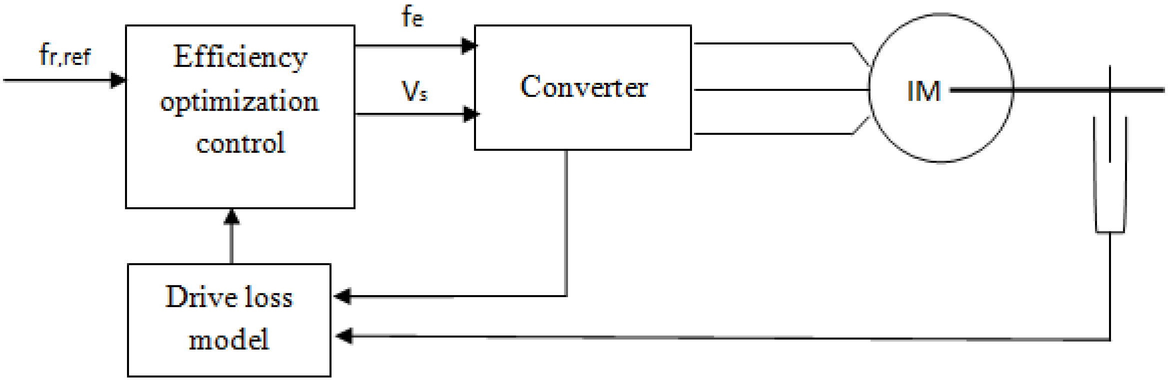

Fig. 5: Block diagram for the model based control method

Search Control Method is the third technique, in which, the on-line procedure for efficiency optimization is carried. The on-line efficiency optimization control on the basis of search, where the stator or rotor flux is decremented in steps until the measured input power settles down to the 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 the 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 the load is low and optimal operating point is found, flux is so low that the 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 the input power must be accurately measured in the control. Also, flux convergence to its optimal value sometimes can be to slow, and flux never reaches the value of minimal losses then in small steps oscillates around it. Difficulties in tuning the algorithm for a given application and the need for precise load information are also there. For these reasons, this is not a good method in industrial drives.

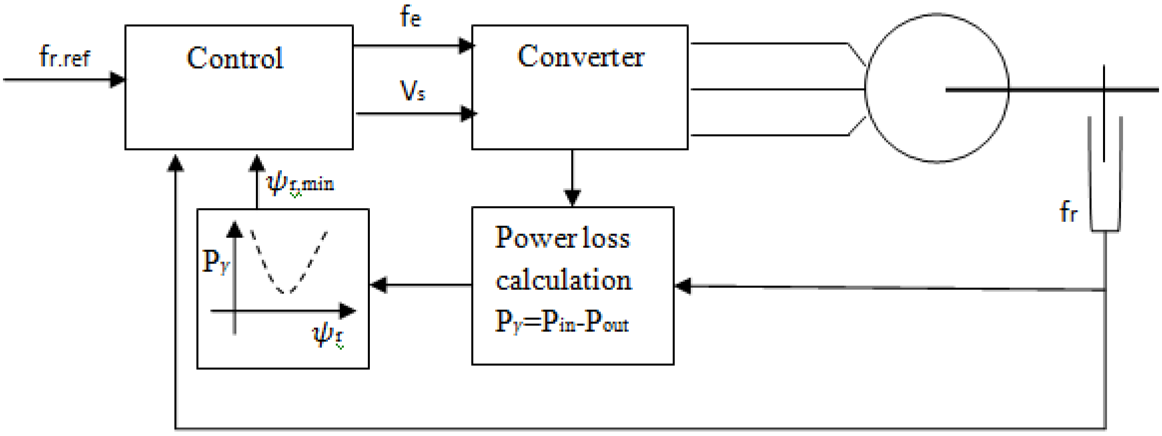

Fig. 6: Block diagram of search control method

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. 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 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 the 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 the continuously changing environment.

5. Simple State Control

A constant-optimal slip control is proposed for increasing the efficiency at light loads, based on an intuitive adaptation of the 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 the losses minimization and verify the dynamic performance of the 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 also noticed that efficiencies, with and without the optimization algorithm, are identical for rated loads.

6. 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,

$$V_{s,opt} = \sqrt{\frac{T_L \omega_s \left(R_{th}+\frac{R_r}{s}\right)^2 + X_{sh}^2}{R_{th}+\frac{R_r}{s}}} \text{ ------------------------ } (2)$$

$$\omega_{sl} = \omega_r \frac{R_r}{s} \text{ -- } (3)$$

The non-ideal factors of core saturation, some harmonics and skin effect affecting the efficiency performance are included in the analysis to yield practical results from computer simulation. Both analysis and experimental results indicate that efficiency performance with VVVF is superior to that of constant flux operation especially in light-load and steady state. 10-15% improvement in the efficiency of a 2-HP induction motor at 0.4 per unit (p.u.) load is achieved as compared to the constant flux operation.

Authors of [6-8] have worked on d-q frame and quantified optimal value of flux component current I_{ds} at which efficiency becomes optimal. In the development of the loss model, there is always a tradeoff between accuracy and complexity. Authors [9] have used natural and reference frame independent quantities (total rotor flux, active torque, rotor speed, and reactive torque corresponding to the reactive power) as state variables. Utilization of the nonlinear geometric control methodology of input–output linearization with decoupling permits the implementation of the control in the stationary reference frame. This approach eliminates the need of synchronous reference transformation and flux alignment required in classical vector control schemes. The new efficiency optimizing formulation yields a reference rotor flux, which ensures a minimum loss and yields an improved efficiency of the drive system especially when driving part load. The established loss minimization methods are designed for steady-state operation (i.e., the drive is operating in constant speed and torque). Dynamic behavior (i.e., a torque transient) is not considered.

Authors of [10-11] consider transient performance also in consideration along with efficiency improvement. Work proposed by [10] applies a dynamic space-vector model for loss-minimizing. Based on the corresponding steady-state loss function, a method is proposed for solving the loss-minimizing flux reference at each sampling period. A flux controller augmented with a voltage feedback algorithm is applied for improving the dynamic operation and field weakening. Both the steady-state and dynamic performance of the proposed method is investigated using laboratory experiments with a 2.2-kW induction motor drive, and it shows fast convergence to the optimum flux level.

In [11] during a torque transient, loss minimization is deactivated, and a minimum time controller (similar to deadbeat control) is activated. This attenuates the problem of slow torque response under reduced flux magnitude. Authors of this paper have investigated whether or not it is required to take the converter loss into account in the efficiency-optimizing control algorithms, based on loss measurements in 2.2-, 22-, and 90-kW motor drives, and agreed to not to include them. The only reason to include the converter losses is that it guarantees a higher robustness against load disturbances [12]. 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. The load torque is replaced by the stator current to remove the necessity of load torque measurement or estimation.

Authors of [13] have emphasized on loss model design. They concluded that speed regulation cannot be ensured in optimal efficiency unless the magnetic circuit nonlinearity is explicitly accounted for in the motor model. Most previous works are done by assuming machine magnetic circuit to be linear and ignoring the machine power conversion equipments. They also suggested to include power conversion equipment in loss model analysis, since the negligence of the power conversion equipments makes it impossible to deal properly with the harmonic pollution issue due to ‘motor – power supply grid’ interaction. The proposed approach in [41] uses the stator current as the control variable and depends on R_s, which is decomposed into R_q and R_d. Efficiency improvement from 5 to 50% at light load is observed.

TABLE 2: POWER LOSS FUNCTIONS AND CONCERNED MINIMIZATION VARIABLES

$\mathbf{P_{loss}}$	**x**
$\left(R_s + \frac{R_{qs}R'_r}{R_{qs} + R'_r}\right) {i_{qs}}^2 + \left(R_s + \frac{{L_m}^2}{R_{qs} + R'_r} {\omega_s}^2\right) {i_{ds}}^2$	i_{qs}
$\lvert {i_s}^2 \rvert R_s + \lvert {i_r}^2 \rvert R'_r + \frac{\lvert V_m \rvert^2}{R_r}$	$\frac{V_s}{\omega_s}$
$R_s \left({i_{qs}}^2 + {i_{ds}}^2\right) + R_s \left(i_{qs} - i_r\right)^2 + R'_r {i_r}^2$	i_{ds}
$\lvert {i_r}^2 \rvert \left(\left(1 + \frac{2\,L_s}{L_m}\right) R_s + R_r + k_{sm} {\omega_r}^2\right) + \lvert {\lambda^2}_m \rvert \left(k_e {\omega_r}^2 + k_h \omega_r + \frac{R_s}{{L^2}_m}\right) + k_{fw} {\omega_r}^2$	λ_m
$k_m \left(k_1 {\omega_{sl}}^3 + k_2 {\omega_{sl}}^2 + k_3 \omega_{sl} + k_4 + \frac{k_5}{\omega_{sl}}\right)$	ω_{sl}

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 the 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 minimum time.

7. Search Control

Input power is a parabolic function of the flux that has strictly positive second derivative with the regime-dependent minimum that can be found by various search procedures [14]. It was concluded [68] that the 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 the induction motor can be determined by the sensitivity power losses equation equal to zero. This is given by:

$$\left(c_l R_s + R_r^{'} + c_{str}\omega^2\right) I_r^{\prime 2} = \left(k_h \omega + k_e \omega^2 + \frac{R_s}{X_m^2}\right) \phi^2 \tag{4}$$

Solving for optimum air gap flux yields:

$$\phi_{opt} = I_s G_s \sqrt{\frac{1+\omega^2 T_s^2}{1+\omega^2 T_{cs}^2}} \text{ -------------------------------- } (5)$$

In Ref [47], 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. Authors of [14, 15] suggested to choose stator current as the controlled variable in spite of input power. It is proved that better results are achieved if the stator current is used as the controlled variable. In addition, the stator current has more sensitivity to the flux variation than input power. They also concluded that the air gap flux should be always kept greater than 0.3 pu independent of control algorithm. It revealed that power input to the drive is smaller in stator current minimization than the power input minimization. [15] These properties allow implementing an adaptive algorithm to determine the proper flux step without waste of time. This adaptive algorithm set a large flux step for transient state to speed up the convergence process and a small flux step for steady state to minimize the flux ripple. Authors of [16 – 18] have considered transient performance also along with efficiency improvement. Optimal flux search slows down the system response to a load and decreases the peak torque which can be developed by the motor. This problem must be addressed if the drive is to maintain satisfactory dynamic performances, suggested in [17].

In [16] Golden-section based search is implemented, which is also valid in high-speed operation. A filter is used to prevent eventual torque ripples caused by flux current variation. For better transient response the efficiency optimization algorithm is only activated when the machine is well in steady state condition. When there is a major change in speed reference, the reference flux current is set to the nominal values corresponding to the conventional vector control. The transient state is easily detected by using the speed error signal, which is shown in the efficiency optimization block. Three controllers are implemented in [18], one performs voltage perturbation for minimum input power and a second controller changes frequency to correct rotor speed loss caused by voltage drops. A third controller produces an initial commanded frequency which compensates for the variation in slip with changing load and speed. Accurate flux and torque estimation is the core of any opted control technique, is suggested by the authors of [19]. An accurate closed-loop voltage model flux and torque estimator that is insensitive to stator resistance variation has been designed. This paper also proposes an offline SC efficiency optimization technique.

8. Hybrid Methods

A perturb and observe technique is presented in [46], where the input variable is the magnetizing flux. The basic P&O algorithm is proposed in [47] where the LMT perturbs the 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. The physics-based techniques vary the frequency of the motor until the reference rotor speed is achieved. The voltage is then varied to reduce the input power. This procedure is repeated when the speed changes. It is suggested that in order to maintain maximum efficiency, the induction motor should operate at a constant slip [68]. The function of the efficiency in terms of slip frequency is derived after considerable algebraic expression is given by:

$$\omega_{sl,opt} = \frac{1-\sqrt{1-4(T_e)^2 d}}{2T_e c} \text{ -------------------------- } (6)$$

The slip frequency that result the maximum efficiency is determined by,

$$i_{s,opt} = \sqrt{T_e}\frac{\sqrt{X_{rr}}}{X_m}\sqrt{\frac{1}{\tau_r \omega_{sl,opt}} + \tau_r \omega_{sl,opt}} \text{ ----- } (7)$$

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 it to zero. The optimal torque current (I_d) for maximum efficiency is given by,

$$I_{d,opt} = I_q \sqrt{\frac{R_s(R_c+R_r)+R_c R_r}{R_s(R_c+R_r)+M_d^2\omega^2}} \text{ -------------------- } (8)$$

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

$$I_{d,opt} = I_q \sqrt{\frac{R_s(R_c+R_r)+L_d^2\omega^2}{R_s R_c+L_d^2\omega^2}} \text{ -------------------- } (9)$$

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

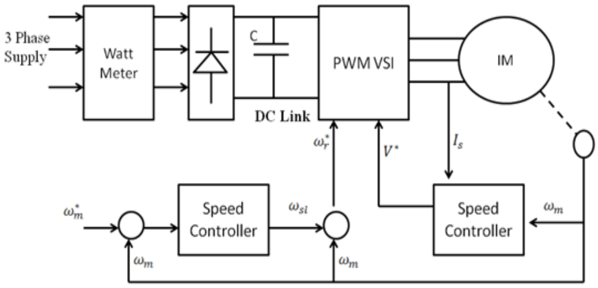

Fig. 8: Block diagram of the LMC of the Induction Motor Drive

Author of [20-23, 32] have utilized good features of both the mode of control. Both the steady-state and dynamic performance are taken care. Fast convergence 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 loss function. The loss function parameters are obtained online from input power measurement and a dedicated identification routine acting in conjunction with the common drive control functions. The 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], the first estimate is from the loss model approach and the subsequent adjustment of the flux is through the search technique. To avoid 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 s. During the 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 I_{dsref}. [51] authors have suggested 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 the corresponding steady-state loss function, a method is proposed for solving the loss-minimizing flux reference at each sampling period. In order to improve the dynamic operation of the drive, a proportional flux controller is applied.

Smooth variations instead step change in control variable to minimize input power of IM was proposed in [17]. Flux producing current (i_{ds}) was considered as variable. 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 equal to q axis power losses. In Ref [77], 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 one.

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 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 the optimum power factor. An optimum is first calculated using the motor model, then fuzzy logic uses speed feedback to compensate for the optimum power factor.

9. Modern Tools of Optimal Control

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

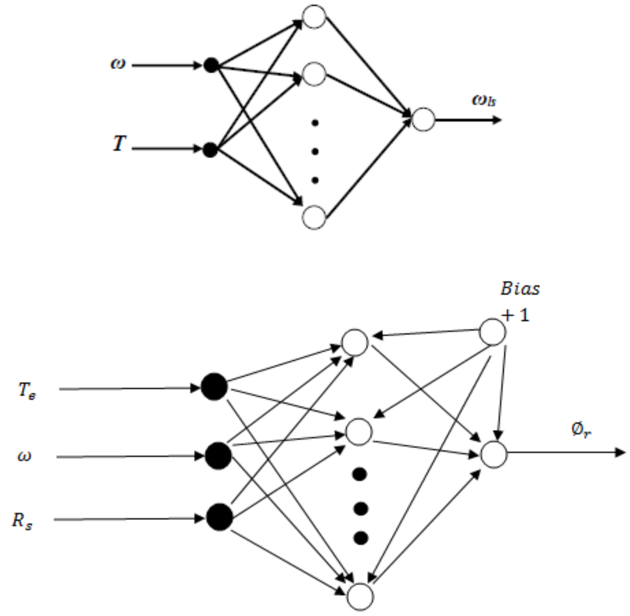

Fig. 9: Various neural network-based efficiency optimization control scheme

In [25] an ANN controller is synthesized and trained offline to determine the optimal flux level that achieves maximum drive efficiency. In [68] authors used a neural network to search in the vector control induction motor drive system. Based on the steady state induction motor model, the motor power losses are calculated as a training data. The back propagation learning algorithm is employed to train the neural network controller in different operating point. Their proposed neural control model has one input layer, two hidden layer and one output layer. The input layer consists of speed and load torque reference signals. The output layer has only one neuron for the 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 parameter uncertainty, fuzzy logic is quite suitable for power electronics and motion control. Fast convergence is reported.

Loss minimization during 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 motor efficiency in [80]. In Ref [81], fuzzy logic was used to decrement flux up to the drives settled down minimum input power. But the speed or torque command changes, the efficiency optimization using fuzzy abandoned and the rated flux was established to get the best transient performance. Feed forward torque compensator used to reduce 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 the optimal flux. When the load torque or the command speed suddenly changes, 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].

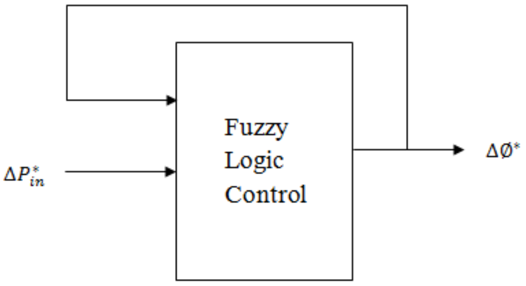

Fig. 10: Proposed fuzzy-logic scheme in [27]

Authors of [28] propose one step change of voltage, irrespective of load change. But they have suggested avoiding too large reduction in voltage since it will 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 the stator voltage per hertz ratio use fuzzy logic controller. Input of the fuzzy logic controller is the change of input power and volt per hertz ratio. The output is the 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 the 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 the voltage reference compensator.

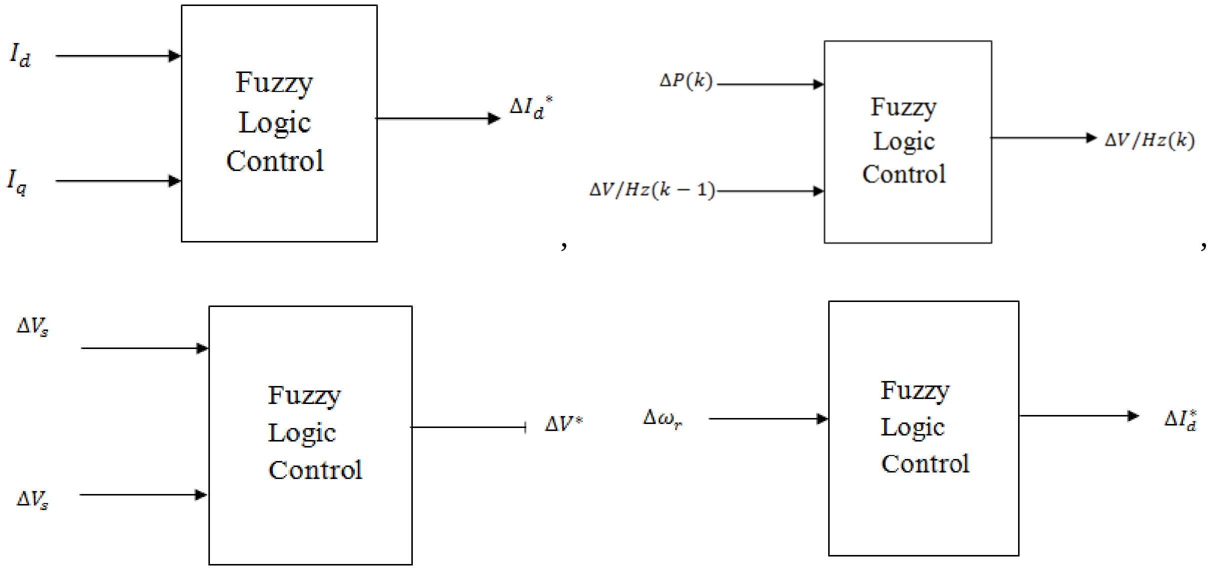

Fig. 11: Various fuzzy-logic control scheme

Few other authors compare the different flux optimization algorithms to improve efficiency at steady state in a vector controlled induction motor drive. In this paper the 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 uses 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 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 steady-state stage.

Authors of [29-30] have implemented ANN for loss minimization. In [29] the controller is designed to generate signal voltage and frequency references simultaneously. This technique allows for control of both the speed and efficiency. In order to achieve a robust BPEOC from variation of motor parameters, an online learning algorithm is employed. Authors of [30] propose a neuro-controller which adjusts the 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 the flux level that results in the minimum input power. Once this optimal flux level has been found, this information is utilized to update the rule base of a fuzzy controller that plays the role of an implicit mathematical model of the system. Initially, for any 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 the 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 the optimum point, thus ensuring true optimal efficiency operation. Authors of [33-35] have utilized all possible methods and mechanisms for performance improvement. All the possible modern tools like PSO, ANN, Fuzzy etc are used for determining optimal operating point. In [33] Fuzzy Pre-Compensated Proportional Integral (FPPI) is used to improve motor’s dynamic performances during the activation of optimal energy control. [34, 35] utilizes ANN and PSO together. In these papers, four strategies for induction motor speed control are proposed. Those four strategies are based 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 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 the loss model. Genetic algorithms to estimate motor parameters and then vary the V/f ratio to reach minimum power loss. Then optimum voltage and frequency arranged as table for the energy saving controller. For light loads on a 1.5 – hp motor, results presented in show loss reduction of more than 75% compared to nominal operation. In Ref. [28], authors used offline 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. 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 the loss model of the induction motor.

A hybrid technique, GA-PSO based vector control of induction motor for loss minimization as well as torque control is presented in [72]. PSO as used for mutation process of GA so that the learning efficiency of GA was improved. Floating point GA is applied in [73] for minimizing IM losses through flux adjustment. Basic GA is used in [74] to identify rotor time constant from the 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 neural network. Change in core loss resistance due to flux and frequency have taken into account. The variation in the iron loss resistance can be found. Where, R_{mb} is the value of R_m at rated frequency and flux.

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

Fuzzy logic is used in [49] to set the optimum d-axis stator current (i_{ds}), which in turn minimizes the input power (P_{in}). Membership functions are built based on derivative estimates $\Delta P_{in}/\Delta i_{ds}$. This determines the relationship between varying i_{ds} and the result in P_{in}, and directs the i_{ds} command towards minimum power. Simulations of the controller show that P_{in} was reduced by 50% during transients, relative to rated flux operation. Fuzzy logic is also used in [50]. Where a neuro-fuzzy combination varies the stator voltage to minimize P_{in}. The membership functions of this controller are dynamically updated using back propagation, and the neural network is trained by varying the input power. Efficiency improved by 27 points at low speeds.

10. Other Methods

The method proposed in [36] is little bit different. Authors have used Fuzzy logic controller in the algorithm for generating the reference speed for optimum energy consumption in belt conveyors. The proposed control structure is developed and tested on the detailed mathematical model of the drive system with the rubber belt. The presented algorithm is implemented on the new variable speed BC system with remote control on an open-pit mine. The measurements were performed to verify the proposed concept during the eight months of exploitation. Pontryagin’s maximum principle is used to improve the efficiency of induction motors during the acceleration and deceleration period in [37]. The approach in [40] is based on optimal control theory. The Hamiltonian of the system is found and optimal control is achieved based on optimal time and optimal losses. This application is verified mathematically, but results are not presented. Several references study loss minimization relative to the rotor flux, as in [42, 44, 45]. In [42], rotor flux is used to minimize losses, and its optimum value is derived from the motor model. Two motor parameters used in the model are estimated online: 1) R'_r; and 2) L_m. The relative convex relation between input power and rotor flux is derived analytically and verified experimentally in [45]. In [52] authors have proposed new approach known as optimal direct torque control (ODTC) which appears to be very convenient for EV, and significant losses have been reduced by this method, since the flux varies depending on the load (operating point) and the current consumed by the machine is reduced therefore, the current delivered by the battery was reduced especially during acceleration and deceleration periods. Authors of [54] stated that, the parameter variations due to different operating conditions and transient in EVs affect the performance of an induction motor drive used in an electric vehicle. A novel modeling methodology for IM is presented wherein motor parameters of various operating conditions are estimated from transient data information using an off-line method, and a correlation analysis is employed to map the parameters to operating conditions. As a result, it is possible to simultaneously estimate multi-parameters of the IM online. The effectiveness of the proposed motor model is verified by the comparison with experimental data.

11. 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. 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 offline and online 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.

REFERENCES

[1] A. M. Bazzi and P. T. Krein, "Review of methods for real-time loss minimization in induction machines," *IEEE transactions on Industry application*, vol. 46, no. 6, pp. 2319-2328, November/december 2010.

[2] J. F. Fuchsloch, W. R. Finley and R. W. Walter, “The next generation motor: designing a new approach to improve the energy efficiency of NEMA premium motors”, IEEE Conf. 2008.

[3] M. Cacciato, A. Consoli, G. Scarcella, G. Scelba and A. Testa, “Efficiency Optimization Techniques via Constant Optimal Slip Control of Induction Motor Drives”, IEEE Conf. SPEEDAM 2006.

[4] M.E.H. Benbouzid, and N.S. Nait Said, “An Efficiency-Optimization Controller for Induction Motor Drives”, IEEE Conf. Power Engineering Review, 1998.

[5] S. Chen and S. N. Yeh, ““Optimal Efficiency Analysis of Induction Motors Fed by Variable-Voltage and Variable-Frequency Source”, *IEEE Trans. Energy Conversion*, Vol. 7, No. 3, 1992.

[6] G. O. Garcia, J. C. Mendes Luis, R. M. Stephan and E. H. Watanabe, "Fast efficiency maximizer for adjustable speed induction motor drive," in *International Conference on Industrial Electronics, Control, Instrumentation, and Automation*, San Diego, CA, 1992.

[7] F. FemBndez-Bernal, A. Garcia-Cerrada and R. Faure, "Model-based loss minimization for DC and AC vector controlled motors including core saturation," in *Thirty-Fourth IAS annual meeting on Industry Applications*, Phoenix, AZ, 1999.

[8] M. N. Uddin and S. W. Nam, "New Online Loss-Minimization-Based Control," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 926 - 933, March 2008.

[9] G. Dong and O. Ojo, "Efficiency optimizing control of induction motor using natural variables," *IEEE transaction on industrial electronics*, vol. 53, no. 6, pp. 1791-1798, December 2006.

[10] Z. Qu, M. Ratna, M. Hinkkanen and J. Luomi, "Loss-minimizing flux level control of induction motor drives," vol. 48, no. 3, May/June 2012.

[11] J.-F. Stumper, A. Dotlinger and R. Kennel, "Loss minimization of induction machines in dynamic operation," *IEEE transactions on energy conversion*, vol. 28, no. 3, pp. 726-735, September 2013.

[12] F. Abrahamsen, F. Blaabjerg, J. K. Pedersen and P. B. Thoegerse, "Efficiency-optimized control of medium-size induction motor drives," *IEEE transaction on Industry Application*, vol. 37, no. 6, pp. 1761-1767, November/December 2001.

[13] A. E. Fadili, F. Giri, A. E. Margi, R. Lajouad and F. Z. Chaoui, "Towards a global control stratedy for indution motor: speed regulation, flux optimization

and power factor correction," *international journal of electrical power and energy system*, vol. 43, pp. 230-244, December 2012.

[14] I. Kioskeridis and N. Margaris, "loss minimization in scalar-controlled induction motor drives with search controllers," *IEEE transaction on power electronics*, vol. 11, no. 2, pp. 213-220, march 1996.

[15] S. Kaboli, M. R. Zolghadri and E. Vahdati-Khajeh, "A fast flux search controller for dtc-based induction motor drives," *IEEE trans. Industrial electronics*, vol. 54, no. 5, pp. 2407-2416, october 2007.

[16] M. C. Ta, C. Chakravorty and Y. Hori, "Efficiency maximization of induction motor drives for electric vehicles based on actual measurement of input power," in *IEEE conference IECON'O*, 2001.

[17] D. S. Kirschen, D. W. Novotny and T. A. Lipo, "On-line efficiency optimization of a variable frequency induction motor drive," *IEEE transaction on industry application*, vol. 21, no. 4, pp. 610-616, 1985.

[18] J. G. Cleland, V. E. Mccormick and M. W. Turner, "Design of an efficinecy optimization controller for inverter-fed ac induction motors," in *Industry application conference*, orlando,FL, 1995.

[19] H. Rehman and X. Longya, "Alternative energy vehicles drive system: control, flux, torque estimation, and efficinecy optimization," *IEEE trans. vehicular technology*, vol. 60, no. 8, pp. 3625-3634, October 2011.

[20] S. N. Vukosavic and E. Levi, "Robust dsp-based efficiency optimization of a variable speed induction motor drive," *IEEE transaction on Industrial Electrinocs*, vol. 50, no. 3, pp. 560-570, June 2003.

[21] C. Chakroborty and Y. Hori, "Fast efficiency optimization techniques for the indirect vector-controlled induction motor drives," *IEEE transaction on industry application*, vol. 39, no. 4, pp. 1070-1076, July/August 2003.

[22] C. Chakraborty, C. T. Minh, T. Uchida and Y. Hori, "Fast search controllers for efficinecy maximization of induction motor drives based on dc link power measurement," in *Power conversion conference*, Osaka, 2002.

[23] Z. Qu, M. Ranta, M. Hinkkanen and J. Luomi, “Loss-Minimizing Flux Level Control of Induction Motor Drives”, *IEEE Trans. Industry Applications*, Vol. 48, No. 3, May/June 2012.

[24] B. Pryymak, J. M. Moreno-Eguilaz and J. Peracaula, "Neural network flux optimization using a model of losses in induction motor drives," in *8th international conference on modeling and simulation f electric machines, converters and systems*, 2006.

[25] O. E. Ebrahim, M. A. Badr, A. S. Elgendy and P. K. Jain, "ANN-based optimal energy control of induction motor drives in pumping applications," *IEEE transaction on energy conversion*, vol. 25, no. 3, pp. 652-660, September 2010.

[26] J. Li and Y.-R. Zhong, "Efficiency optimization of induction machines based on fuzzy search controller," in *machine learning cybernetics*, 2005.

[27] G. C. D. s. B. K. B. and J. G. c. , "fuzzy logic based on-line efficiency optimization control of an indirect vector controlled induction motor drive," in *International Conference on Industrial Electronics, Control, and Instrumentation*, Maui, HI, 1993.

[28] K. Sundareswaran and S. Palani, "fuzzy logic approach for energy efficient voltage controlled induction motor drive," in *IEEE International Conference on Power Electronics and Drive Systems*, 1999.

[29] A. H. M. Yatim and W. M. Utomo, "Efficiency optimization of variables speed induction motor drives using online back propogation," in *Power and energy conference*, 2006.

[30] I. Choy, S. H. Kwon, J. Y. Choi, J. W. Kim and K. B. Kim, "On-line efficiency optimization control of a slip angular frequency controlled induction motor drive using neural network," in *industrial electronic,control, and instrumentation IECON 22nd International Conference*, Taipei, 1996.

[31] B. K. Bose, N. R. Patel and K. Rajeshekara, "A neuro-fuzzy-based on-line efficiency optimization control of a stator flux-oriented direct vector-controlled induction motor drives," *IEEE transaction on Industrial electronics*, vol. 44, no. 2, pp. 270-273, April 1997.

[32] D. D. S. Almeida, W. C. P. D. A. Filho and G. C. D. Sausa, "Adaptive fuzzy controller for efficiency optimization of induction motors," *IEEE transaction on Industial motors*, vol. 54, no. 4, pp. 2157-2164, August 2007.

[33] T. R. Chelliah, J. G. Yadav, S. P. Srivastava and P. Agrawal, "Optimal energy control of induction motor by hybridization of loss model controller based on praticle swarm optimization and search controller," in *Nature & Biologically Inspired Computing*,

Coimbatore, 2009.

[34] R. H. Hamid, A. Amin, M.A. and A. A. A. El-Gammal, "optimal operation of induction motors using artificial neural network based on particle swarm optimization Pso," in *IEEE*, 2006.

[35] R. H. Hamid, A. M. Amin, R. S. Ahmed and A. A. El-Grammal, "New technique for technique for maximum efficiency and minimum operation cost of induction motors based on practicle swarm optimization," in *IEEE industrial electronic*, Paris, 2006.

[36] B. L. Risti'c and B. L. Jefteni, "Implementation of fuzzy control to improve energy efficency of variable speed bulk material transportation," *IEEE trans. on industrial Electronics*, vol. 59, no. 7, 2012.

[37] C. M. Vega, J. R. Arribas and D. Ramirez, "Optimal regulation of electric drives with constant load torque," *IEEE transaction on Industrial Electronic*, vol. 53, no. 6, pp. 1762-1769, 2006.

[38] S. M. Yang and J. Chin, "Loss minimization control of vector-controlled induction motor drives," vol. 26, no. 1, 2003.

[39] I. Kioskeridis and N. Margaris, "Loss-minimization in induction motor adjustable-speed drives," *IEEE trans. Ind. Electron*, vol. 43, no. 1, 1996.

[40] L. Kawecki and T. Niewlerowicz, "Bi-criterial optimization in induction motors speed control taking into consideration the elcrtromagetic transients," *International Symposium on Industrial Electronics*, vol. 2, pp. 931-939, 1996.

[41] J. Liu, L. Fei, S. Hu and T. Q. Zheng, "Optimal efficinecy control of linear induction motor for linear metro," in *Conference on Industrial Electronics and Applications*, Harbin, 2008.

[42] G. Mino-Aguilar, J. M. Moreno-Eguilaz, B. P. and J. P. , "An induction motor drive including a self-tuning loss-model based efficiency controller," in *Applied Power Electronics Conference and Exposition*, Austin, 2008.

[43] S. Sujitjorn and K. L. Areerak , "Numerical approach to loss minimization in an induction motor," *Applied Energy*, vol. 79, no. 1, pp. 87-96, 2004.

[44] E. Poirier M. Ghribi and A. Kaddouri, "Loss minimization control of induction motor drives based on genetic algorithms," in *International Electric Machines and Drives Conference*, Cambridge, MA, 2001.

[45] A. M. Bazzi and P. T. Krein, "Input power minimization of an induction motor operating from an electronic drive under ripple correlation control," in *Power Electronics Specialists Conference*, Rhodes, 2008.

[46] K. Kioskeridis and N. Margaris, "loss minimization in scalar-controlled induction motor drives with search controllers," *IEEE transaction on power electronics*, vol. 11, no. 2, pp. 213-220, march 1996.

[47] P. Famouri and J. J. Cathey , "Loss minimization control of an induction motor drive," *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 32-37, Jan/Feb 1991.

[48] T. Ohnishi H. Miyazaki and H. Kitsu , "High efficiency drive of an induction motor by means of V/F ratio control," in *14 Annual Conference of Industrial Electronics Society*, singapore, 1988.

[49] L. R. S. P. C. S. C. A. K. S. and Y. H. S. , "Efficiency optimization of induction motor using a fuzzy logic based optimum flux search controller," in *International Conference on Power Electronics, Drives and Energy Systems*, new delhi, 2006.

[50] A. H. M. Yatim and W. H. Utomo, "Neuro-fuzzy on-line optimal energy control for variable speed compressor motor drive system," in *International Conference on Power Electronics and Drives Systems*, 2005.

[51] N. K. T. R. Chelliah and S. S. , "Adaptive control schemes for improving dynamic performance of efficiency-optimized induction motor drives," *ISA Transactions*, vol. 57, pp. 301-310, 2014.

[52] F. Tazerart, Z. Mokrani, D. Rekioua and T. Rekioua, "Direct torque control implementation with losses minimization of induction motor for electric vehicle applications with high operating life of the battery," *International journal of hydrogen energy*, vol. 40, no. 39, pp. 13827-13838, 19 October 2015.

[53] M. A. Magzoub, S. B. Nordin and R. B. Ibrahim, "Efficiency improvement of induction motor variable speed drive using a hybrid fuzzzy-fuzzy controller," in *Clean, Efficient and Affordable Energy for a Sustainable Future: The 7th International Conference on Applied Energy*, 2015.

[54] Y. L. "Modeling and simulating of the induction motor in electric vehicle applications," in *27th Chinese Control and Decision Conference*, Qingdao,

2015.

[55] A. C. and S. H. , "investigation and analysis of high performance green energy induction motor drive with intelligent estimator," *Renewable Energy*, 2015.

[56] C. Zhu, Y. Wang and L. Hou, "improved direct torque control for induction motor with fuzzy-PI controllers," in *International Conference on Logistics Engineering, Management and Computer Science (LEMCS 2015)*, Shenyang, 2015.

[57] F. Abrahamsen, "Energy optimal control of induction motor drives," Institut for Energiteknik, Aalborg Universitet, denmark, 2000.

[58] B. Blanusa, "New trends in efficiency optimization of induction motor drives," university of banja luka, bosnia and herzegovina, 2010.

[59] A. M. A. and O. T. H. , "Swarm Intelligence Applications in Electric Machines," in *Computer and Information Science » Numerical Analysis and Scientific Computing*, Rijeka, Croatia: Intech LTD., 2009, pp. 11-50.

[60] M. H. Rashid, "Artificial Neural Network Applications in Power Electronics and Electrical Drives," in *Power Electronics Handbook: Devices, Circuits and Applications*, second ed., Sydney, New South Wales: Elsevier Inc., 2007.

[61] B. Karanayil, M.F. Rehman, Artificial Neural Network Applications in Power Electronics and Electrical Drives", Sydney, New South Wales, Australia, Chapter 36.

[62] S. A.-H. Soliman and A.-A. H. Mantaw, mathemetical optimization techniques, modern optimization technique with applications in electric power system, 1, Ed., New York: Springer-Verlag, 2012.

[63] R. Krishnan, Electric Motor Drives: Modeling, Analysis, and Control, New Jersey: Prentice Hall, 2001.

[64] B. K. Bose, modern power electronics and ac drives, vol. 1, new jersy 07458: Prentice Hall, 2002.

[65] S. S. Rao, enggineering optimization: theory and practice, john wiley & sons: John Wiley & Sons, Inc., 2009.

[66] M. Clerc, Particle swarm optimization, London: ISTE Ltd., 2006.

[67] D. Gan, "sensorless and efficiency optimized induction machine control with associated converter PWM modulation schemes," Tennessee Technological University, 2005.

[68] Y. Yakhelef, "Energy efficiency optimization of induction motors," Boumerdes University, Boumerdes, Algeria, 2007.

[69] A. H. M. Yatim and W. M. Utomo, "To develop an efficient variable speed compressor motor system," universiti teknologi Malaysia (UTM), Skudai, Malasia, 2007.

[70] "Induction motor fed by PWM frequency inverter," WEG Equipamentos Elétricos S.A., International Division, Jaraguá do Sul - SC - Brazil.

[71] T. Fletier, W. Eichhammer and J. Schleich, "Energy efficiency in electric motor systems: Technical potentials and policy approacehs fir developing countries," United Nations Industrila Development, Vienna, 2011.

[72] D. H. Kim, "ga-pso based vector control of indirect three phase induction motor," *Applied Soft Computing*, vol. 7, no. 2, p. 601–611, 2007.

[73] 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

[74] L. R. Valdenebro and E. Bim, "A genetic algorithm approach for adaptive field oriented control of induction motor drives," in *International Conference Electric Machines and Drives*, Seattle,WA, 1999.

[75] E. S. Abdin, G. A. Ghoneem, H. M. Diab and S. A. Deraz, "Efficiency optimization of a vector controlled induction motor drive using an artificial neural network," in *The 29th Annual Conference of the IEEE Industrial Electronics Society*, 2003.

[76] S. K. Sul and M. P. Ho, "A novel technique for optimal efficiency control of a current-source inverter-fed induction motor," *IEEE Transactions on Power Electronics*, vol. 3, no. 2, pp. 192-199, 1988.

[77] S. L. and K. N. , "Loss minimization control scheme for induction motors," in *Electrical Power Application*, 2004.

[78] J. Moreno-Eguilaz, J. Peracaula, M. Cipolla and P. J. Da Costa Branco, "induction motor optimum flux search algorithms with transient loss minimization using fuzzy logic based supervisor," in *28th Annual IEEE Power Electronics Specialists Conference*, St. Louis, MO, 1997.

[79] k. Sundareswarn and s. Palani, "Fuzzy logic approach for energy efficient voltage controlled induction motor drives," in *Power electronic and drive system*, 1999.

[80] G. C. D. Sousa, B. K. Bose and J. G. Cleland, "Fuzzy logic based on-line efficiency optimization control of an indirect vector-controlled induction motor drives," *IEEE transaction on Industrial Electronics*, vol. 42, no. 2, pp. 192-198, April 1995.

[81] J. M. "Fuzzy logic based improvements in efficiency optimization of induction motor drives," in *Proceedings of the Sixth IEEE International Conference on Fuzzy Systems*, barcelona, 1997.

V. K. Gupta received the B.E. in Electrical & Electronics Engineering from CIT, Rajnandgaon, CSVTU, (C.G), and pursuing M.E. in Power Electronics from RCET, Bhilai, CSVTU (C.G.) India. His research interests include power electronics and optimal control of drives. He has rewarded with fellowship on Rashtriya avishkar abhiyan from AICTE. He is student member of IEEE.

B. 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 optimal control of machines. She has rewarded with fellowship on Rashtriya avishkar abhiyan from AICTE. She is student member of IEEE.

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