Efficiency Improvement of Induction Motor Drives used in Pumping Applications

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Abstract – Induction motors more used in industries because of its power/mass relation, robustness, efficiency, low cost and nearly maintenance free in operation from its life cycle. However, motors with higher losses, waste a lot of energy that will increase its operational cost. The high energy uses and the huge number of operating units, even a small improvement in efficiency gives the greater effect for entire energy consumptions and operational cost. This thesis uses key features of loss model control (LMC) for estimation and reproduction current optimal I_{ds}. At first, loss model of induction motor is used for loss-minimization expression considering core saturation and loss expression is used to derive an optimal I_{ds} expression and estimated for various load profiles and finally tabulated, a look-up table in MATLAB is designed for 100 HP, 575 Volt, and 60 Hz induction motor. These lookup tables reproduce optimal I_{ds} value, according to the run-time load profile, in feed-forward manner, and this eliminates run-time loss model complex computation. Two different loss model control approaches are compared with conventional rated flux operation in variable load conditions, their Loss Minimization Factor (LMF) and consequently optimal value of flux component of current (I_{ds}) are evaluated and corresponding efficiency rise are compared together as well as with constant flux mode of operation.

Index Terms – Induction motor, neural network control, efficiency optimization, loss model control, search control.

1. INTRODUCTION

Most the electricity generation is from non-renewable or fuel resources like oil, coal and natural gases. The limited resource, greenhouse effects, increasing price, increasing load demand are some factors that encourage efforts for energy-saving. Globally, around 65-70% of the total electricity is consumed by electric motor, and around 85-90% of this electricity is utilized by a three-phase squirrel-cage induction motors of various capacities ranging up to 100 HP, along with annual expansion rate of 1.5% in the industrial sector and 2.2% in the tertiary sector. Since huge numbers of such motors are operational worldwide and every year their numbers are increasing, a small improvement in efficiency will contribute towards the saving of revenue, fuels uses and other associated factors. Globally, every 1% improvement in motor efficiency might lead to savings of over $1 billion per annum in energy prices, 5.4-9.1 million tons less per annum of combust coal and nearly 13.6-18.1 million tons less greenhouse emission into the atmosphere, as per reports available. Surveys done in developing countries by various international agencies conclude that a full implementation of efficiency improvement choices might scale back worldwide electricity demand up to 7 percent, hence considerable savings of energy. Various energy efficiency audits also suggest implementing best minimum energy performance standards (MEPS) for all electric motors that are operational worldwide. This will result 325 terawatt hours of annual electrical energy-saving, hence CO_2 reduction by 206 million tons, by the year 2035. [24]

The motors those are idling; partially loaded or oversized waste a lot of electricity in many applications and hence great loss of revenue occurs. In general, the partial loading happens more often for prolonged period in many applications. Electric power research institute (EPRI) report indicates that 60-65% of industrial motors are operating below 60% of their rated load capacity. That is, 35-40% of the motors are endlessly wasting the electricity due to its poor efficiency in partial loading, is being focused as wide area for energy-saving, reflects the share of motor systems in the total electricity consumption in developed countries. Some of electricity consuming segments are pumping, fan and compressed gas systems, HVAC (heating ventilation and air conditioning), refrigeration are the major applications. In a report produced by energy information administration (EIA) survey, done for heating, ventilation and air conditioning (HVAC) applications, it is assessed that the electricity consumed in HVAC applications is nearly 50% the full electricity consumed in a typical commercial building use in Malaysia, and most of time induction motors used there, and spend much time running at low loading. The pumping systems account for nearly 20% of the world's energy used by electric motors. Such applications have a wide aspect of energy-saving by having energy-efficient control of variable frequency drive (VFD) is used. Besides this, the many applications, like-electrical vehicles, traction, marine vehicles, where electrical energy needs to be consumed with the best method and use of motor in such application needs an energy optimization control strategy required [24]. This thesis proposes a work an energy-efficient optimal control with the LMC (loss minimization control) scheme for induction motor drives used in a pumping, where we get significant efficiency improvement, and hence energy-saving, while operating at partial load, especially at steady-state conditions, by simply adapting optimal flux operation, instead rated flux operation all the time for the projected load.

2. METHODS OF OPTIMAL FLUX OPERATION

All the optimal control schemes are mostly divided into three categories, the Simple State Control, Loss Model Control and Search Control. Many authors only recognize these two types (SC and LMC), since SSC can be viewed as a simpler form of LMC. The first strategy is Simple State Control which is based on the control of a one specific variable or predefined relation in the drive. The goal running the motor by predefined reference values the control variable must be measured, this value and its value are again used in feedback control of the drive. In these strategy controls mostly variable used as slip frequency or power factor displacement. Which one is chosen is depends on which one is measurement signals is available. In this strategy, it is simple, but gives good results only for a narrow set of operating conditions. Also, it is sensitive to the parameter changes due to the temperature and magnetic saturation in the drive system. In strategy overall, these methods only yield suboptimal operation since parameter variations do not take into account due to changes in temperature and saturation effects.[23]

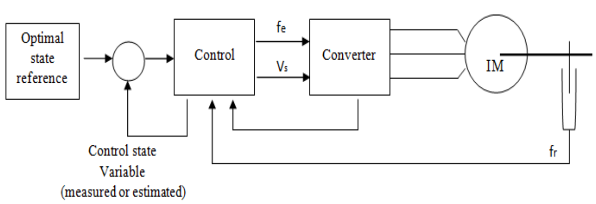

Fig.1: Block Diagram of Simple State Control Method

Loss Model Control is second strategy, in this for finding optimal value of drive a loss model are used. The machine model is used for computing the losses, and also selecting the flux level that minimizes these losses. The optimal control is directly calculated from loss model so that this approach is fast. But, for finding of the optimal operating conditions for power loss modeling and calculation is complex. These strategies are also sensitive to any variations in parameter in the drive. [23]

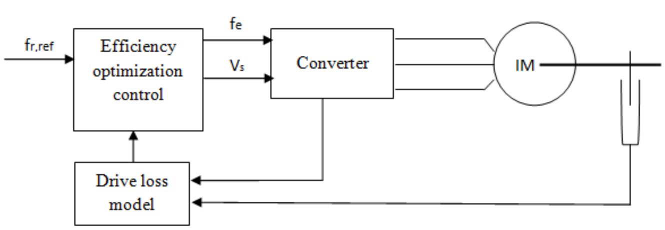

Fig. 2: Block Diagram of Model Based Control Method

Search Control is the third technique, in this method the on-line procedure used for efficiency optimization. The search is based on on-line for efficiency optimization control, where the stator or rotor flux is decremented in steps till the input power measured value is settles to the lowest value and it is a very effective result. As compared to other strategies method Search strategy has some important advantage. The main advantage of this method is completely insensitive to parameter variations while the other strategies the effects of the parameter variation caused due to temperature and saturation was much expressed. Besides all the good characteristics, there is some problem with Search strategy. When the optimal operating point was found at that time the load is low, so the flux is low so the motor is very sensitive to the load perturbations. Also, sometimes it can be slow for flux convergence for its optimal value, and the flux never reaches minimal loss values than its present small steps oscillates around it. [23]. In various literature review uses of soft computation technique techniques like an artificial neural network (ANN), nature inspired algorithms (NIA), expert systems and fuzzy logic system, Genetic algorithm and differential schemes evolution is used in optimization, have significant utility in flux optimization in IM drives. AI controllers there many types are available and it applies to IM for optimization, control as well as design and is discussed in various literatures.

3. SIMPLE STATE CONTROL

This paper deal a field-oriented scheme of induction motor drive gives good efficiency optimization with the power factor tracking. Simulation results demonstrate the efficiency is optimized in the light load region. In this noticed that efficiencies, with and without the optimization algorithm, are also being identified for rated loads. This algorithm is used all types of loads as a new induction motor field oriented controller are proposed in this author. It is clearly illustrated that the light loaded motor speed and torque (load torque), for a nominal speed reference (with and without the optimization algorithm) rotor dynamics transition is quite good. However, the torque capabilities are significantly increased and its efficiency is significantly increased. [4] In light loads a constant-optimal slip control is proposed for the efficiency improvement, based on an intuitive adaptation of the well known Maximum Torque per Ampere (MTA) algorithm, for this make ensure a constant-optimal slip. MTA strategy imposes a constant optimal slip control and it is the equal inverse of the time constant of the rotor [3].

4. LOSS MODEL CONTROL

Many works has been recounted to minimize losses in IM by using different variables for different strategies. Few use slip speed, excitation current, rotor flux, voltage, speed etc, few others is using ANN derived offline, or estimate the parameters on line and then optimize minimum losses. Fig 3 simple block diagram of loss minimization method which is more use in many authors in various literature reviews.

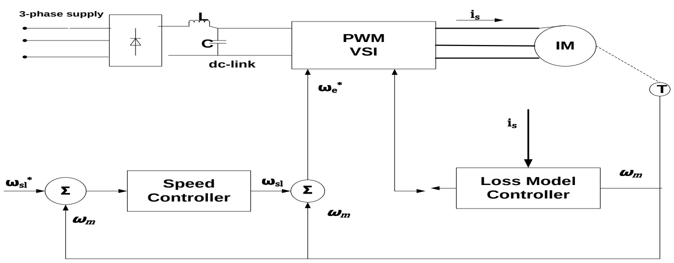

Fig. 3: Block diagram of the LMC of the Induction Motor Drive.

Authors have used the loss model; it is derived optimal value voltage and frequency. The optimum voltage and slip frequency are achieving the minimum power losses, under specific speed and torque for without any consideration of harmonic frequency, are defined,

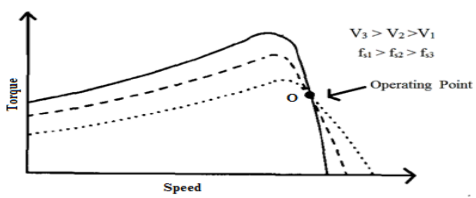

Fig.4: Steady-state torque speed characteristic curves.

In VVVF method their each load speed and torque, there are exists many different combinations of the input voltage and input frequency to yield this operation. However the efficiencies are different among those Combinations of input voltage and frequency. The purpose of this paper is to find out, by analysis and simulation, the optimal efficiency set of input voltage and frequency and to construct the test system for experimental justification. The non-ideal factors such as core saturation, harmonics and skin effect cause affecting the efficiency performance are also included in analysis of practical simulation in computer. For light-load and steady state experimental results show that efficiency performance with VVVF is superior to that of constant flux operation. [5]

This author has worked on d-q frame and flux component current I_{ds} at which efficiency becomes optimal. There is always a trade-off between accuracy and complexity for the development and analysis of the loss model. The implementation to control stationary reference frame Utilize the geometric control, nonlinear methodology of the input–output linearization with decoupling co-efficient phenomena. This approach excludes classical vector control requirement schemes, such as the need of synchronization reference transformation and flux alignment. The new optimizing efficiency formulation yields by a reference rotor flux. It is ensuring that the minimum loss and yields an improved efficiency, especially in driving in part loads, of the drive system. The designed the operation of steady-state (i.e., the drive is operating at constant speed and constant torque) are considered in loss minimization methods. And it does not consider the Dynamic behaviour (i.e., a torque transient). [6]

After applying maxima, minima principle, optimal efficiency condition is achieved

$$i_{ds} = \sqrt{\frac{R_q}{R_d(\omega)}}\, i_{qs} = K_{min}(\omega)\left|i_{qs}\right|, \quad (1)$$

Where

$$K_{min}(\omega) \triangleq \sqrt{\frac{R_s\left(R_{qls} + R_r\right) + R_{qls}\, R_r}{R_s\left(R_{qls} + R_r\right) + M_d^2\omega^2}}$$

This is called loss minimization factor (LMF).

Authors discussed the mathematical relation, the condition for minimum losses, that minimizes copper and iron losses as a function of speed and torque are fulfilled if following relation holds good, between the two currents, that is torque component and flux component of current, I_{qs} and I_{ds}, shown in equation

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

The natural and reference frame independent quantities (total rotor flux, active torque, rotor speed, and reactive torque corresponding to the reactive power) used as a state variable in. The implementation to control stationary reference frame Utilize the geometric control, nonlinear methodology of the input–output linearization with decoupling co-efficient phenomena. This approach excludes classical vector control requirement schemes, such as the need of synchronization reference transformation and flux alignment. The new optimizing efficiency formulation yields by a reference rotor flux. It is ensuring that the minimum loss and yields an improved efficiency, especially in driving in part loads, of the drive system. The designed the operation of steady-state (i.e., the drive is operating at constant speed and constant torque) are considered in loss minimization methods. And it does not consider the Dynamic behavior (i.e., a torque transient). [9]

In this paper it considered transient performance along with the efficiency improvement consideration. For dynamic space-vector model applied for loss-minimizing proposed in this work. In this paper model takes hysteresis losses and eddy-current losses as well as the magnetic saturation into the account and it is also improves the flux estimation and rotor-flux-oriented control. The proposed method is solving the loss-minimizing flux reference by using a steady-state loss function corresponding, at each sampled time period. In this for the dynamic operational improvement and the field weakening, flux controller augmented is applied along with a voltage feedback algorithm. Performance shows for both the steady-state performance and dynamic performance and it shows fast convergence optimum flux level. [10]

In This paper it also considered the transient performance along with the efficiency improvement consideration. In this loss minimization is deactivated and a minimum time controller (similar to the deadbeat control) during a torque transient state it is activated. The flux is controlled such that a desired asymptotic torque response is obtained, while the iron and ohmic losses are minimized, and this will optimizing efficiency is achieve under a constrained output value. This slow torque response problem attenuates by using of reduced flux magnitude. The authors have investigated efficiency-optimizing control algorithms, whether the converter loss is required or not, based on loss measurements in 2.2-KW, 22-KW, and 90-KW motor drives, and agreed to not to include them. [11]

This paper has accentuated on loss model design. They concluded that for optimal efficiency, speed regulation cannot ensure, unless the magnetic circuit nonlinearity is explicitly accounted for in the motor model. The machine, magnetic circuit is assumed to be linear and ignoring machine power conversion equipments are most of the previous work. They also suggested for loss model analysis the power conversion equipment are also included, since the negligence of equipments makes it impossible to deal with the harmonic related issues due to 'motor – power grid supply' interaction [13].

5. LOOK-UP TABLE CONTROLLER

In this thesis, two efficiency optimization methods using loss model concept are utilized. For implementation of optimal efficiency control, I_{ds}^* command signal in conventional vector control loop of internal both are redefined based on speed and torque signal required by the load. Block diagram is shown in figure 5.1 optimal controller is switched when change in torque and speed is sensed zero, which gives enhanced efficiency performance. Investigation is done on MATLAB with simulink. The existing conventional vector control loop is redefined for 100-HP, 575 V and 60 Hz with consecutive changes in subsystem as well, as per practical data defined from water treatment plant.

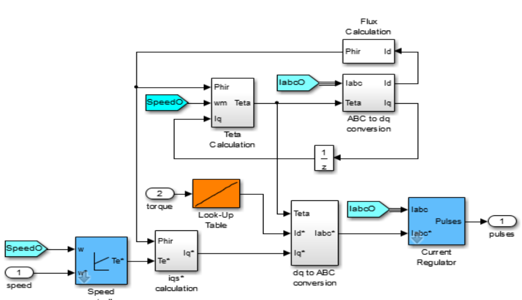

Fig. 5: Proposed Optimal Controller

In optimal operation, LMC is used for development of optimal I_{ds} values for efficiency optimization and a look-up table is designed which basically reproduces the value of I_{ds} as command signal, in conventional vector control loop instead of its constant I_{ds} value. The equations used in development of optimal

$$I_{dsref} = I_{qs}\sqrt{\frac{(R_s+R_r)R_c}{R_s\{(R_c+R_r)+R_c\}+L_d^2\omega_r^2}} \quad (3)$$

$$I_{d,opt} = I_q\sqrt{\frac{R_s(R_c+R_r)+R_cR_r}{R_s(R_c+R_r)+M_d^2\omega^2}} \quad (4)$$

Loss Minimization Factor (LMF), is estimated for partial load condition. LMF is estimated at various load torque for a various speeds. The speed variation effect is seen negligible while estimating LMF. For those estimated values of LMF are again used for estimation of the optimal reference flux component of current values (I_{ds}*), eq 3, 4 which are finally tabulated to developed the look-up table in MATLAB. For a three-phase induction motor 100 HP, 60 Hz, 575V, the optimal reference I_{ds}* values for the different load torques, at 150 rad/sec speed at steady – state conditions are shown in Table 1.

Table 1 Optimal I_{ds} Values at Steady-State for 180 Rad/s

Torque (N-m)	400	350	300	250	200	150
Id* Optimal 1	39.52	34.96	30.32	25.62	20.92	16.20
Id* Optimal 2	48.31	42.73	37.05	31.32	25.57	19.80
I_d* Rated (A)	27.67	27.67	27.67	27.67	27.67	27.67

6. RESULTS AND DISCUSSIONS

The proposed scheme uses load torque information at a known speed in feed-forward way, and generates proper value of flux component of current (I_{ds}), that maximize the motor efficiency at that given load profile, with the help of look-up table. The look-up table basically serves as reference value (I_{ds}*) generator in the conventional vector control model available in MATLAB. In MATLAB simulation the output efficiency is compared with different load torque condition has shown in Table 1 and Table 2 for at speed of 180 rd/s and 90 rad/s. The simulation result shows that at full load torque both methods is saving same input power but if decreases in load torque 2nd is more energy saved as compared to 1st method. The result is shows that two energy saving efficiency operations method 2nd operations is taken less input power as compared to optimal 1st operation so the overall efficiency of motor is increase and energy saving possible. A significant efficiency improvement is achieved by the two methods as well as 2nd method offer additional 1-2% margins as compared to first method of efficiency optimization using loss model concept, in partial load condition and steady state. This result is also shows that for both the method optimal operation are soupier to that of vector control operation in various loads. This simulation performed on 100 HP, 575 Volt, 60 Hz induction motor, at various load torques at wide range of speed. The dynamic performance as well as steady state performance also is satisfactory for optimal operation and vector control respectively.

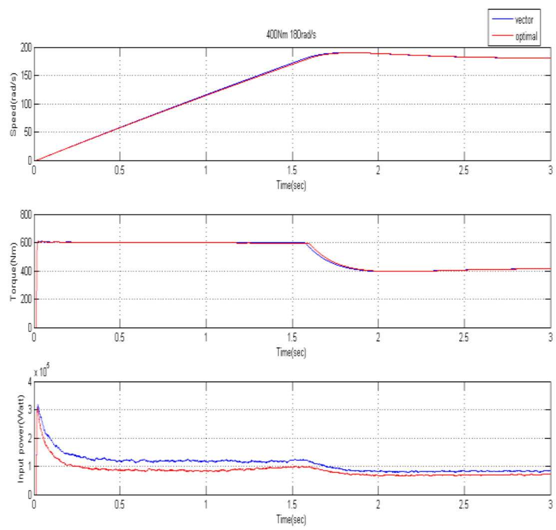

Fig. 6: Speed, Torque and Input Power performance at rated load torque (400N-m) at 180 rad/sec speed for optimal 1 operation

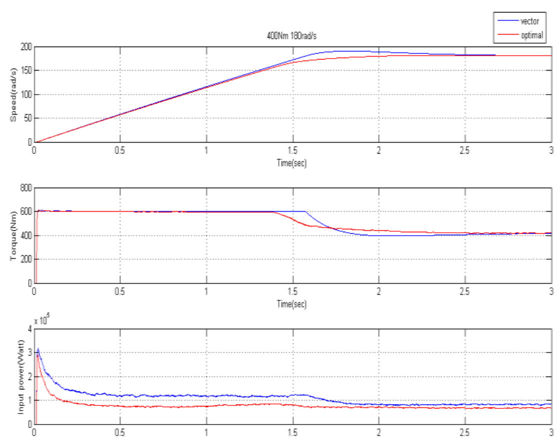

Fig. 7: Speed, Torque and Input Power performance at rated load torque (400N-m) at 180 rad/sec speed for optimal 2 operation.

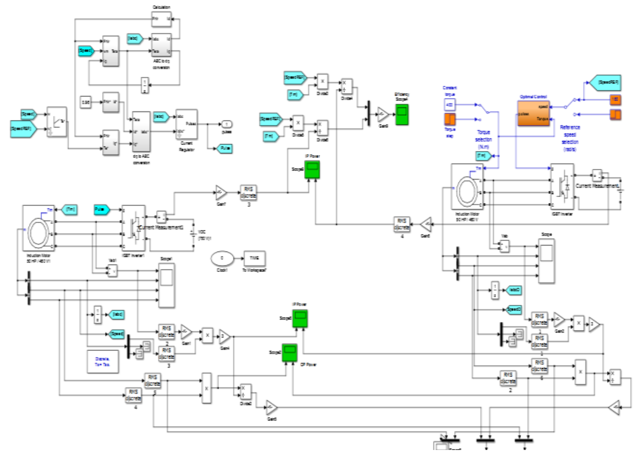

Fig. 8 Matlab Model with look-up table Controller for reproduction of I_{ds}

7. CONCLUSION

In this thesis, two efficiency optimization methods using loss model concept are utilized. For implementation of optimal efficiency control, I_{ds}^* command signal in conventional vector control loop of internal both are redefined based on speed and torque signal required by the load. Investigation performs on MATLAB with simulink. The existing conventional vector control loop is redefined for 100-HP, 575 V and 60 Hz with conceptive changes in subsystem as only, as per practical data defined from water treatment plant. In this along with comparison the two methods is used for best efficiency performance and for energy saving of induction motor are vector control and optimal control are used for efficiency comparison. The result is conclude that optimal 2 operation is take less input power at same load and speed so overall efficiency are increased. The result is also conclude that optimal operation is taken less input power as compare to the vector control for same input, so input power saved and efficiency.

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