Energy-Optimized Fuzzy Control of Induction Motors Based on Nonintrusive Efficiency Estimation

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Abstract—Electricity is the main type of energy consumed by industry. Awareness of opportunities for reducing electrical consumption has brought an emphasis on electrical energy saving for research such as in power electronics. This paper proposes an energy optimized control using fuzzy logic for induction motors based on nonintrusive efficiency estimation. The presented control is viewed as a direct energy saving technique since it takes into account both the input and output powers of the induction motor, through feedback of the efficiency estimate.

I. INTRODUCTION

TRADITIONAL requirements from the industry, such as improving product quality, reducing manufacturing cost, and lessening material/energy consumption, are being highlighted and become new demands for the research in control application. As electricity is the main type of energy consumed by industry, awareness of opportunities for reducing electrical consumption has brought an emphasis on electrical energy saving for research such as in power electronics [1].

Three-phase, squirrel-cage induction motors are the predominate type of electric motors. As in-service induction motors are often oversized, or the load may well below the rated level, average efficiency of such motor systems is inferior. In many cases, it is expensive to employ an inverter that adjusts both the supply frequency and the applied voltage. Often, induction motors can be equipped with voltage regulators instead. Power electronic soft-starters are the primary variety of such regulators.

It is concluded [2] that the research of power electronics will be driven not by itself but the application integration for electric transformation, and the issue of energy saving will undoubtedly be an emphasis of power electronic technology [3]. For energy saving of induction motor operation, more efforts should be made on the detection of the motor operation and the control of the regulator.

Efficiency detection is a key part of the integrated techniques for energy saving. Many researches have been made about the efficiency detection of induction motors during the last decade [4-5]. There are about 30 methods for efficiency detection available with varied intrusion and precision levels. However, most of them are usually not suitable for in-service application due to factors such as complexity, high cost and intrusiveness.

In [4], several candidate methods were recommended for nonintrusive efficiency detection, which make use of information from motor terminal quantities and motor nameplate data so as to eliminate the need for mechanical transducers. Among these approaches, the air-gap torque (AGT) method proposed in [5] gives very high precision. The main intrusiveness of AGT method results from the need of direct measurements of stator resistance and rotor speed. This problem can be solved by the usage of two advanced techniques. One is digital spectrum estimation that extracts speed information from rotor slot harmonics in the stator current. The other is signal-injection-based stator resistance estimation. Appropriate adoption of these two enabling methods [6-8] can greatly reduce the intrusion level of the AGT method and the resultant modified AGT method can be employed for online efficiency detection.

Although energy saving control is essentially the enhancement of operation efficiency, precisely major works for such research is focused on techniques termed as the energy-optimized control (EOC) [9], when nonintrusive efficiency detection was unavailable. EOC techniques are divided into three categories: 1) simple state control; 2) model-based control; and 3) search control. These methods are indirect in nature for the purpose of energy saving.

With the nonintrusive efficiency-estimate method available, this paper proposes a direct EOC method that serves the energy saving. Fuzzy logic is adopted to design the controller which is adaptive to uncertainty of motor parameters. This approach is based on the feedback of the efficiency estimate.

II. NONINTRUSIVE EFFICIENCY ESTIMATION

A. Efficiency-Estimation Methods for Induction Motors

There have been many studies about efficiency estimation for induction motors, with various methods proposed. Some of these methods, such as the dynamometer method, cannot be used on field, whereas some other methods, such as the equivalent circuit method, dependent on motor parameters.

Among these methods, the AGT method is one of the most accurate. It is based on the well-known air gap equations and uses measurements of instantaneous input line voltages and
line current and a set of integral equations to compute the average air gap torque. The data required by the method can be quickly obtained with an inexpensive microprocessor. In addition, this same processor can be employed to quickly solve the air gap equations with numerical integration routines [5].

The air-gap torque is obtained through the integral of the stator voltages subtracting the stator IR drop with zero initial conditions as in (1). Then a moving average window removes the dc offset in the air-gap flux.

\[
T_{\text{air-gap}} = \frac{P}{2\sqrt{3}} \left[ (i_A - i_B) \cdot \int [v_{CA} - R_s (i_C - i_A)] dt \right. \\
\left. - (i_C - i_A) \cdot \int [v_{AB} - R_s (i_A - i_B)] dt \right]
\]  

(1)

Once the air gap torque is obtained the efficiency is computed by

\[
\eta = \frac{T_{\text{shaft}} \cdot \omega_r}{P_{\text{input}}} = \frac{T_{\text{air-gap}} \cdot \omega_r - W_{f_s} - W_{L_s}}{P_{\text{input}}} \quad \text{(2)}
\]

where the motor speed value is needed. Furthermore, as the temperature effect cannot be neglected, online stator resistance detection is also required.

**B. Modified AGT Method**

The development of the advanced techniques of sensorless speed estimate [6] and in-service stator-resistance estimation [7] simplify the efficiency estimation procedure. Combined with these two advanced techniques, the AGT method can be modified to estimate the motor efficiency nonintrusively. These two techniques utilize the motor terminal voltage and current, which are already available in the air-gap torque method. This advanced efficiency estimation, the modified AGT, provides a solid foundation for the study of a novel EOC strategy as proposed in section three.

**C. Two Enabling Techniques**

A speed sensor is undesirable in a drive because it adds cost and reliability problems besides the need for a shaft extension and mounting arrangement. From the research that aims essentially at an induction motor drive without any speed sensor come the rotor-speed estimation techniques. These methods are divided into three categories [9]: 1) model-based calculation of speed and flux; 2) speed signal generation through closed-loop control, such as speed adaptive flux observer or model referencing adaptive system, which utilizes the characteristics of the PI controller; 3) speed signal generation from magnetic saliency harmonics, which needs no model of the motor and thus eliminates the effect of parameter variation.

Slot harmonics provide robust speed estimation that is independent of motor parameters. The slots on the rotor surface of the induction motor produce reluctance modulation. As a result, induced stator voltage and current will contain a ripple component, the frequency of which is related to the rotor speed. By means of spectral estimation, the rotor speed information can be extracted with high accuracy.

Because of the high cost and difficulty of installing thermal sensors, online stator resistance estimation has been an interest of research over the years. A highly accurate estimation is the signal-injection-based stator-resistance estimation [7]. For the implementation of this technique, an additional circuit is added between the source and the motor terminal to inject a dc-voltage offset online. This offset is valid only intermittently through a simple controlled switching to reduce the power dissipation and possible torque distortion. This technique is capable of providing an accurate stator resistance estimate under load variation.

**III. ENERGY OPTIMIZED FUZZY CONTROL**

Energy optimized control is expected to take effect in a large time scale, for example, regulate once every half a minute after the transient state ends. In this way, it will perform any-time optimal since most of the potential for electrical energy saving comes from regulation on the steady state operation. Considering this fact and the need to eliminate the dependency on parameters, PI or MRAC controller is not suitable. Either approach is created to implement in continuous processes. Instead, fuzzy logic is chosen here to take the efficiency estimate feedback signal for an optimal control.

**A. Tracking the Optimal Efficiency**

Analytical insight can be demonstrated and seen from a simulation on an induction motor with a dynamic model that takes into consideration various categories of losses such as the iron loss [10]. The result is shown in Fig. 1.

From Fig. 1, change in the efficiency of the motor with the voltage reduction is shown under constant load torque. There is not a global maximum efficiency point but an optimal efficiency line instead. It is difficult to preset a value for the optimal efficiency. An alternative approach other than the way a command signal is given to a PI controller is needed.

![Fig. 1. Efficiency variation with change in applied voltage](image-url)
zero. Therefore, the process for efficiency to shift to the optimal point is also the one for the change rate of the efficiency to fall to zero. Consequently, through the control procedure of driving the change rate to zero, the optimal point for the due load can be reached. This principle of tracking the optimal efficiency can be utilized in the design of an energy optimized control.

**B. Design of the Energy-Optimized Fuzzy control**

The actual control is made up by two categories of procedures. One procedure is executed where the voltage needs to be increased and the other when decreased voltage is applied, both stepwisely.

Change in voltage and change in motor efficiency are represented by fuzzy variables [11, 12]. The fuzzy optimal system is shown in Fig. 2, where $\Delta \eta$ is the change in motor efficiency, $L \Delta V^*$ is the last change in applied voltage, and $Z^{-1}$ is the delay unit.

![Fig. 2. Scheme of the energy optimized fuzzy control](image)

The fuzzy variables are each defined with nine fuzzy subsets, and the associated rule matrix for the optimal control is given in Table I.

| PB   | PM   | PS   | PVS  | ZE   | NVS  | NS   | NM   | NB   |
|------|------|------|------|------|------|------|------|------|
| PB   | PB   | PM   | PS   | PVS  | ZE   | NVS  | NS   | NM   |
| PM   | PM   | PM   | PS   | PVS  | ZE   | NVS  | NS   | NM   |
| PS   | PM   | PM   | PS   | PVS  | ZE   | NVS  | NS   | NM   |
| PVS  | PM   | PM   | PS   | PVS  | ZE   | NVS  | NS   | NM   |
| ZE   | NB   | NM   | NS   | NVS  | ZE   | PVS  | PS   | PM   |
| NVS  | NM   | NM   | NS   | NVS  | ZE   | PVS  | PS   | PM   |
| NS   | NM   | NM   | NS   | NVS  | ZE   | PVS  | PS   | PM   |
| NM   | NM   | NM   | NS   | NVS  | ZE   | PVS  | PS   | PM   |
| NB   | NB   | NM   | NS   | NVS  | ZE   | PVS  | PS   | PM   |

Fig. 3 and Fig. 4 depict the two scenarios of voltage regulation. In Fig. 3, the voltage change following load decrease is carried out in the first quadrant, where the effective region occupies only one section of this quadrant, according to the fuzzy rule matrix. The negative half of the horizontal axis represents the situation where the motor operation is changed to the region for voltage decrease due to load reduction while the change in voltage is zero. The third quadrant shows the case where $\Delta V<0$ and a load plunge causes the efficiency to decrease, the motor state will be relocated to the voltage decrease region under the fuzzy rule matrix.

Similar to Fig. 3, Fig. 4 explains the voltage increase procedure. The serial voltage increase is in the forth quadrant. The positive half horizontal axis and the second quadrant represent the relocations of motor state to the voltage increase region for the cases of load increases under steady operation and during voltage decrease, respectively.

Taken as the initialization of the fuzzy control, a perturbation on applied voltage should be given at the beginning.

![Fig. 3. Fuzzy energy optimized control: voltage decrease](image)
Fig. 4. Fuzzy energy optimized control: voltage increase

IV. SIMULATION

A 3 kW, 4 pole induction motor was chosen for the simulation. Its parameters: nominated speed \( n_N = 1420 \text{ rpm} \), rated torque \( T_r = 21.45 \text{ Nm} \), rated stator current \( I_s = 6.8 \text{ A} \), nominated unload current \( I_0 = 3.27 \text{ A} \), rated iron loss \( P_{Fe} = 127 \text{ W} \), stator resistance \( r_s = 1.898 \Omega \), rotor resistance \( r_r = 1.45 \Omega \), stator inductance \( L_s = 196 \text{ mH} \), rotor inductance \( L_r = 196 \text{ mH} \), mutual inductance \( L_m = 187 \text{ mH} \), nominated inertia \( J = 0.0067 \text{ km}^2 \text{ s}^{-2} \), time constant \( T_L = 135.2 \text{ ms} \).

Based on range of variation, \( \Delta \eta \) is fixed between (-100%, 100%), and \( \Delta V \), (-120, 120). \( \Delta \eta \) is assigned with nine fuzzy subsets which are NB, NM, NS, ZE, PVS, PS, PM, PB, centered on -8%, -4%, -2%, -1%, 0, 1%, 2%, 4%, 8%. \( \Delta V \) is assigned with nine fuzzy subsets which are NB, NM, NS, ZE, PVS, PS, PM, PB, centered on -80, -40, -20, -10, 0, 10, 20, 40, 80. Asymmetrical triangular-type membership functions are used for the fuzzy variables.

A simulation was made for the case when the torque of the motor operating at rated power is plunged to 20% of the rated output value. The fuzzy control takes the following steps to optimize the motor efficiency.

1) The applied voltage is 380 V. Efficiency \( \eta \) is 74.5%, \( \Delta \eta \) is 74.5%-85.4%=-10.9%. The fuzzy output is processed with height defuzzification and the crisp output is \( \Delta V = 80 \text{ V} \).

2) The applied voltage is reduced to 300 V. Efficiency \( \eta \) is 81.3%. \( \Delta \eta \) is 81.3%-74.5%=6.8%. With height defuzzification, the crisp output is \( \Delta V = 68 \text{ V} \).

3) The applied voltage is reduced to 232 V. Efficiency \( \eta \) is 85.3%. \( \Delta \eta \) is 85.3%-81.3%=4%. With height defuzzification, the crisp output is \( \Delta V = 40 \text{ V} \).

4) The applied voltage is reduced to 192 V. Efficiency \( \eta \) is 86.1%. \( \Delta \eta \) is 86.1%-85.3%=0.8%. With height defuzzification, the crisp output is \( \Delta V = 8 \text{ V} \).

5) The applied voltage is reduced to 184 V. Efficiency \( \eta \) is 86.0%. \( \Delta \eta \) is 86.0%-86.1%=-0.1%. With height defuzzification, the crisp output is \( \Delta V = 0 \text{ V} \).

At step 5, the efficiency optimization is completed. The motor efficiency is improved from 74.5% to 86%. Energy saving is calculated as \((140+86)-(30.4+76) = 119.6 \text{ W}\). The mechanical output power is 650 W.

The simulation result shows that the proposed control can be an effective approach for energy-saving of the induction motor operation.

V. CONCLUSION

As consumption of energy is being highlighted as a key issue in industry, energy management has become an important dimension of engineering. Consequently, energy saving is now an important area of research for comprehensive industrial automation.

This paper proposes a new approach for energy saving of induction motors. Considering that fuzzy control is adaptive in that it eliminates dependency of motor parameters, it is employed for the implementation of this energy optimal approach for induction motors.

Based on nonintrusive efficiency estimation, the proposed method takes both the input and output powers into consideration for the optimal operation of induction motors. In this sense, it is viewed as a direct energy optimal control.

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