ADAPTIVE FUZZY CONTROLLER FOR INDUCTION MOTORS EFFICIENCY OPTIMIZATION

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Abstract – **This paper introduces a new technique for efficiency optimization of adjustable speed drives, with an emphasis on vector-controlled induction motor drives. The technique combines two distinct control methods, namely, on-line search of the optimal operating point, with a model based efficiency control. For a given operating condition, characterized by a given speed (ω_m) and load torque (T_L), the search control is implemented via the "Rosenbrock" method, which determines the flux level that results in the minimum input power. Once the optimal flux level has been found, this information is utilized to update the rule base of a fuzzy controller, which 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 several operating conditions are identified, the rule base is progressively updated, such that the fuzzy controller learns to model the optimal operating conditions for the entire torque-speed plane. After every rule base update, the Rosenbrock controller output is reset, but it is kept active to track possible minor deviations of the optimum point.**

KEYWORDS

Induction motor drives, efficiency optimization, vector control, fuzzy controller, and adaptive control.

I. INTRODUCTION

The majority of drives operates from a fixed frequency supply, but adjustable speed drives are becoming increasingly popular, due to higher productivity and energy efficiency gains that they bring. The presence of a converter in a drive system enables an extra degree of freedom, namely, flux adjustment. In fact, efficiency optimization in adjustable speed drives is usually obtained by machine flux control. This is due to the fact that in electric machines, maximum efficiency is achieved when the copper losses become equal to the core losses. Typically, under partial load operation, rated flux condition results in relatively large core losses, small copper losses, and poor efficiency. By decreasing the flux, the core losses are reduced, whereas an increase in copper losses takes place. The total losses, however, are reduced, and the efficiency is improved, what will be discussed in details later. The methods usually employed to improve the drive efficiency can be classified into three categories: simple state control, model based control and search control.

In this work, a new efficiency optimization technique is introduced. It is applicable to any adjustable speed drive, but it is illustrated here for a speed control IM vector control system. The technique combines two distinct control strategies, namely, on-line search and model base control. For a given operating condition, characterized by a given speed (ω_M) and load torque (T_L), the search control is implemented via the Rosenbrock method, which determines the flux level that results in the minimum input power. Once the optimal flux level has been found, this information is utilized to update the rule base of a fuzzy controller, which plays the role of an implicit mathematical model of the system. The technique is particularly adequate for drives that operate at steady state condition during part of the load cycle, what makes it possible for the fuzzy controller to be tuned. A good example is electric traction, where rated power is required only during acceleration and up hill driving..

II. EFFICIENCY OPTIMIZATION

For a vector-controlled IM drive system, the flux component of the stator current is normally made constant, in order to obtain fast transient response for speed values below base speed. As mentioned before, rated flux results in excessive core losses under light load torque conditions, and poor efficiency. Another aspect worth mentioning is the need to prevent machine torque disturbance during the efficiency optimization control. Under vector control, the developed torque can be expressed as:

$$T_e = k_t \psi_r i_{qs} \qquad (1)$$

where ψ_r is the rotor flux and i_{qs} is the torque component of the stator current, and k_t is a constant. If the flux is reduced to improve efficiency, i_{qs} must be increased accordingly, such that their product remains constant at any given time.

The Rosenbrock Method

This is a very simple method, and guaranteed to converge. The reference for the flux component of the stator current (i_{ds}^*) is modified in small steps in a given direction, while the system approaches the optimum efficiency point, i.e., the measured change in input power in the n-th step is negative ($\Delta P(n) < 0$). When the method recognizes that an "overshoot" has occurred ($\Delta P(n) > 0$), it reverses the search direction, with a reduced step size. The search process can be mathematically expressed as in (2):

$$i_{ds}^*(n+1) = i_{ds}^*(n) + k\Delta i_{ds}^*(n); \qquad \begin{cases} k = 1; & \text{if } \Delta P(n) < 0 \\ k = -\dfrac{1}{2}; & \text{if } \Delta P(n) > 0 \end{cases} \tag{2}$$

where: $\Delta P(n) = P(n) - P(n-1)$ e $\Delta i_{ds}^*(n) = i_{ds}^*(n) - i_{ds}^*(n-1)$.

III. DESCRIPTION OF THE PROPOSED SYSTEM

The indirect method of vector control is applied to the IM speed control system, as depicted in Figure 1. It derives the reference for the torque component of the stator current (i_{qs}^*) from the speed error, utilizing a conventional proportional-Integral (PI) controller. As the system operates with variable flux, a compensation block is introduced at the output of the speed PI controller. Essentially, this block multiplies the original PI controller output by the ratio rated flux / actual flux (estimate). The goal is to prevent machine torque disturbance when the search for the optimum flux is taking place.

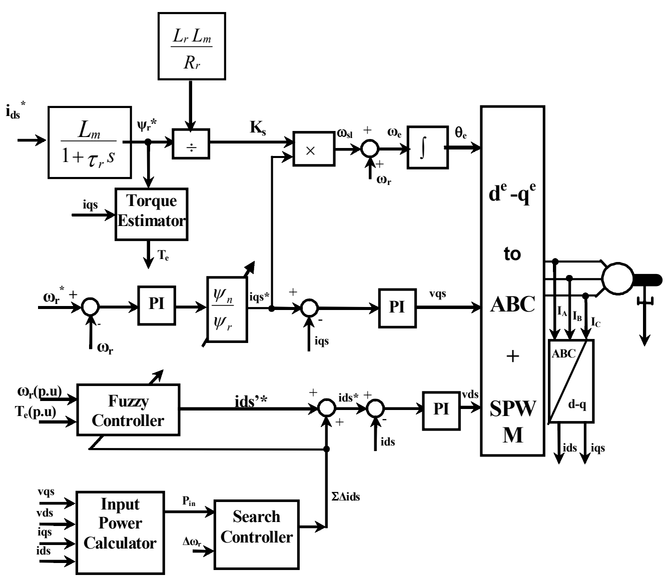


Fig. 1: Proposed control system with novel efficiency controller.

The reference for the flux component of stator flux (i_{ds}^*) is not kept constant here, as in the majority of high performance IM drive systems. It is defined as the sum of two block outputs: $i_{ds}^*(k) = i_{ds}'^*(k) + \Sigma\Delta i_{ds}'^*$. The first term ($i_{ds}'^*$) is obtained from a fuzzy controller, that from two inputs (speed (ω_r) and the estimate of load torque(T_L)), derives a preliminary reference ($i_{ds}'^*$) through fuzzy inference. The second one ($\Sigma\Delta i_{ds}'^*$) is the actual output of a search controller, based on the Rosenbrock method. Its value represents the accumulated control actions taken by the controller during the search process up to the current iteration (n).

When the system is turned on for the first time, the rule base of the fuzzy controller contains rated d-axis current reference ($i_{ds}'^*$) for all rules, i.e. for any speed and load torque point. When a steady state condition is detected, the search controller becomes active. After a few steps, it reaches the optimum efficiency point by imposing the $\Sigma\Delta i_{ds}'^*$ change to the original reference ($i_{ds}'^*$) from the fuzzy controller. Once the controller recognizes this optimum condition, the rule base can be updated to reflect the knowledge of the optimum flux level for this particular operating point (load torque and speed). At the same time, the search controller output must be reset, to prevent erroneous operation. When the optimum point is found, the rule base is updated, and the output of the search controller reset, such that, effectively, $i_{ds}^*{}_{opt} = i_{ds}'^*$.

As the optimum efficiency points related to the several operating conditions are identified, the rule base is progressively updated, such that the fuzzy controller "learns" the optimum flux level for the entire torque-speed plane. Once completed the learning process, the output of the fuzzy controller already reflects the optimum flux level, and the fuzzy controller is capable of driving the system to the optimum efficiency operation without delays. To prevent sub-optimal operation, the search controller remains active to track possible deviations of the optimum point. Under transient conditions, the search process is cancelled, and the flux reference is solely derived from the fuzzy controller. It is worth noticing that no switching of strategies is required, since higher torques demands are normally met by imposing higher flux levels, i.e., the optimum level of flux for higher torques is close to the rated flux value.

The Fuzzy Efficiency Controller

The fuzzy sets for the input variables are shown in Fig. 2. Both utilize normalized universes of discourses, to make the controller easier to port for different machine ratings. The output variable ($i_{ds}'^*$) is represented by singletons, and is not shown here. The rule base for the fuzzy controller is illustrated in Table 1. It is typically initialized with rated $i_{ds}'^*$ (1 p.u.), and it is progressively updated to incorporate the knowledge of the maximum efficiency points as they are found by the search controller, as described above.

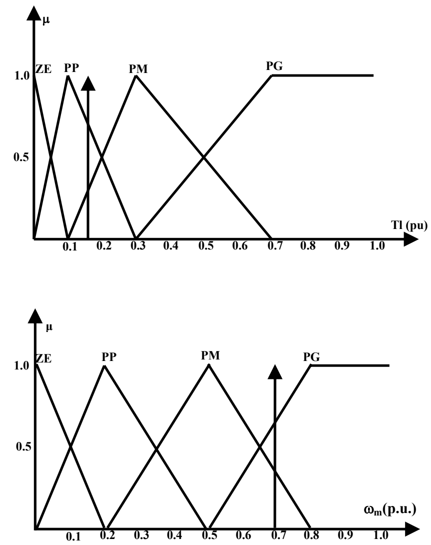


Fig. 2 – Fuzzy sets for the input variables load torque and speed

TABLE 1 – Rule base for the fuzzy controller

T_l \ ω_r	ZE	PS	PM	PL
ZE	1	1	1	1
PP	1	1	$I_{A(n+1)}$	$I_{B(n+1)}$
PM	1	1	$I_{C(n+1)}$	$I_{D(n+1)}$
PG	1	1	1	1

The primary flux reference current $i_{ds}{}^{'*}$ is obtained by fuzzy sup-min inference, and the height method of defuzzification:

$$i_{ds}{}^{'*} = \frac{\sum_{i=A}^{D} I_{i(n+1)} \times \mu_{Ri}}{\sum_{i=A}^{D} \mu_{Ri}} \qquad (3)$$

At steady state condition, whenever the search controller identifies an optimum flux level, the rule base must be updated. This process can be summarized as follows:
a)

1) Identify the fired rules in the Rule Base (e.g., rules A,B,C,D in Table 1);

2) Compute the degree of truth for each rule, by applying the minimum (min) operator over the degree of membership for the input variables T_L and ω_r: $\mu_{Ri} = \min(\mu_{Tl}, \mu_{\omega r})$;

3) Evaluate the proportionality factor K, given by (4);

4) Compute the correction term $\Delta I_i(n) = K x \mu_{Ri}$ for each fired rule as the product of its degree of truth and factor K;

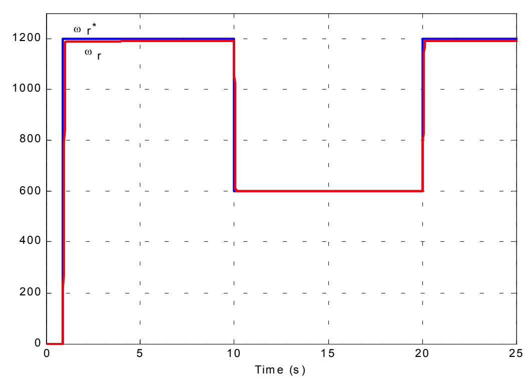
5) Get the new value for each fired rule i (i=A,B,C,D) by (5).

$$K = \frac{\sum_{i=A}^{D} \mu_{Ri} \times \sum \Delta i_{ds}(pu)}{\sum_{i=A}^{D} \mu_{Ri}^2} \qquad (4)$$

$$I_i(n+1) = I_i(n) + \Delta I_i(n) \qquad (5)$$

IV. SIMULATION RESULTS

A reference speed step of 0.67 pu, 0.33 pu and 0.67 pu is applied at t=1s, t=10s and t=20s, respectively, as shown in Fig. 3(a). After the initial transient, at t=2s, the search begins. At t = 7.5s the controller identifies that an optimum point has been found, and proceeds to update the rule base. Up to this point, the output of the fuzzy controller (i_{ds}'*) was the rated value for magnetizing current, but from this time on, its output is made equal to the optimum value. Simultaneously, the output of the search controller is reset ($\sum \Delta i_{ds} = 0$), as can be seen in Fig. 3(b). The rotor flux response follows a first order filter profile of the reference current (i_{ds}*) as expected, and is shown here multiplied by a factor of 10. The changes in flux level have a direct impact on the input power, Fig. 3(d), as well as in the torque component of stator current reference ($i_{qs}{}^{*}$), as expected, but the electromagnetic torque is unaffected, due to proper feed-forward compensation in $i_{qs}{}^{*}$, as shown in Fig. 3(c).



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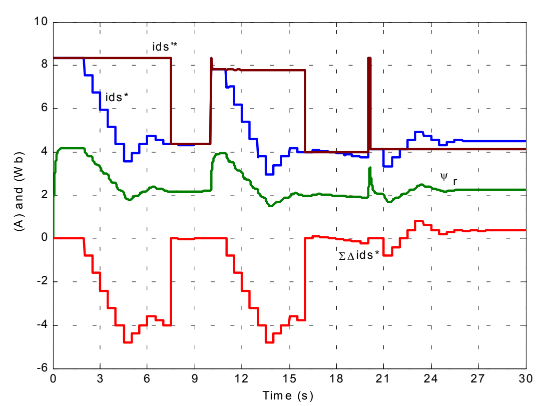

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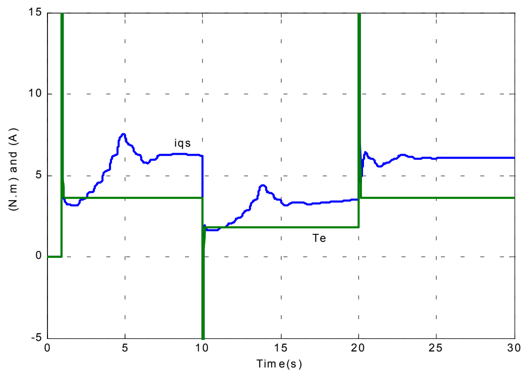

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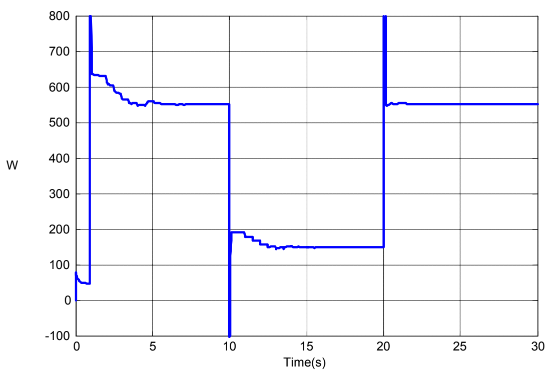


d)

Fig. 3 – Efficiency optimization with rule base update.
a) Reference and actual speeds; (b) Flux components of stator current from fuzzy controller, search controller, as well as flux response (x10); (c) Reference stator current for torque component and actual IM torque; (d) Input power of IM.

V. EXPERIMENTAL RESULTS

The experimental results were obtained with a 5 cv induction motor drive system, making use of a dc generator as the mechanical load. A conventional diode rectifier and IGBT inverter topology was employed, whereas all the control functions were implemented in a Dalanco Spry board, constructed around the TMS320C25 DSP from Texas Instruments Inc. A 486 PC was utilized as a host computer to the board, and interface with the operator.

Reference speed steps of 0.2 (pu), 0.1 (pu) and 0.2 (pu) were applied to the system, as shown in Fig. 5(a). After the initial transient, the search begins. At t = 17s the controller identifies that an optimum point has been found and proceeds to update the rule base. Up to this point, the output of the fuzzy controller ($i_{ds}'^{*}$) was the rated value for magnetizing current, but from this time on, its output is made equal to the optimum value. Simultaneously, the output of the search controller is reset ($\sum \Delta i_{ds} = 0$), as can be seen in Fig. 5(b). As can be seen in Fig. 5(c), the rotor flux response follows the reference current (i_{ds}*) as expected. At t = 21s, after the first step, another step is applied and a new search begins. At t=34s the controller identifies that an optimum point has been found, and proceeds to update the rule base once more. When a third step is applied, at t=39s, the rule base immediately supply optimal value, since it is a "known" point of operation. As also seen in the simulation results, the changes in flux level have a direct impact on the input power, Fig. 5(f). Figures 5(d) and 5(e) show the i_{qs}^{*} component of the stator current, and the torque estimate, respectively. Here, the torque presents some disturbances, possibly due to the use of an open loop flux estimator, as well as noise from the speed and current sensors.

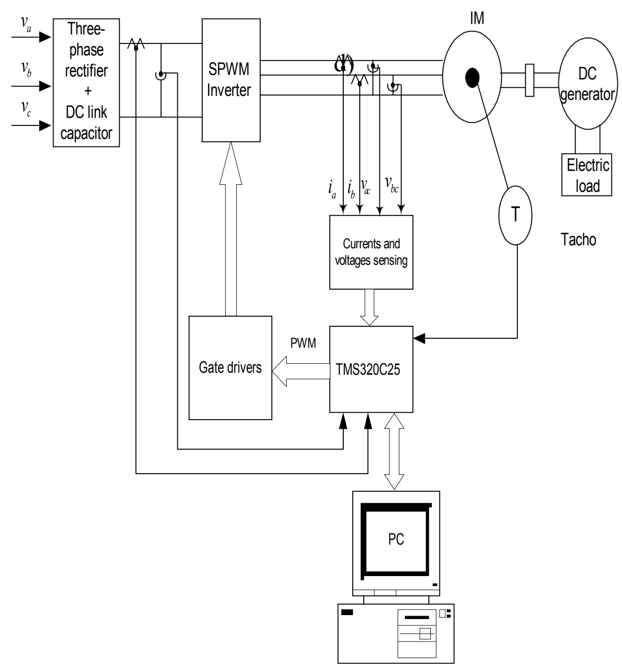
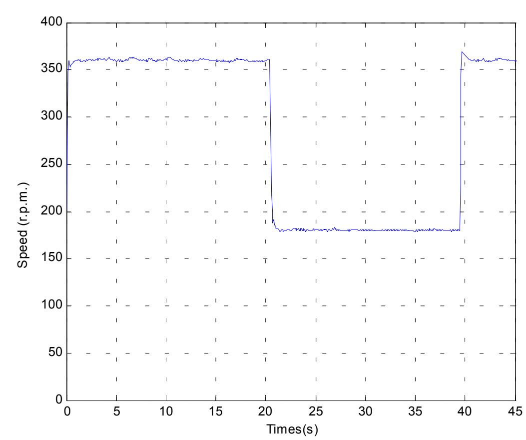


Fig. 4 - Block diagram of the experimental system.



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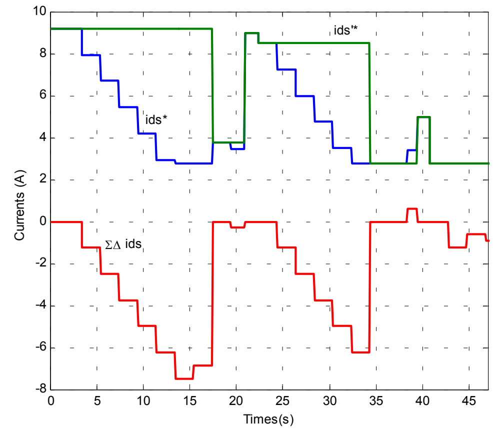

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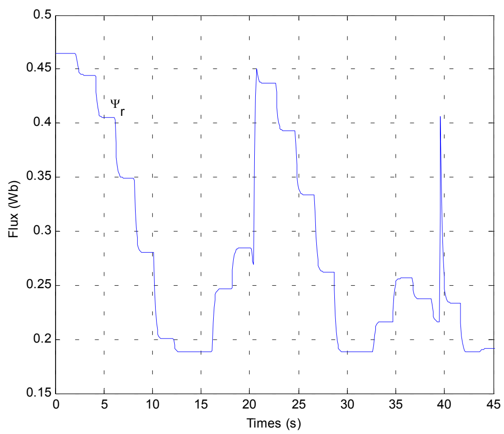

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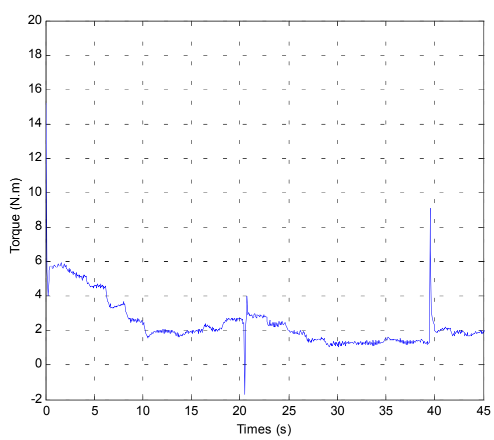

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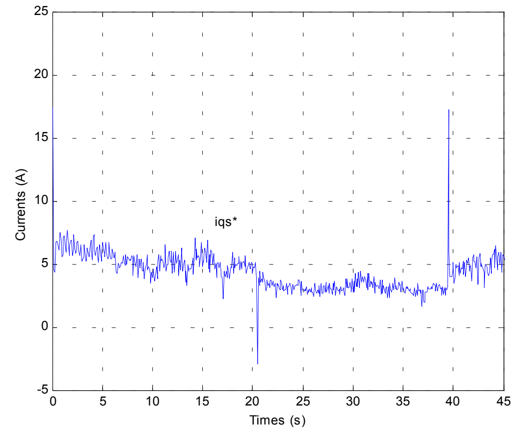

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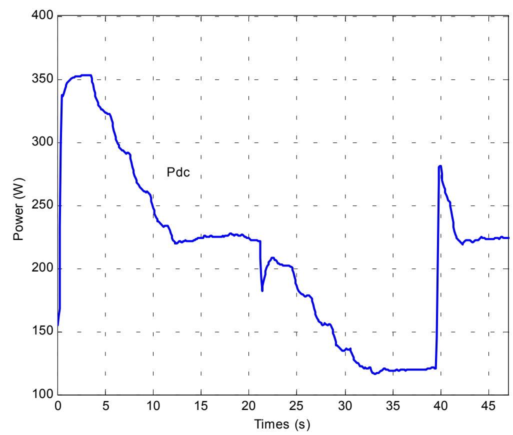

f)

Fig. 5) The dynamic system behavior for a step of T_L=0.12 (p.u.) and speed steps of 0.2 (p.u.)→ 0.1(p.u.)→ 0.2(p.u.). a)speed; b) currents i_{ds}*, i_{ds}'* and $\Sigma\Delta i_{ds}$; c) rotor flux; d)torque current i_{qs}*; e) torque estimate; f) input power.

VI. CONCLUSION

The proposed control strategy consists of a more effective way to implement the efficiency optimization via flux control in an IM. The salient features of this technique are summarized next: i) It is applicable to any machine size, and does not require knowledge of machine parameters; ii) The self tuning of the rule base is progressive, and does not need any intervention from the operator; iii) Once tuned, the system is capable of operating all times at optimum efficiency, without delay from one steady state condition to another, with significant energy savings; iv) During transients the rule base is kept active, as a consequence, there is no switching from one control strategy (for steady state) to another (during transients), provided the tuning has been completed; v) Proper disturbance compensation is included, such that no correction is need to keep torque and speed constant during the optimization process; and vi) The system is capable of tracking slow deviations in parameters, such that true optimum efficiency is guaranteed.

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