

Fuzzy Logic Based Online Electromagnetic Loss Minimization of Permanent Magnet Synchronous Motor Drives

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Abstract-The objective of this paper is to give an insight about the development of a fuzzy logic efficiency control system which is incorporated to a standard adjustable speed drive control (i.e. Indirect Vector Control) in order to improve the online efficiency in Permanent Magnet Synchronous Motor (PMSM) drives for both transient and steady state operation. The search criterion in steady state is the minimization of the drive power losses by reducing the stator flux while meeting the speed and load torque demands. The power losses are calculated as the difference between the measured input DC-link power and drive's output power. The power losses are calculated at every sampling step and the change of power losses are calculated over a constant time interval as it is needed by the efficiency control algorithm. Variables in the operating characteristics of the PMSM, such as DC input voltage/current and actual speed are inputs to the fuzzy control system, making the control system independent of any specific load. Our system combines two fuzzy logic designed efficiency controllers which are introduced as *Fuzzy(1)* and *Fuzzy(2)* controllers in order to generate the magnetizing current (d-axis component of the stator current). They are separately activated during the steady and transient state respectively. The *Fuzzy(1)* controller is a search controller (SC) operating in steady state, so to decrease the stator flux for higher efficiency. The *Fuzzy(2)* controller is a SC operating in transient state, so to increase at minimum the magnetizing current, to achieve fast tracking capability, less steady state error and robust to load disturbance during transient state. The torque component of the stator current is generated by the vector controller in order to achieve higher motor performance. The fuzzy logic controllers (FLCs) prototypes were created and tested using Simulink® simulations. Simulations are accomplished in Simulink® in order to validate our method (i.e. efficiency improvement, less torque ripple with flux changes and the less speed sensitivity to load disturbances). Experimental results will be available upon conclusion of the laboratory testings. Future experimental deployments will include a DSP board which will be directly programmed in assembler language via Simulink®.

I. INTRODUCTION

“Direct-Drive” AC motors expand the future of industrial drives. The elimination of the gearbox reduces the parts subjected to maintenance and overall noise, while permits low speeds that potentially increase the operational life. The result is far greater reliability than can be achieved with a conventional geared induction motor. “Direct-Drive” motors

are PMSM with a high number of poles. “Rare earth” (NdFeB) permanent magnets have high magnetic energy density, achieving higher efficiency. The PM motor family incorporates two designs: internal rotor and external rotor. Both designs are industrially rated and adopted in critical applications such as elevator winches and wind power generators. The PM motors can be used in Vector Control (VC) or so called Field Oriented Control applications [1]. In VC method the state variables are transformed to a coordinate system synchronously rotating with the rotor. In rotor frame coordinates the PMSM behaves like a separately excited DC motor. The exact value of the rotor position is mandatory: to control the speed; to transform the state variables; to achieve a high efficiency. The VC method is the de facto standard for quickly changing loads as well as for reference speeds. The VC achieves the best dynamic behavior, but requires shorter control cycle times for good lead and disturbance behavior, and does not optimize the overall drive efficiency. Several efficiency optimization control methods have been introduced to cooperate with VC method for the PMSM drives. The literature [2]-[6] describes different strategies. The [4]-[6] are dealing with loss minimization and high-performance speed (torque) control of PMSM, which are based upon nonlinear control schemes based on feedback linearization and decoupling methods using motor models in which the core loss is represented with core-loss resistances. [4] presents a method for both copper and iron loss minimization of an interior PM motor based on flux-weakening control. However, the proposed condition is complex and cannot be easily implemented. Another control method for efficiency improvement of PMSM, by keeping power factor equal to unity, is described in [7]. However, although the real to apparent power ratio (kW/kVA) of the PMSM motor is maximized, power losses are not minimized. In [1] a maximum torque-per-ampere current control is accomplished by online controlling the flux stator component i_{ds} while keeping i_{ds} equal to zero ($i_{ds} = 0$). In surface PM motor drives, copper loss is minimized.

An efficiency optimization control method that uses online power searching algorithms to adjust one of the drive variables (e.g. magnetizing current, stator voltage) is materialized with

controllers which are called Search Controllers (SCs) [8]. The SCs control principle is the minimization or maximization of a significant parameter by trial and error. The criterion could be the minimization of the: DC link power or DC link current or stator current or drive losses, etc, [10]. The SCs in [11]–[13] minimize the drive input power by iterative adjustments of the flux level in relation to the load torque and to the rotor speed. The SCs only yield suboptimal operation since parameter variations due to temperature changes and saturation effects are not taken into consideration [14], [15]. The no need for precise knowledge of the motor loss function parameters is the main advantage of the SCs. The problem of slow convergence toward optimum efficiency point, is the main drawback of the SCs. The experimental convergence time of the SCs is no less than 4s. The torque pulsations around the optimum operating point is a problem for the SCs and may lead to a large drift and instability. Back in 1995, G. D. D. Sousa, B. K. Bose, J. G. Cleland [10] proposed fuzzy efficiency SC for steady states. In 1996-97 and 2006, J. Moreno, M. Cipolla, J. Peracaula, [22]–[23] and E. Sergaki, G. Stavrakakis [9] respectively, introduced efficiency optimization during transient states using fuzzy SCs.

In the present work, the proposed fuzzy efficiency control system is inspired by [9], [10], [22], [23] and improves the drive efficiency of a PMSM with inset magnets and weakening capabilities, during transient and steady state performances. The optimization criterion is the online minimization of the drive losses instead of the motor power losses. It is known that the flux stator component current i_{ds} the one that provides maximum torque-per-ampere current ratio in interior PMSM drives, is a function of the stator torque component current i_{qs} and opposes the excitation field of the PMSM, [11], [16]–[18]. Thus, the PMSM's reluctance torque is produced by controlling the flux stator component current i_{ds} , according to various load and speed conditions.

The outline of our method is explained as follows: The drive power losses are sampled and calculated by a calculating means. The drive power losses value is then compared with a previous value by a comparing means. A change in DC link current value is determined from this comparison, since the DC voltage is essentially constant, by a determining means. A stator flux decrement value is calculated by a calculating means. The stator flux decrement value is based on the change in DC link current value. A stator current value is generated by a generating means. The stator current value is based on the stator flux decrement value. Finally, the stator flux is reduced by a reduction means, based on the stator current value. The flux component of the stator current, i_{ds}^* , is generated by the fuzzy SCs based on the stator flux decrement value. The torque component of the stator current, i_{qs}^* , is generated by the vector controller based on the i_{ds}^* value, in order to keep the developed electromagnetic torque T_e constant. A decrease in stator flux results in a decrease of i_{ds}^* and a subsequent increase of i_{qs}^* , in a way to keep the T_e constant. The iron loss in the drive system decreases with a subsequent increase of copper loss, in order for the total system loss to be reduced.

II. POWER LOSS MODELING

The drive loss minimization criterion includes motor and the converter losses. The influence of the converter losses does not improve the drive's efficiency, but it guarantees higher optimum flux level than this from the motor loss minimization criterion. That improves the drive's robustness. The PMSM drive's total power losses are calculated as the difference between input and output drive power:

$$P_{total} = P_{in} - P_{out} = V_{DC}I_{DC} - \omega_r T_e, \quad (1)$$

where: P_{in} , P_{out} are the drive input, output power respectively, V_{DC} and I_{DC} are voltage and current in the DC link, ω_r is the motor speed and T_e is the electromagnetic torque. The voltage V_{DC} and current I_{DC} can be directly measured, over a samples of consequent time intervals. T_e is a known variable in a drive and speed ω_r , can be measured or estimated. So, we are able to calculate the total drive power losses without the need of knowledge of the motor's parameters and independently of the parameter's changes (i.e. due saturation and heating). The minimization of P_{total} translates into the minimization of P_{in} , which is the minimization of the DC link current I_{DC} , since the DC link voltage V_{DC} is virtually constant. The change of P_{total} , ΔP_{total} represents at each instance the difference between the current and a previous value over a constant time interval. A negative value of ΔP_{total} indicates a power input efficiency improvement. The *Power Loss Processing Unit* is incorporated into the proposed fuzzy efficiency system in order to calculate the drive's power losses, during steady states, by (1).

III. FUZZY LOGIC CONTROLLERS IMPLEMENTATION

The main advantages of the fuzzy logic control is the fast convergence by using an adaptive step size of the control variable and that it can infuse inaccurate signals (corrupted by noise) without introducing operational instability. The proposed fuzzy logic controllers are of PI type. The actual value of the controlled variable for the PI type fuzzy controller is obtained by the equation:

$$\text{Variable}(\text{new}) = \text{Variable}(\text{old}) + \Delta(\text{new}),$$

where Δ is an adaptive size step for the control variable. The change of the output control variable Δ is computed according to the measured change of the fuzzy state variable and the sign and magnitude of the last change in Δ , which is labeled $L\Delta$.

The proposed efficiency fuzzy control system includes two fuzzy efficiency-optimization controllers, the *Fuzzy(1)* and the *Fuzzy(2)*. They are activated separately, for both steady and transient states respectively. The *Fuzzy(1)* controller is activated during steady state. Three main tasks are accomplished by the *Fuzzy(1)* controller: (i) Determination of the steady state (when the speed error maintains a particular value for a predetermined period of time and there is no change in torque or when does not exceed a predetermined threshold level); (ii) Direction test (decrement or increment); (iii) Loss minimization. The control block diagrams and the membership functions for the *Fuzzy(1)*, (2) are shown in Fig.1, 2, respectively.

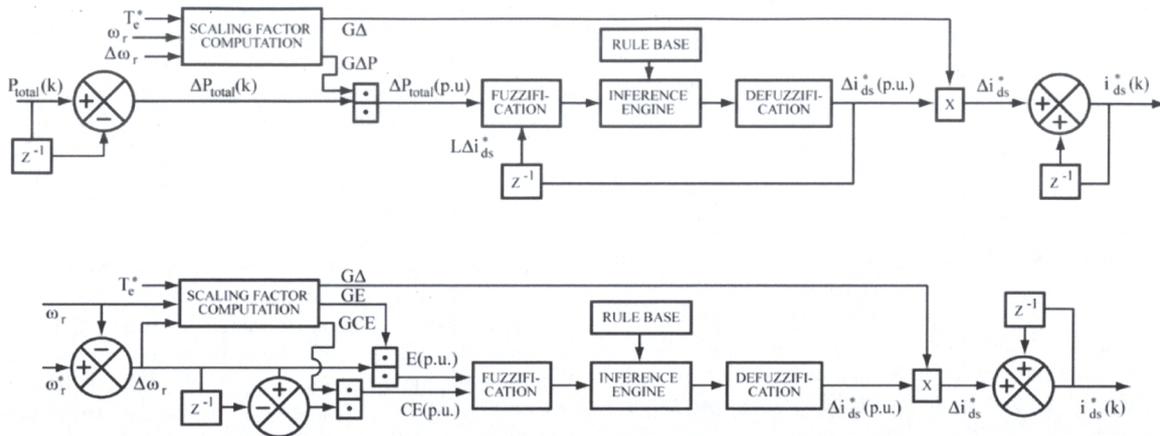


Fig. 1 Top to bottom: Details of the control block diagram of the *Fuzzy(1)* and *Fuzzy(2)* controllers.

In Fig.2, the small symmetrical overlap of the positive (P) and negative (N) membership functions is required to prevent indeterminate result in case $L\Delta i_{ds}^*$ approaches zero. The selected placement of the triangles' peaks and bases provides finer partitioning of the discourse of universe of the small to medium regions, where the sensitivity of the output control variable $i_{ds}^*(k)$ to input is greater. Each triangle's base length is determined by trial and error iterations in order to fine tune the *FLC*'s performance and to provide satisfactory control sensitivity and response. Due to the use of input and output gains, all variables are normalized in the universe of discourse $[-1,1]$. Triangular membership functions are chosen to represent the linguistic variables.

The MAX-MIN inference operators are used. The output membership function of each rule is given by the min operator. The combined fuzzy output is given by the MAX operator. The defuzzification is based on the centre of gravity (centroid) method.

For the *Fuzzy(1)* controller the first fuzzy state variable is the sign and step of power losses decrement $\Delta P_{total}(k)$. The second fuzzy state variable is the control action $L\Delta i_{ds}^*(k-1)$ of the previous step. The control variable is the d-axis stator current component i_{ds}^* . The variable $\Delta P_{total}(k)$ requires 7 memberships and the past control variable $L\Delta i_{ds}^*(k-1)$ requires 2 memberships since the main information is the sign. The spectrum of the 7 linguistic variables is defined from positive large (PL) to negative large (NL) and the spectrum of the 2 memberships includes the positive (P) and negative (N). Upon, the sampling of the power losses $P_{total}(k)$ is compared to the previous value of $P_{total}(k-1)$ in order to derive the sign and the step change of power losses decrement ΔP_{total} . Additionally, the previous action of the magnetizing current decrement $L\Delta i_{ds}^*(k-1)$ is reviewed. The new decrement step size Δ of the $i_{ds}^*(k)$ is generated from fuzzy rules through fuzzy inference and defuzzification. The adjustable gains, generated by the scaling factors computation block, convert the state and control variables to per unit (p.u.) values.

Because these gains are speed dependant for different speed and torque conditions, the same $L\Delta i_{ds}^*(k-1)$ (p.u.) will result to different $\Delta\phi^*(k)$ and $\Delta i_{ds}^*(k)$. If the last control action indicates a decrease of power losses, the *Fuzzy(1)* controller proceeds in searching towards the same direction. In the case of an increase of power losses, the search direction is reversed, and the Δ step size is reduced to attenuate oscillations in the search process. The steps of the *Fuzzy(1)* controller are as follows:

1. Sample $P_{total}(k)$.
2. Compute the decrement $\Delta P_{total}(k)$.

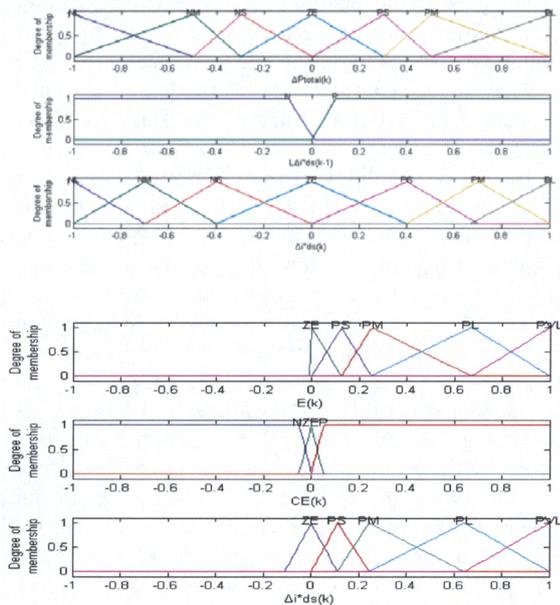


Fig. 2: Top to bottom: The membership functions of the *Fuzzy(1)*, *Fuzzy(2)* controllers.

overcome a higher torque demand, even with the relaxed current $I_{limit(1)} = 1.5 I_{rated}$. In such a case, to overcome the problem of torque stability and to keep it at a safe level (in order to protect the drive to stall during a transition of a steady to a transient state), a current $I_{limit(2)}$ equal to the rated motor current is imposed.

The torque stator current component is calculated by the feedback speed control loop as indicated by the equation:

$$i_q^* = T_e L_q / \phi p L_m \quad (2)$$

the T_e , L_q , L_m , ϕ , p are defined in nomenclature.

The actual values i_{ds}^* and i_{qs}^* are inputs in the decoupling current controller in order to calculate the corresponding feed forward (F-F) voltage commands v_d^* and v_q^* by the following equations:

$$v_d^* = v_{F-F d}^* + v_{PI d} \quad (3)$$

$$v_{PI d} = R_s(i_{F-F d}^* + v_{F-F d}^* / R_c) \quad (4)$$

$$v_{F-F d}^* = -\omega_r L_q i_{F-F q}^* + L_d(d i_{F-F d}^* / dt) \quad (5)$$

$$v_q^* = v_{F-F q}^* + v_{PI q} \quad (6)$$

$$v_{PI q} = R_s(i_{F-F q}^* + v_{F-F q}^* / R_c) \quad (7)$$

$$v_{F-F q}^* = \omega_r(L_d i_{F-F d}^* + \phi) + L_q(d i_{F-F q}^* / dt) \quad (8)$$

the R_s , R_c , L_q , L_d , ω_r , ϕ , are defined in Nomenclature.

The equations (3)-(8) are based on the synchronous frame D-Q model of the PM motor [24]. The i_d refers to the fuzzy stator flux current component, i_q refers to the stator torque current component, generated by the speed controller. The v_d , v_q voltages are transformed to the three phase voltage commands v_a^* , v_b^* , v_c^* , in the reference stationary frame and are applied to the pulse width modulation (PWM) unit. The PWM unit calculates an asymmetric pulse pattern. To generate the phase voltages with variable amplitude and frequency a 3-phase inverter is used, based on an insulated gate bipolar transistors IGBTs technology. Our proposed system includes a tachogenerator to measure the speed, a resistor divider to sense the voltage bus (VBUS), and a resistor sensor on the line (IBUS) to estimate the phase currents.

V. SIMULATION RESULTS AND DISCUSSION

Simulations are accomplished by using Simulink® and a normalized in per unit d-q PMSM dynamic model, including iron losses, as given by [16]. The specifications and the motor parameters for the interior PMSM are listed in table I.

TABLE I

Parameter Values In P.U. For Simulation Of An I-PMSM 3 pole pairs, 220 V three phase 50 Hz, 1.5 kW, 7 A; 209.3 rad/s				
ϕ	L_d^*	L_q^*	R_s	$R_c = R_{co} \omega_r (1 + \omega_r)$
0.857	0.35	0.6	0.104	$R_{co} = 52$
* experimental inductances values for currents lower than 0.5 p.u. [25]				

The simulator is modeled as in Fig. 3, without including the computations for the vector rotator, the PWM and the encoder. The current is sampled every 0.1 ms, the speed is sampled every 1ms, and the efficiency control system is activated every 0.26 s (the time interval of 0.26 s natural considers the slow

dynamics of the stator flux, is related with the motor time constant). The input power is calculated by using a sampling period 1 ms, same as the speed loop, and then averaged over 20 ms, by the equation:

$$P_{in} = 3(v_{ds} i_{ds} + v_{qs} i_{qs}) / 2 \quad (9)$$

The process of simulation and the efficiency improvement by using the complete proposed efficiency system for the drive is given in Fig. 4. The efficiency control system is activated when the 1st steady state is detected, after the rated flux is established and the motor starts up from zero to rated speed, under 0.3 p.u. constant load torque.

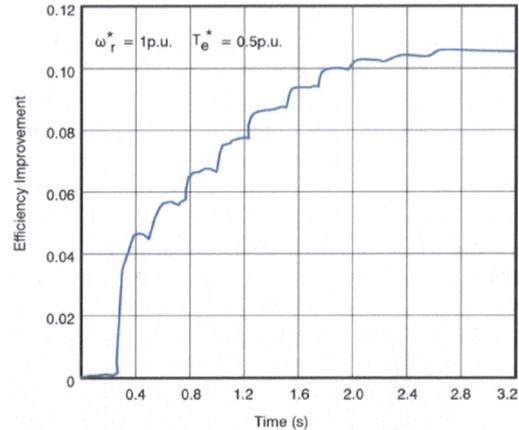


Fig. 4 Simulation results of the response of the drive's efficiency and its improvement. The motor operates at a constant rated speed 1 p.u. under a 0.3 p.u. load torque. In such a case the efficiency optimization, achieved after 10 iterations (of average duration 2.6 s), is 10.6%.

Fig. 5 shows the simulation results of the PMSM drive power losses in the case of its control by the proposed fuzzy efficiency system (black line) and in the case of operating the motor at rated flux (red line). When the motor operates under torque load of 0.3 p.u and constant reference speed of 1 p.u., the power losses from 49.3 ± 4.0 W are reduced to 30.7 ± 4.0 W (minimization rate 37%). When a step torque transition occurs from 0.3 to 0.7 p.u, the power losses from 80.1 ± 6.7 W are reduced to 79.1 ± 6.7 W (minimization rate 1.2%). There is no peak of power during transient states.

The green line in the graph of Fig. 6 shows the simulation results which validate the importance of the *Fuzzy(2)* controller during transient states. The proposed control system is simulated without using the *Fuzzy(2)* controller. In this case, at the transient point $t=100$ s, the power losses increase instantly to 106.5 W, and a speed disturbance occurs (Fig. 7). During the transient state, the calculated consumed energy losses are decreased from 210.6 J to 168.0 J (decrease rate 19.9%).

Fig. 7 represents the simulation results of the motor's speed response. At the transient point $t=100$ s, the motor's rated speed decreases from 2000 rpm to 1920 rpm (-0.04%). At the transient point $t=150$ s, the speed value of 2000 rpm increases to 2065 rpm (+0.032%). The speed decrease is about three times less than the one that occurs without the use of the

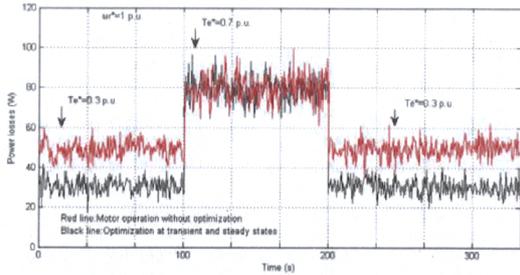


Fig. 5. Simulation results for the case of a step torque load increase of 0.3 to 0.7 p.u., under constant speed, 1 p.u.. Red line: the motor operates at rated flux. Black line: the efficiency is optimized during steady and transient states. The power losses improvement is 37% and 1.2% for the cases of torque 0.3 and 0.7 p.u. respectively.

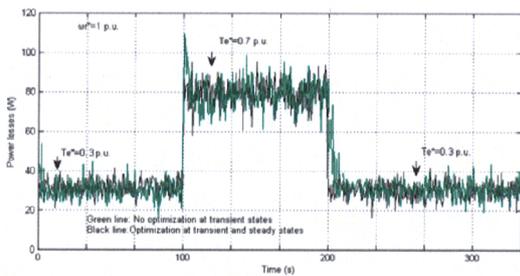


Fig. 6. Simulation results of the proposed efficiency control system as the *Fuzzy(2)* controller is not activated (green line). The black line indicates the efficiency control during transient and steady states. The torque load increases from 0.3 to 0.7 p.u and the reference speed is 1 p.u. The decrease of energy losses (J) during the torque step transition is 19.9%.

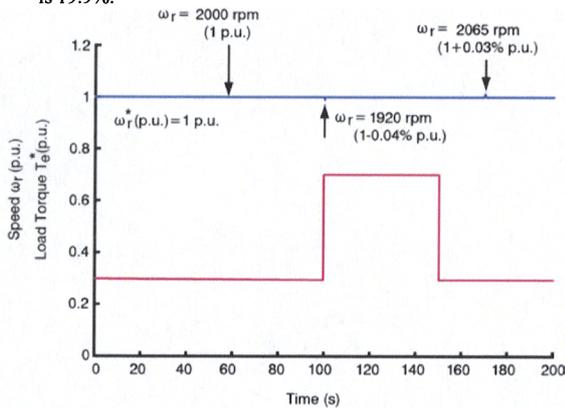


Fig. 7 Simulation results of the motor's speed response when is efficiency controlled by the complete proposed system, for a step torque load increase of 0.3 to 0.7 p.u., under constant reference speed, 1 p.u.

fuzzy(2) controller and five times smaller than the one that occurs without optimization control. The calculation time for the fuzzy controllers is 5 μ s, and for the vector control system is less than 0.14 ms.

VI. CONCLUSION

The proposed method achieves very satisfactory results in the overall losses minimization of a motor drive system as it considers both cases of operation: transient and steady state. The described scheme offers no reduction in the maximum shaft torque, due to the advantages of the fuzzy energy optimizers enabled.

Moreover, the proposed system can be easily incorporated into an existing vector drive system with a minimum of extra hardware implementation and is furthermore independent of the various machine models. Additional software can be executed easily by the included system processor.

The outline of the advantages of the present method are summarized as follows:

(i) The proposed fuzzy efficiency control system accounts for both the PMSM losses and power supply converter losses. That guaranties higher flux level and improves the drive robustness for speed and torque disturbances. Moreover the efficiency improvement is greater for bigger motors where the inverter losses become more significant; The proposed system is independent of drive parameters and can materialized with a minimum of extra hardware, easily incorporated to any size or type of speed drive. The efficiency improvement, for low loads (0 to 0.3 p.u.) and rated speed, is about 35% and for high loads (e.g. 0.7 p.u.) is 1%.

(ii) The proposed system achieves very good results of the overall loss minimization of the motor drive system as it takes in account both transient and steady state operation. For many Industrial control applications, transient response of the drives is of extreme importance. The energy losses during transient states are about 20% for torque disturbances and more than 30% in the case of speed disturbances.

(iii) The torque stator current component is generated by the vector controller based on the speed demand and the stator flux value, for higher motor performance.

VII. NOMENCLATURE

- * Superscript indicates reference values
- _s subscript indicates the ones in stationary frame
- _{d, q} subscript indicates the d-axis, q-axis components
- F-F subscript indicates feed –forward value
- _{PI} subscript indicates value generated by PI controller
- G capital first letter indicates gain factor
- d/dt indicates time derivative
- T_e is the electromagnetic torque in p.u.
- L_q is the q-axis inductance in p.u.
- L_m is the magnetizing inductance in p.u.
- ϕ is the flux produced by the permanent magnets in p.u.

p is the number of pole pairs
 R_s is the equivalent stator copper-loss resistance in $p.u$
 R_c is the equivalent stator iron-loss resistance in $p.u$.

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