Algorithm Implementation of an hybrid Efficiency controller incorporated to a PMSM standard FOC variable speed motor drive

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Abstract—**The objective of this paper is to give an insight about the methodology of developing the algorithm for a DSP controlled motor drive in order to reduce complexity and development time by using re-useable software modules from TI® library, and by constructing the flow block diagram within the Incremental System Build (ISB) levels logic frame. The proposed methodology is applied for the implementation of the algorithm of an innovative hybrid efficiency control scheme which is incorporated to a standard speed Field Oriented Control (FOC) drive, in order to improve online the efficiency for various types of motor drives (i.e ASI, PMSM drives) for both steady state and transient operation under load and speed variations. The hybrid efficiency control system combines a fuzzy logic controller and an LMC (Loss Model Controller). In order to validate the efficiency improvement and to test the good dynamic performance of this innovated efficiency control system, the software code is build up by many smaller re-useable software modules and is simulated in Simulink® environment. For the hardware emulation the Code Composer Studio is used. The DSP code is emulated using the XDS510PP JTAG Emulator. The innovated fuzzy logic controllers (FLCs) prototypes are created and tested separately, using the Simulink® graphical programming. The present improved control scheme is validated by hardware emulation in Code Composer Studio TI® environment by using the Digital Spectrum ® eZdspF2812 as computing engine and the Digital Spectrum ® DMC1500 as inverter.**

I. INTRODUCTION

It is important in industry on getting quality products out to market in a timely manner, which in economy is crucial. Thus, there are software and hardware products for rapid control prototyping and performing real-time simulations [1-2]. The different simulation tools (i.e. SIMsystem, dSPACE, ARTS, Night Hawk, Inc. MATRIXx/RealSim, MATLAB/ SIMULINK, ACSL/ACSLrt, LabVIEW, XANALOG/RT, PICS Simulation for Windows, VisSim/RT), are simulators which offer visual design concepts and libraries of models for various components of a power electronic system, in order to accelerate the algorithm designing process. Moreover, in order to translate special systems (i.e. fuzzy systems) into specific code for DSP controllers [3] there are many design environments, such as FIDE, FuzzyTECH, rFLASH, Xfuzzy 3, MicroFPL. The Real-Time Workshop® Embedded Coder™ and embedded target (Embedded IDE Link™ CC) allows Real-Time Workshop code to run in DSPs environments.

By using block diagram tools is able to build consistent systems by mainly dragging and connecting specific blocks instead of writing code. The choice of the designing methodology of a Digital Control System in order to reduce complexity and development time is especially important for complex systems, such as Digital Motor Control. The designing methodology must satisfy the following specifications: smoother system integration, reducing debug and trouble-shooting time, providing a higher degree of visibility inside the software (s/w), and quicker system re-configuration. The engineers use to visualize the control strategies in the form of classical signal flow blocks diagram. This useful representation has several limitations which are evident when trying to relate these diagrams to an actual s/w implementation. It is not clear how the s/w variables are related to the signal parameters on the diagram, or where are the boundary between s/w and hardware (h/w). Through the above The Mathworks® Embedded Target for TI C2000 DSP and the Texas Instruments (TI) are offering specific “Module software” libraries for Digital Motor Control (DMC) plus numerous DMC systems based upon these library “building blocks”. These “module software blocks” allow to re-arrange the classical signal flow block diagram with a new one, with well defined input and output ports. The ease connect ability of these “modules” allows to have a number of “incremental build levels” [4]. This allows the development of s/w in a step-by-step manner. In each step the code is compiled, debugged, run in Real-Time, and the target is correctly functioned. Thus in each step is achieved to validate the output “signs” and to check the h/w.

The incremental build approach, by interconnecting re-usable library blocks or custom s/w blocks, can greatly reduce the time and effort required. A summary of the advantages and features of “incremental building blocks” are the following:

- The system block diagram has a clear one-to-one mapping to the modular system s/w.
- Each “module graphic” or “block” represents a self contained s/w function or object of same name.
- Input and output terminals of each “module” correspond exactly to “global” variables within the s/w function.

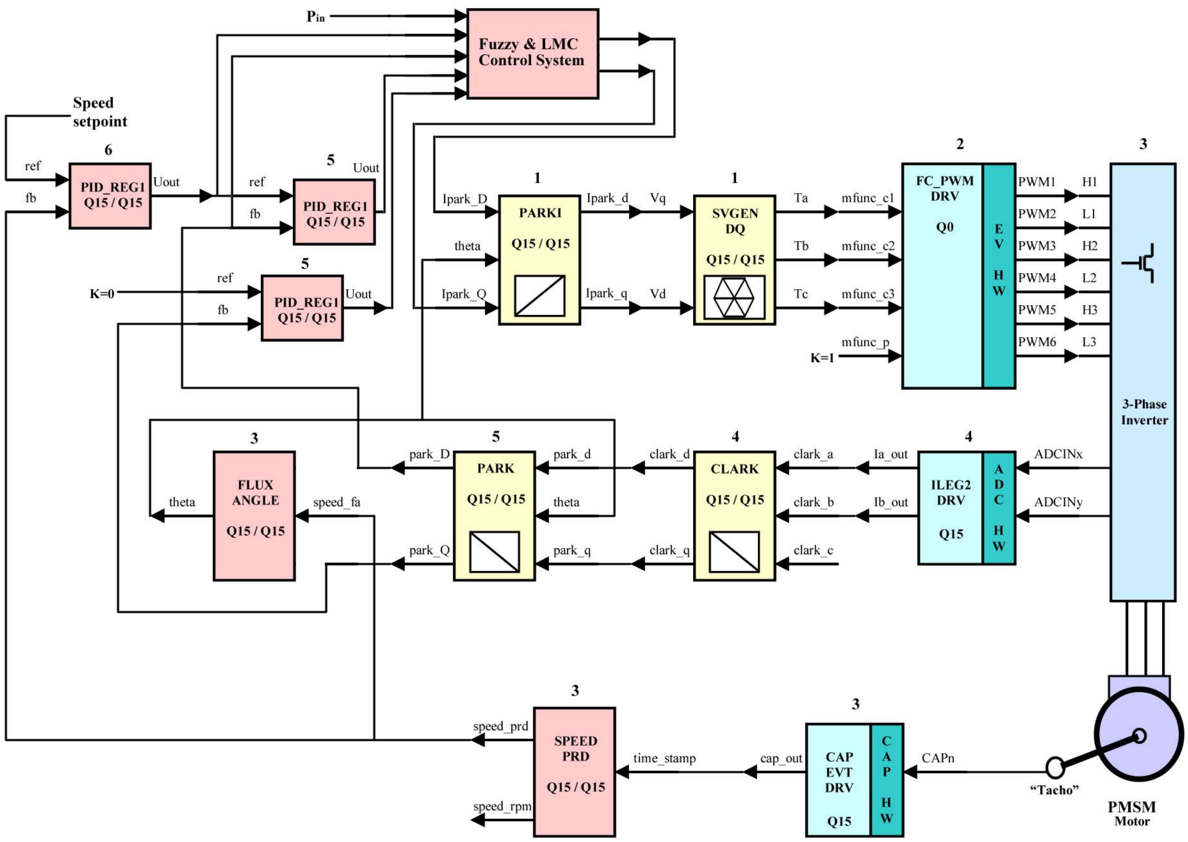

Fig. 1: The final Simulinc® signal flow block diagram one to one mapping to s/w of PMSM drive of sensored Field Oriented control (FOC) of a PMSM, incorporating the improved fuzzy efficiency control system []. The PMSM3-1 "Module" of the TI® DMC library is a re-used framework [4].
The s/w module labeled by 1 (PARKI, SVGEN DQ) consists the Build level 1.
The s/w modules labeled by 1 and 2 (PARKI, SVGEN DQ, FC_PWM DRV) consist the Build level 2.
The s/w modules labeled by 1, 2 and 3 (PARKI, SVGEN DQ, FC_PWM DRV, SPEED PRD, CAP EVT DRV, FLUX ANGLE) consist the Build level 3.
The s/w modules labeled by 1, 2, 3 and 4 (PARKI, SVGEN DQ, FC_PWM DRV, SPEED PRD, CAP EVT DRV, FLUX ANGLE, CLARK, ILEG2 DRV) consist the Build level 4.
The s/w modules labeled by 1, 2, 3,4 and 5 (PARKI, SVGEN DQ, FC_PWM DRV, SPEED PRD, CAP EVT DRV, FLUX ANGLE, CLARK, ILEG2 DRV, two PID_REG1,) consist the Build level 5.
The s/w modules labeled by 1, 2, 3,4 and 5 (PARKI, SVGEN DQ, FC_PWM DRV, SPEED PRD, CAP EVT DRV, FLUX ANGLE, CLARK, ILEG2 DRV, three PID_REG1,) consist the Build level 6.
The s/w modules labeled by 1, 2, 3,4 and 5 (PARKI, SVGEN DQ, FC_PWM DRV, SPEED PRD, CAP EVT DRV, FLUX ANGLE, CLARK, ILEG2 DRV, three PID_REG1, Fuzzy+LMC System) consist the Build level 7.

· "Modules" are categorized to clearly designate dependencies on peripherals and target h/w.
· Connections between "modules" show data flow via the corresponding input/output variables.
· Each "Module" is re-useable and has it's own documentation explaining usage and instantiation.

To demonstrate the above technique an Efficiency PMSM drive with an Hybrid Fuzzy Efficiency controller, including custom and ordinary blocks, is designed using the MATLAB/Fuzzy ToolBox™, the Simulink®, and the eZdspF2812 as computing engine. In addition the Mathworks® Embedded Target library for TI C2000 DSP [16] and the TI library for Digital Motor Control (DMC) are used.

For many industrial control applications, during motor drive work cycle the energy losses during transient states [4] can reach the amount of 20% for torque disturbances and even more than 30% for speed disturbances [5-6], thus the power conservation is of greater importance over other working parameters. Our previous work [5], proposes an efficiency control scheme which combines a Loss Model Controller (LMC) (7-12) to control the transient states and a Fuzzy Logic Search Control system (FLSC) [13] to control steady states, by using the technique of motor's air-gap flux adjustment, in order to minimize energy losses and minimize the convergence time of the improvement efficiency algorithm. The LMC is based on a simple generalized model [14] for various motor types with low accuracy, which provides the real time fast gross approximation of the optimum motor flux, as a function of the torque and speed operating conditions, not causing significant torque ripples [12]. Sequencely the FLSC part of the efficiency control scheme, which consists of two separately fuzzy controllers, provides the real-time refinement of the motor's flux adjustment on the basis of search during the steady states. Due to the FLSC the motor's flux level fluctuates in steps until the measurement of drive's power losses settles at a minimum. As Fig. 2 shows, our present work implements an improved hybrid efficiency control scheme by replacing the fuzzy part of our previous [5] by an improved fuzzy system.

Although our previous work [5] is tested by Simulink® simulations and the software is accomplished by using the classical signal flow blocks diagram, our present work is implemented by redesigning the software using re-useable and custom software modules in an Incremental Build approach. The present improved control scheme is designed in Simulink® environment, is simulated in Code Composer Studio TI® environment and is emulated by using the Digital Spectrum ® eZdspF2812 as computing engine and the Digital Spectrum ® DMC1500 as inverter.

II. THE INNOVATIVE EFFICIENCY HYBRID CONTROL SCHEME

The new efficiency control scheme is given in Fig. 2. As Fig. 1 shows, the hybrid control system labeled as "Fuzzy + LMC Control System" is an outer loop to an existing FOC [15, 7-8] motor drive for a PMSM.

The fuzzy part of the innovative hybrid efficiency control scheme combines two fuzzy logic PI type search controllers which are introduced as FLC1 and FLC2. These fuzzy controllers are separately activated during the steady and transient state respectively. The FLC1 controller is operating in steady state in order to decrease the stator flux and to achieve optimum efficiency. The FLC2 is operating in transient state, in order to increase at minimum the stator flux current, and to reduce the nominal value of the motor air-gap magnetic flux. The search criterion in steady state is the on-line minimization of the drive power losses by reducing the air-gap 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.

As in Fig. 2 is shown, the "LMC" control unit is an ordinary unit (non-fuzzy), PID type [5]. The "FLC1" and "FLC2" are fuzzy PI type controllers. The "Torque Compensation" unit is an ordinary (non-fuzzy) unit which derives the torque producing stator current component, i^*_{qs}, as the sum of the output signal of the vector control unit and the last compensating signal of the torque producing current component Δi^*_{qs}, according to the equations:

$$i^*_{qs}(k)=i^*_{qs}(k-1)+\Delta i^*_{qs}(k) \qquad (1)$$

$$\Delta i^*_{qs}(k)=[\Phi(k-1)-(\Phi(k)]\, i^*_{qs}(k-1)/\Phi(k) \qquad (2)$$

Where: $\Phi(k-1)-\Phi(k)$ is the step change of the estimated steady-state values of rotor flux Φ of k-th step change of i^*_{qs}, L_m is the magnetizing inductance, T_r is the rotor time constant. The rotor flux Φ is estimated from the equation:

$$d(\Phi(k)/dt=(L_m\, i^*_{ds}-\Phi)/\tau_r \qquad (3)$$

The ordinary (non-fuzzy) "Steady or Transition State detection and P_{losses} calculation" unit calculates the total drive power losses, determines the motor's operation state (i.e. transient or steady), recognizes the torque and speed demand (i.e. higher or lower load torque of the motor drive) and in response to the determination of the motor's state of operation activates independent and mutually coordinated control methods of the LMC or the FLCs (FLC1 or FLC2).

The LMC and FLCs control the variation of the motor's air-gap magnetic flux and calculate the optimum flux producing current component (d-axis). In-reverse, the torque producing current component (q-axis) is generated of the ordinary mathematical model of the FOC controller The torque compensator unit generates the compensating step of the torque torque producing component current Δi^*_{qs}, in order to adjust the component of torque producing current (q-axis).

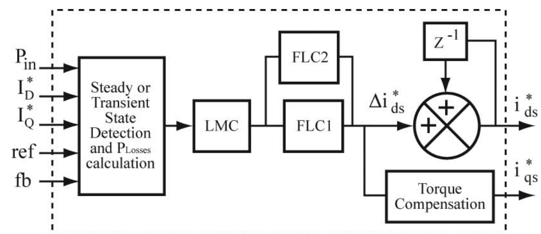

Fig. 2 The improved hybrid efficiency control scheme which can be incorporated as an outer loop to an FOC variable speed motor drive.

TABLE I
FUZZY RULES FOR POWER EFFICIENCY OPTIMIZATION
for the FLC1 and FLC2 state control variables

$P_{d(k)} \backslash I_{ds(k)}$	N	P	
PB	PM	NM	PB: Positive Big
PM	PS	NS	PM: Positive Medium
PS	PS	NS	PS: Positive Small
ZE	ZE	ZE	ZE: Zero
NS	NS	PS	NB: Negative Big
NM	NM	PM	NM: Negative Medium
NB	NB	PB	NS: Negative Small

The torque current compensation determines motor torque compensation, reduces the ripples of motor torque and consequently reduce motor fatigue and increase its reliability and longevity. The FLC1 and FLC2 controllers have the same input state control variables which are the total power losses $P_{total(k)}$ and the last optimum step change of the flux producing current component $L\Delta i^*_{ds}$. For both controllers the control variable is the new step change of the flux producing current component Δi^*_{ds}. The Table I contains the 14 rules for the fuzzy state control variables. The actual value of the fuzzy controllers output is obtained by the equation:

$$i^*_{ds}(k)=i^*_{ds}(k-1)+\Delta i^*_{ds}(k) \qquad (4)$$

III. METHODOLOGY OF THE IMPLEMENTATION OF THE EFFICIENCY FOC MOTOR DRIVE

A. TI® signal flow of FOC sensored PMSM drive one to one mapping to s/w

At the beginning the classical signal flow block diagram [5] is developed in Simulink® environment. The DMC software (s/w) modules" from TI® library [4] are re-used in our proposed control scheme in order to convert the classical signal flow to the TI® signal flow, one to one mapping to s/w. The final build control system of the proposed control scheme is shown in Fig.1.

B. Custom "Hybrid Efficiency Control system" s/w module

The new Hybrid Efficiency Control System consists of the Fuzzy part and the LMC parts. Between the different design environments [16] the Simulink® is selected in order to design of the proposed custom fuzzy controllers. Each FLC is separately designed using the Fuzzy Logic Toolbox® as native MATLAB M-files. The simulation in MATLAB/Simulink® environment allows the designer to model the fuzzy controller, to tune and allows the fast gross approximation of the scaling factors environment. The custom s/w module of the Hybrid System is incorporated into the drive framework after the hardware emulation of the FOC controlled PMSM drive has completed.

IV. INCREMENTAL SYSTEM BUILD STRATEGY

A. Build level 1 "Checking system output signs"

The PMSM drive of sensored Field Oriented control (FOC), is an interrupt driven, time sampled system, meaning that the modules shown in Fig. 1 are executed on every interrupt. *Build level 1* must confirm that the output signs are ok and the Space vector Generator waveforms at the outputs of T_a, T_b and T_c show the characteristic 3 phase space vector (SV) shape. Hence in level 1, the block diagram includes the software modules, labeled by 1, SVGEN_DQ and PARKI-Q15/Q15. The output of RAMP_GEN via the DAC_VIEW utility and the output of SVGEN confirm that system interrupts are being generated. A "watch window" is connected at the output of the RAMP_GEN and another "watch window" is connected at the output of the PARKI. The two "watch windows", the RAMP_GEN and the DAC_VIEW utilities are not shown in Fig.1.

B. Build level 2 "Check PWM generation at the target h/w"

In order to verify that the Space vector signals T_a, T_b, and T_c are correctly modulating the PWM outputs, the s/w module FC_PWMDRV labeled by 1, and a RC filter not shown in Fig.1, are added in the block diagram of the previous build level. The two "watch windows", the RAMP_GEN and the DAC_VIEW utilities from the build level 1 remain in the subsystem and are not shown in Fig.1.

C. Build level 3 "Check power inverter h/w and open loop motor operation"

In this level the CAP_EVT_DRV and the FLUX_ANGLE modules, labeled by 3, are added in the block diagram of the previous level, in order to validate that position information is being measured correctly and to check whether the speed measurement varies appropriately. Moreover, the SPEED_PRD module is added in order to check that the speed measurement varies appropriately. A third "watch window" is connected at the output of SPEED_PRD module. The speed is varied by modifying the synchronous frequency applied to stator by changing the RAMP_GEN output frequency. The angular position feedback input for the Park Transformation PARKI module is the output of the RAMP_GEN. The three "watch windows" and the RAMP_GEN are not shown into Fig.1.

D. Build level 4 "Closed loop motor operation under voltage control"

In order to tune the current feedback loop the ILEG2_DRV and the CLARK_Q15/Q15 s/w modules, labeled by 4, are added in the previous block diagram. Moreover, the speed is varied by changing the I_{park_D} input of the PARKI module (is voltage controlled). The speed is depended of the applied stator voltage and the torque load. In this build level the angular position feedback input for the Park Transformation PARKI module is replaced by the actual measured electrical angle, instead the output of the RAMP_GEN in the previous diagram. Thus, the RAMP_GEN module and the "watch window" connected on it are replaced. Now the DAC_VIEW utility is connected on the CLARK module. The "watch window" on SPEED module remains in the subsystem but it not shown into Fig.1.

E. Build level 5 "Closed loop current control, in constant Torque mode operation"

In the present build level two PID_REG1_Q15/Q15 s/w modules (labeled by 5) are added in the block diagram. Thus the torque control setting can be changed by setting the PID controller reference input, *ref*, via a "watch window module". Moreover, the PID proportional, integral and derivative constants can now be tuned in real time by trial and erroe test, while the motor is spinning under load. Again the "watch window module" showing K_p, K_i and K_d is useful for this purpose. Moreover, during the tuning process the 120^o phase currents and the rotating reference frame currents (park_D, park_Q) can be viewed in real time allowing response to changes to be monitored immediately and visually.

F. Build level 6 "Closed loop current control in constant speed mode operation under torque variations"

In build level 6 one more PID_REG1_Q15/Q15 module is added in the exciting block diagram in order to adjust the motor torque continuously.

G. Build level 7 "Closed loop current control in constant speed mode operation incorporating the innovative hybrid efficiency control system"

In build level 7 the proposed custom module of the hybrid control block system is added in the exciting block diagram in order to improve the drive efficiency. The regulation of the Fuzzy controllers scaling factors can now be precisely tuned in real time by the same way as in build level 6. This can be easily achieved by the trial and error method.

V. SIMULATION-EMULATION RESULTS

A. Hardawe and Software

As Fig. 3 shows the experimental setup consists of a Laptop, the Spectrum Digital eZdsp F2812 for TMS320F2812 of TI® as computing engine, the Spectrum Digital DMC1500 platform as power inverter. The eZdsp is connected to the PC via a parallel port. The MATLAB/Fuzzy ToolBox™ and the Simulink® software are used to design the custom s/w modules and to interconnect the s/w modules. The re-usable s/w modules are offered from Mathworks® Embedded Target library for TI C2000 DSP [16] and the TI library for Digital Motor Control (DMC). The Real Time Workshop® translates the native MATLAB m-files to ANC® C code. The C code is compiled by the CCS IDE ® and is downloaded through the. By using the CCS TI IDE®, an on board JTAG emulator download the C code into the memory of the eZdsp h/w, through the PC's printer port.

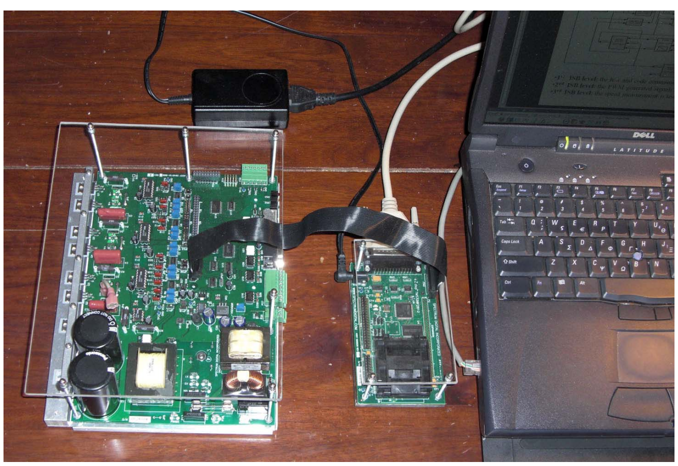

Fig. 3: The h/w used for emulation experiments. The Simulinc ® algorithm is translated to C-code and run on the eZdspTM F2812 from Spectrum Digital Inc.® based on the TMS320F2812 DSP by Texas Instruments®. The eZdsp controls the compatible inverter from Spectrum Digital Inc.® the DMC1500 (350V, 7,5A).

B. Simulations

As Fig. 4 shows, initially the drive operates under a constant speed of 1 p.u. and a load torque of 0.05 p.u. At the transient point t=150 s, a step torque increment from 0.05 p.u to 0.4 p.u. is applied. In this case the load demand increases, thus when the 1st steady state is recognized the FLC2 is activated (black line of power losses process). In order to validate the importance of the LMC controller, the same control scheme is implemented with the LMC turn-off. The power losses increase from 20.6±7.6 W to the peak 53.5 W (instead of 110.9 W when the LMC is turn-off - gray line of process). For both case studies, LMC activated or turn-off, as the efficiency algorithm of the FLC2 converges, the power losses settle to 53.5±9.2W. As Fig. 4 shows, the convergence time of the fuzzy part of the proposed control system is much faster when the LMC is activated. The simulations of the final code of the proposed control system are accomplished by using the eZdsp as computing engine. The specifications and the motor parameters which are used for the generalized LMC are listed in [17].

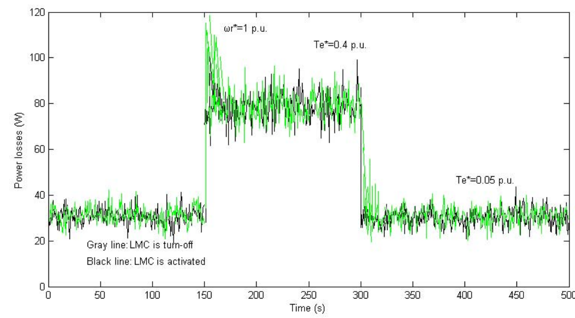

Fig. 4: The Simulation results of the power losses process of the proposed efficiency control system. The Simulinc ® algorithm is translated to C-code and run on eZdsp. Gray line: the LMC controller of the hybrid control scheme is turn-off and the efficiency is achieved by the fuzzy part. Black line: the LMC is activated before the fuzzy part for fast gross efficiency approximation, the fuzzy part is activated after the LMC in order to achieve refinement.

VI. CONCLUSION

The proposed Incremental System Build (ISB) levels logic frame implementation method reduces the complexity and development time of the algorithm. Moreover, this method allows to tune in real-time the PID proportional, integral and derivative constants separately, while the motor is spinning under load. In the final emulation level the optimum scaling fuzzy factors of the fuzzy controllers are fast and precisely tuned in real-time, because this designing method is allowing the real-time response to changes to be monitored immediately and visually.

The proposed innovated efficiency motor drive which consists of the fuzzy efficiency part, the LMC part and the ordinary FOC speed control part has many benefits which are summarized as follows: Is very fast due to the implementation of the *LMC* in transient states and precise due to the FLCs fuzzy part. This is important in cases in which during motor drive work cycle the power conservation is of greater importance over other working parameters. Because the *LMC* transient controller is based on a generalized loss- model, the proposed efficiency system can be easily incorporated to any size or type of speed drive. Moreover, main advantages are the simplicity in designing, hardware implementation, and low installation cost to an existing analog or digital vector controlled motor drive.

NOMENCLATURE

* Superscript indicates reference values

s subscript indicates the ones in stationary frame

d, q, subscript indicates the d-axis, q-axis components

T_e is the electromagnetic torque in p.u.

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