A Comparative Analysis of Fuzzy Logic and PI Speed Control in High-Performance AC Drives Using Experimental Approach

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***Abstract*—One of the frequently discussed applications of artificial intelligence in motion control is the replacement of a standard proportional plus integral (PI) speed controller with a fuzzy logic (FL) speed controller. Regardless of all the work, it appears that a thorough comparison of the drive behavior under PI and FL speed control is still missing. This paper attempts to fill in this gap, by providing an in-depth comparison of operation of a vector-controlled permanent-magnet synchronous motor, using at first an experimental rig. Speed responses, obtained under PI and FL speed control, are recorded and compared for a variety of operating conditions. The transients studied include response to large step speed command from standstill with nominal inertia and an increased inertia, response to small step speed reference change. and response to step load torque application. The transient behavior is examined for various initial speed settings, so that a thorough comparison is enabled. Experimental results are further supplemented with a set of simulation results, obtained using a different permanent-magnet machine and a different FL controller. Better generalization of the results is enabled in this way. It is shown that superiority of the FL speed control is less pronounced than it is often portrayed in the literature on the basis of limited comparisons. Indeed, in a number of cases, PI speed control provided a superior speed response.**

***Index Terms*—Comparative analysis, fuzzy logic speed control, porportional plus integral speed control, vector-controlled ac drives.**

I. Introduction

A STANDARD approach for speed control in industrial drives is to use a proportional plus integral (PI) controller. Recent developments in artificial-intelligence-based control have brought into focus a possibility of replacing a PI speed controller with a fuzzy logic (FL) equivalent [1].

Fuzzy logic speed control is sometimes seen as the ultimate solution for high-performance drives of the next generation [2]. Such a prediction of future trends is based on comparison of the drive response under PI and FL speed control, which has been compared on a number of occasions. Design of a speed controller is always based on the required response for a single operating point (called "design case" further on). The existing comparisons fall into one of the two categories: speed response with PI and FL speed control for the design case is substantially different [3]–[9], or the speed response is more or less the same [10]–[15]. Comparisons related to the first category are meaningless and they only serve the purpose of proving superiority of the FL control. Any valid comparison necessitates such an initial tuning of the two controllers that the speed response for the design case is at least similar, if not identical.

Even when tuning of the controllers is appropriate so that a fair comparison is enabled, comparison is usually based on a very limited selection of transients [10], [12]–[15]. These typically include one reference speed setting and application/removal of the load torque at one reference speed. Robustness testing is sometimes included as well, again for a single operating point. Comparison is usually based on the controller design for aperiodic speed response, in which case PI control is known to exhibit sluggish disturbance rejection properties [11]. However, provided that the controller tuning is appropriate, even limited selection of transients for comparison may indicate that FL speed control is not necessarily superior to PI speed control. Improvement of response obtained by FL control in [14] appears to be marginal. The same conclusion is arrived at in [15]. An indication that there are transients in which PI control will yield better response is provided in [10], while [12] shows some transients for which response of PI and FL control is essentially the same. Studies reported in [12], [14] are based on simulation only, while [10], [13], [15] include some experimental results.

The most complete comparative analysis, available at present, is the one of [11]. Experimental study [11] compares speed responses for load rejection transient, step application of the speed reference, and examines speed tracking capability and robustness to rotor resistance variation. It shows that better overall behavior is obtainable with FL speed control. However, only a single reference speed setting is again elaborated.

Regardless of all the existing work regarding PI and FL speed control, it appears that a detailed comparative analysis of the drive behavior under PI and FL speed control, based on experimentally recorded and/or simulation speed responses, has not been done so far. The goal of this paper is to provide such a comparison for a variety of operating conditions. A vector-controlled permanent-magnet synchronous motor (PMSM) drive is at first realized in the laboratory. PI and FL speed controllers are designed and implemented using a PC. The speed response to rated speed command under no-load conditions, with motor

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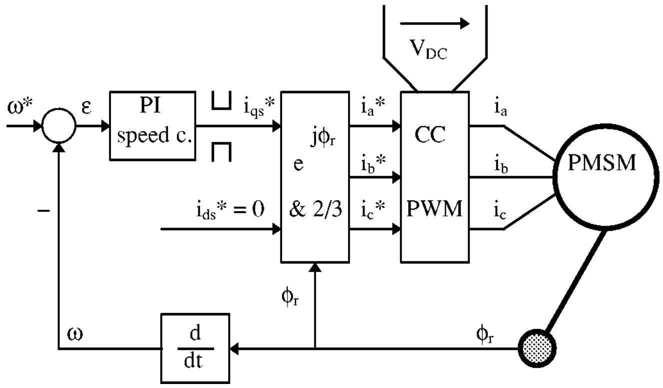


Fig. 1. Configuration of a rotor-flux-oriented PMSM drive.

inertia only, is made as similar as possible (aperiodic), so that a fair comparison is enabled. Speed response is further compared for large step speed commands from standstill other than rated (without and with connected load, so that a comparison of the drive robustness to inertia variation is enabled), for small step change of the speed command and for step application of a load torque. A simulation study is performed next, using a different permanent-magnet synchronous machine and a different FL controller. The underlying idea behind this approach is that more general conclusions are enabled, since the performance of a FL controller is largely dependent on the design.

It is shown that the only case in which FL control is always superior is the load rejection transient. In a number of transients other than this one, PI speed control provided better speed response. Considering the results of the study and taking into account all the difficulties encountered in FL speed control implementation, discussed in [15] and addressed here as well, it is concluded that superiority of the FL speed control, claimed by many authors, is a somewhat relative notion.

Vector control of a three-phase current-fed induction motor or a PMSM converts the machine, from the control point of view, into its dc equivalent. Therefore, in speed control loop design, it is irrelevant whether the actual machine is a dc machine or a vector controlled ac machine and the results of the study are universally applicable to all high-performance drives, as long as the speed controller is under consideration.

II. Experimental Setup and Speed Controller Tuning

Control scheme of a PMSM drive with rotor-flux-oriented control is shown in Fig. 1. A 150-Hz six-pole 3000-r/min motor is used, of 0.54-kW and 1.7-N·m continuous power and torque output rating, respectively, at rated speed. Motor inertia is 0.000 256 kg·m^2. The pulsewidth modulation (PWM) voltage-source inverter is controlled by means of three independent hysteresis current controllers. The inverter input dc voltage is 330 V. An integrator antiwindup mechanism is included within the PI speed controller.

The FL speed controller is of standard structure. Inputs are speed error and change of speed error. Seven membership functions with overlap, of triangular shape and of equal width, are used for each input variable, so that a 49-rule base is created. It is recognized that a better behavior of the FL controller can be achieved by modifications suggested in [11] and this is explored in simulation, while the behavior of the basic FL speed controller is investigated experimentally. As a FL controller on its own is a PD controller equivalent, output of the speed FL controller is integrated in order to yield PI like behavior. The output of the FL speed controller is the stator q-axis current increment; the output of the integrator is therefore stator q-axis current command (denoted as i_{qs}^* in Fig. 1). An equivalent antiwindup feature is included.

Position of the drive is measured using a six-pole resolver. The resolver-to-digital converter is based on an AD2S80A chip. The chip provides a signal proportional to the speed of rotation, which is used to record the actual speed. This signal is, after 12-b A/D conversion, used as the feedback speed signal for the speed control algorithm as well. Coordinate transformation is realized by means of an AD2S100 single processor chip. The outputs of the coordinate transformation board are the three stator phase current references that are updated every 80 μs. Hysteresis current controllers are realized using analog means. Actual phase currents are measured using Hall-effect sensors. The hysteresis band is constant and equal to ± 0.2 A. Stator q-axis current is limited to 2 A.

The speed control algorithms (PI and FL) are implemented in a PC (Intel Pentium 166 MHz). The output of the speed controller, stator q-axis current reference, is after 12-b D/A conversion supplied as the input into the coordinate transformation chip. The speed control algorithm is operated at 2.5 kHz, so that sampling and computation times are 0.4 ms and stator q-axis reference updating takes place every 0.4 ms.

PI and FL speed controllers are developed and tuned using Simulink/Matlab and Fuzzy Logic Toolbox. Speed response to rated step speed command (3000 r/min) without a load connected to the shaft (rated motor inertia condition) is required to be the fastest possible aperiodic response. The controllers were tuned manually, without resorting to any of the optimization algorithms. Final controller parameter values are: proportional and integral gain of the PI speed controller equal to 1.5 and 20, respectively, and scaling factors for error, change of error, and output equal to 0.002, 0.2, and 1.2, respectively, for the FL speed controller.

Real-time control is based on additional utilization of the Real-time Workshop Toolbox. Two possibilities for real-time control exist: Simulink and Real-time Workshop Toolbox can be configured based on a Windows platform (called further on “Simulink mode”) or the program for online control can be executed under a DOS platform (called further on “real-time mode”). Real-time control using a PI speed controller is possible using either of the two modes. Maximum computation and sampling frequencies for the Simulink mode and Real-time mode were found to be 5 and 100 kHz, respectively. Implementation of the FL speed control in real time using Simulink mode was found to be impossible, due to long processing time and large size of the executable programs. The FL speed controller could only be implemented in real-time control using Real-time mode. However, even in this mode, it was necessary to first modify the rule table, so that the required 2.5-kHz sampling frequency can be achieved. The total number of rules, initially equal to 49, had to be reduced to only 20 rules. This

TABLE I
IMPLEMENTED FL SPEED CONTROLLER RULE BASE

ce | e	NL	NM	NS	ZE	PS	PM	PL
NL							
NM			NL	NM	NS		PS
NS			NM	NS	ZE		PM
ZE			NS	ZE	PS		PL
PS			ZE	PS	PM		PL
PM			PS	PM	PL		PL
PL							

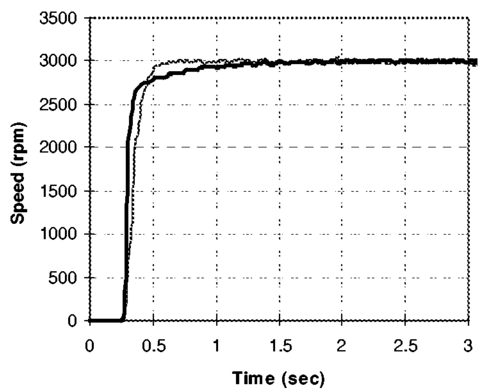


Fig. 2. Experimentally obtained speed responses with PI and FL speed control: rated step speed command from standstill, under no-load conditions, with rated motor inertia (black = PI, gray = FLC).

enabled processing time to be reduced to 0.33 ms, so that the required 2.5-kHz frequency could be met. The rule base is modified by removing rules related to medium positive, and medium and large negative speed errors. This modification has a very minor impact on all the transients that are considered further on. The rule base of the implemented FL controller is shown in Table I.

As implementation of the FL speed control had to be done using Real-time mode, PI speed control is implemented in the Real-time mode as well, so that all the experimental results apply to the Real-time mode.

Experimentally recorded speed response to rated step speed command with disconnected load, obtained using PI and FL speed controllers, is illustrated in Fig. 2. Although the two responses are not identical (PI speed control response is somewhat slower), it is believed that the two responses are close enough to enable a good comparison for other transients. The black trace in Fig. 2 and in all the subsequent experimental figures is the speed response with PI control, while the gray trace is the one obtained with FL speed control.

III. Comparison of Experimentally Obtained Speed Responses

A. Response to Step Speed Command From Standstill, Rated Inertia

The drive is initially at standstill without any load connected to the shaft. Fig. 3 presents recorded speed responses for speed references equal to 1000, 1500, 2000, and 2500 r/min (the 3000-r/min case is shown in Fig. 2). The FL speed controller provides very good speed response in all cases, consistent with

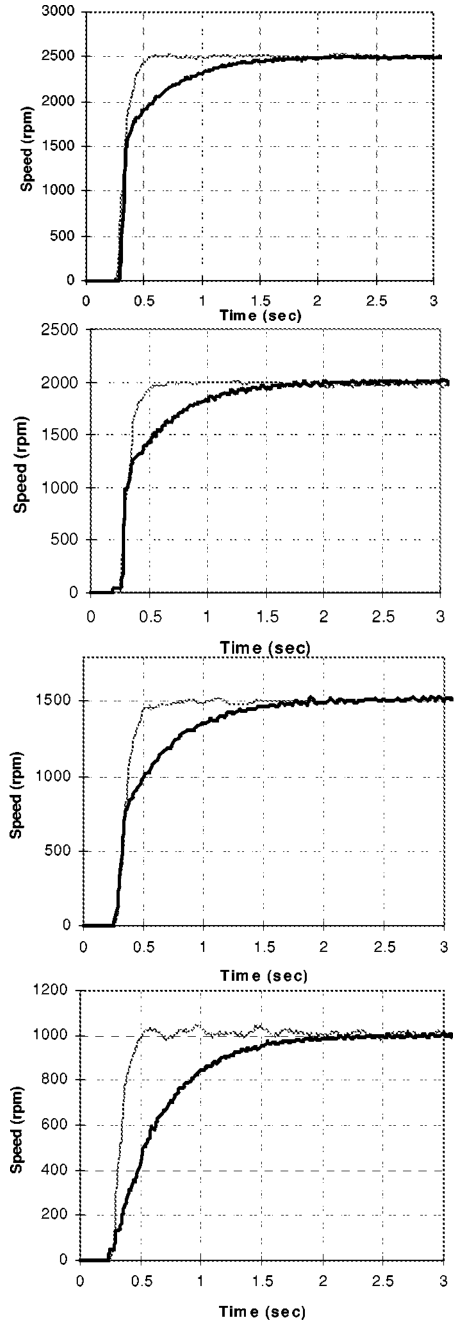


Fig. 3. Response to 2500-, 2000-, 1500-, and 1000-r/min step speed commands from standstill, rated inertia (black = PI, gray = FLC).

the one of Fig. 2. The response remains aperiodic for all the speed commands except for 1000 r/min, and the settling time is very much the same for all the speed references. In contrast to this, the response with PI speed control worsens as the speed reference is reduced. Although it remains aperiodic in all cases, the settling time increases with the decrease in the reference speed setting.

B. Response to 10% Step Reduction of the Speed Command, Rated Inertia

Response to large step speed reference represents a transient during which operation in the current limit normally takes place. As the motor was accelerated without the load connected to the

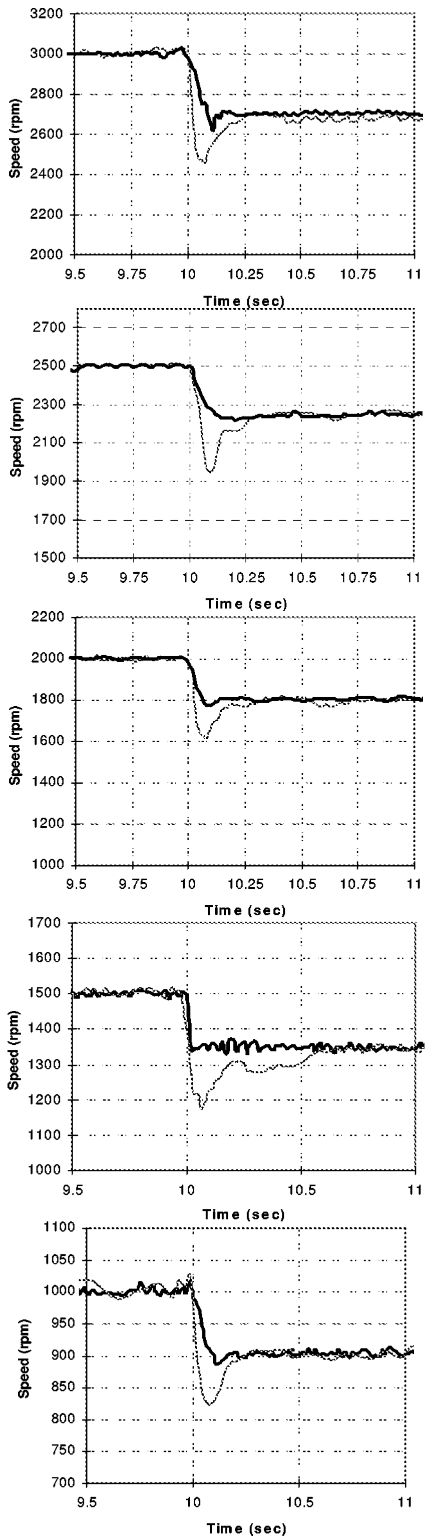


Fig. 4. Response to step 10% speed reference reduction (rated inertia; previous steady states in Figs. 2 and 3; black = PI, gray = FLC).

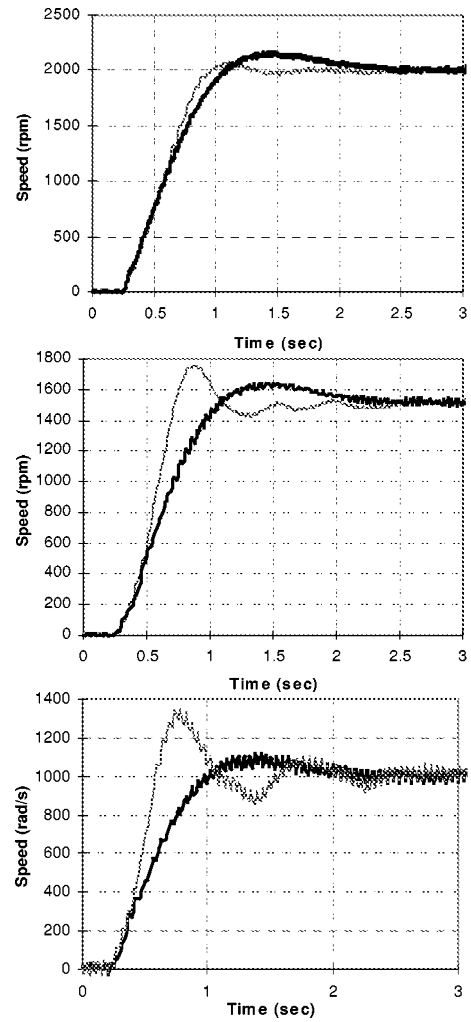


Fig. 5. Response to 2000-, 1500-, and 1000-r/min step speed commands from standstill, increased inertia (black = PI, gray = FLC).

shaft, operation in the current limit took place for a very short period of time for transients of Figs. 2 and 3. However, once the load is connected (Section III-C), operation in the current limit during prolonged time intervals will take place. In contrast to this, a small change in the reference speed setting does not require operation in the current limit regardless of whether the load is connected or not.

The machine initially operates in a steady state arrived at in Figs. 2 and 3. A step speed command reduction, equal to 10% of the previous reference setting, is applied. The results are given in Fig. 4. The response obtained with the PI speed controller is much better in terms of both the undershoot and the settling time for all the initial speed settings. This is a consequence of the fact that the PI speed controller is characterized by a slightly slower speed response (Fig. 2), which is beneficial for the transient considered in Fig. 4.

C. Response to Step Speed Command From Standstill, Increased Inertia

PMSM is now coupled to a dc motor, whose armature terminals are left open. An effective increase in inertia is, therefore, achieved, of the order of 3:1. As the dc motor rated speed is 2000 r/min, testing is restricted to, at most, this speed value. Fig. 5 shows response to application of step speed references equal to 2000, 1500, and 1000 r/minm. Operation in the current limit now takes place for a prolonged period of time.

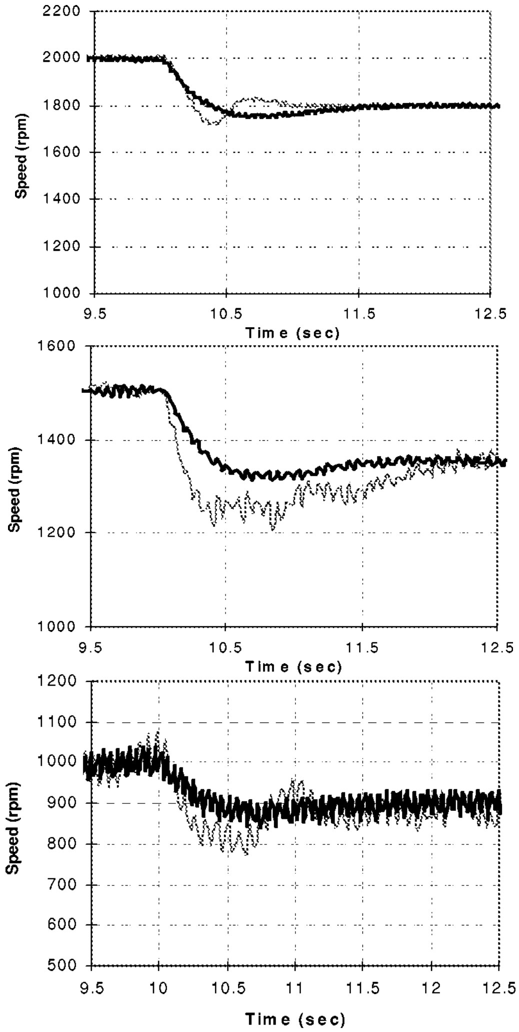


Fig. 6. Response to step 10% speed reference reduction (increased inertia; previous steady states in Fig. 5; black = PI, gray = FLC).

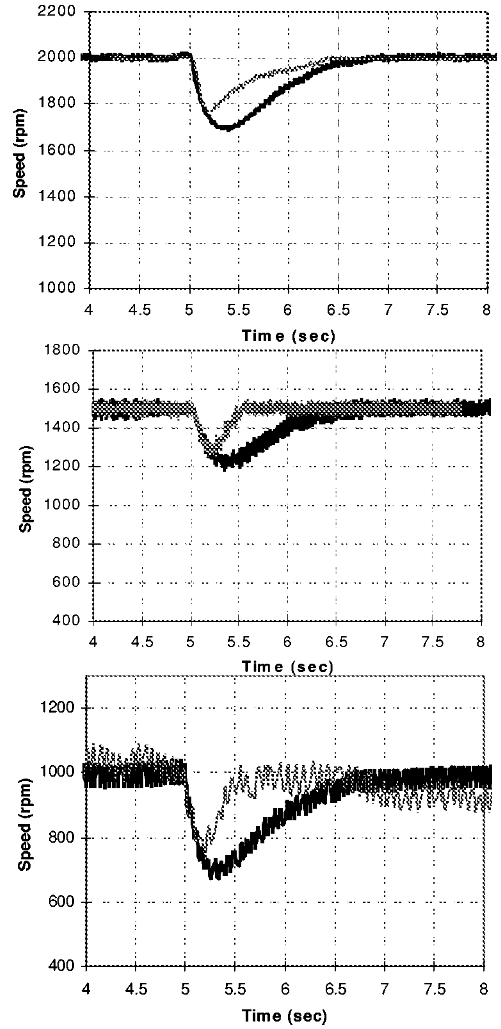


Fig. 7. Response to step load torque application at 2000-, 1500-, and 1000-r/min reference speed settings (black = PI, gray = FLC).

The FL speed controller yields superior response for the 2000-r/min speed reference, with very small overshoot and small settling time. Better robustness with respect to inertia variation is one of the most frequently cited advantages of the FL speed control over the PI control. However, a decrease in the speed reference setting leads to substantial deterioration of the speed response with FL control. Overshoot for 1500-r/min and 1000-r/min speed reference settings is around 110 r/min with PI control, while with FL control it is 240 and 340 r/min, respectively. Settling time is approximately the same for the two controllers.

D. Response to 10% Step Reduction of the Speed Command, Increased Inertia

The same transient, described in Section III-B, is analyzed once more. The dc motor is now connected, so that the effective inertia is increased. Speed response to step 10% reduction of the speed reference, with previous steady-state operation at 2000, 1500, and 1000 r/min (Fig. 5), is illustrated in Fig. 6.

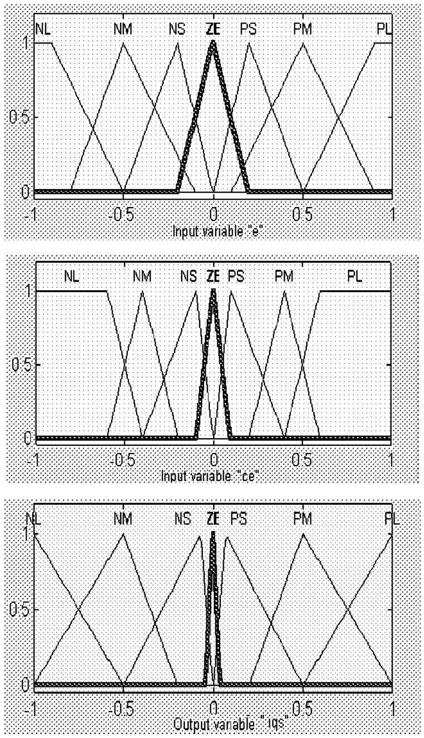
Once more, behavior with PI control is advantageous for all the considered cases, the reasons being the same as in Section III-B.

E. Load Rejection Transients

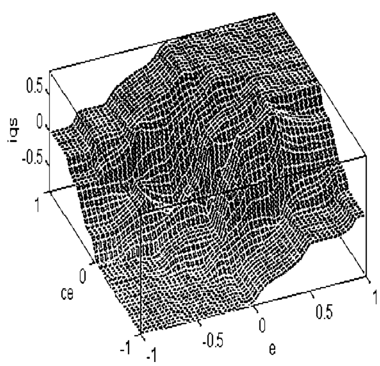
Load is applied in a stepwise manner in steady-state no-load operation, by connecting the dc motor armature terminals to a resistance bank. If the resistance bank setting is constant, the load torque seen by the PMSM is approximately proportional to the speed of rotation. In order to emulate the constant load torque behavior at different speeds, the resistance bank setting is changed appropriately for each speed at which testing is performed. Results of the load rejection transient are given in Fig. 7 for 2000-, 1500-, and 1000-r/min reference speed settings. FL speed control offers superior speed response, with smaller speed dip and shorter recovery time, regardless of the speed reference setting. This is another frequently cited advantage of the FL speed control, which is fully verified by the results of Fig. 7.

IV. Simulation Study

The control scheme studied in simulation is identical to the one used in experiments (Fig. 1). An 86-Hz six-pole 6.2-A 1720-r/min motor is used now, of 1.1-kW and 6.1-N·m continuous power and torque rating, respectively, at rated speed. Motor inertia is 0.001 76 kg·m^2. Hysteresis current control



(a)



(b)

Fig. 8. (a) Membership functions of error, change of error, and output and (b) three-dimensional control surface of the offline-optimized FL speed controller used in simulations.

is applied again, with a hysteresis band of ± 0.5 A. The inverter input dc voltage is 220 V and stator q-axis current is limited to 3.4 times the rated stator current. The PI speed controller is again provided with an integrator antiwindup. The output of the FL speed controller is integrated once more and the controller is provided with an equivalent antiwindup mechanism.

Both speed controllers are again tuned to yield an identical aperiodic speed response, with minimum settling time, to the application of the step rated speed command (180 rad/s) under no-load conditions with rated inertia. The PI controller is designed first, using Ziegler–Nichols method and subsequent manual fine tuning through simulation. The FL speed controller is designed next. Once more, seven triangular membership functions with overlap are used for both error and change of error, so that a 7×7 rule base is obtained. In contrast to the experimental FL controller, where membership functions were of equal width and with centered peaks, membership functions

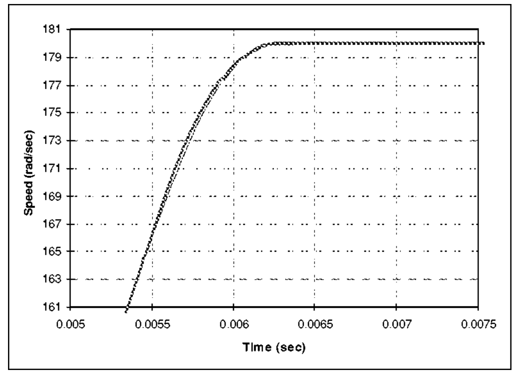


Fig. 9. Comparison of the speed response, obtained with PI and FL speed control, for the design case (rated speed command, no-load conditions).

of this FL controller were fine tuned manually, through many simulation runs, so that the best possible response is achieved. Fig. 8 illustrates membership functions of the offline optimized FL speed controller, which are of unequal widths and with asymmetrically positioned peaks, and the corresponding three-dimensional control surface in the normalized universe of discourse.

Final controller parameters are: proportional and integral gain of the PI speed controller equal to 2.22 and 111, respectively, and scaling factors for error, change of error, and output equal to 0.0023, 0.41, and 3, respectively, for the FL speed controller. All 49 rules of the FL speed controller are used.

The speed response of the two speed controllers, obtained for the "design case," is compared in Fig. 9 (zoomed extract in vicinity of steady state). As can be seen, both controllers provide aperiodic speed response with identical settling time.

A simulation study is performed over the range of operating speeds from 10 rad/s up to the rated speed (180 rad/s). Overshoot in speed response for large reference speed step change under no-load conditions, dip due to sudden stepwise rated load torque application, and undershoot that follows small 10% reference speed change are extracted from simulation results for PI and FL control, together with the duration of the transient (which is taken as the time needed for the speed error to become smaller than 0.1 rad/s). Results are summarized in Figs. 10–12 (the black trace once more applies to PI control, while the gray trace is valid for the FL speed control).

Response to the large step speed reference change is basically the same with PI and FL control for speed commands between 120–180 rad/s (Fig. 10), in terms of both speed overshoot and settling time. It is worth noting that a small speed overshoot exists with both controllers for all the speed settings, except for the design case. FL control is superior between 40–120 rad/s, while PI control is better up to 40 rad/s. Disturbance rejection is considerably better with FL control at all speed settings (Fig. 11), since the restoration time is significantly shorter (although the dip in speed is essentially the same for speed commands between 120–180 rad/s). Response to a small step speed reference change (Fig. 12) is better with PI control for initial speeds up to 60 rad/s, since the settling time is shorter, while there is no undershoot for either PI or FL speed control. In the region from 60 to 180 rad/s, response is better with FL control, since the undershoot is smaller, while the settling time is essentially the same.

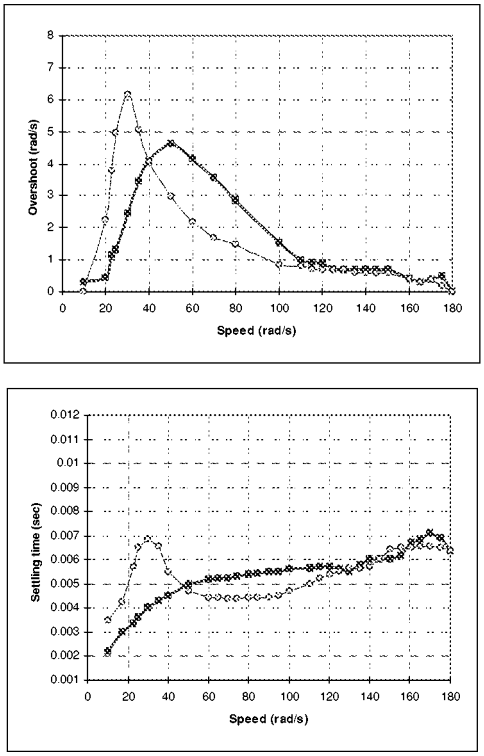


Fig. 10. Comparison of PI and FL speed control over the entire speed region: overshoot and settling time for step application of large speed command (black = PI, gray = FLC).

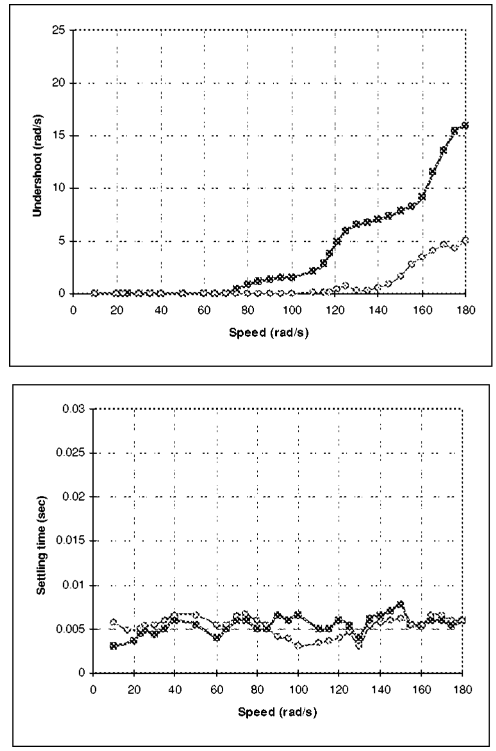


Fig. 12. Comparison of PI and FL speed control over the entire speed region: speed undershoot and settling time for small 10% step change in the speed command (black = PI, gray = FLC).

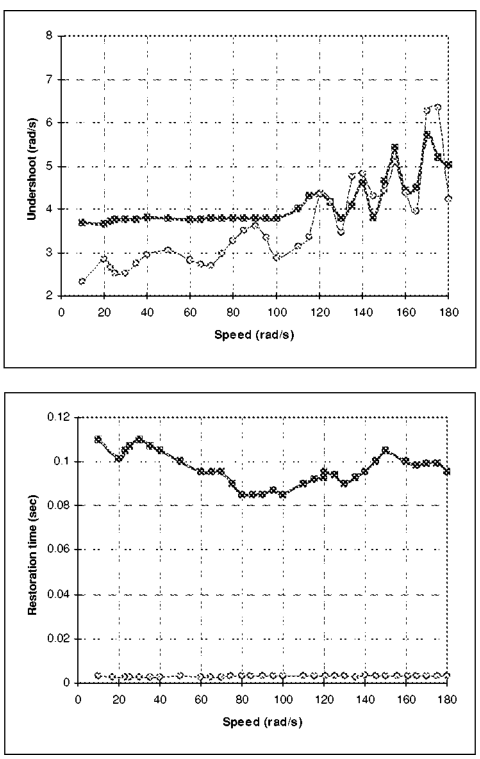


Fig. 11. Comparison of PI and FL speed control over the entire sped region: speed dip and restoration time for rated load torque application (black = PI, gray = FLC).

V. Discussion

The paper presents results of extensive comparative experimental and simulation studies, related to PI and FL speed control in high-performance drives. Two different permanent-magnet motor drives are considered, in conjunction with two different FL controllers: a very basic one (with reduced number of rules, membership functions of equal width and with centered peaks) used in the experimental investigation, and an offline optimized one (with full rule base, membership functions of unequal widths, and asymmetrical peaks) used in the simulation study. Transients encompassed by the study include speed response from standstill to large step speed reference application, speed response to small step reference speed change, and load rejection transient. The cases of nominal inertia and an increased inertia are covered by experiments, while the case of nominal inertia only is investigated by simulation. The transients are examined for a variety of different speed commands, thus enabling a thorough comparison to be made. The main conclusions may be summarized as follows.

- The transient in which FL speed control is undoubtedly superior to PI speed control in all the operating conditions is the load rejection transient, as confirmed by both experimental (Fig. 7) and simulation results (Fig. 11). However, it has to be noted that this statement is restricted to the case when the controllers are designed for zero overshoot (aperiodic speed response).
- Response to the large step speed command under no-load conditions was found to be very dependent on the speed setting. Simulation results show that there are speed regions where either PI (low speed settings), or FL controller (medium speed range) offer better behavior, as well as a region (high speeds) where the two controllers yield essentially the same response (Fig. 10). Such situation is

confirmed in the experimental study, for the case with an increased inertia, where PI controller was found to yield a better response at lower speeds (1500- and 1000-r/min settings in Fig. 5), while the FL controller was better at higher speeds (2000-r/min setting in Fig. 5).

- Speed response to small reference speed change depends on how close the speed responses of the two controllers are for the design point (rated step speed reference with rated inertia here). The PI speed controller has demonstrated in the experimental work much better response to all the small reference speed changes (Figs. 4 and 6), primarily because its response for the design point was slightly slower. In the simulation study, the PI speed controller was found to be better for speed settings below 1/3 of the rated speed, while the FL controller offered better behavior in the remainder of the speed control range (Fig. 12). This difference between simulation and experimental results clearly shows how important it is to try to provide identical speed responses of the two controllers for the design case (the goal fully accomplished in simulations and only partially in the experiments).

VI. Conclusion

The dependence of the speed controller response on the speed set point is usually overlooked. Furthermore, two speed controllers that are to be compared are rarely designed in such a way that they offer the same speed response for the design point. The paper clearly shows the following.

- A meaningful comparison is possible only if the two controllers are designed in such a way that a more or less identical speed response is obtained for the design point.
- Once designed for a certain operating point, neither the PI nor the FL speed controller is likely to offer a superior behavior for all the transients over the entire speed control region. This statement is proved by both experimental and simulation results, although two quite different FL speed controllers were considered.
- The PI controller, being a standard industrial speed controller solution at present, will continue to be compared to various novel forms of speed controllers that will emerge in the future (including adaptive FL controllers). It is important that, in such cases, a detailed comparative analysis of the drive performance is always performed. Comparison based on a single operating point or a single transient is more than obviously insufficient.

Considering all the differences between the two FL controllers and the two drives studied by simulation and by experiment, it seems fair to say that the experimental and simulation results are in reasonable agreement, since both show the same underlying trends.

The testing procedure for the speed controller performance, utilized in this paper (and supplemented with some additional operating regimes), could be regarded as a proposal for a set of benchmark tests for evaluation of the speed controller performance. Comparison should be performed with regard to an equivalent PI speed controller. The tests would need to be performed for a number of reference speed settings, ideally, for all of the following transient operating regimes:

- large step speed command from standstill, under rated inertia condition and with an increased inertia;
- small reference speed change, with rated and with increased inertia;
- step load torque application;
- reversing transient.

Speed tracking behavior [11], if of interest for the intended application, should be encompassed by the comparative analysis. In the case of an indirect rotor-flux-oriented machine, robustness to rotor resistance variation should be included in the comparison as well [11].

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