Permanent Magnet Synchronous Motor Drive Using Hybrid PI Speed Controller With Inherent and Noninherent Switching Functions

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The performance of the fuzzy logic controller (FLC) is better under transient conditions, while that of the proportional plus integral (PI) controller is superior near the steady-state condition. The combined advantages of these two controllers can be obtained with hybrid fuzzy-PI speed controller. The computations involved with the FLC are much higher as compared to that of the PI controller. Generally, the FLC output is near the maximum permissible value at the beginning of a transient condition but reducing with the reduction in the speed error. In this paper, instead of the FLC, a fuzzy equivalent proportional (FEP) controller is used along with the PI controller to make it a hybrid PI (HPI) controller which eventually is much faster and less computation intensive. The performance of the vector-controlled permanent magnet synchronous motor drive with this HPI controller is obtained with six switching functions, namely: 1) saturation; 2) hyperbolic tangent; 3) polynomial S function; 4) output of FEP controller only; 5) output of PI controller only; and 6) combination of the outputs of both the PI and FEP controllers. From the results, it is observed that the polynomial S switching function based HPI controller is better in general for most of the performances.

***Index Terms*—Fuzzy controller, hybrid fuzzy-PI (HFPI) controller, hybrid PI (HPI) controller, motor, motor control, permanent magnet motor, PI controller, permanent magnet synchronous motor (PMSM), vector control.**

I. INTRODUCTION

IN the vector-controlled permanent magnet synchronous motor (PMSM) drive, the outer speed loop provides the reference value of the current for the inner current loop and any disturbance in the speed controller output would cause erroneous currents, thus degrading the system performance. Hence, proper operation of the speed controller is of great importance for the appropriate drive performance. The use of proportional plus integral (PI) controller suffers from performance degradation under system disturbances due to the fixed proportional gain K_p and integral time constant T_i [1], [2]. This problem can be overcome with fuzzy logic controller (FLC) [1], [2]. An FLC is free form mathematical modeling and is based on the linguistic rules formed from the experience with the system [1]. But as compared to the PI controller, the FLC involves approximations, increased complexity, more computations and higher memory requirements. The performance of the FLC is superior only under transient conditions while the performance of the PI controller is superior under the steady-state condition [3]. Gain scheduled PI speed controllers have been reported but suffer from the need of apt selection of the limits for controller gains and the rate at which they would change [4]. Sliding-mode controllers [5]–[7] have fast dynamic response and insensitivity to parameter variations and system disturbances, but necessitate compensation to eliminate chattering. Artificial neural network-based speed controllers are computationally intensive and require on-line or off-line learning with the help of training algorithms and a predefined dataset [8].

The merits of FLC and PI controller can be obtained with a hybrid fuzzy-PI (HFPI) controller [9]–[12]. Generally, in HFPI speed controllers, the output of the PI controller has more prominent effect on the HFPI controller output, while the FLC has more prominent effect on the controller output under the transient conditions. One of the major components of the HFPI controller algorithm is the switching function which decides the prominence of the FLC and PI controller under the operating conditions. Usually, in the HFPI controller, a set of rules or a separate FLC is used to determine the prominence of the output of the two controllers [3], [9], [10]. The activation of the FLC in HFPI controller is based on the detection of the overshoots, undershoots, and oscillations which requires continuous monitoring [9], [10]. The use of FLC to determine the weights of the HFPI speed controller for PMSM control [11] needs an additional FLC which demands a larger computational time as two FLC algorithms need to be executed and more gain constants need to be tuned. The increased computations reduce the switching frequency and result in higher torque ripples. To reduce the computational burden and execution time in HFPI speed controllers, the inherent and noninherent switching functions are implemented [3], [12]. The major portions of computations in HFPI controller are associated with the FLC. To further reduce the computations and complexity in the tuning needs, a hybrid PI (HPI) controller with noninherent and inherent switching functions in which FLC is replaced by a fuzzy equivalent proportional (FEP) controller is proposed in this paper. An FEP controller is a simple proportional (P) controller with a large gain constant; and it replicates the performance of the FLC under transient conditions and becomes inactive during the steady state.

II. HPI SPEED CONTROLLER

In spite of the use of noninherent and inherent switching functions, the execution time for the HFPI speed controller is far higher as compared to the PI controller. Also as the performance of the PI controller is superior under the steady-state condition, the operation of the FLC is of least prominence at steady state, in spite of the high execution time associated with it. With a view of reducing the computations without sacrificing the controller

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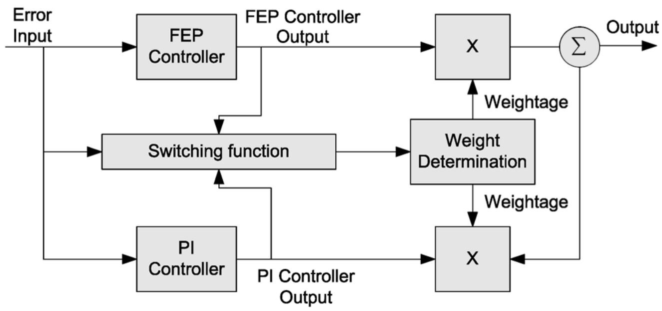

Fig. 1. Schematic diagram of the HPI speed controller with switching function.

performance, HPI speed controller has been analyzed. From the observations pertaining to the FLC for speed control, it has been observed that the FLC output is near the maximum permissible output value at the starting of a transient, and with the reduction in speed error it reduces. The operation of the FLC is replaced by an FEP controller where the error input is utilized to generate controller output which aids HPI controller to achieve satisfactory performance in terms of speed response. The FEP controller is a proportional controller with the gain tuned in such a way that with the help of a limiter the controller output is comparable to that of the FLC under the beginning of a transient.

In this paper, three noninherent and three inherent switching functions have been utilized for HPI controllers to decide the weights for the two controller outputs. Noninherent switching functions, namely: 1) saturation; 2) hyperbolic tangent; and 3) polynomial S functions, have been utilized. In the case of the inherent switching functions the output of the 1) FEP controller; 2) PI controller; and 3) combination of the two controller outputs are utilized for the weight determination. The noninherent and inherent switching functions are based on one common rule that, during the transient conditions, the output of the FEP controller output has more weightage on the output of the HPI controller and during the steady-state condition, the PI controller output has more weightage. There is no abrupt change in weights associated with the controller outputs that would result in chattering. The switching functions in the HPI speed controller reduce the torque ripples. The HPI speed controller is simple and also robust.

The PI controller in discrete time domain and the FEP controller in discreet time domain are expressed in the following equations:

$$U[k] = K_p E[k] + K_i T_s \sum_{i=0}^{k} E[i] \quad (1)$$

$$Q[k] = K_e E[k] \quad (2)$$

where $U[k]$ is the output of the PI controller at the k^{th} sampling instant, $E[k]$ is the speed error, K_p is the proportional gain, K_i is the integral gain, T_s is the sampling time, $Q[k]$ is the output of the FEP controller, and K_e is the gain constant.

Fig. 1 shows the schematic diagram of the HPI controller. The speed error is processed by the FEP controller and the PI controller. Depending on the switching function, appropriate weights are assigned to the output of the two controllers, based on which the output of HPI controller is determined. For an inherent switching function, the output of the two controller are required as input, whereas for noninherent switching function the speed error is required as input for weight determination. With reduced computations and complexity, HPI controller provides fast dynamic response and good steady-state response. The tuning needs are reduced and due to the absence of rule base, memory requirements are also reduced. Lesser computations facilitate the use of higher switching frequency leading to lower torque ripple, losses, and ease of filtering.

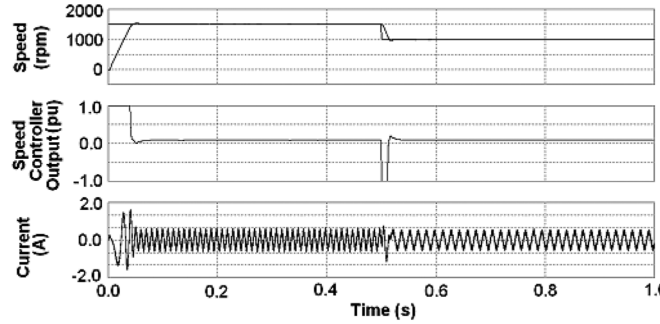

Fig. 2. Reference and actual speed, speed controller output, and line current of the vector-controlled PMSM drive with HPI speed controller based on saturation switching function.

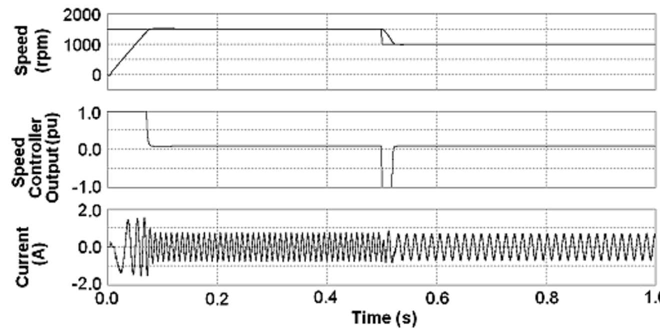

Fig. 3. Reference and actual speed, speed controller output, and line current of the vector-controlled PMSM drive with HPI speed controller based on hyperbolic tangent switching function.

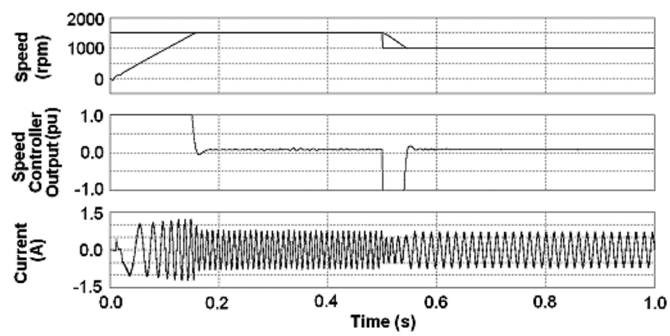

Fig. 4. Reference and actual speed, speed controller output, and line current of the vector-controlled PMSM drive with HPI speed controller based on polynomial S switching function.

III. Results

Simulations have been carried out in PSIM for the HPI speed controller with all the three noninherent and three inherent switching functions for the vector control of a 100 W, 24 V PMSM with stator resistance of 0.14 Ω, d and q axes inductances of 0.27 mH, back emf constant of 3.94 V per 1000 r/min, torque constant of 37.6 mNm/A, rotor inertia of 96×10^{-7} Kg.m^2, and mechanical time constant of 1.9 ms. The reference speed is 1500 r/min with a step reduction to 1000 r/min at 0.5 s. Figs. 2–4 show the plots for the actual and

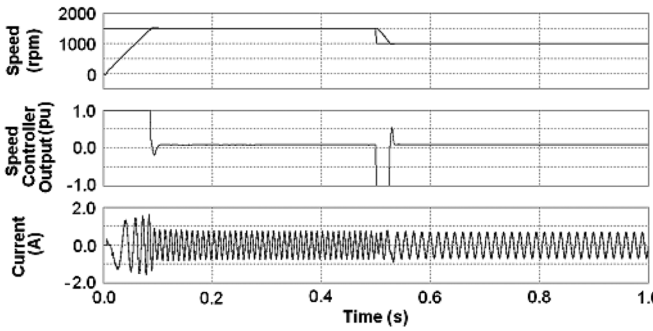

Fig. 5. Reference and actual speed, speed controller output and line current of the vector-controlled PMSM drive with HPI speed controller with switching function based on the output of FEP controller only.

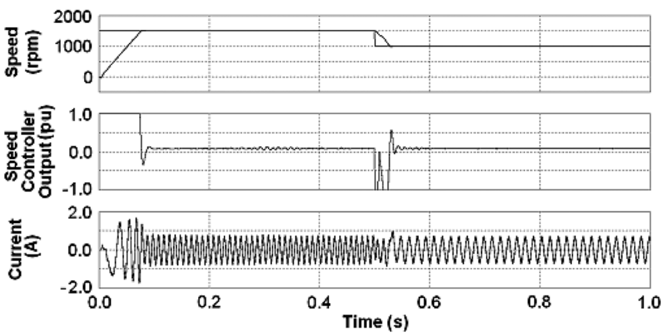

Fig. 6. Reference and actual speed, speed controller output and line current of the vector-controlled PMSM drive with HPI speed controller with switching function based on the output of PI controller only.

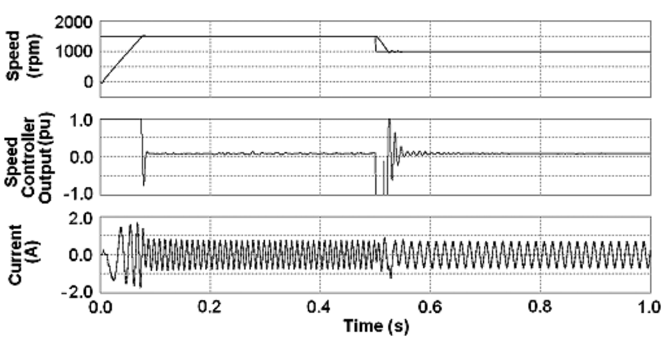

Fig. 7. Reference and actual speed, speed controller output, and line current of the vector-controlled PMSM drive with HPI speed controller with switching function based on the average of output of both the FEP and PI controllers.

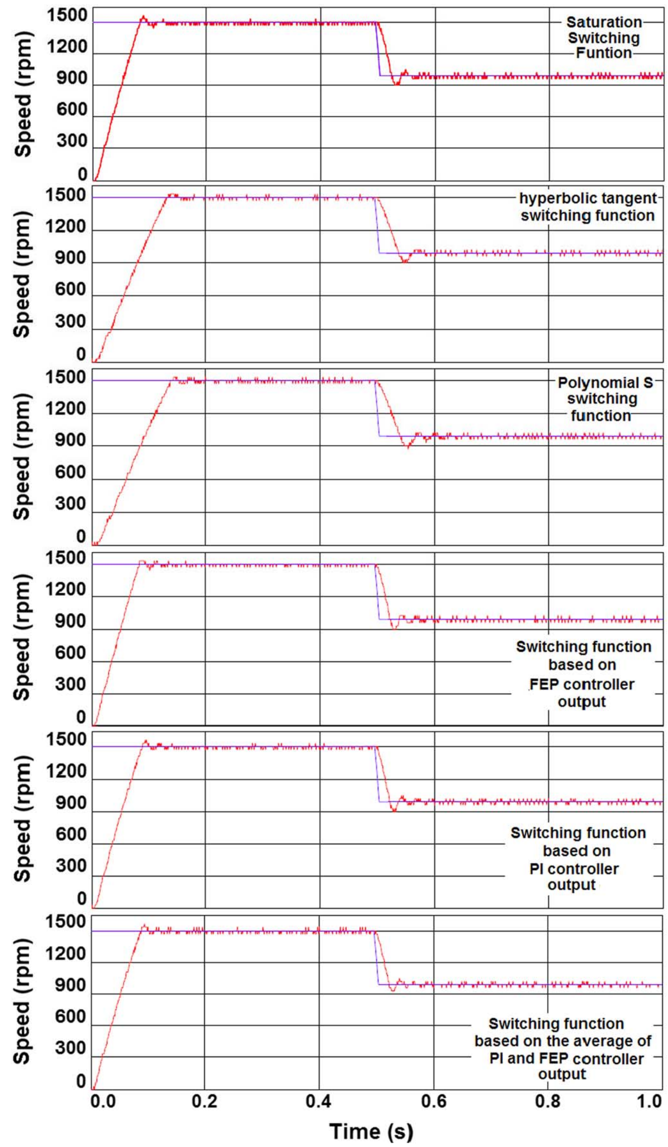

Fig. 8. Experimentally measured speed of the vector-controlled PMSM drive with HPI speed controller with noninherent and inherent switching functions.

reference speeds, speed controller output, and line current of the vector-controlled PMSM with HPI based on noninherent switching functions. On comparing the drive performance of the HPI speed controllers for the vector-controlled PMSM, it is observed that among noninherent switching functions, the saturation-based switching function yields fastest speed response with maximum value of the peak starting current among the three cases. On the other hand, with the polynomial S-based switching function, the peak overshoot is the least, 6 r/min, but with the slowest response and minimum value of peak current at the starting. The performance with the hyperbolic tangent based switching function is between the ones obtained with the other two noninherent switching functions. Also with the step reduction in the reference speed at 0.5 s, the time required to reach the reference speed of 1000 r/min is least in this case.

Figs. 5–7 show the plots for the actual and reference speeds, speed controller output, and line current of the vector-controlled PMSM with HPI based on inherent switching functions. With inherent switching functions, the speed response is marginally better with the combination of the two controllers over the other two inherent switching functions, where the output of only one controller has been utilized for the derivation of weights. The maximum current at starting is the minimum in the case of inherent function with the FEP controller.

The details of the simulated drive performance with the HPI speed controller with the six different switching functions have been tabulated in Table I. From the tabulated values, it is observed that the performance of the vector-controlled PMSM with HPI speed controller based on polynomial S switching function is better in general. The reason for the nearly linear speed response during the transient period is due to the fact that the FEP controller output has a prominent weightage during the transient period. With a high gain, it drives the motor speed toward the reference value with the absolute maximum speed controller output.

A comparison of the drive performance with inherent and noninherent switching functions results that the speed response

TABLE I
PERFORMANCE COMPARISON OF THE VECTOR-CONTROLLED PMSM DRIVE WITH THE HPI SPEED CONTROLLER

Switching function	Saturation	Hyperbolic	Polynomial S	FEP output only	PI controller output only	Average of FEP and PI outputs
Time required to reach the reference speed of 1500 rpm from rest (s)	0.100	0.140	0.170	0.100	0.090	**0.089**
Maximum speed attained during starting (rpm)	1513	1515	**1506**	1521	1510	1522
Maximum peak starting current (A)	1.76	1.55	**1.22**	1.72	1.75	1.70
Steady state peak current at 1500 rpm (A)	0.90	0.76	0.78	0.80	0.80	0.78
Steady state speed for the reference speed of 1500 rpm (rpm)	1501	1500	1500	1500	1499	1501
Maximum value of speed controller output (pu)	1.00	1.00	1.00	1.00	1.00	1.00
Average value of steady-state speed controller output at 1500 rpm (pu $\times 10^{-3}$)	90.0	90.6	90.4	89.5	90.6	90.0
Time required to reach the reference speed of 1000 rpm from 1500 rpm (ms)	**25**	**25**	57	47	56	50
Minimum speed attained during speed transition (rpm)	**992**	990	**992**	976	972	964
Maximum peak current under speed variation (A)	1.76	0.87	**0.60**	0.90	0.98	1.20
Steady state peak current at 1000 rpm (A)	0.83	0.72	0.73	0.72	0.72	0.72
Steady state speed for the reference speed of 1000 rpm (rpm)	1001	1000	1000	1000	1001	1000
Minimum value of speed controller output (pu)	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
Average value of steady-state speed controller output at 1000 rpm (pu $\times 10^{-3}$)	89.0	90.2	90.0	89.0	90.0	90.0

is fastest with the inherent switching functions, while the maximum current at the start is the minimum with the noninherent switching functions. Thus, depending on the system requirements in terms of speed, current response, execution time, computational burden, and load requirement, appropriate switching function can be utilized for HPI speed controller for the vector control of the PMSM. These results are matching well with the simulated values given in Table I.

The control algorithm has been implemented in hardware with TMS320F2812 DSP processor. Fig. 8 shows the plots for speed response obtained from hardware implementation. With the three noninherent switching functions, the motor attains the reference speed of 1500 r/min in 0.09, 0.12, and 0.14 s, respectively. With the three inherent switching functions, the motor attains the reference speed of 1500 r/min in 0.08, 0.09, and 0.09 s, respectively.

IV. CONCLUSION

The HPI speed controllers with the three inherent and three noninherent switching functions provide far better performance in the vector-controlled PMSM drive. The mathematical simplicity of the FEP controller and that of the inherent and noninherent switching functions result in HPI controller being computationally simpler as compared to the HFPI controller. The HPI controller employs the FEP controller to draw the motor toward the reference speed and the PI controller is utilized near the steady state to stabilize the motor speed at the reference value. It is observed that the overall performance of the vector-controlled PMSM drive with HPI speed controller using polynomial S switching function in better on most counts. The simulation results have been validated by the experimental results.

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