Smooth Switching Controllers for Reliable Induction Motor Drive Operation after Sensor Failures

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***Abstract*— This paper presents a switching control method that can be actuated by a supervisory controller, with emphasis on smooth transitions between various open and closed loop controllers in real time. Through conversion of commands into non-periodic voltage values in the synchronous *qd0* reference frame, hand-off transient reduction is achieved by controlling the rate of change of stator voltage commands during changeover. Through this method, smooth switched supervisory control can be achieved without synchronization or phase coordination between different commands from different controllers. Controllers are selected based on available sensor feedback. A system containing three controllers is simulated and tested with simulated sensor loss. Results of the proposed smooth switching controller compared to abrupt switching between control commands are compared. The proposed scheme is shown to reduce current and torque transients and maintain smooth operation of the drive. Given that multiple controllers and the switching logic are computationally intensive from an embedded system perspective, the proposed method is verified to operate in a processor-in-the-loop (PIL) environment on a Texas Instruments C2000 microcontroller.**

***Keywords*— Supervisory control, smooth switching, transient reduction, processor in the loop, induction motor drive**

I. Introduction

Control methods of inverter-fed electric machines vary in complexity and accuracy, with open-loop V/f control allowing for basic system operation without the use of external sensors while lacking in output accuracy and overall response [1, 2], to closed–loop methods that can establish more desirable electric drive dynamics [3]. To measure the necessary feedback information (rotor speed, phase current etc.), electric drives must include mechanical and/or electrical sensors and/or estimators. Sensor loss or removal may thus cause a loss of output control in addition to undesired transients. Therefore, a solution should be found to maintain drive operation within ratings and other constraints, especially with more penetration of electric drives in safety-critical applications, e.g. transportation systems.

One solution to compensate for sensor loss is the utilization of state estimators, but their reliability and accuracy may vary significantly depending on the accuracy of known motor parameters, as well as variations in the rotor time constant [1]. Switching between various controllers that require different sensor feedback has been proposed, however, this may also cause instabilities in the system due to the inherent inconsistencies in command signals generated by multiple controllers operating in tandem [4, 5]. It is possible that moving between command signals may cause unintended transients, e.g. torque or current transients at magnitudes greatly exceeding motor’s ratings [6]. As approximately 40% of induction motor breakdowns are attributed to failures in the winding insulation, any damage due to an over current condition greatly increases the likelihood of an eventual catastrophic failure [7].

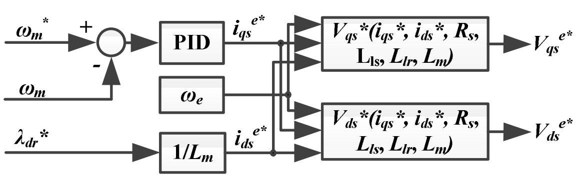
Previous work has been done in the field of fault tolerant control, with techniques developed specifically to mitigate the transients caused during control system hand-offs. Additional focus is given to the reduction in hand-off time or dwell time, as lengthy operation in an unhealthy state may lead to secondary faults [4]. The phase matching approach proposed in [4] focuses on monitoring the shift between system command signals to determine the ideal moment of transitioning. This passive method can lead to undesirably long periods of unhealthy control, during which the drive must operate in a crippled control scheme while waiting for the shift to minimize. A different approach to the phase matching method reduces the transition period by actively forcing the incoming control output phase in line with the previous controller output which requires additional calculations to manage inter-system phase synchronization [8]. Both systems have shown reduced transient behaviour, but are limited in that they must work with the synchronization of periodic signals.

The proposed method removes this passive delay without requiring cross-control synchronization, rapidly engaging the healthy controller while mitigating hand-off transients through the use of a limited rate transition between non-sinusoidal voltage control command outputs. This is made possible through the conversion of typical voltage or current command outputs in the $\alpha\beta$ stationary reference frame or *qd0* synchronous reference frame, e.g., current hysteresis indirect field oriented control (IFOC), direct torque control (DTC) using switching tables, and V/*f* control into voltage commands in the qd0 synchronous reference frame, thus eliminating the need to synchronize AC voltage or current commands from different controllers. Engagement of different controllers is assumed to come from a higher level supervisory controller that is coupled to a sensor fault diagnosis method.

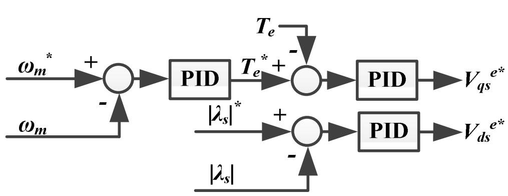
Section II introduces all three controllers in the synchronous reference frame. Section III compares abrupt switching between controllers due to an emulated sensor failure with the controllers being as typically presented in the literature vs. as described in Section II. Section IV describes the proposed smooth switching method with focus on the variable rate transitioning capability. Section V presents results of the proposed method compared to abrupt switching between controllers. Section VI demonstrates the implementation of the proposed method on a real processor in a PIL environment, and Section VII concludes the paper.

II. Open-Loop and Closed-loop Controllers in the Synchronous Reference Frame

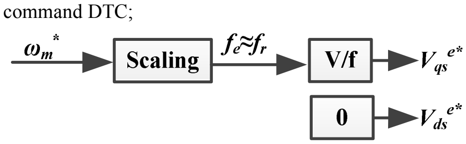
The first step to validate the proposed method is to transform all controllers into the same reference frame, and have similar control commands. For this paper, stator voltage output commands from the controller are selected to be in the synchronous reference frame to eliminate AC terms and since all three controllers, IFOC, DTC, and V/*f* can be modified to produce such commands. IFOC, DTC, and V/*f* can thus be modified from their typical implementations [9] to be as shown in [5]. Note that each controller output will typically differ due to design assumptions and dynamics. A voltage command based variant of IFOC is implemented as shown in Figure 1 (a) resulting in outputs in the desired frame, and readers are referred to [5] for further model details. DTC is implemented as shown in Figure 1 (b) which calculates command voltages through multiple PIDs for speed, torque and stator flux. The electrical frequency (ω_e) is detected using a simple phase-lock-loop (PLL) of the current sensor feedback. Therefore, IFOC as shown in Figure 1 (a) utilizes stator current and speed feedback, while DTC as shown in Fig. 1 (b) uses stator current and voltage feedback. Values for the PID blocks in Figure 1 (a) and (b) were found using non-linear plant tuning within Simulink and verified by simulation of various speed command and load combinations. Finally, open loop V/*f* control (c) is offered as a final fail-safe controller after failure of all feedback signals. Note that in Figure 1, ω_m is the mechanical speed, λ is flux linkage, i is current, V is voltage, r is resistance, T_e is electromechanical torque, f_e and ω_e are the stator frequency in Hz and rad/s, respectively, and L_{ls}, L_{lr}, and L_m are stator leakage inductance, rotor leakage inductance, and magnetizing inductance, respectively. Also in Figure 1, subscripts s, r, q, and d stand for stator, rotor, quadrature, and direct, respectively, and superscript e is for the synchronous reference frame, while superscript * is for a command quantity. Note that voltage commands are fed into a PWM generator for inverter control.



(a) Speed command IFOC;



(b) Speed command DTC;



(c) Speed command V/f control;

Fig. 1. Two closed-loop and one open-loop controllers with speed command input and stator voltage command outputs in the synchronous frame.

III. Comparison of Controllers with Typical vs. Synchronous Reference Frame Implementation

Previous work in the field of transient reduction has focused on problems inherent in the transition between sinusoidal voltage or current command values provided by different controllers. This leads to differences in command phases and frequencies when these commands are sinusoidal. On the other hand, if a common reference frame is used to generate the same command quantities from different controllers, the periodic portion of the control signals can be removed from calculation, resulting in a pair of DC command signals. Stator voltages in the *qd0* frame are used here where the synchronous reference frame was originally proposed by Park [10].

Controllers shown in Figure 1 were all implemented on a 3 hp induction motor drive including a 4-pole Dayton motor and a three-phase hex-bridge inverter. A constant command speed ω_m*=1000 RPM and load torque T_L=0.85T_{rated} are used to illustrate the effect of switching between two controllers.

The first set of simulations used typical implementations of IFOC, DTC, and V/f as presented in [9] where inverter gate signals are switched from one controller to the other in the *abc* frame without any consideration to having smooth transitioning or transitioning in a common frame. For example, gate signals provided by current-hysteresis IFOC are abruptly replaced by those from a switching-table-based DTC when an emulated speed sensor failure occurs.

The second set of simulations used the controllers shown in Figure 1 where all commands into the PWM generator are for stator voltages in the synchronous reference frame and with a speed command input. When needed, stator current feedback is used to estimate the electrical frequency using a PLL. Figure 2 shows the switching control action in the motor drive without any smooth transitioning. The supervisory control block is shown here for completeness, but switching between controllers has been manually induced for now assuming that sensor faults can be detected.

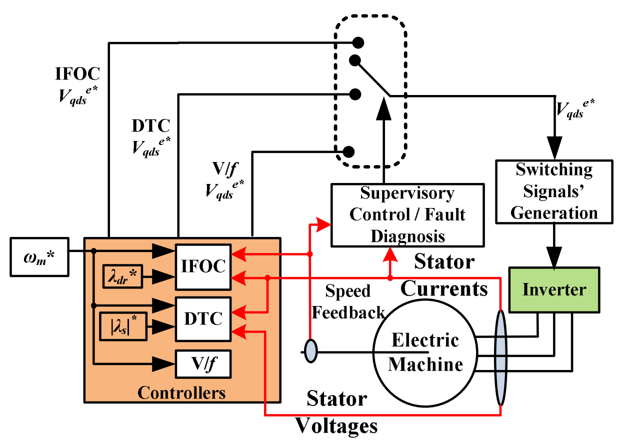


Fig. 2. Abrupt switching between three controllers when a sensor fails.

Results of switching between IFOC, DTC, and V/f at t=1s for a total of six switching combinations are shown in Figure 3. Switching from IFOC to DTC could be due to speed sensor or encoder loss, DTC to V/f due to speed sensor or encoder loss followed by current or voltage sensor loss, and IFOC to V/f due to current sensor loss, in addition to switching in the opposite directions due to sensor recovery.

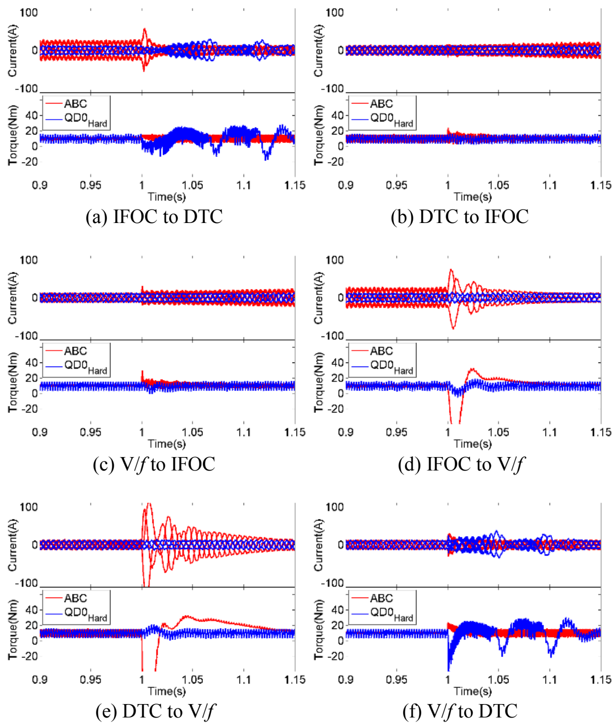


Fig. 3. Comparison of current/torque dynamics of typical and synchronous frame controllers due to abrupt switching under steady state conditions.

Table I. The magnitude reduction in switching transients from *abc* into *qd0* commands for each switching case.

	DTC to IFOC	DTC to V/f	IFOC to DTC	IFOC to V/f	V/f to DTC	V/f to IFOC
Current	6.4 %	88.2 %	76.9 %	72.3 %	29.2%	30.1 %
Torque	1.9 %	89.4 %	-129.9 %	71.8 %	-493 %	-43.2 %

Percentage reductions in transient torque and current magnitudes are presented in Table I. It can be seen that the reference frame conversion of commands results in an overall reduction in current transients for all cases, and reduction of torque transients in 4 of the 6 possible transitions. It should be noted that the system does not perform well when transitioning into DTC due to multiple DTC PIDs which are difficult to tune for faulty conditions resulting in large torque transients.

IV. Proposed Smooth Switching Control Scheme

The proposed control scheme is shown in Figure 4 and differs from that in Figure 2 by adding a rate limiting block. Controllers produce three sets of command signals in the *qd0* frame and are engaged in an order of priority as desired by the drive operator. Typically, IFOC (or DTC) would be the controller of choice, followed by DTC (or IFOC) as the second priority, then V/f as the least desirable, depending on available sensor feedback. Note that Figure 4 also shows shaded portions of the drive that are implemented on an embedded system for use in Section VI.

Upon detection of a system critical sensor feedback loss or fault, controller selection will transition into a method which does not utilize the failed feedback sensor, via a signal selection command (C^*) sent from the supervisor to the main switch (dotted box in Figure 4). The addition of a variable rate limiter on the selection output allows for a smooth transition between command values. Once this handoff between controllers is complete, the drive becomes directly controlled by the new controller without the appearance of potentially damaging system transients. The variable rate limiter block is illustrated in Figure 5.

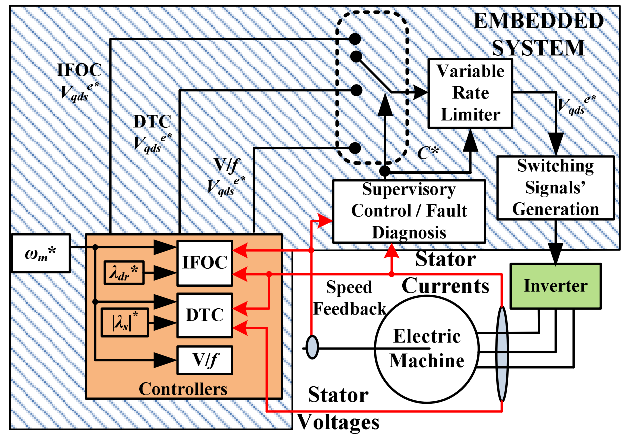


Fig. 4. Proposed smooth switching between controllers.

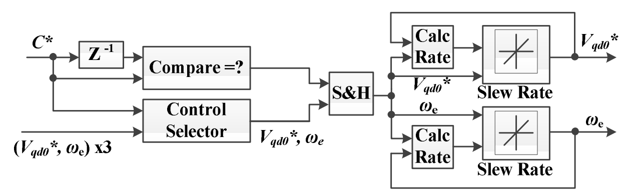


Fig. 5. Basic implementation of the variable rate limiter block.

C^* is monitored by the rate limiter block, which will react to a changes in C^* by sampling the initial state of the secondary command values to be used as a baseline healthy comparison during transition. This sample and hold (S&H) prevents any momentarily amplified speed ripple from having a pronounced effect on the reference frame conversions, which would otherwise lead to poor convergence of the initial and desired command values. The calculated rate or variable rate transition (VRT) depends on a comparison of commands at $V_{qd0}^*(t_0^-)$ and $V_{qd0}^*(t_0^+)$ where T_0 represents the time at which a change in C^* is applied, and the subscript E is dropped for convenience. VRT is calculated separately for both V_d^* and V_q^*, even though this is not shown in Figure 5, allowing for tandem convergence between values over a uniform transition period. Under healthy and normal operating conditions, VRT is assumed to be infinite. Once a change in C^* is detected, the rate value is calculated through a comparison $V_{qd0}^*(t_0^-)$ and $V_{qd0}^*(t_0^+)$.

With a focus on preventing abrupt transitions between command values while also allowing for rapid convergence, an equation for the limited VRT is proposed to model the transition based on a time-scaled calculation of the difference in magnitude between the commands $\Delta V_{qd0}^*=V_{qd0}^*(t_0^+)-V_{qd0}^*(t_0^-)$. As shown in (1), by calculating the integral of ΔV_{qd0}^* and taking the square of that integral to achieve a positive VRT, smooth transitions into and out of the two different sets of commands can be achieved. To allow for further refinement of the convergence period, a user defined constant A is included as a gain to control the transitioning speed from one controller to the other. The effect of A on rate transitioning of example V_q* and V_d* is shown in Figure 6 where a higher value of A leads to faster switching between controllers but potentially larger transients in the electric drive.

$$VRT_{qd} = A\left(\int \Delta V_{qd}^{*} dt\right)^{2} \tag{1}$$

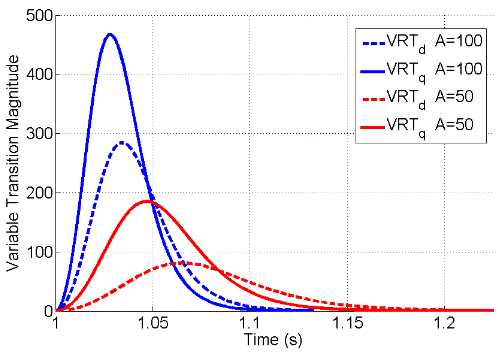


Fig. 6. VRT calculations for an identical transition with various A values.

Once the rate limited command values are within an acceptable window of deviation (ε) from the desired system commands, immediate control is released and command values are once again fed directly through from the selected controller. This tuneable constant ε adds additional refinement of system behaviour, with higher ε values allowing for a more immediate transition between controllers, while a lower ε will lead to longer dwell time when switching between controllers.

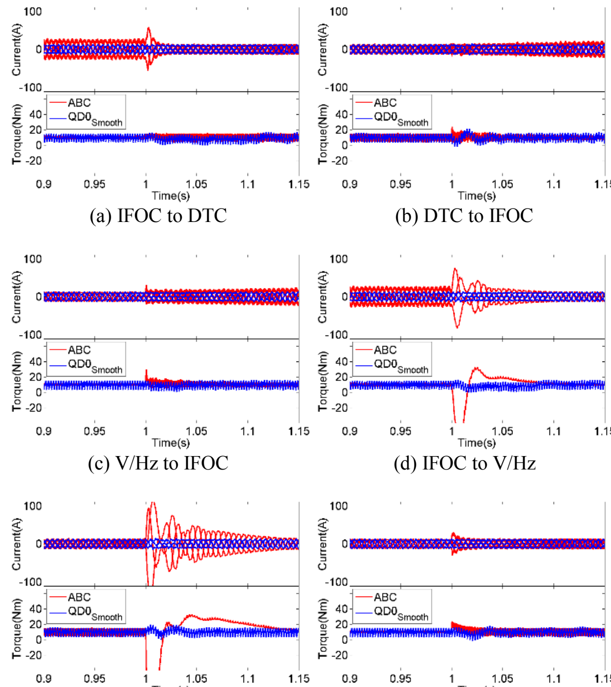
V. Implementation Of The Proposed Methodology

The proposed smooth switching control scheme was implemented in simulation using Matlab/Simulink, with the system running at ω_m*=1000 RPM and load torque T_L=0.85T_{rated} for illustrative purposes. ε and A are set to 0.1 and 5, respectively. Results are presented in Figure 7 for six switching combinations between IFOC, DTC, and V/f as explained in Section IV. Results shown in Figure 7 compare the abrupt switching between typical controllers with smooth switching as proposed in Section V. Figure 7 shows that benefits from the smooth transitioning of *qd0* commands are more pronounced , and the large torque transients caused by transitioning into the *qd0* DTC system are greatly reduced compared to those in Figure 3. The resulting percentage reductions in transient magnitude between smooth switching *qd0* and the original *abc* control methods are presented in Table II.

Table II. Transient results for each potential switching case, values given in magnitude reduction percentage from *abc* to *qd0* based commands with additional smooth switching control.

	DTC to IFOC	DTC to V/*f*	IFOC to DTC	IFOC to V/*f*	V/*f* to DTC	V/*f* to IFOC
Current	7.2	87.3	75.6	72.9	54.6	31.1
Torque	-23.9	89.8	-28.1	80.0	-40.2	-27.6

Although not all current and torque transients are shown to be reduced, inspection of the negative improvement values shows that these conditions result in either negligible or desirable effects on system behaviour. Even though the maximum deviation from the desired torque magnitude in cases b and f is increased, the peak value is reached on an extended time scale, which prevents the harsh immediate transient shown in the original *abc* control results. As the desired result of control is to reduce the potential for system/plant damage due to harsh torque transients, this behaviour is in itself a more desirable response.



(a) IFOC to DTC (b) DTC to IFOC

(c) V/Hz to IFOC (d) IFOC to V/Hz

(e) DTC to V/Hz (f) V/Hz to DTC

Fig. 7. Comparison of current/torque transients of abrupt switching between typical controllers and the proposed smooth switching control.

Additionally, a direct comparison of the systems in Figures 2 and 4, i.e. with and without the proposed smooth switching method, was simulated with results presented in Table III. These results show large reductions in torque transient magnitude for the majority of cases, particularly when switching to DTC.

Table III. Transient results for each potential switching case, values given in magnitude reduction percentage from simple *qd0* to *qdo* with additional smooth switching control.

	DTC to IFOC	DTC to V/*f*	IFOC to DTC	IFOC to V/*f*	V/*f* to DTC	V/*f* to IFOC
Current	0.8	-7.4	-5.7	1.8	35.9	1.5
Torque	-26.4	4.0	44.3	29.2	76.4	10.9

VI. Hardware Viability Testing

When proposing the implementation of a novel modification to existing control systems, attention should be paid to the feasibility of system implementation in existing hardware environments. For this reason, processor-in-the loop (PIL) testing was used to determine the effect of the proposed method with added complexity on the embedded system. A digital signal processor (DSP) is used as the target processing platform for fully developed C code as a means of accurately simulating embedded system behavior under advanced algorithm controls in conjunction with a simulated plant model including inverter and motor Simulink models.

The embedded system portion of Figure 4 was implemented in C code and loaded into a Spectrum Digital F28335 eZdsp platform. The test platform is shown in Figure 8 where the eZdsp board uses a Texas Instruments (TI) c2000 TMS320F28335 processor which is a 32 bit DSP common in motor control applications. The model was then run with all code executions occurring on the DSP through the use of TI Code Composer v3.3 with online communication between the eZdsp board and simulated plant through USB.

System benchmarks for code size, memory usage, and calculation intensity in Clock Cycles per Sample (CCPS) were recorded. A comparison was then made between values recorded during use of the basic synchronous frame controllers and those recorded during use of the proposed smooth switching control, noting a 10.5% increase in binary size and 21.3% in memory consumption when the proposed control method is implemented. In terms of available system memory, these increases represent an additional consumption of 3.9% and 1.9%, respectively. Such increases are minor compared to the added functionality and drive reliability resulting from the proposed method. Direct comparison of calculation intensity was measured for each of the six potential transitions, resulting in a consistent increase of approximately 1800 CCPS (24% over the equivalent hard transitioning synchronous control) during operation. Although the resulting increase requires a reduction in maximum sample rate to approximately 19 kHz when implemented on the 150 MHz processor of the c2000, this cost is only experienced during the transition period itself and will not affect steady state operation of the system past the minor additional memory and binary requirements.

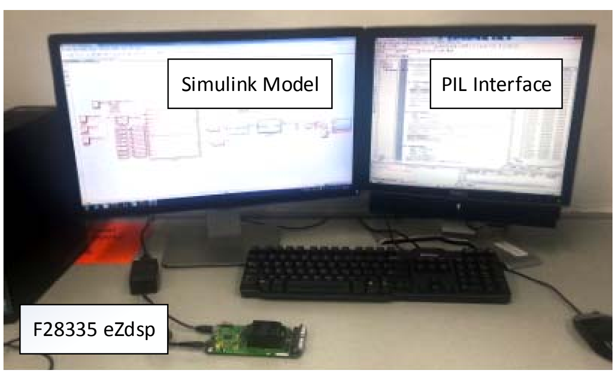


Fig. 8. Hardware implementation of smooth switching control method on Spectrum Digital F28335 eZdsp.

VII. Conclusion

A new smooth switching control method is presented for motor drive applications where safety is critical and sensors could fail. The proposed method relies on having multiple controllers, each dependent on different sensor feedbacks, which are engaged one at a time depending on which sensors are lost or fail. The proposed method implements several controllers which use the same speed set point and provide the same output commands (stator voltages in the synchronous reference frame) even though these commands could differ in values between different controllers. These commands are then smoothly transitioned using a variable rate transitioning scheme proposed to minimize abrupt transients in the electric machine currents and torque.

Reduction in current and torque transient response is shown through direct comparisons between conventional current-controlled IFOC, switching-table-based DTC, and V/*f* with IFOC, DTC, and V/*f* controllers in the synchronous reference frame using the smooth switching control method. Particular benefits are realized when the system underwent simulated feedback loss, with transient reductions in torque and current of over 80% and 70%, respectively, experienced when torque actuation methods (IFOC or DTC) are transitioned into simple open-loop control (V/f). This reduction is realized without time-based periodic synchronizations or additional hardware, and allows for continued operation of induction motors throughout various stages of sensor failure, creating a robust motor control with multiple safe and stable feedback configurations.

Additionally, code level testing through the use of a PIL system showed that the presented smooth switching controller technique is a viable addition to existing switched control hierarchy systems operating on a common embedded platform. The additional processing and negligible memory costs of the method can be easily justified against the additional robustness provided to the motor and inverter when performance requires continued safe operation.

Future work will focus on integrating the embedded system with actual inverter and electric machine, establishing sensor fault diagnosis algorithms, and integrating supervisory control capabilities to sensor fault diagnosis.

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