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RESEARCH ARTICLE

ROBUST SPEED CONTROL OF A TWO-CONVEYOR WHEAT MIXING SYSTEM USING CONVENTIONAL PID AND PSO-OPTIMIZED PID UNDER MOTOR PARAMETER UNCERTAINTIES

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Abstract

This study presents an integrated control framework for a two-stream wheat conveying and mixing system driven by 4 kW induction motors. The proposed model couples the induction motor, indirect field-oriented control, conveyor dynamics, wheat mass flow, and mixing-ratio regulation within a unified simulation environment. Three operating strategies are investigated: a conventional uncontrolled system, a classically tuned proportional–integral–derivative (PID) controller, and a PID controller optimized using Particle Swarm Optimization (PSO). The PSO-based strategy is designed to improve control performance while considering variations in operating conditions. The robustness of the controllers is evaluated through independent variations of key electrical and mechanical parameters, including stator resistance, rotor resistance, mutual inductance, mechanical inertia, and load torque. The proposed strategies are further assessed for 50/50, 60/40, and 70/30 wheat mixing ratios. Performance is evaluated using speed and flow tracking, mixingratio error, root mean square error, integral absolute error, recovery time, total energy consumption, and specific energy consumption. The study also performs a sensitivity analysis to identify the parameters that most influence system behavior. The results provide a comparative assessment of conventional, classical PID, and PSO-optimized PID operation from the perspectives of process accuracy, robustness, and energy performance.

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The proposed framework provides a basis for evaluating optimized motorspeed control as a means of improving flexibility and regulation in industrial wheat conveying and mixing applications.

Introduction:-

The milling industry requires reliable and flexible material-handling systems to ensure continuous production and accurate control of wheat processing operations [1],[2]. In flour mills, electric-motor-driven conveyor systems transport wheat from storage silos to processing units [3]. The rotational speed of these conveyors directly affects the mass flow rate and, consequently, the proportion of wheat supplied by each stream during mixing. In conventional installations, conveyor motors typically operate under fixed-speed or start–stop control, limiting the ability to continuously adjust material flow to production requirements. Improving conveyor speed regulation is therefore important for achieving accurate and flexible wheat-flow control.

Moreover, induction motors are widely used in industrial conveyor applications because of their robustness and reliability [4], [5]. However, their coupled electrical and mechanical dynamics make precise speed regulation more complex than conventional on–off operation [6], [7], [8]. In this case, Indirect field-oriented control (IFOC) effectively regulates induction-motor speed by decoupling the flux- and torque-producing components of the stator current [9], [10]. Also, Proportional–integral–derivative (PID) controllers are widely used in industrial applications because of their simple structure and ease of implementation [11]. However, their performance depends strongly on the selected gains and may deteriorate when the operating conditions differ from those considered during tuning.

Optimization techniques can improve the selection of PID parameters by searching for gains according to a predefined performance criterion. Particle Swarm Optimization (PSO) is particularly suitable for this purpose because it provides a population-based search mechanism with relatively simple implementation [12], [13], [14]. However, controller evaluation under nominal conditions alone does not fully characterize its industrial performance. Variations in motor electrical parameters, mechanical inertia, and load torque can modify the system dynamics and affect the resulting process variables [7], [8], [15]. In addition, evaluating only motor speed does not provide a complete assessment when the motor directly controls a material-handling process.

In a two-stream wheat conveying system, the speed of each motor determines the corresponding conveyor flow, while the combination of the two flows determines the final mixing ratio. Therefore, an appropriate evaluation should consider both the electrical drive and the process-level response. This motivates an integrated approach combining induction-motor dynamics, IFOC, conveyor operation, wheat mass flow, mixing-ratio regulation, robustness, and energy consumption within a common simulation framework.

In this study, an integrated model of a two-stream wheat conveying and mixing system driven by 4kW induction motors is developed. The induction-motor model is coupled with an IFOC structure and a conveyor-flow model to establish the relationship between motor speed and wheat mass flow. Three configurations are considered : a conventional uncontrolled system, a classically tuned PID controller, and a PID controller optimized using PSO. The conventional configuration provides a reference corresponding to fixed-speed operation, while the two controlled configurations are evaluated under the same operating conditions.

The robustness of the control strategies is investigated by introducing parameter variations during steady-state operation while keeping the controller parameters unchanged. The considered uncertainties include a 20% increase in stator resistance, a 20% increase in rotor resistance, a 10% decrease in mutual inductance, a 20% increase in mechanical inertia, and a 50% increase in load torque. The control strategies are also evaluated for three target mixing ratios : 50/50, 60/40, and 70/30. Performance is assessed using speed and flow response, mixing-ratio error, RMSE, IAE, recovery time, total energy consumption, and specific energy consumption. A sensitivity analysis is additionally performed to identify the parameters with the greatest influence on system performance.

The main contributions of this work are: (i) development of an integrated induction-motor, IFOC, conveyor, wheat-flow, and mixing model; (ii) comparative evaluation of conventional operation, classical PID control, and PSO-optimized PID control; (iii) robustness assessment under electrical and mechanical parameter uncertainties; (iv) validation for different wheat mixing ratios; (v) evaluation of energy and specific energy consumption; and (vi) sensitivity analysis and joint assessment of accuracy, robustness, and energy performance.

The remainder of this paper is organized as follows. Section 2 presents the system description and mathematical modeling. Section 3 describes the control strategies and the PSO optimization procedure and performance criteria.

Section 4 defines the simulation scenarios, the robustness, uncertainty analysis and discusses the main results, while Section 5 presents the multi-ratio validation, Section 6 analyzes energy consumption, section 7 the sensitivity analysis. Section 8 discusses the accuracy–energy–robustness trade-off. Section 9 presents the limitations, and Section 10 presents the conclusion.

System Description and Proposed Control Architecture:-

Existing Conventional Wheat Conveying System:-

The industrial process considered in this study is based on a two-stream wheat conveying and mixing system. Wheat is stored in two separate silos and is transported toward a common mixing stage through two independent conveyor lines. Each conveyor is driven by an induction motor. The two material streams are subsequently combined to obtain the required wheat mixture.

In the existing conventional configuration, the conveyor motors are operated using a simple start–stop control mode. The operator can start or stop each motor according to the production requirements, but the motor rotational speed is not continuously regulated. Consequently, the conveyor operates without a closed-loop speed-control system, and no feedback signal is used to automatically adjust the motor speed according to the required wheat flow.

The conventional operating principle presents several limitations from a process-control perspective. First, the absence of continuous speed regulation restricts the ability to adjust the wheat flow dynamically. Second, the lack of a closed-loop feedback mechanism means that variations in the motor operating conditions or mechanical load cannot be automatically compensated for through speed adjustment. Third, changing the proportion of the two wheat streams cannot be achieved through continuous speed regulation of the individual conveyors.

For the two conveyor lines, the corresponding wheat flow rates are denoted by Q_1 and Q_2 .

The total flow entering the mixing stage is given by:-

$$Q_T = Q_1 + Q_2$$

The mixing proportions are determined by the relative contribution of the two streams.

The contribution of the first stream is expressed as :-

$$R_1 = \frac{Q_1}{Q_1 + Q_2} \times 100$$

while the contribution of the second stream is:-

$$R_2 = \frac{Q_2}{Q_1 + Q_2} \times 100$$

Proposed Integrated Control Architecture:-

To overcome the limitations of the conventional configuration, an integrated control architecture is proposed. The new architecture retains the two-silo and two-conveyor structure of the existing process but introduces closed-loop speed control for the induction motors. Each conveyor motor is associated with a speed-control loop based on a PID controller and an indirect field-oriented control (IFOC) strategy. The PID controller generates the torque-producing current reference according to the difference between the desired motor speed and the measured motor speed. The IFOC subsystem then converts this reference into the appropriate electrical control signals for the induction motor. The architecture is evaluated using two PID tuning approaches. In the first configuration, the PID parameters are determined using a conventional tuning method. In the second configuration, the PID parameters are optimized using Particle Swarm Optimization (PSO). Thus, the proposed framework allows the effect of controller tuning to be evaluated while maintaining the same motor, IFOC, conveyor, and wheat-flow models. Figure 1 shows the system architecture.

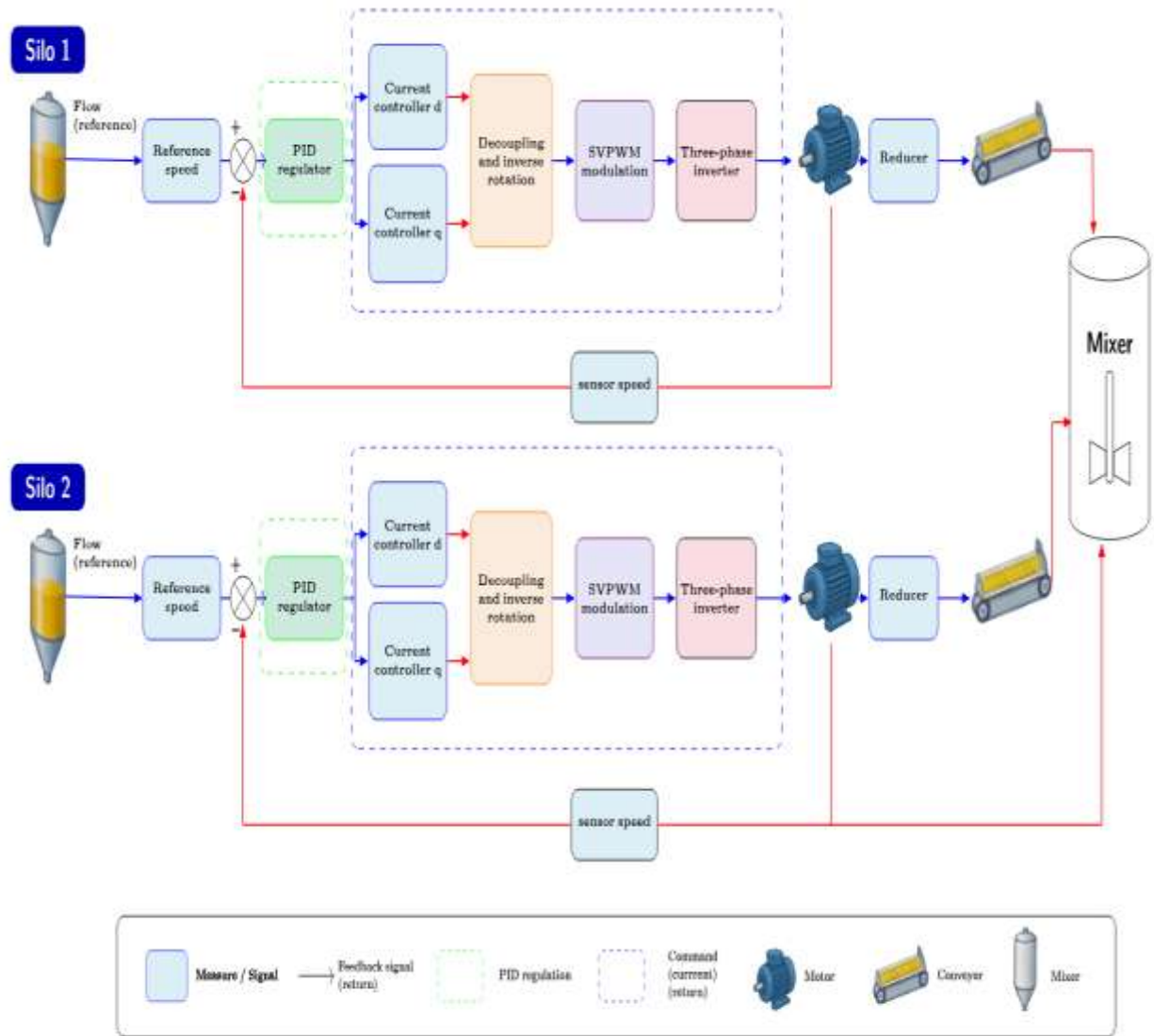


Figure 1: Existing Wheat Extraction System

Induction Motor Model:-

The conveyor drives are represented by three-phase squirrel-cage induction motors. The motor model is formulated in the rotating dq reference frame and includes the electrical and mechanical dynamics required to reproduce the behavior of the drive system.

The stator voltage equations are expressed as [5], [7], [8].:-

$$\begin{cases} u_{ds} = R_s i_{ds} + \frac{d\phi_{ds}}{dt} \\ u_{qs} = R_s i_{qs} + \frac{d\phi_{qs}}{dt} \\ 0 = R_r i_{dr} + \frac{d\phi_{dr}}{dt} + \omega_r \cdot \phi_{qr} \\ 0 = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - \omega_r \cdot \phi_{dr} \end{cases}$$

The electromagnetic torque is calculated as:-

$$C_e = \frac{pM}{L_r} \phi_r \cdot i_{qs}$$

The mechanical dynamics are described by:-

$$J_T \frac{d\Omega}{dt} = C_e - f_v \cdot \Omega - C_r$$

Conveyor and Wheat Mass-Flow Model :-

The mechanical output of each induction motor is used to drive a conveyor. The Conveyor model establishes the relationship between motor rotational speed and the transported wheat flow [1], [2]. The linear conveyor speed is related to the rotational speed of the motor and the transmission ratio.

The linear conveyor speed is related to the rotational speed by:-

$$v_c = \frac{r}{N} \omega_m$$

where r is the effective sprocket radius and N represents the transmission ratio

The transported mass flow is then related to the conveyor velocity by:-

$$\dot{m} = \rho A_f v_c$$

where ρ is the bulk density of the wheat and A_f represents the effective cross-sectional area occupied by the transported material. Considering the filling factor α , the flow rate can be expressed as

$$Q = \rho A_f \alpha \frac{r}{N} \omega_m$$

The corresponding expression is applied independently to the two conveyors streams:-

$$Q_1 = \rho A_f \alpha \frac{r}{N} \omega_1$$

$$Q_2 = \rho A_f \alpha \frac{r}{N} \omega_2$$

The model consequently establishes a direct process-level relationship between the controlled motor speeds and the wheat mass flow. A modification of the speed reference therefore propagates through the drive and conveyor dynamics and produce a corresponding change in the material flow

Control Strategies:-

Classical PID Speed Control:-

The second configuration introduces a closed-loop PID controller to regulate the rotational speed of each induction motor. The objective is to reduce the difference between the reference speed and the measured motor speed.

The speed error is defined as:-

$$e(t) = \omega_{ref} - \omega(t)$$

The conventional PID control law is expressed as:-

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

In the present application, the controller output is used to generate the appropriate torque-producing control command for the IFOC structure. The proportional term contributes to the immediate response to the speed error, the integral term reduces the steady-state error, and the derivative term provides a response related to the variation of the error [7]. The PID parameters in this configuration are obtained using a conventional analytical tuning approach based on the nominal system model. The resulting controller is subsequently evaluated without changing its gains during the different operating and uncertainty scenarios. For the comparison presented in this study, a conventional PID controller is used as the baseline controller. The controller parameters are determined analytically using a pole-placement approach based on the desired second-order closed-loop dynamics. A damping ratio of $\zeta=0.707$ and a natural frequency of 50 rad/s. are selected to define the desired dynamic response. The resulting controller gains are $K_p = 0.92607$ and $K_i = 32.75$. These gains are calculated once from the nominal system model and are kept constant during the subsequent simulations.

PSO-Optimized PID Control:-

The third configuration uses the same PID control structure, but its parameters are determined using Particle Swarm Optimization (PSO). The purpose of the optimization is to identify controller gains that provide an appropriate compromise between tracking accuracy and dynamic performance over the operating conditions considered in the study. Unlike the classical tuning procedure, which determines the controller parameters from a predefined analytical relationship, PSO searches for suitable values of the controller gain within a specified parameter space.

For a candidate PID parameter vector [13], [16],:-

$$X = [K_p \ K_i \ K_d]$$

the quality of each candidate solution is evaluated using a predefined objective function. The optimization problem can therefore be written as:-

$$X^* = \arg \min J(X)$$

subject to the specified bounds on the PID parameters. The objective function is constructed from the speed-tracking error and can incorporate additional performance terms according to the optimization framework. A general error-based criterion can be expressed as

$$J = \int_0^T |e(t)| dt$$

where T represents the simulation duration. The optimization process starts with a population of candidate solutions. Each particle represents a possible set of PID gains. During successive iterations, the particles update their positions according to their individual best solution and the best solution found by the swarm. The general PSO velocity update is expressed as [12], [13], [14]:

$$v_i^{t+1} = w v_i^t + c_1 r_1 (p_{best,i}^t - x_i^t) + c_2 r_2 (g_{best}^t - x_i^t)$$

Where w is the inertia coefficient, c_1 and c_2 are the cognitive and social cognitive. And social coefficient, r_1 and r_2 are random variables, $p_{best,i}$ is the best position previously found by particle i , and g is the best solution found by the entire swarm.

Performance Evaluation Criteria:-

The performance of the three configurations is evaluated at both the drive and process levels. The principal variables considered are motor speed, individual conveyor flow, total wheat flow, mixing ratio, and energy consumption. The speed-tracking error is defined equation (12). The integral absolute error (IAE), used to quantify the accumulated magnitude of the tracking error is

$$IAE = \int_0^T |e(t)| dt$$

The root mean square error (RMSE) is defined as

$$RMSE = \sqrt{\frac{1}{T} \int_0^T e^2(t) dt}$$

At the process level, the mixing-ratio error is evaluated by comparing the actual ratio with the desired ratio:

$$e_R = R^*(t) - R(t)$$

The energy consumption is evaluated by integrating the instantaneous electrical power over the simulation period [3], [17]. Power over the simulation period:

$$E_{total} = \int_0^T P_{el}(t) dt$$

The specific energy consumption is then calculated from:

$$SEC = \frac{E_{total}}{M_{processed}}$$

where $M_{processed}$ represents the total mass of wheat transported during the considered period. These indicators are used together rather than relying on a single performance measure. This allows the subsequent analysis to examine the control strategies from three complementary perspectives: tracking accuracy, robustness, and energy consumption.

Simulation Setup and Operating Conditions:-

Simulation Configuration:-

The proposed framework is implemented in a numerical simulation environment that reproduces the electrical, mechanical, and process dynamics of the two-conveyor wheat conveying system. The two conveyor lines are modeled independently but operate under the same General motor and conveyor parameters. The reference speed and process condition are modified according to the considered operating scenario. The main simulation parameters are summarized in Table 1. The conventional, classical PID, and PSO-PID configurations are simulated under Equivalent operating to ensure a consistent comparison.

Table 1. Main simulation parameters

Parameter	Symbol	Value
Rated power	P_n	4 kW
Rated voltage	U_n	400 V
Rated current	I_n	9 A
Rated frequency	f_n	50 Hz
Number of poles	P	4
Pole pairs	p	2
Stator resistance	R_s	1.405 Ω
Rotor resistance	R_r	1.395 Ω
Stator leakage inductance	L_{ls}	0.0058 H
Rotor leakage inductance	L_{lr}	0.0058 H
Mutual inductance	L_m	0.1722 H
Mechanical inertia	J	0.0131 kg·m ²

Reference Operating Conditions:-

The principal operating condition corresponds to a target mixing ratio of 70/30. This condition is used as the main reference case for comparing the three control configurations. Additional operating conditions are subsequently considered: 50/50, 60/40, 70/30. These cases allow the ability of the controlled system to adapt to different production requirements to be evaluated

Disturbance Conditions:-

To evaluate the dynamic response of the controlled system, changes in the mechanical operating conditions are introduced during the simulation. The disturbance is applied after the system has reached its initial operating condition. This makes it possible to distinguish the initial transient response from the response caused by the disturbance. For the uncertainty experiments, the controller gains are kept constant before and after the perturbation. Therefore, the observed recovery is produced by the existing control structure rather than by controller retuning.

Results and Discussion:-

Conventional System Response:-

The conventional system provides the reference behavior of the industrial configuration without closed-loop speed regulation. Since the motors are operated through start–stop commands, the system does not continuously regulate the motor speed according to a reference. The corresponding speed and flow responses are used as baseline results. The absence of continuous speed regulation results in a limited ability to modify the individual conveyor flows and consequently to adjust the mixing ratio dynamically. The speed and flow rate of the current system are given by Figures 2 and 3, which illustrate the dynamic behavior of the conventional fixed-speed mixing system, configured for a mass distribution ratio of 70% wheat for Conveyor 1 and 30% for Conveyor 2. To fulfill these proportions, Conveyor 1 operates at its nominal speed of 84 rad/s while Conveyor 2 is calibrated to run at 36 rad/s.

The analysis highlights two critical weaknesses of this unregulated operation mode. Initial mixing accuracy ($t = 0$ to 2 s): Although Conveyor 1 successfully reaches its 84 rad/s steady-state reference, Conveyor 2 exhibits a slight deviation from its theoretically required value, which potentially degrades the initial accuracy of the wheat mixing ratio. Effect of the load disturbance ($t = 2$ s): At $t = 2$ s, applying an external mechanical load specifically to Conveyor 2 induces an immediate speed drop from 36 rad/s down to 35 rad/s. Lacking an active control strategy, the system fails to reject this perturbation, and the speed remains degraded until the end of the simulation. This prolonged speed drop permanently disrupts the strict 70%/30% mixing ratio, leading to a dosage imbalance in the final wheat mixture.

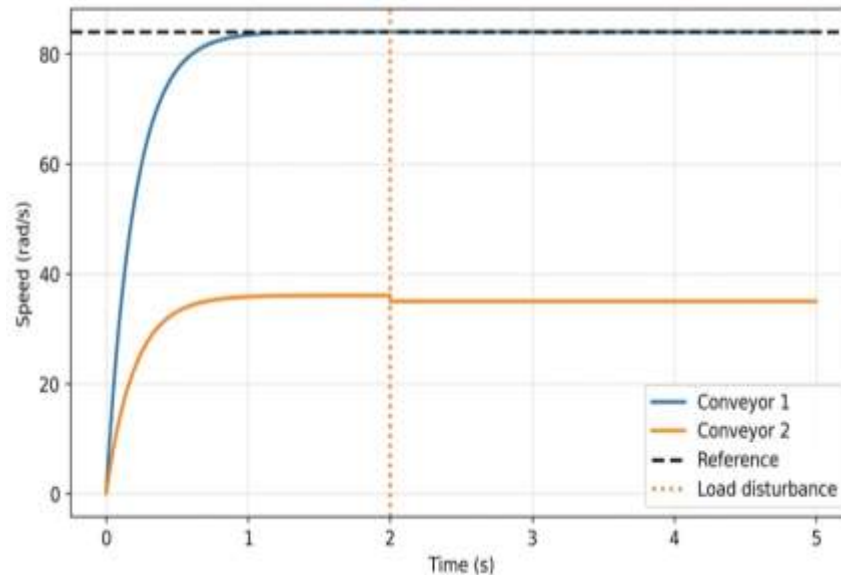


Figure 2. Conventional fixed-speed operation - conveyor speeds.

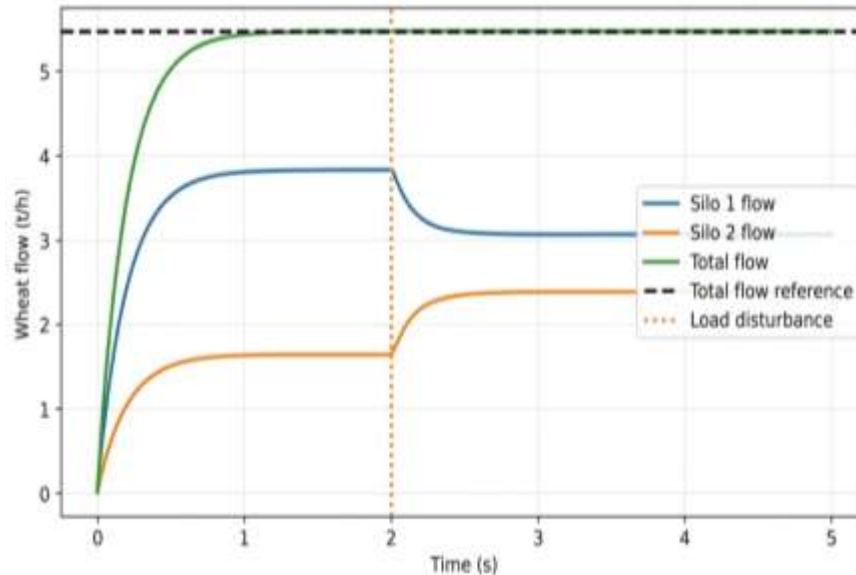


Figure 3 : Speed-varying operation with load compensation-wheat flow

Classical PID Performance:-

The classical PID controller introduces closed-loop speed regulation. The controller adjusts the motor command according to the instantaneous speed error, allowing the conveyor speed to follow the specified reference. The speed response of the classical PID is given by Figure 4. The corresponding conveyor flows are presented in Figure 5. Figure 4 illustrates the time response of the Conveyor 2 speed using the classical PID controller. During the no-load startup phase from $t=0$ to $t=2$ s aimed at reaching the 36 rad/s step reference (black dashed line), the system shows a fast rise time but exhibits a pronounced overshoot peaking near 41 rad/s before stabilizing around $t=0.6$ s. This

significant transient peak highlights the lack of damping inherent to standard PID tunings during un-loaded startup dynamics.

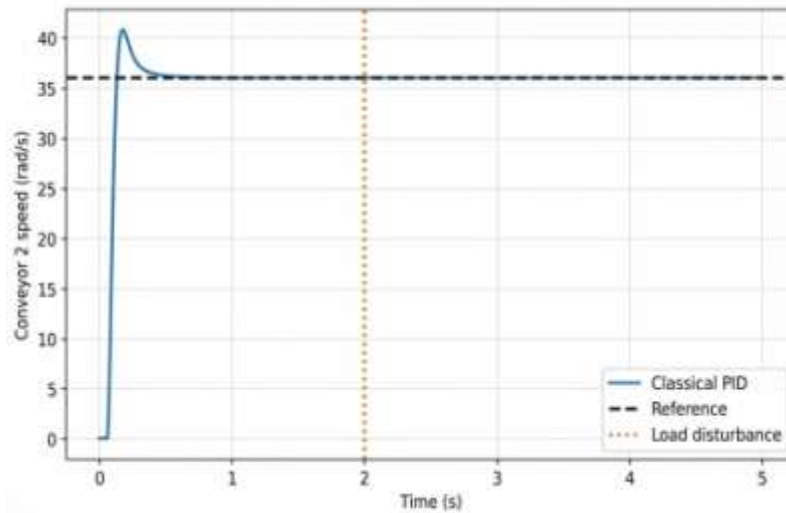


Figure 4 : Classical PID speed response

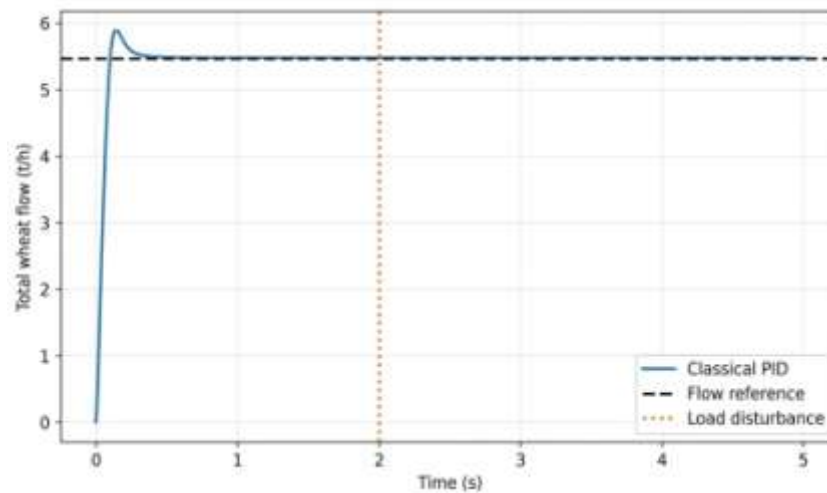


Figure 5 : Classical PID flow response

PSO-PID Performance:-

The PSO-optimized controller uses the same PID structure as the classical configuration, but its parameters are obtained through the optimization procedure described in Section 3. Figure 6 displays the convergence curve of the PSO algorithm. A sharp and monotonic decrease in the objective function value is observed during the first steps, dropping from 2.93×10^{-1} at the initial state to approximately, 2.873×10^{-1} at iteration 4. Beyond this point, the curve flattens completely to reach the optimal PID parameters for the rotor field-oriented control of the induction. The resulting motor-speed response is presented in Figure 7.

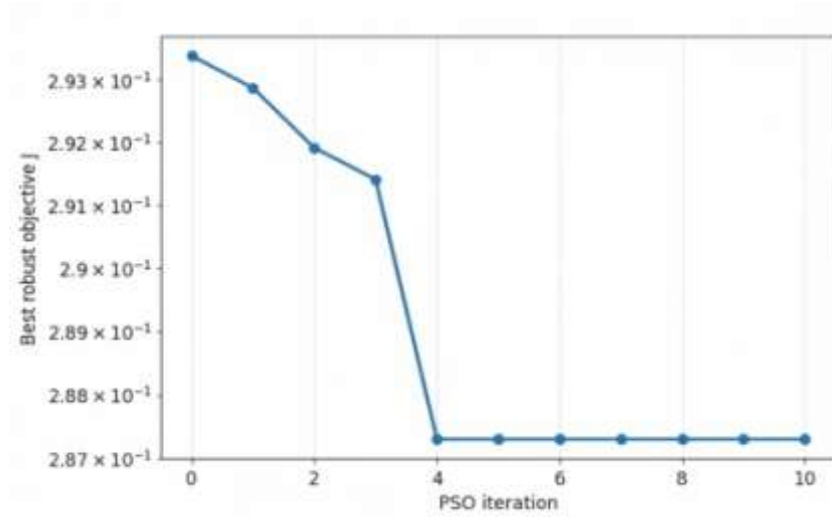


Figure 6 : PSO convergence for robust PID tuning

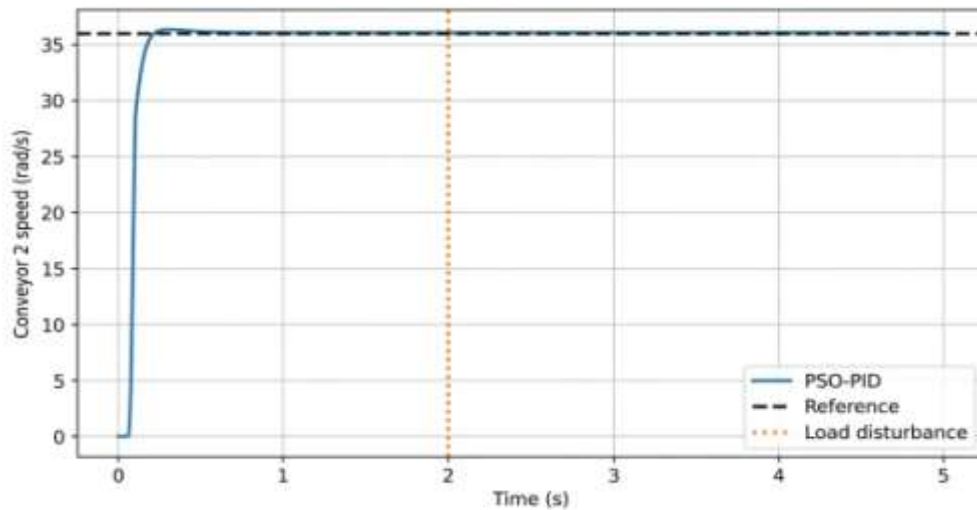


Figure 7: PSO-optimized PID speed response

Figure 7 depicts the time response of conveyor 2 speed using the PSO-PID controller. Under a reference step of 36 rad/s, the system exhibits excellent transient behavior with a fast rise time under 0.2s and negligible overshoot. In steady-state, the tracking Error is successfully eliminated. The corresponding wheat-flow response is presented in Fig. 8. The flow rate perfectly tracks the reference value of 5.5t/h, which demonstrates the High performance of the PSO algorithm. The resulting mixing ratio for silo1 is shown in Figure 9

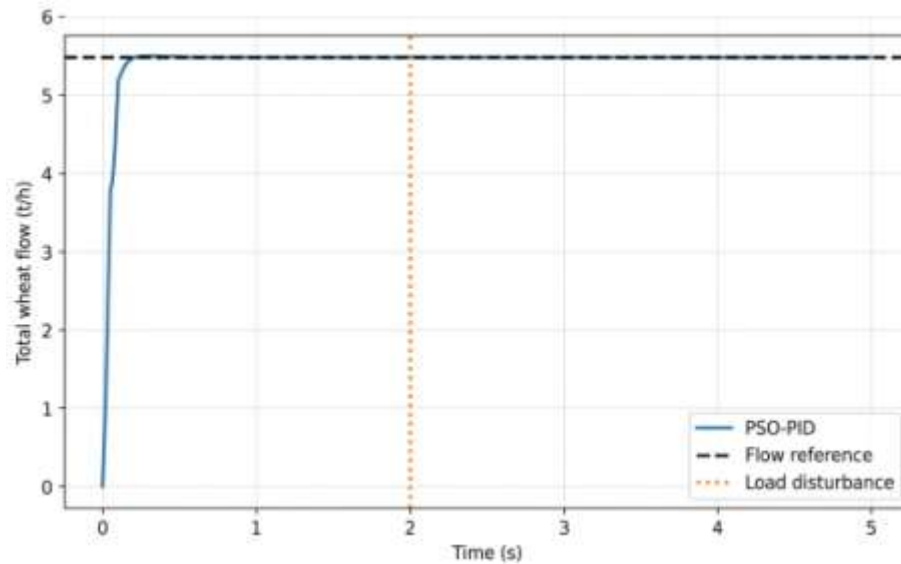


Figure 8 : PSO-optimized PID flow response

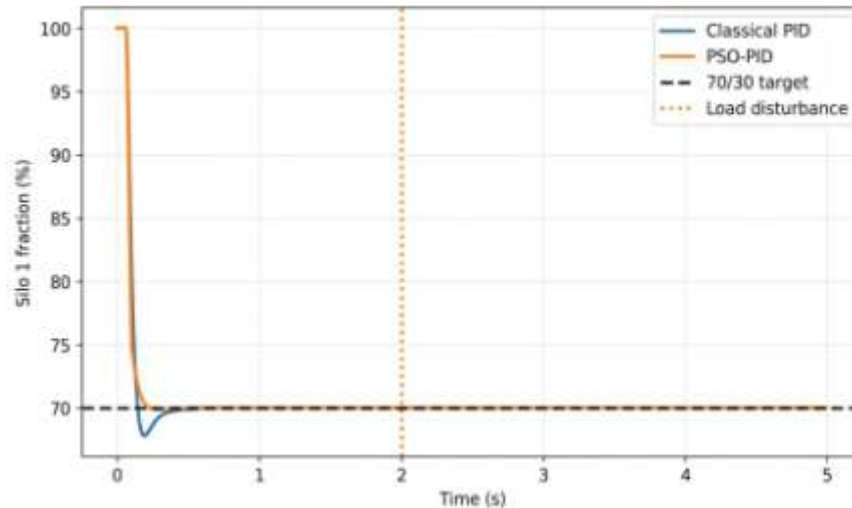


Figure 9: Mixing-ratio comparison

Robustness and Uncertainty Analysis:-

In this section, the motor parameters are varied to evaluate the robustness of the System against parameter variations. The considered values are as follows: The rotor resistance is increased by 20%: $R_r' = 1.2R_r$, The mutual inductance is reduced by 10%: $L_m' = 0.9L_m$. The mechanical inertia is increased by 20%: $J' = 1.2J$. A 50% increase in load torque is applied $C_r' = 1.5C_r$ Figure 10 shows the behavior of the system with the classical PID controller under parameter uncertainties. At ($t = 0$ to 0.5 s): The system exhibits a pronounced overshoot, peaking near 41 rad/s before stabilizing around $t = 0.6$ s. This transient peak can introduce undesirable stress on the conveyor's mechanical components. At $t = 2$ s upon applying the +50% load impact, the speed drops sharply down to 31 rad/s. The classical controller demands a significantly longer recovery time approximately 0.1 s to eliminate the tracking error. At $t = 3$ s When parameter drifts are activated, a transient deviation and mild oscillations become apparent, notably for the mutual inductance decrease scenario $L_m - 10\%$. This confirms the classical PID's vulnerability to induction motor parameter variations.

Figure 11 shows the behavior of the system with the PSO-PID controller under parameter uncertainties Figure 11 depicts the dynamic behavior of the Conveyor 2 speed under a 36 rad/s step reference (black dashed line) using the PSO-PID controller. This plot superimposes the system responses under various individually applied parameter

uncertainty scenarios. During the initial transient phase ($t = 0$ to 0.5 s), the system exhibits a fast tracking capability and a perfectly damped response with zero overshoot across all test cases. At $t = 2$ s, a severe +50% load disturbance is introduced (purple curve), causing a minor and transient speed drop down to approximately 34 rad/s. This perturbation is almost instantly rejected (in less than 0.03 s), restoring the steady-state operation. At $t = 3$ s (indicated by the orange dotted line), the individual parameter variations are activated. The perfect superposition of all trajectories along the reference line proves the complete insensitivity of the PSO-PID controller to electrical and mechanical parameter drifts.

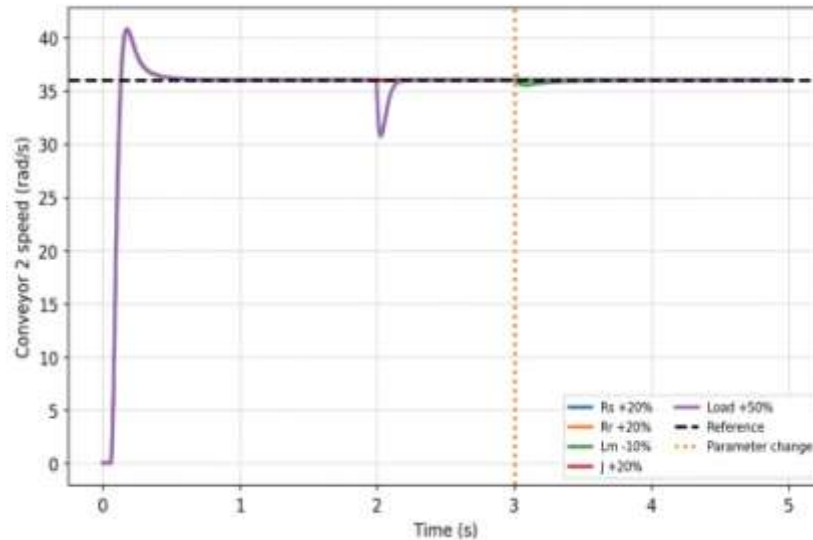


Figure 10: Classical PID under individual parameter uncertainties

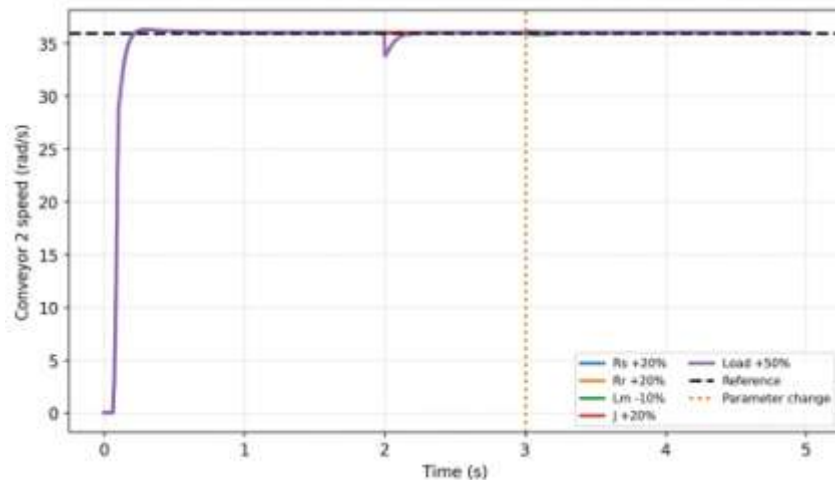


Figure 11: PSO-PID under individual parameter uncertainties

Figure 12 shows the speed behavior subject to combined parameter variations. Figure 12 illustrates the time response of the Conveyor 2 speed under a 36 rad/s step reference, comparing the classical PID (blue curve) and the proposed PSO-PID. Initial transient state ($t = 0$ to 0.5 s): The classical PID exhibits a significant overshoot, peaking near 41 rad/s before stabilizing. Conversely, the PSO-PID yields a perfectly damped response with zero overshoot while maintaining a swift rise time. Load disturbance ($t = 2$ s): When a load torque is applied at $t = 2$ s, the classical PID suffers from a severe speed drop down to 31 rad/s along with a noticeable recovery delay. In contrast, the PSO-PID successfully attenuates this impact, limiting the drop to 34 rad/s with an almost instantaneous return to the setpoint. Combined parameter uncertainty ($t = 3$ s): The activation of combined parameter variations at $t = 3$ s causes a

transient oscillation in the classical PID loop. Meanwhile, the PSO-PID exhibits outstanding robustness, remaining virtually unaffected and strictly tracking the reference line.

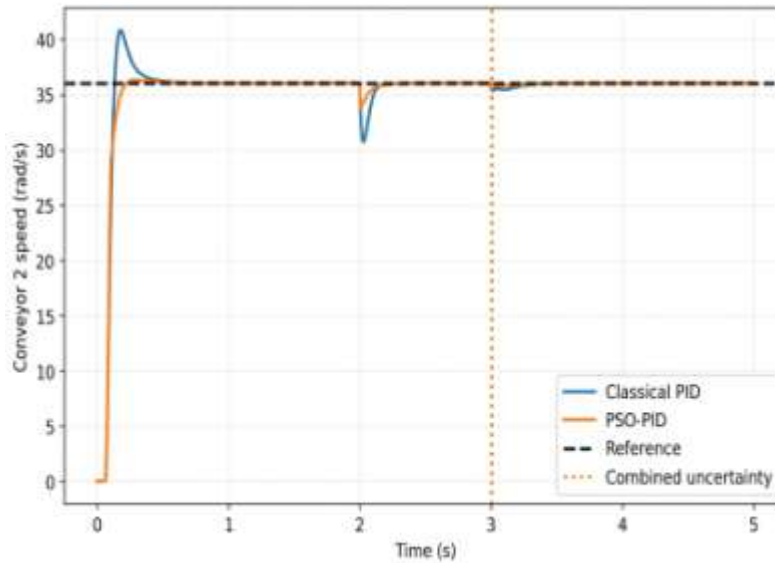


Figure 12: Speed response under combined parameter uncertainty

Table 2. Robustness assessment

Scenario	Controller	RMSE_mix (%)	Max_error (%)	Flow_drop (%)	Recovery_time (s)	Energy (kWh)	SEC (kWh/t)	Saturation_fraction
Nominal	Classical PID	0.0126	0.1082	0.0000	0.0000	0.0038	0.5042	0.0083
Nominal	PSO-PID	0.0060	0.0500	0.0000	0.0000	0.0038	0.5099	0.0140
Load +20%	Classical PID	0.1338	1.2533	1.7589	0.0508	0.0044	0.5824	0.0083
Load +20%	PSO-PID	0.0488	0.5324	0.7549	0.0000	0.0044	0.5884	0.0140
Load +50%	Classical PID	0.3407	3.2196	4.3972	0.0898	0.0054	0.7154	0.0083
Load +50%	PSO-PID	0.1223	1.3465	1.8872	0.0286	0.0054	0.7219	0.0140
Rs +20%	Classical PID	0.0151	0.1202	0.1715	0.0000	0.0039	0.5132	0.0083
Rs +20%	PSO-PID	0.0071	0.0948	0.1352	0.0000	0.0039	0.5190	0.0140
Rr +20%	Classical PID	0.0147	0.1098	0.1566	0.0000	0.0039	0.5110	0.0083
Rr +20%	PSO-PID	0.0070	0.0909	0.1297	0.0000	0.0039	0.5167	0.0140
Lm -10%	Classical PID	0.0450	0.2512	0.3652	0.0000	0.0039	0.5199	0.0083
Lm -10%	PSO-PID	0.0173	0.0861	0.1245	0.0000	0.0040	0.5257	0.0140
J +20%	Classical PID	0.0126	0.1082	0.0000	0.0000	0.0038	0.5042	0.0083
J +20%	PSO-PID	0.0060	0.0500	0.0000	0.0000	0.0038	0.5099	0.0140
Combined stress	Classical PID	0.3470	3.2196	4.3972	0.0898	0.0060	0.7917	0.0083
Combined stress	PSO-PID	0.1250	1.3465	1.8872	0.0286	0.0060	0.7984	0.0140

Energy Consumption Analysis:-

The results of the five uncertainty scenarios are summarized using the principal robustness indicators. The electrical energy consumed by the motors is evaluated for the three control configurations [3], [17]. Figure 13 shows an evaluation of the energy consumption of the three strategies. Figure 13 illustrates a comparative evaluation of the total energy consumption (ex-pressed in Wh) for the three investigated control strategies.

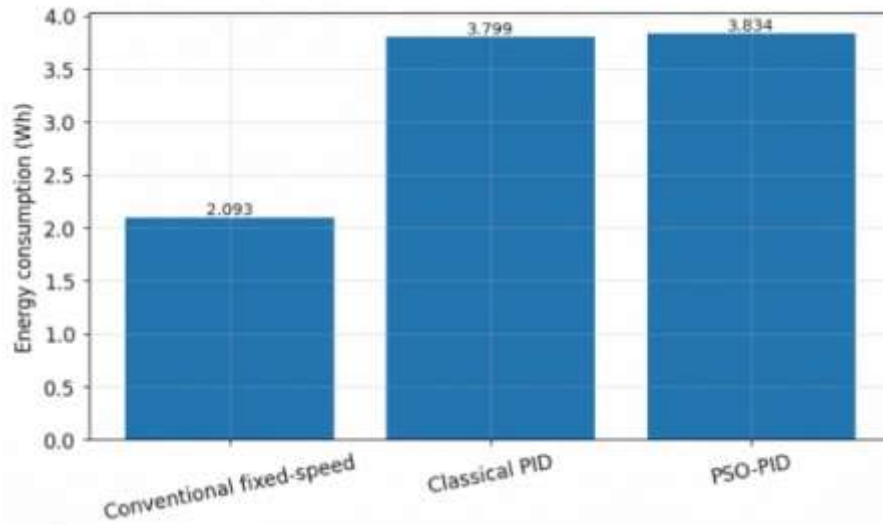


Figure 13 : Energy consumption during 70/30 operation

The conventional fixed-speed mode exhibits the lowest consumption at 2.093 Wh. However, as highlighted in the previous speed profile analysis, this lower energy baseline is a direct consequence of the system's degraded behavior, where Conveyor 2 suffers from a permanent speed deficit and fails to deliver the required mass flow rate. Activating the dynamic controllers to ensure the strict 70%/30% mixing ratio logically increases energy consumption, as more power is required to actively reject disturbances and maintain the tracking references. Consequently, the classical PID consumes 3.799 Wh. Remarkably, the optimized PSO-PID controller consumes only 3.834 Wh, representing a negligible increase of just 0.9% compared to the classical PID. This crucial finding demonstrates that the superior dynamic performance of the PSO-PID (zero overshoot, instantaneous disturbance rejection, and parametric robustness) is successfully achieved without sacrificing the energy efficiency of the drive system.

Sensitivity Analysis:-

The sensitivity analysis is performed to identify the parameters that have the greatest influence on the behavior of the controlled system. Each parameter is varied independently while the remaining parameters are maintained at their nominal values. The resulting variation in the selected performance indicators is then evaluated. A normalized sensitivity coefficient can be expressed as

$$S_x^y = \frac{\Delta y/y}{\Delta x/x}$$

where x represents the perturbed model parameter and y represents the selected performance indicator. The parameters investigated include R_s , R_r , L_m , J , Cr .

Table 2 : Sensitivity of the principal performance indicators to model parameters

Parameter scenario	Relative RMSE change (%)	Relative change SEC (%)	Flow drop (%)	Recovery Time (s)
Charge +20%	7.1691	0.1538	0.7549	0.0000
Charge +50%	19.4594	0.4156	1.8872	0.0286
R_s +20%	0.1926	0.0177	0.1352	0.0000

Parameter scenario	Relative RMSE change (%)	Relative change SEC (%)	Flow drop (%)	Recovery Time (s)
Rr +20%	0.1744	0.0133	0.1297	0.0000
Lm -10%	1.8952	0.0309	0.1245	0.0000
J +20%	0.0000	0.0000	0.0000	0.0000
Stress combiné	19.9199	0.5657	1.8872	0.0286

Table 2 presents the relative variations in performance metrics for the PSO-PID controller under various parameter uncertainties and load disturbance scenarios. These results serve to validate the overall robustness of the optimized field-oriented control (FOC) system. It can be observed that variations in the motor's electrical (R_s , R_r) and mechanical J parameters induce only negligible deviations. For instance, a 20% increase in rotor resistance R_r results in a minor rise of only 0.17 in the Root Mean Square Error (RMSE) and 0.01% in the specific Energy consumption (SEC), with a recovery time of zero. Furthermore, the impact of inertia variation $J+20\%$ is strictly null, demonstrating the optimized controller's insensitivity to mechanical dynamics fluctuation.

The most severe scenarios involve sudden load variations. Under a +50% load impact, the RMSE increase reaches 19.46%, which remains well within controlled limits. The corresponding flow rate drop is limited to just 1.89%, with an extremely fast recovery time of 0.03 s. Ultimately, under the extreme conditions of the Combined stress scenario, which simultaneously aggregates all parametric variations and the maximum load, the system maintains outstanding performance. The RMSE degradation caps at 19.92%, while the specific energy consumption (SEC) increases by a mere 0.57%. The total wheat flow rate undergoes a transient drop of only 1.89%, which is successfully rejected within 0.03 s. These quantitative findings confirm the superior robustness and stability of the proposed PSO-PID controller under highly critical industrial operating conditions.

Accuracy–Energy–Robustness Trade-Off:-

The previous sections evaluate control accuracy, robustness, and energy consumption separately. However, an industrial control strategy should be considered from these three perspectives simultaneously. The classical PID and PSO-PID configurations are therefore compared using a set of complementary indicators including

Table 3 : Comparative performance of the evaluated models

Controller	Nominal RMSE(%)	Nominal SEC(kWh/t)	Mean robust RMSE (%)	Mean Flow drop (%)	Robustness score
PID classique	0.012648	0.504228	0.115184	1.405825	1.665008
PSO-PID	0.005976	0.509928	0.042440	0.614843	0.693033

Table 3 provides a comprehensive comparative summary of the nominal performance and robustness of both investigated controllers. The results undeniably demonstrate the superiority of the PSO-PID approach over the classical PID, under both nominal conditions and external disturbances. Under nominal operations, the PSO-PID regulator achieves a significantly higher tracking accuracy with a nominal RMSE of 0.0060%, representing a twofold reduction compared to the classical PID (0.0126%). This improvement is achieved at the expense of a negligible increase in Specific Energy Consumption.

The benefits of the particle swarm optimization become even more prominent when evaluating the mean robustness indicators. The PSO-PID cuts the mean robust RMSE by nearly a factor of three (0.0424% vs. 0.1152%) and restricts the mean flow drop to a mere 0.61% compared to 1.41% for the classical PID. Ultimately, the overall robustness score of the PSO-PID (0.6930) is substantially lower than that of the classical PID (1.6650). Since a lower index indicates superior stability, these quantitative criteria definitively prove that the PSO metaheuristic provides the vector control system with highly enhanced resilience against critical industrial operating uncertainties.

Limitations:-

The present study is based on a simulation model and therefore does not constitute a direct experimental validation on the industrial installation. Some conveyor-related parameters are represented using model assumptions and should be identified experimentally before practical implementation. Furthermore, the control architecture focuses primarily on motor-speed regulation and its effect on the resulting material flow. Real industrial implementation would require additional considerations, including flow measurement, actuator constraints, sensor uncertainty, communication delays, safety interlocks, and protection systems. The results should therefore be interpreted as a simulation-based assessment of the proposed control strategies. Experimental validation under representative industrial operating conditions would constitute an important next step.

Conclusion:-

This study presented an integrated control framework for a two-stream wheat conveying and mixing system driven by 4kW induction motors. The proposed model combines induction-motor dynamics, indirect field-oriented control, conveyor operation, wheat mass flow, and mixing-ratio calculation within a common simulation framework.

Three operating configurations were considered : the conventional start-stop system without speed regulation, a classically tuned PID controller, and a PSO-optimized PID controller. This structure allowed the effect of introducing closed-loop speed regulation and subsequently optimizing the controller parameters to be investigated under the same process conditions. The robustness of the control strategies was evaluated through independent variations of key electrical and mechanical parameters, including stator resistance, rotor resistance, mutual inductance, mechanical inertia, and load torque. The proposed framework was also evaluated for different mixing requirements, namely 50/50, 60/40, and 70/30.

In addition to speed and flow regulation, the study considered mixing-ratio accuracy, tracking error, recovery behavior, total energy consumption, and specific energy consumption. A sensitivity analysis was further introduced to identify the parameters with the greatest influence on system behavior. The results provide a unified framework for assessing induction-motor control strategies at both the drive and process levels. In particular, the comparison between classical PID and PSO-PID makes it possible to evaluate the effect of automated controller tuning beyond nominal speed tracking. The combined consideration of accuracy, robustness, and energy performance provides a broader basis for evaluating the suitability of optimized PID control for industrial wheat conveying and mixing applications. Future work should focus on experimental validation of the proposed model and control architecture using measured conveyor-flow data and real-time implementation of the optimized controller. Further developments may also consider online flow measurement, adaptive control, and real-time optimization to improve the capability of the system to respond to changing industrial operating conditions.

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