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Function Block for Rotary Kiln Coating Disintegration Detection

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Abstract: Condition monitoring is an important field that can boost manufacturing processes to produce high quality and more quantities. This work presents the design of new Programmable Logic Controller (PLC) Function Block (FB) dedicated to the instantaneous detection of any coating piece disintegration from the wall coating formed by the processed material sticking naturally on the inner side of the cement rotary kiln. The detection is based on the on-line analysis of the kiln spinning electrical motor's signal. The FB makes use of differences between the adjacent signal's measurements values and logic functions to hide false alarms for the user whenever they break out due to kiln velocity set point abrupt changes. In steady state process operation, the technique provides highly reliable and accurate detection. Its application can be extended to any similar instantaneous abrupt changes occurring in other manufacturing processes.

Keywords: modeling, rotary kiln, condition monitoring

Nomenclature

t : Time indices; P : Power Amplitude; P_{min} : Lower power measurement

P_0 : Middle power measurement; P_{max} : Higher power measurement

Nb : Number of measured points; J : Mechanical inertia; T : Mechanical Torque

$\dot{\theta}$: Angular velocity; $\ddot{\theta}$: Angular acceleration

1. INTRODUCTION

In the recent years, only few automation software companies worldwide are trying to elaborate particular libraries dedicated to industrial equipment and processes condition monitoring. Among them one famous company that established a short library containing only five function blocks.

Two blocks to monitor some of the widely used actuators in a process plant such as pumps and valves. In addition to three others for plant signals and parameters monitoring in addition to plant Emergency Shut Down (ESD) components safety and availability testing [1]. This kind of blocks is status based monitoring software that is designed purely for monitoring purposes and does not affect directly the process except for those of Safety Instrumented Functions (SIF) testing where limited interactions with the process may occur. In order to optimize the monitored equipment over a long term, these blocks make available their outputs for further data processing and if needed undertake an active action over the plant actuators. Furthermore, some blocks perform themselves basic statistical analysis as part of their internal functionality and make it available to the user.

In general, the blocks can be classified into three main categories, the first group is for equipment monitoring, where deviations from an expected characteristic curve are visualized and results reported to the control room operators. These characteristic curves are established by the equipment manufacturers. The blocks can warn for some equipment potential damage or wear limit been reached and so, provide an early detection of imminent faults. The second group of blocks is devoted to in situ and online check of Safety and ESD actuators in order to testify that they are performing as intended for a specific Safety Integrity Level (SIL). The third group is for process operation condition monitoring such as monitoring pressure drops and flow resistances in some industrial equipment and watching for the steadiness or unsteadiness of dynamical systems. This behavior may point out in continuous processes to either process or field device disturbance outbreak or disappear, whereas, in batch production processes, it points to the end of the current basic operation; this type of blocks makes use of data statistical analysis such as variance and variability analysis, filtering or transformation techniques.

These functionalities are cost-efficient solutions to leverage companies potential for saving time and money in the way that they employ the existent signals process and don't need additional

hardware implementation. They are helpful means for improving maintenance scheduling and resources planning and hence increasing global plant availability. The present work can be classified among the third group. The proposed function block can be used for prompt detection of coating pieces disintegrations of any scale that appears in cement, plaster or lime production process rotary kilns where the material stuck may form a protective layer for the kiln shell.
This paper is organized as follows, first, a brief process presentation is given, then the problem is stated, after that the FB design procedure is given. The subsequent section discusses the simulation results, and after that comes the section where is shown how this FB can be implemented on PLCs and finally the conclusion is derived.

2. PROCESS PRESENTATION

Rotary kilns are used mainly in cement manufacturing, simultaneously as heat exchangers and chemical reactors. They are huge cylinders made of steel shell where the inner side is covered by refractory bricks to minimize the heat losses and preserve energy [2]. The processed material flow is preheated in a preceding pre-heater, then supplied to the kiln where it is severely exposed to hot gas counter current stream. As result, the material experiences many consecutive physical and chemical reactions. The powder material is first decomposed to less basic molecules, then the liquid-like phase roses and re-combination process starts which gives birth to new compounds owning specific physical and chemical properties [3]. The kiln discharge is called clinker. Afterwards, this material is cooled and further processed to get the so called cement.
The kiln slopes few degrees downwards in favour of material movement and mass transfer. In addition to its inclination, the kiln is spun around its horizontal axis by one or two induction motors acting together on the rotary kiln peripheral tangents.

3. PROBLEM STATEMENT

In addition to shell and refractory bricks layer, the processed material itself should form a second internal coating layer stuck above the bricks, after few days of operation. This layer is called coating; the thickness and stability of coating is an important factor to long-term protection of refractory bricks and energy consumption optimization.

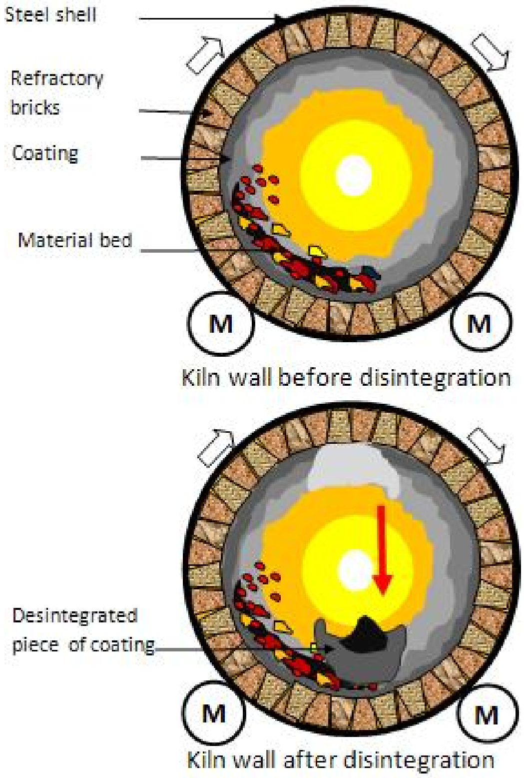

Fig. 1. Kiln Cross-section diagram showing. In top kiln wall before disintegration, in bottom while in disintegration

Therefore, it has a major role in long operation life cycle for the whole system. When in operation and for some reasons related to the supply material quality and burning conditions, the kiln coating may be unstable, coating pieces may fall down adding their weight to the processed material bed load.
Fig.1 in its upper part shows kiln cross-section presentation of the rotary kiln cut through a perpendicular plan to bed material movement. The inner layer with an uneven surface represents coating. It is grown by the material deposits that stick to the underneath bricks. When the coating is stable the layer has a cylindrical-like shape. Kiln motor current and power are dependent on the material bed load that follows a sinusoidal-like function whose amplitude and frequency are dependent on kiln angular velocity, repose angle and much other time-varying factors, see [4] and references therein. A clear description of the disintegration phenomenon is given in Fig. 1. It is represented in the lower part of this figure the exact instant when the disintegration happens. If any coating piece cracks, it goes apart from the whole layer and falls down when it is under the full gravitational force component, that is in the in the maximum height of its circular trajectory. The event is accompanied by an abrupt positive change in the motor power and this is what we hope to capture. The change amount is directly proportional to the material weight added to the material bed load. Fig.2 in its upper part shows the kiln motor power signal behaviour during normal operation and the abrupt jump caused by coating disintegration at time index 280.
Moreover, Any change in the kiln angular velocity generates a proportional change in the power too, as the driving objective is to keep the motor torque at a constant value. These last power Changes are a source of mismatch and confusion and so the proposed technique should isolate and distinguish them from those of the earlier class that is due to disintegration phenomena. All the changes in kiln velocity set point made by the operator during the chosen study period are shown in the lower part of Fig.2. In general, when the kiln is going to chill, the operator abruptly decreases the material feed rate along with the angular velocity until the chill is taken off. Then, the two input will be increased with small amplitude steps (stair form). So, unlike other works which are concerned with the detection of mean values drifts in process values that are almost signs of process global healthy operating conditions [5] our main focus here is to detect the instantaneous abrupt jumps. the equations linking the motor's power to the angular velocity are further explained in the next section.

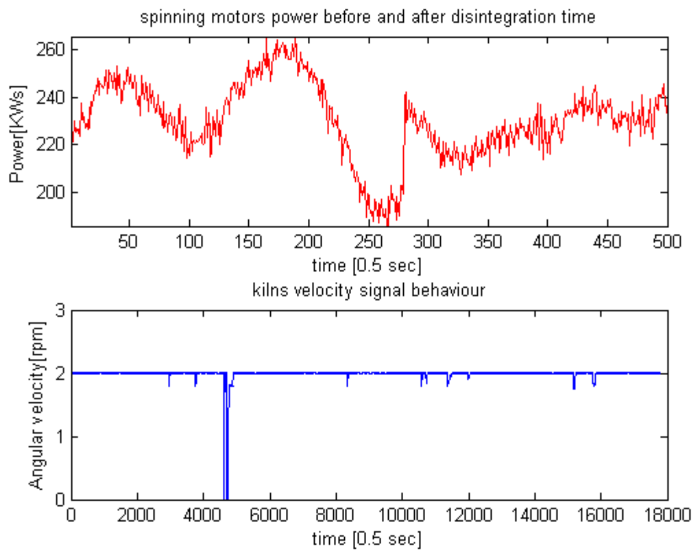

Fig. 2. In the top Kiln power during disintegration at time index 280.
In the bottom, kiln angular velocity changes behaviour with transients
(chilling and stop / start-up periods)

4. DESIGN PROCEDURE

The changes in the power signal can merely be estimated by the differences between signal adjacent values, that is if P_t is the current power measured value and the P_{t-1} is the n-th previous one, then the difference can be computed as

$$\Delta P_t = P_t - P_{t-n} \tag{1}$$

Equation (1) is the first order derivative approximation over n time measurement steps. Depending on the signal acquisition chain speed rate, the abrupt change can appear using one-step differences or more, the faster is the signal the more are the measurement points needed to compute this change. So, the choice of n obeys to practical considerations and the function block should encapsulate this functionality. As will be shown in simulation results, bud choice of derivation time length can lead to high rate of miss detections.

In the other side, not only the disintegration phenomena lead to abrupt changes in the motor power's but also any changes in kiln angular velocity as discussed earlier. The motor velocity and torque are controlled by means of the electronic drive. The drive can impose to the motor two different operating modes, that is the constant torque mode which lasts from the operating speed of zero up to the motor rated speed (called also base speed and base frequency point) then, beyond this operating point the drive enters the constant power mode [6]. The first mode is extensively exploited in many industrial applications.

The general law that governs motor torque acting against a load torque with inertia is the well known second Newton laws of dynamics.

$$\sum T = J_{tot}\ddot{\theta} \tag{2}$$

where J_{tot} is the total inertia acting on the motor shaft including the load inertia, $\ddot{\theta}$ is the angular acceleration and T denotes torque.

Torque balance on the motor shaft gives

$$T_{mot} = J_{tot}\ddot{\theta} + T_{load} \tag{3}$$

where T_{load} is the torque demand and T_{mot} is the torque need. As it is shown in (3) the torque produced by the motor is variable according to the variation in $\ddot{\theta}$; it is high when in acceleration ($\ddot{\theta} \succ 0$), low when in deceleration ($\ddot{\theta} \prec 0$) and constant when the angular velocity is constant ($\ddot{\theta} = 0$). The motor produces this torque according to the following equation

$$T_{mot} = \frac{P}{\dot{\theta}} \tag{4}$$

where $\dot{\theta}$ is the motor shaft angular velocity. So in constant torque mode, the drive needs to increase the power in response to any positive change in the angular velocity to maintain the torque at its previous value. Therefore, any change in the velocity set point from the plant control room will be followed by a change in the power measured value. This rise in power should not, in any case, be assimilated to the change caused by coating disintegration event. Hence, kiln velocity parameter (measurement or set-point) have to be considered in the detection scheme. The small steps by which velocity is increased after kiln chilling or during first start-up should be distinguished from any disintegration by considering the maximum steps amplitudes' used by the operator as a threshold in the detection scheme and check whenever a change in power occurs whether it is caused by velocity increase or it is an actual disintegration.

The scheme for detecting the coating disintegration is explained below, for $n = 1$.

1- *Set the power threshold willing to detect.*

2- Set the velocity threshold used by the operator after chilling or during start-up.

3- initialize the fault Boolean indicator to 'FALSE'.

4- Initialize the memory values for power and velocity.

5- Read the power and velocity signals current values.

6- Compute the differences in power signal (current minus previous).

7- Compute the differences in velocity signal (current minus previous).

8- IF the power difference is greater than the pre-setted threshold AND the difference in velocity is less than the pre-setted threshold.

8-a- Set fault indicator to 'TRUE'.

8-b- ELSE keep the fault indicator to 'FALSE'.

9- Memorize the power and velocity values as previous ones.

10- go to step (5) and repeat the procedure.

5. SIMULATION RESULTS AND DISCUSSION

The simulation is performed using MATLAB® software. The upper part of Fig.3 shows the actual kiln power signal collected from Ain El Kebira cement plant in eastern Algeria (ancient production line). It lasts for 01 hour and 28 minutes and marked by two periods of kiln shut-down that are zoomed in, in Fig.4. The zoom shot shows the huge impulses in the power derivative when stopping and restarting up the kiln; notice that the complete restart and the end of the transition phase is achieved around the time 4910. During the transition period, many overshoots in power derivative signal are noticed, these may result in many false alarms. However, the inclusion of the velocity differences in the scheme as detection condition with an appropriate threshold (which is here taken equals to 0.15 rpm) would attenuate considerably their effects on the detection scheme and reduce the false alarms rate. Moreover, in order to overcome sensor and process noises, velocity set-point can be used instead of the measured signal, since the system dynamic is fast enough.

Before we proceeded with simulations, a manual check of the power signal was done to localize and extract the actual faults (disintegrations) folded in it and having more than 35 KWs amplitudes. Those disintegrations are in practice considered as dangerous in the sense that they create a material avalanche along the rotary kiln that may submerge the cooler system (the subsequent equipment after the kiln) which then fails to work correctly. Table 1 shows the six actual disintegrations occurred during the studied period with the respective occurrence times and amplitudes.

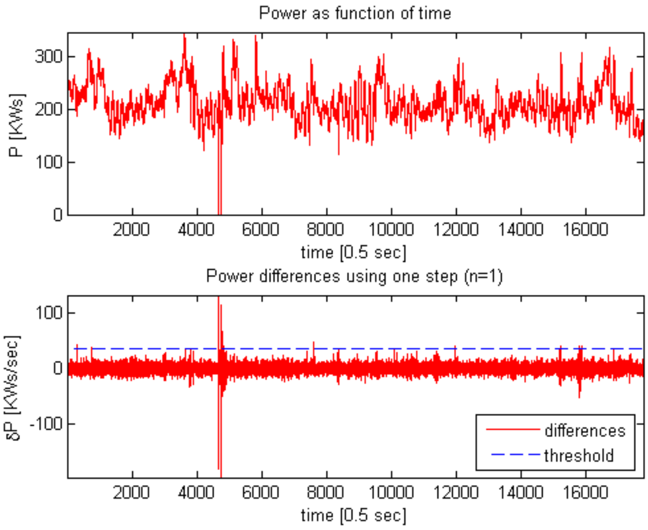

Fig. 3. In the top, the power signal during the whole studied period.In the bottom its first forward derivative approximation over one back step

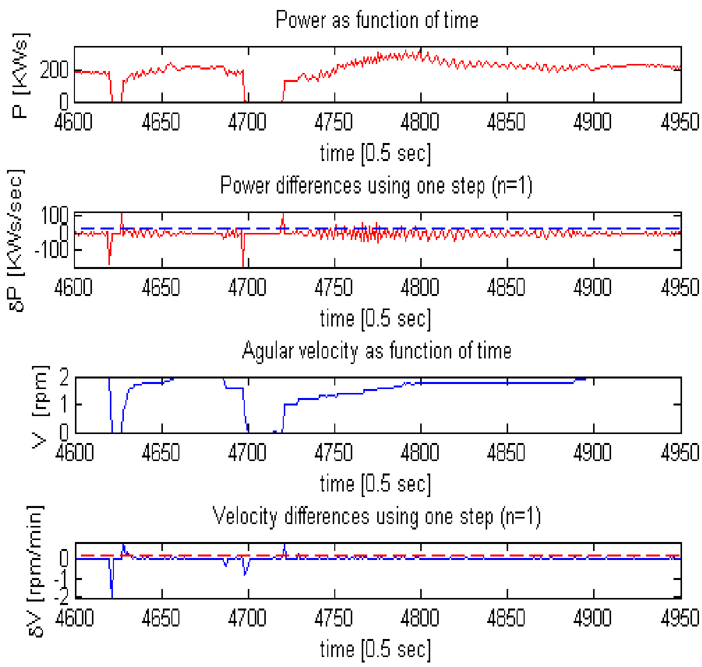

Fig. 4. From top to bottom: zoom in showing the two kiln shut down periods of: 1st the power signal, 2nd its first derivative approximationover One back step, 3rd angular velocity and 4th angular velocity derivative

The manual check results were also gathered in a vector, the corresponding Boolean indices (called also in some literatures as fault indicators or variables) were reproduced and plotted in the upper part of Fig. 5 against the obtained scheme simulation results. The simulations are realized using two computation forms for the differences, that is for $n = 1$ and for $n = 2$.
For the first case, i.e. one step back differences computations that are shown in the midst of the aforementioned figure. Exactly 05 faults over the 06 were detected and 01 was missed, but along with two false alarms groups, the first one composed of 14 false alarms appeared between the time indices 4600 and 4800 and the second group of 03 false alarms between time indices 15200 and 15900, in addition to 01 standalone false alarm at time index 8351. The first group corresponds to the two periods when the kiln was shut-down and their start-up transients, whereas the second sequence corresponds to two successive chilling periods where the kiln was slowed down after a while it regained slowly by steps in form of stairs the initial velocity which is also a transient period, Fig.2 shows in its lower part the changes in velocity operated during the whole studied period and all transient periods contained in. Every change (decrease then increase) is a transient. The second simulated case is that where two measurement back steps were used to compute differences, with results shown in Fig.5 in its lowest part. In this case, more false alarms appeared, particularly in the transient periods. However, in contrast to the first case, the missed alarm was nicely detected here because it appeared over two measurement steps; with each step, the amplitude is less than the fixed threshold on the power's signal.

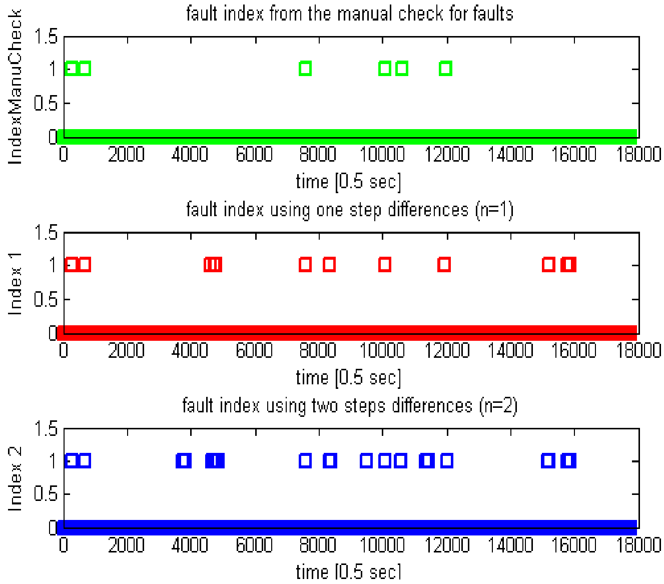

Fig. 5. From top to bottom: 1st actual fault index (checked manually),2nd fault index using one back step derivation, 3rd fault indexusing one back step derivation

Table 1. Actual Alarms folded in the Signal Checked Manually

t	P	P_{min}	P_0	P_{max}	Nb
279	41.4	199.1	-	240.5	1
700	37.9	254.6	-	292.5	1
7592	46.1	197.7	-	243.8	1
10058	35.9	179.5	-	215.4	1
10595	48.2	172.3	193.7	220.5	2
11963	41.2	215.5	-	256.7	1

6. IMPLEMENTATION

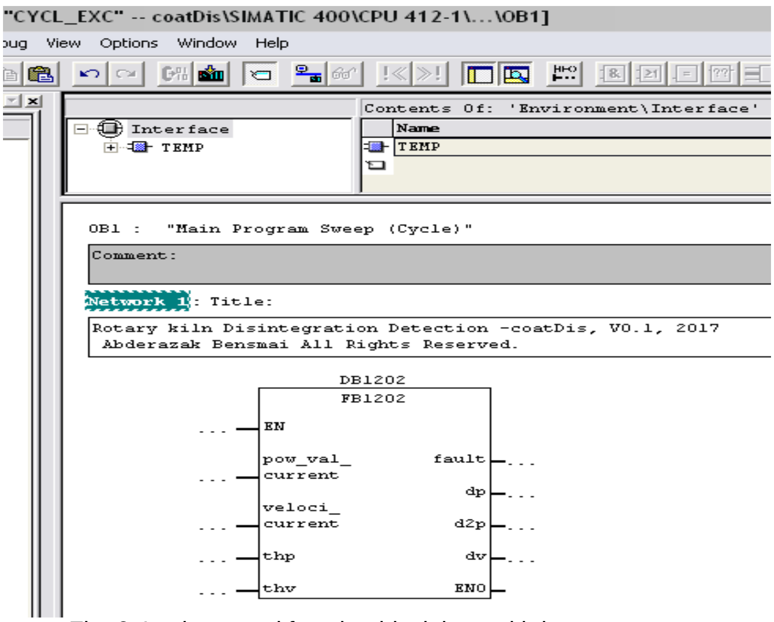

Fig. 6. Implemented function block icon with its parameters.

The implementation of the function block in the Automation system is carried out using S7-SCL© (Structured Control Language) V5.3 + SP1 + HF1, Which is a PASCAL-oriented high-level language for programming PLCs.
Fig.6 shows the bloc icon's with its input and output parameters. It was given the number 1202 that is in users blocks range according to the PCS7© engineering specifications, the instance data block (DB) has the same number. The implemented FB computes the differences in power signal in two ways; using one ($n=1$) and two ($n=2$) acquisition back steps, but uses only the first case to set the Boolean fault indicator, which is suitable for the studied system as it generates less false alarms.

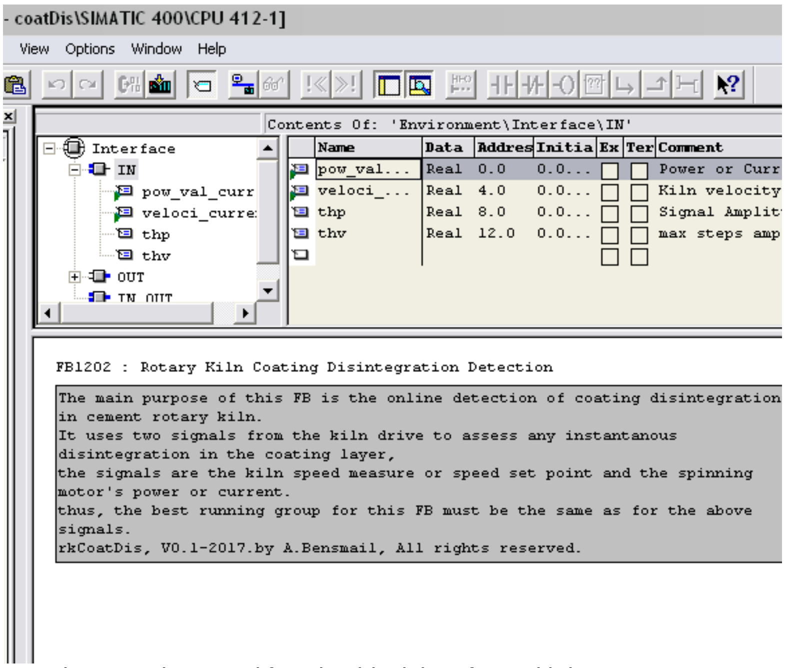

Fig. 7. Implemented function block interface with it's parameters.

The function block interface shown in Fig.7 has as inputs, the two signals and their respective thresholds. As outputs, the logic fault indicator and the three computed differences that makes available for any further processing in the automation or monitoring system.

7. CONCLUSION

The studied problematic subject is chosen from the industry realm. The proposed technique has the advantage to be cost-efficient, in the sense that uses only the available signals from the plant and does not require any additive hardware. Furthermore, it can be implemented online with minimal computation resources.
The proposed technique is very suitable for the steady processes, i.e. when the rotary kiln is operating under constant angular velocity. For the kiln velocity transient changes points, more enhancement should be investigated in future works in order to overcome false alarms issues. The introduction of robust or adaptive techniques such as adaptive or dynamic thresholds would give better results.

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