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Energy savings and operation improvement of rotating cement kiln by the implementation of a unique new drive system

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Abstract: Analysis, simulation, implementation and results of a new kiln drive system consisting of two AC motors of 315 kW each, on an existing common tooth gear, as a new contribution for the operational optimisation of rotating kilns, are presented in this study. Two separate inverter units control the two asynchronous motors with a common rectifier. This study also illustrates how backlash problems on tooth gear and maintenance needs are eliminated while reducing operational costs, down-times and energy consumption, by applying contemporary technology, including power electronics and dynamic performance in control systems.

1 Introduction

It is well known that in the field of heavy industry, the stability and continuity of the operation of the production systems are of major importance. Downtimes of machinery parts cause production losses as well as unwanted side effects such as increase in machinery wear, imbalance of the production system and other problems and damages during the restart of the production line [1]. This paper aspires to contribute to the heavy industry sector by presenting a successful application of power electronic techniques in a cement kiln drive system illustrating how modern technology facilitates a scientific method for reducing energy consumption and required resources while improving operational efficiency and performance.

2 Description of rotary kiln

Cement kilns are long, steel plate cylinders, lined with bricks, which slowly rotate at between 30 and 250 revolutions per hour, with a diameter of 3–5 m and a total length reaching up to 200 m, built with a small slope (1–4°) to assist material flow inside them. They are used for the pyroprocessing stage of manufacture of hydraulic types of cement and are considered to be the most energy-consuming and greenhouse-gas emitting stage of cement manufacture process. Thus, efficiency improvement is of high importance [1, 2]. Raw meal is fed in at the upper end, and the rotation of the kiln causes it to gradually move downslope to the other end where the fuel is injected. Rotary kilns are typically stopped for only a few days, once or twice a year, for essential maintenance [1, 3].

Of high importance is also the physical condition of the kiln shell itself, especially the preservation of its ‘circular’ shape while rotating. The kiln’s shape is a key factor to system alignment and consequently to the distribution of the kiln’s mechanical load over the rim gear and support bearings. The kiln shell, due to high thermal loads, tends to lose its circular shape and resembles more to an ellipse. This kind of flexing and distortion of the kiln’s shell shape greatly increases mechanical wear, especially gear tooth wear and leads to roller, bearing and backlash problems [3, 4].

The required torque for the rotation is transmitted to the kiln through a dual drive system, where the output speed of two separate drive motors is reduced to achieve the required kiln rotational velocity. The motor speed is first reduced via gearboxes which in turn drive two parallel torsion shafts. As shown in Figs. 1*a* and *b*, the torsion shafts are keyed to two pinion drives through which torque is transmitted to the kiln via a gear rim, which surrounds the kiln circumference (girth gear), further reducing the speed [1, 5]. Depending on the kiln manufacturer and design limitations for power transfer per pinion, size, and general constraints based on mechanical and economic data, single or dual drive arrangements can be used. In this case, we were required to develop and upgrade a specific kiln drive system that was manufactured in 1971. The kiln drive system utilised a dual drive arrangement which represented the best available technology of that time, in order to exhibit improved power transfer characteristics and smoother operation. This dual drive imposed the use of two separate DC drives at 250 kW each, one for each pinion, which in turn were controlled by two separate thyristor converters.

3 Pre-existing conditions

The pre-existing operational conditions that were first encountered included loud noise and very high vibrations of the girth gear, the spring plates, the pinion bearings and the torsion shafts. The unwanted phenomena were caused by extensive wear of gear and pinion teeth which, combined with the high forces generated by the kiln rotational inertia and the internal material mass, caused serious backlash problems [6]. More specifically, as shown in Figs. 1*c* and *d*, the existing tooth wear caused one of the two drive motors to operate under no load for a very short amount of time due to the lack of contact between their teeth and the girth gear’s teeth. Simultaneously, the second drive motor became overloaded and was forced to rotate the girth gear by itself, thus causing electrical overload problems.

This unwanted situation was further aggravated by the additional effect of ‘false bottoming’, which typically occurs when the wear on the tooth flank causes a ‘ridge’ across part or all of the width of the gear [3, 6]. Additionally, Fig. 1*d* illustrates the condition whereby the false bottoming effect causes the same vibration problem, as if teeth were pounding against the bottom land of the gears. We can safely assume that the problem escalated whenever the kiln

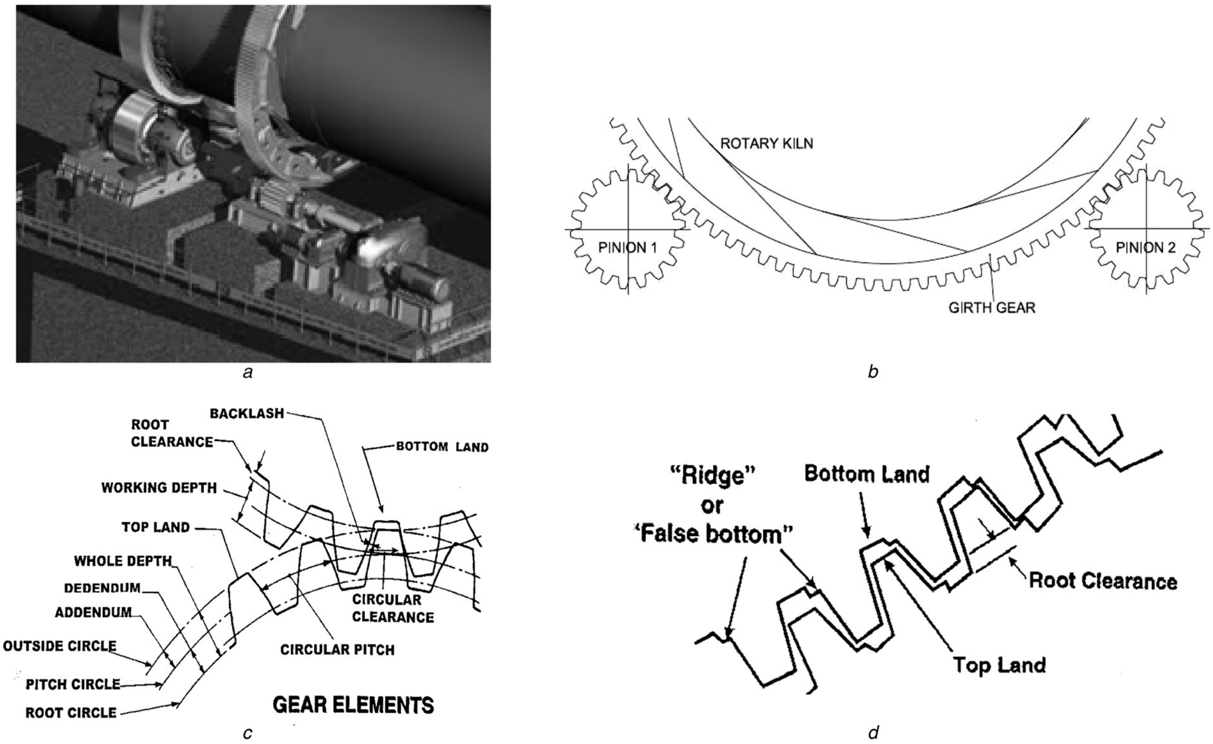

Fig. 1 *Kiln girth gear and drive general arrangement [1] and presentation of the mechanical coupler problematic conditions [3]*

a Schematic presentation of the kiln
b Girth gear and pinions
c Schematic presentation: backlash effect
d Schematic presentation: false bottom issue effect

reached high operational temperatures, due to the shift in the centre of gravity and, more importantly, the centre of rotation shifting somewhat lower. The rotation of the kiln causes the material inside it to move upwards due to the friction and the inertial forces that pin it against the kiln's cylindrical walls, until part of it drops back down again, eliminating these forces [7]. This effect, shown in Fig. 2*a*, causes reverse inertial forces that are critical to the system's balance. Due to these forces, the kiln's centre of gravity as well as its centre of rotation constantly changes, resulting in extensive gear tooth wear and other problems. The above-mentioned state appeared quite stressful for the components due to torsional oscillations [8]. Some initial measurements showed defects in the electronic components of the DC drive, which in turn caused more wear. The situation was disconcerting since malfunctions of electronic components and serious machinery damages were frequent and unpredictable.

It must be noted at this point that the entire operation of the plant, including the kiln section, was controlled by fuzzy logic techniques, minimising human intervention while maintaining an effective and stable production process, on a continuous basis. The observed problematic conditions are illustrated in Fig. 2*b*.

The black and grey lines represent the speed trends of each old DC motor while the white line represents the trend of the kiln torque. This is a typical printout from supervisory control and data acquisition (SCADA) operation screens, located in the plant's control room which highlights how the mechanical installation suffered from stresses and the other unwanted conditions previously described. As seen in Fig. 2*b*, since the blue line represents the most irregular changes in speed values it also represents the speed trend of the DC motor suffering the most gear tooth wear. The printout gives an idea of the unstable operation caused by the problem exasperation which led to an actual brief kiln stoppage. Typically, the unexpected peak value of the blue line, which occurs during the motor's increase in speed, offers a clear image of how backlash effects affect the whole process. More specifically, when motor gear no. 2 rotates, say counterclockwise, so that the kiln is forced to rotate in a clockwise direction, its worn teeth do not come in direct contact with the girth gear's teeth, thus leaving a gap in between. Motor gear no. 2 is now being pushed by the girth gear for a very short time interval until the motor responsible for motor gear's no. 2 rotation, which now operates under no load, accelerates as shown in Fig. 2*b*. When contact is reestablished between the girth gear's teeth and the teeth of motor gear no. 2, motor gear no. 2 speed drops until it matches the speed of motor gear no. 1. Following the problematic operational intervals described above and while in direct contact with the gear rim, they eventually reach working load speed, such that the system returns to normal operation, albeit one with limited stability [9, 10].

The task was thus to implement a technical modification which would ensure a smooth rotation of the kiln by effectively eliminating the backlash problems and general malfunctions, machinery damages, downtimes and the excessive maintenance previously required by the existing wear. We were to achieve this without having to perform drastic changes to the original kiln mechanical configuration (such as replacing the girth gear or the drive gears) which would otherwise cause significant capital expenditure and major production losses due to the amount of time required for such works [11].

4 Investigation of system requirements

In cement kiln applications, the starting torque required can be significantly higher than the steady-state torque needed to rotate the kiln [1]. The starting torque needed for this particular application was estimated to reach almost 200% of the rated torque of the motor in order to overcome system inertia, the behaviour of the material inside the kiln, as illustrated in Fig. 2*a* and the corresponding setbacks, as described before [12]. Furthermore, the wear of the gear's teeth created backlash effects which in turn caused a non-continuous rotation transmission, which led to rapid and unpredictable regenerative operation of the motor, as well as machinery vibration. The idea, as presented in this paper, was to address these adverse effects by introducing new

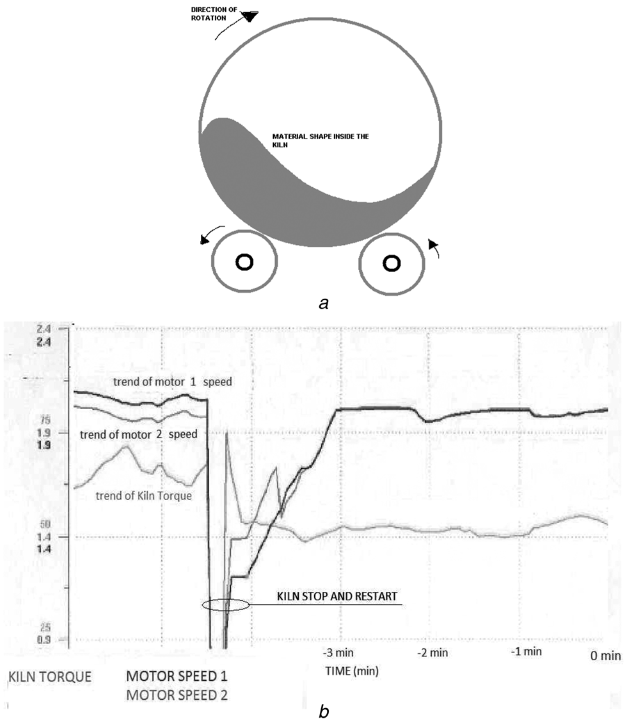

Fig. 2 *Situation experienced, material behaviour inside the kiln and electrical problematic effects*

a Material behaviour inside the kiln during the rotation
b Electrical effects and system behaviour that resulted in unwanted kiln stoppages
Startup conditions are also shown, reflecting problems that frequently occurred prior to the intervention due to mechanical problems (printout of plant's control room computer screen before the intervention)

AC drives of modern technology in place of the old DC ones, while maintaining the same mechanical configuration and ensuring the following [13, 14]:

(i) Torque sharing between motors on a fast change bases on the AC motors.
(ii) Instant availability of high torque (more than 200%) during low-speed startup in order to overcome load inertia.
(iii) Reference speed behaviour improvement during load change (process requirement).
(iv) Accommodation of the different power requirements between the two drives parts.
(v) Allowing for fast changes in the required power in order to reduce mechanical stresses and the effects of load changes (process requirement).

Minimisation of the time required for implementation (such as during a scheduled kiln stop).

5 Concept presentation

On the basis of the above criteria, the new AC drive system implementation is illustrated in Fig. 3.

Only minor changes of the mechanical installation were required to be implemented, such as new couplings in order to fit the new asynchronous 315 kW motors on the existing gear boxes. New supply cables and protection switchgear were additionally installed. The effect of the girth gear wear, as discussed previously, presented the most pressing matter to be solved. This was overcome by applying a master–follower structure with a common DC bus powered by a diode rectifier supply and individual inverters connected to the DC bus. The new AC drive system aimed at controlling the torque of the two motors, which represented the basic control variable of the kiln's drive system, affecting not only the rate of change of speed but also the stator current and consequently the voltage output of the inverter.

The typical advantage of the DC bus system is that it allows the energy to flow from a generating machine to a motoring machine during the phase when material mass inside the rotating kiln rotates upwards against the walls before falling back down again onto itself as shown in Fig. 2*a* and due to the backlash effect. In case a single drive were to be used, instead of a common DC bus, the returning energy would have to be dealt with by applying a brake chopper, so any energy savings would be very limited this way.

To cope with these undesirable phenomena, apart from the utilisation of two separate inverters to drive each of the motors, the structure shown in Fig. 3*b* was implemented to control their rotation. The philosophy of direct torque control (DTC) [15] was

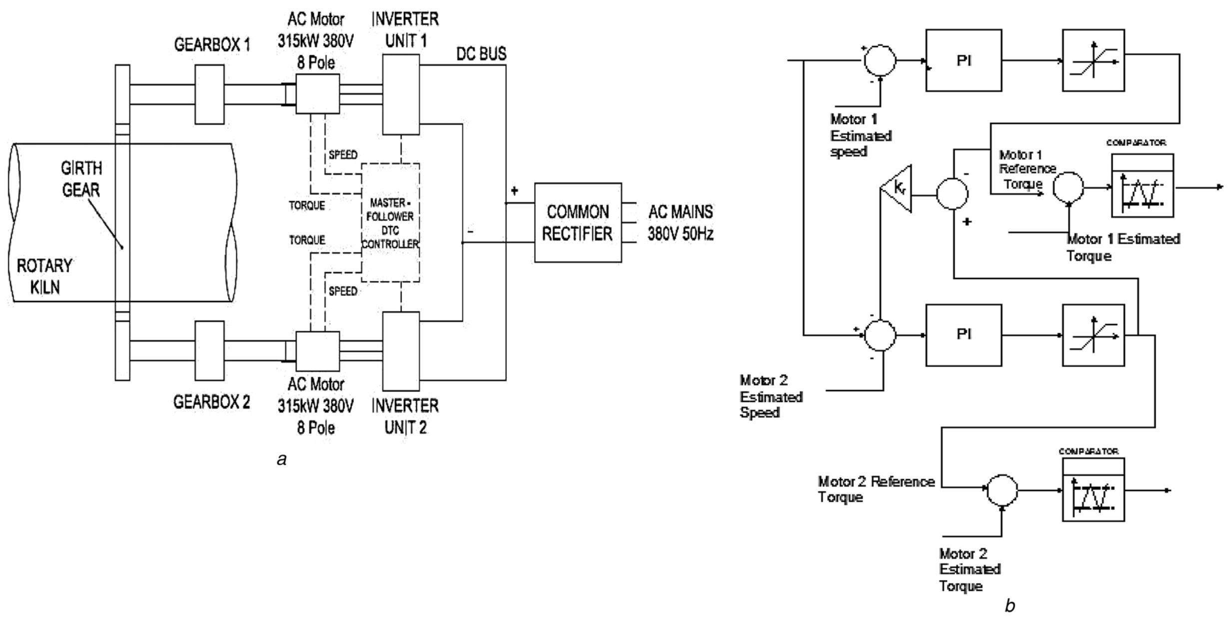

Fig. 3 *Presentation of the application*

a Schematic presentation of the application [7]
b 'Master–slave' structure[15]

chosen as a starting point, so that the balanced sharing of torque and load between the two motors was achieved [16, 17]. The two controllers, operating at the same reference velocity as the runner, have their output torques compared and the difference (the 'reference torque' of the motors), multiplied by the feedback gain k_f, is fed into the negative velocity error of the motor (defined as 'slave') [18]. This control principle results in an equal distribution of the load between the two motors. For example, when the 'slave' motor assigns higher torque than the 'master' motor, the feedback of the torque difference leads to the reduction of the 'slave's' proportional–integral (PI) control input signal and therefore to its reference torque reduction.

As a result, the 'master' machine's requirement for torque increases at the same time, so that it maintains the total output torque stable and thus the load can continue to move at constant speed. This process is repeated until the two motors achieve equal torques. In the opposite case, where the 'slave' motor assigns less torque than the 'master', the process can be correspondingly described as above. In reference to the following study, the motor which does not lose contact with the drive gear, in case of abnormality is 'number 1' while the one that loses contact with gear and momentarily rotates freely, is referred to as 'motor number 2'.

As generally illustrated in Fig. 3*a*, due to the reducers in the output of the motors and also due to the geometry of the main gear of the kiln, the total reduction ratio between the motor and the kiln is 375.93/1, calculated for each gearbox, as follows:

$$n_1 = n_2 = \frac{750}{23.10}\frac{220}{19} \tag{1}$$

For practical purposes it is considered that since the mechanical systems (reducers and girth gear) are identical in both drive systems, the total reduction ratio is the same for both systems. Although, after 30 years of operation of the mechanical equipment, corrosion will have brought about minor changes in the reduction ratio due to reductions in clearance gaps and so on, such a problem is considered negligible compared with the problem of the girth gear backlash, which is the topic of this present work [3].

6 System modelling and simulation

To model the mechanical system with adequate approximation, the motors '1', '2' are modelled as torque sources $S_{T,1}$, $S_{T,2}$ respectively, which are applied to the axis of these motors. Each motor has a specific moment of inertia which affects the dynamics of the system. To treat the DTC which is implemented in the drives, we consider that it comprises of two parts: the speed and torque control loops. The speed controller is realised through a PI controller. This control output is the reference torque which enters the torque control. For reasons of modelling simplification, the electric motors '1', '2', which are forming the sources of torque $S_{T,1}$, $S_{T,2}$, respectively, for the whole system, are effectively considered to be equal to the respective reference torques (for practical purposes, experience shows that the time constant of the torque control can be safely considered to be negligible, in the following analysis).

The modelling of the mechanical part of the system, considering $S_{T,1}$, $S_{T,2}$ inputs, was based on bond graph methodology [19, 20]. Accordingly, the following cases arise.

6.1 *Case 1: the two motors are in contact with the load*

In this case, the system has a single independent state variable. As such, the angular velocity of motor '1' is selected. The equation which describes this system is (see (2))

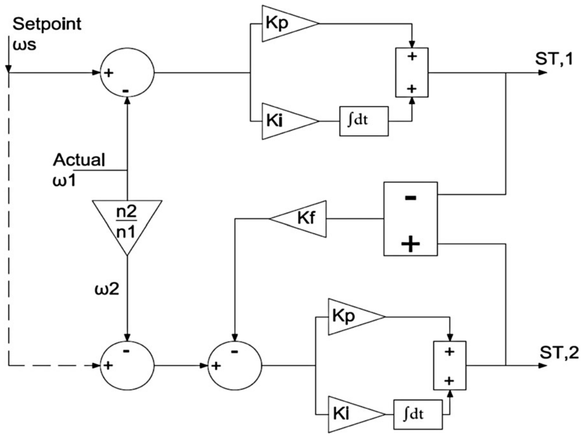

Fig. 4 *Basic control circuit for simulation (Matlab) purpose*

where J_1, J_2 are the moments of inertia of the system motor–reducer for both motors; B_1, B_2 are the factors of sliding friction of two motion machine (including motor–reducer); J_l is the moment of inertia of the load (kiln's load); T_l is the load of the kiln (external torque); B_l is the sliding friction factor of the load (kiln's load); n_1, n_2 are the reduction ratio of each motion system.

For the angular velocities of the kiln and motor '2', the following are, respectively, applied

$$\omega_l = \frac{\omega_1}{n_1} \tag{3}$$

$$\omega_2 = \frac{n_2}{n_1}\omega_1 \tag{4}$$

Equation (2) thus becomes

$$J_{\text{total}}\frac{d\omega_1}{dt} + B_{\text{total}}\,\omega_1 = S_{T,1} + \frac{n_2}{n_1}S_{T,2} - \frac{T_l}{n_1} \tag{5}$$

$$J_{\text{total}} = J_1 + \frac{J_l}{n_1^2} + \frac{n_2^2}{n_1^2}J_2, \tag{6}$$

where

$$B_{\text{total}} = B_1 + \frac{B_l}{n_1^2} + \frac{n_2^2}{n_1^2}B_2 \tag{7}$$

The above equations demonstrate the influence of the reducer on the moment of inertia of the load.

6.2 *Case 2: motor '1' is in contact with the load while the motor '2' moves without any load*

In this case, there are two state variables of the system, namely the angular velocities of the two motors. As in case 1, the appropriate state equations are correspondingly as follows

$$\left(J_1 + \frac{J_l}{n_1^2}\right)\frac{d\omega_1}{dt} + \left(B_1 + \frac{B_l}{n_1^2}\right)\omega_1 = S_{T,1} - \frac{T_l}{n_1} \tag{8}$$

$$J_2\frac{d\omega_2}{dt} + B_2\omega_2 = S_{T,2} \tag{9}$$

$$\frac{d}{dt}\omega_1 = \frac{1}{J_1}\left[S_{T,1} - B_1\omega_1 - \frac{1}{n_1}\left[B_l\omega_l + T_l + J_l\frac{d}{dt}\omega_l - n_2\left(S_{T,2} - J_2\frac{d}{dt}\omega_2 - B_2\omega_2\right)\right]\right] \tag{2}$$

Table 1 Electric motor 315 kW, 380 V AC parameters

nominal power	315 kW	inertia	16 kg m^2
nominal speed	741 rpm	stator resistance	0.00610 Ω
efficiency, %	96%	rotor resistance	0.0049 Ω
nominal torque	4060 Nm	stator inductance	0.21474 mH
nominal current	580 A	rotor inductance	0.1006 mH
power factor (cosφ)	0.82	magnetisation inductance	7.19708 mH

Following the above patterns, the model is implemented, as presented in the following circuit diagram of Fig. 4.

In addition to the modelling, each electric motor manufacturer's parameters are presented in Table 1.

6.3 Simulation

To qualitatively study the influence of system parameters k_p, k_i, k_f, a number of simulations were performed [20]. Each simulation was divided in the following time interval segments: the first 5 s time interval, where both motors started uncharged and simultaneously accepted the common load, and the second 9 s time interval where one of the two motors lost contact with the load and therefore operated uncharged, while the other motor bore the whole load. The maximum duration of this state, defined by the step of the main gear teeth and the speed of the load, was calculated to be 0.15 s. Thereafter both motors were equally loaded, gradually balancing the load on both motors. The simulations were performed for both motor 1 being the master and motor 2 being the master. The desired value of velocity (reference) was arranged such that it reached 750 rpm with a rise time of 0.5 s. This treatment cannot be practically applicable in industry, however, as far as the model is concerned, it presents a case under adverse conditions and can therefore lead to safe design conclusions prior to installation. In practice, in industrial applications, the time required for any electric drive to reach a reference set speed exceeds several seconds due to load or production requirements and constrains and machinery inertia. As followed from Fig. 4*b*, the $S_{T,1}$, $S_{T,2}$ with feedback gain $k_f = 0$ as a starting point, are

$$S_{T,1} = K_p(\omega_s - \omega_1) + K_i \int_{t=0}^{t} (\omega_s - \omega_1)\mathrm{d}t \tag{10}$$

$$S_{T,2} = K_p\left(\omega_s - \frac{n_2}{n_1}\omega_1\right) + K_i \int_{t=0}^{t} \left(\omega_s - \frac{n_2}{n_1}\omega_1\right)\mathrm{d}t \tag{11}$$

By replacing $S_{T,1}$, $S_{T,2}$ as the closed-loop control outputs of the DTC controllers of both motors and transforming (5) by Laplace with zero initial conditions, we obtain that the closed-loop system is of second degree [19] and the characteristic equation is

$$S^2 + \frac{B_{\text{total}} + k_p\left(1 + (n_2/n_1)^2\right)}{J_{\text{total}}}s + \frac{k_i\left(1 + (n_2/n_1)^2\right)}{J_{\text{total}}} = 0 \tag{12}$$

The above equation for a second-degree circuit could be written as

$$S^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{13}$$

Where the eigenfrequency of the system is

$$\omega_n = \sqrt{\frac{k_i\left(1 + (n_2/n_1)^2\right)}{J_{\text{total}}}} \tag{14}$$

and

$$\zeta = \frac{1}{2\omega_n}\frac{B_{\text{total}} + k_p\left(1 + (n_2/n_1)^2\right)}{J_{\text{total}}} \tag{15}$$

where k_p is the proportional gain and k_i is the internal gain.

The rate of response depends on the natural eigenfrequency of the system, which is influenced only by k_i and the damping ratio ζ. For certain k_p we choose k_i to lead the damping ratio close to 1 in order to avoid severe overshoots and oscillations.

As shown in Figs. 1*b* and *c*, due to the mechanical coupling, both motors operate under common load until the moment where the irregularity occurs. The motors startup unloaded and achieve the reference speed within the interval of 5 s, when the common load is applied. On the first interval, as observed in the simulation diagrams (Fig. 5), the velocity displays an overshoot, while the startup torque is high. This is attributable to the moment of inertia of the motors and to the very steep climb gradient applied in the simulation. In practice, the climb gradients are too shallow, resulting in no such phenomena. At the 5 s mark, due to the implementation of the common load, the common speed of the two motors is reduced while at the same time the torque is increased such that the kiln obtains the desired speed. The two motors acquire the reference speed and consequently at the 9 s mark, unevenness is shown to occur on the gear. During this unevenness, the speed of motor '1' is reduced with a simultaneous increase in torque, while in motor '2' the exact opposite takes place. After a time of 0.14 s both motors come into contact and, as expected, motor '2' acquires the speed of motor '1'. It must be emphasised at this point that the damage occurs to the two gears, when the unevenness stops, due to the speed difference of the two motors. The aim of this research was to reduce this difference by applying an equal distribution of loads during normal operation and to alleviate the previously described unwanted situation, as depicted in Fig. 2*b*. The conclusions regarding the values of the parameters k_p, k_i, k_f are presented below:

(i) For feedback gain $k_f = 0$ due to the k_i, a total term of the system that acts as 'memory', the two motors while continuing to move at the same speed (after the discontinuity), they have different torque. Given that during the period of the unevenness of gears motor '1' had greater torque than motor '2', the contribution of motor '1' is greater than that of motor '2'. Therefore, the greater the difference of torques during the unevenness and its duration, the greater the difference of the two torques.

(ii) The introduction of the gain feedback ensures that the two motors, after restoration of the unevenness, gradually acquire equal torques. The bigger the feedback value, the faster the restoration occurs. At the same time, as expected, the increase of the feedback value leads to an increase in the maximum divergence of motor '2' speed, during the unevenness of the two gears.

(iii) A more 'rigorous' PI control leads to the following results: (i) reduces the relative divergence of both motors during the unevenness, (ii) reduces the time needed for the machines to achieve steady state during startup and (iii) produces higher motors torques, not only during the startup but also at the occurrence of both gears anomalies.

In addition, it is evident that very high gains can lead to sharp torque increases to any additional unevenness that may occur in the system. To conclude, Fig. 5 illustrates the simulation results of the behaviour of the system with the final chosen values for $k_p = 125$, $k_i = 130$, $k_f = 0{,}002$. Those values have been chosen as a result of a large number of simulations while taking into account all the above conclusions. To highlight the idea of the common DC link and its purpose to allow the energy flow from one inverter to another, we performed a simulation case of the kiln operation, assuming that the problem of the girth gear can be considered (for demonstration purposes only since this is a non-permanent condition) as gear ratio difference of a value of

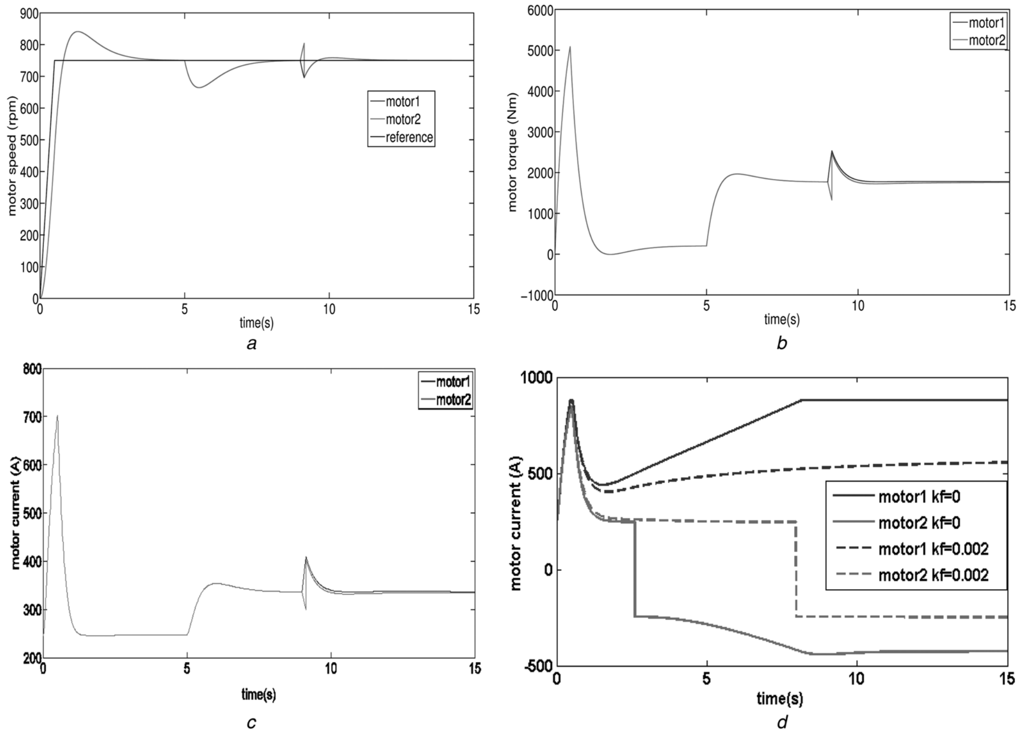

Fig. 5 *Results of simulation for $k_p = 125$, $k_i = 130$, $k_f = 0{,}002$ (motor 1 is the master)*

a Response of motor speed
b Response of motor torque
c Response of motor current
d Response of motor's currents during a regenerative phase

11% or $n_1 = 1, 11\ n_2$. In case of $k_f = 0$, the difference between the two gear ratios results in a constant decrease of the motor's 2 torque, current and power. This motor 2 acquires negative power/current and acts as a load for the motor 1. Motor's 2 current flows back via the common DC link to motor 1.

The motor's 1 torque constantly increases until its nominal limit imposed by the protection unit of the drive. The usage of $k_f = 0.002$ improves the situation. At the steady state, the two motors reduce torque difference and operate under their limits. Nevertheless, motor 2 still acts as a load for motor1. Further increase of the feedback gain results in a reduced difference of the two motors output torque and faster convergence. This simulation shown in Fig. 5*d* is an extreme example which presents the possibility that the kiln operates with one machine as a motor and the second as a generator. The one machine absorbs the other's regenerative power via the common DC link. In practice, the abnormalities of this type have short duration and the roles are exchanged. Thus, the selected feedback $k_f = 0{,}002$ results to a satisfactory response.

7 New kiln drive system realisation

The new AC drive system was designed such that its installation would maintain the existing configuration of the mechanical parts and infrastructure unchanged, in order to save time, resources and materials. From a mechanical point of view, only the motor couplers were replaced in order to accommodate the new AC motors. Since the frame size of the new AC motors was similar to the size of the old DC motors, light modifications on the concrete base were required as well as new anchoring by applying chemical anchor bolts. As regards the electrical installation, only the low-voltage power cables were replaced from the inverter to the motors, while the low-voltage line from the main supply to the common rectifier was disconnected from the old system and terminated to the new one. The installed complete system is presented in Fig. 6. In particular, Fig. 6*b* depicts the unaffected mechanical installation and the minor extent of concrete works needed for the accommodation of the new motors. The overhead

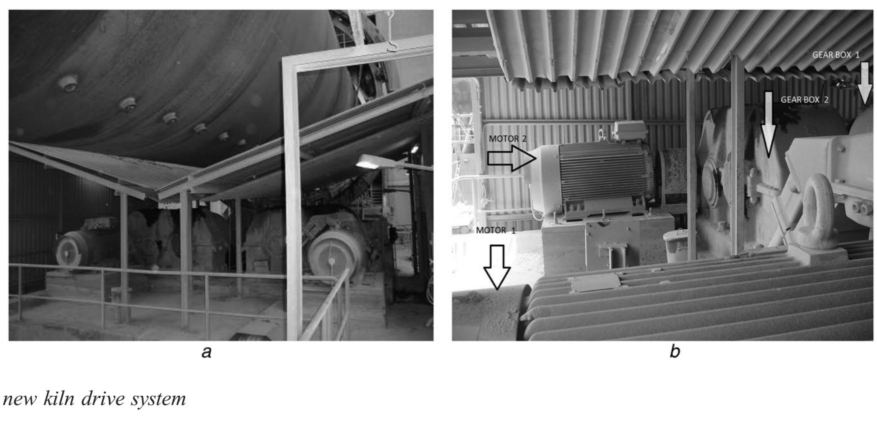

Fig. 6 *Presentation of the new kiln drive system*

a Overall system view
b Side view of the new motors and gearboxes

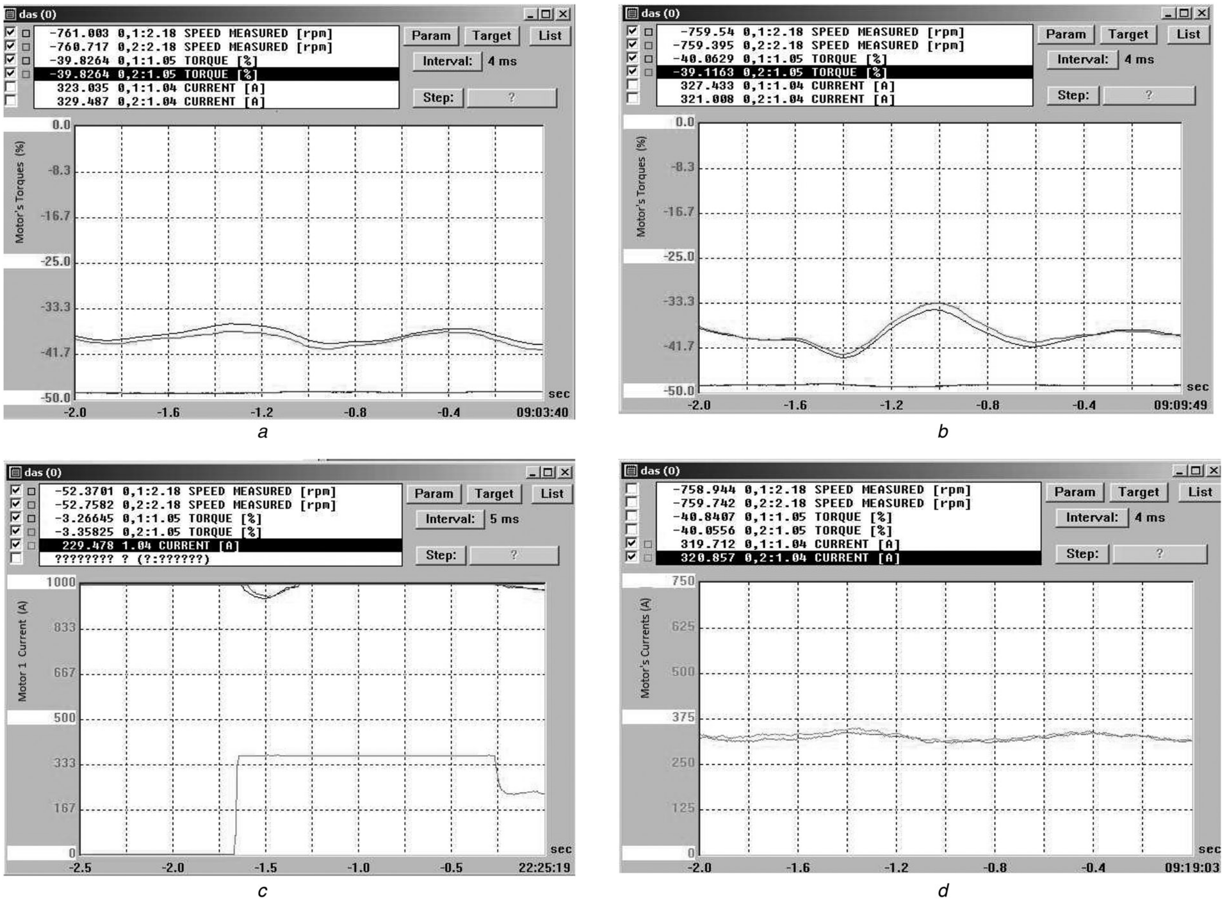

Fig. 7 *Actual SCADA system's computer screen trend printouts of the electrical behaviour of the new system*

a, b Motor torque of the new installed 315 kW AC motors recorded in two different instances of plant's operation
c Motor current, speed and torque of the new system recorded at a startup
d Motor currents during kiln normal operation

plates act as heat shields in order to protect the equipment from the high temperatures of the Kiln's.

8 Results of the intervention

The actual operation of the system was successfully verified by the simulation analysis. The smooth behaviour of the kiln as a complete system, in several instances of operation, is shown in Fig. 7, in the form of trend printouts from the plant's SCADA system. Note that the horizontal axis [time scale (s)] corresponds to the time already passed in which the parameter value was monitored and recorded. At the printout moment, the measured values – as spot – are given on the top part of each figure in black colour. In particular, in Fig. 7*c*, the startup condition current reached a maximum value of 366 A to overcome inertia, subsequently reducing to 229 A once the kiln is in rotation (green line).

It is worth noting that the simulation analysis is verified by comparing the sharing of load and torque between the two motors (graphs: blue and red lines, for the two motors, respectively) as in the simulation of Fig. 5 and their balanced sharing as real operating values of the 315 kW motors from the industrial application, as presented in Figs. 7*a* and *b* (black and grey lines for the two motors, respectively, as given in the printouts from the plant's SCADA system). All this equal and smooth sharing of load and torque between the motors and the related machinery accomplishes a fully improved kiln operation. According to the simulation analysis in Fig. 5*b*, both motors obtain shared torque (∼equal) in 2–3 s. In the real industrial application as given in Fig 7*c*, this is obtained in 0.5–1 s. In fact, in simulation analysis we exploited the worst case scenario concerning the contact of the gear tooth in order to be on the safe side prior the industrial intervention.

The new drive system compensates most of the transient effects of production and the nature of the load. Comparing the new operational status with the one shown in Fig. 2*b*, before the intervention, it is easy to understand the major improvement gained by the presented intervention. Furthermore, the implementation of the new system which incorporated the results described previously, reflected in an overall annual improvement of the kiln operation and reduction in energy consumption. This is demonstrated in Fig. 8 diagrams. More specifically, in Fig. 8*a*, the mean value of kiln operation is obtained by dividing the monthly operational hours of the kiln by the total hours per month. It is important to point out that the kiln should function 24 h/day, during every single day of the year. The lower percentages in the diagram during for example March 2004 and June 2005, refer to scheduled maintenance services (which typically take place twice a year). All the above data, as well as the data on diagrams and graphs were produced by factory staff as part of the annual reports of the Titan Kamari Plant, which was where the system was installed [21]. This elimination of all downtimes minimised energy consumption due to eliminating the relatively high levels of energy required during restarts and by effectively balancing all the kiln's systems. The above-mentioned benefits are presented in the diagram of Fig. 8*b*. During the year 2003, the average cost per 1 kWh was 0.046€, while after the installation of the system in March 2004, this cost was reduced to 0.043€. Despite the increase in electricity costs in September 2005, when the Hellenic Public Power Corporation – PPC – raised its prices by 3.5% the cost remained at 0.043 €/kWh [21].

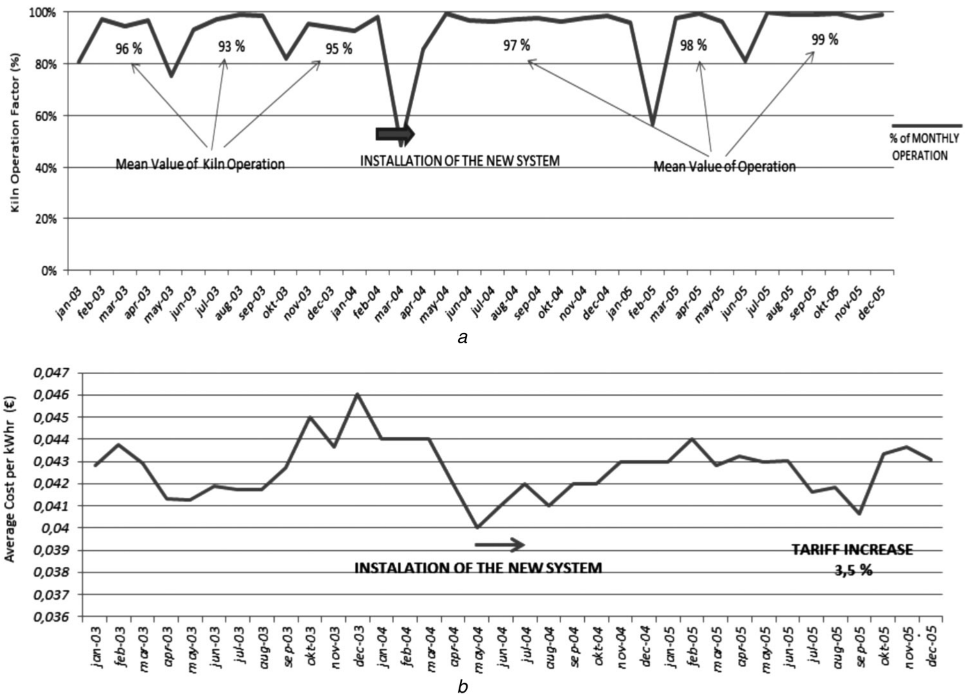

Fig. 8 *Operational conditions before and after the new system installation [21]*

a Cement kiln operation performance
b Cost of electrical energy

9 Contribution

The main objective of this paper was to demonstrate the advantages of the implementation of an electrical drive system in solving long-term mechanical problems with the minimum possible capital expenditure, down time and resources requirement in the cement industry.

Within this context, the contribution of this work can be summarised as follows:

(a) The innovation of the design compared with traditional configurations: the motor system was implemented consisting of two controllable AC motors of 315 kW each, which function connected to a common peripheral gear and which are controlled by two separate frequency inverters supplied by a common rectifier. Furthermore, the project was realised contrary to existing DC motors arrangements available in the market which, in the case of rotating kilns, presently dominate the market.
(b) The energy savings and improvements in operational efficiency and downtimes: substitution of old DC motoring systems with AC motoring systems in existing implementations without any intrusive mechanical intervention, using the method described by the present work, ensured the reduction in energy consumption and capex requirements due to the improvements in operational characteristics and the increase of the kiln's efficiency as a productive system.
(c) The increase in the efficiency factor of the kiln's operation from 95 to 98%, with all its positive consequences, such as thermal energy savings, fuel consumption savings, product quality stabilisation and so on. Furthermore, the raise of that specific factor resulted in a general improvement of all electrical energy utilisation, which in turn led to the reduction of the average cost of electrical energy.
(d) The reduction in component wear rate, since the electrical part of the intervention as standalone prevented further fatigue damage to the mechanical equipment by eliminating the backlash phenomenon consequences on the gear teeth.
(e) Finally, based on the successful results obtained in three consecutive years of operation of this implementation on both kiln 1 and kiln 2 at the Titan Cement Kamari Plant, Greece, this work defined an improved technique to treat such installations, proving by comparison that traditional configurations of DC motors in rotating kilns to be outdated and inefficient.

10 Conclusion

An electrical system for efficient kiln drive operation was designed, developed, simulated and installed to improve the mechanical operation of the incorporated machinery, absorbing forces and oscillations caused by existing wear and production process changes. All interventions were only focused on the electrical part of the existing system, leaving the mechanical parts completely unaffected for capital expenditure and time savings. Furthermore, the excellent results of this first intervention to the one kiln led to the installation of the same system to the second kiln of the plant, proving the high level of success of its contribution to the optimisation of this heavy industry's machinery operation.

More specifically, all production requirements were successfully addressed (i.e. high torque provision at low-speed start, speed reference behaviour improvement during load change, accommodation of fast changes to the power needed to address load changes and provisioning of reliable control). Following the implementation, mechanical relief became also immediately apparent while all reported adverse effects were eliminated. Furthermore, during the first year of operation no downtime due to mechanical or electrical fault occurred. This elimination of downtimes reduced energy waste by saving the relative high portion of energy required for restart and for bringing all kiln systems to operational equilibrium. Additionally, costly maintenance work requirements were significantly reduced compared with the previous situation with the DC motors and their corresponding regular needs for cleaning and frequent brush replacements. Furthermore, the selection and installation of a system with a common rectifier DC bus instead of the installation of two separate converters led to significant savings in capital expenditure. Finally, the intervention in only the electrical part of the kiln drive as described in this paper succeeded in drastically improving its mechanical behaviour, and thus, postponing or even eliminating altogether scheduled high-cost maintenance works, which in turn led to financial savings.

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