Overcurrent Mitigation in a Crop Cobble Shear System for Steel Rolling Mill

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A solution for Overcurrent Mitigation developed for a Crop Cobble Shear System operating in a Steel Rolling Mill

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Abstract

The paper describes the utilization of the Direct Torque Control (DTC) drive technology to control the Crop Cobble Shear (CCS) system in a steel rolling mill. The CCS is a highly dynamic load that requires a drive capable for high performance torque control. During the CCS cobble cutting mode, depending on the bar length, the original DTC drive experienced overcurrent faults that cause production downtimes. A suitable model developed for the overall system provided the parameters, considered for simulating the system. Simulation analysis of the CCS operation, made possible performance improvement. The simulated DTC induction motor drive faced a comparison with the existing system from a steel plant. Measured data from the original system in the steel mill compared to results determined through simulations. This comparison shows the successfully simulated system, appropriate for the determination of a suitable approach to improving the CCS operation. Identification of new control strategies recommended carrying out new simulations regarding the modified system. Furthermore, follow this new round of simulations, the overall system, subjected to new modifications at this stage, suffered a reassessment through measurements: they certified an improvement. The paper contains useful results, obtained through simulations and measurements as well. The last section contains the conclusions of this work.

Keywords: Crop cobble shear, cobble cutting current, direct torque control, short term overload, stator voltage space vector, stator voltage flux vector

1 Nomenclature

I_{2base} – Nominal Heavy Duty Current, I_{2max} – Short Term Overload Current (2xI_{2base}), I_{const}- Cobble Cutting Current (Constant Speed), I_{ramp} - Cobble Cutting Current (Speed Changes), T_e- Electromagnetic Torque, $\underline{v}_s$- Stator Voltage Space Vector, $\underline{\Psi}_s$ - Stator Flux Space Vector, $\underline{\Psi}_r$- Rotor Flux Space Vector, $\underline{i}_s$ – Stator Current Space Vector, L_m – magnetizing inductance, L_s – stator inductance, L_r – rotor inductance, σ – leakage coefficient ($\sigma=1-(L_m^2/L_sL_r)$), P – number of poles, ε- angle between $\underline{\Psi}_s$ and $\underline{\Psi}_r$, α- angle between $\underline{\Psi}_s$ and $\underline{i}_s$

2 Introduction

The Direct Torque Control (DTC) concept, introduced around year 1985, disseminated in industry more readily than vector control [1]-[3]. DTC is a significantly newer concept compared to field-oriented control. Instead of requiring a thorough mathematical modeling of the induction machine, DTC takes a significantly different approach. This control strategy makes use of the physical interactions between the drive and machine, such that it can directly control the torque and stator flux of a machine. This requires the real-time application of a suitable voltage space vector at the output of the inverter, possible when a selection through a lookup table. The DTC control unit is composed of two parallel closed loops: one for the stator flux and one for the torque [1]-[3]. Whereas the control unit operates in torque mode, the torque reference signal appears as a direct input. Alternatively, the output of the speed controller delivers the torque reference signal, whether the DTC operates in speed mode. According to [1]-[3], this type of control system shows significant differences when compared to vector control:

a) No coordinate transformation is required and the induction motor system is modeled in the stator reference frame;
b) Direct control of the flux and torque;
c) Instead of knowing the exact position of stator flux linkage space vector, only the sector in which the stator flux linage space vector is positioned is required;
d) Current controllers are not required;
e) Since speed information is never required in the torque mode of operation, DTC is inherently sensorless;
f) No requirement for separate voltage modulation block. This is usually required in a vector drive.

3 Principles of Direct Torque Control

From the DTC Block diagram shown in figure 1, whereas the CCS DTC drive operates in torque control mode, the torque reference comes from an external high-level speed controller. The speed controller relies on a PI regulator and the output is a torque set point applied to the DTC controller block. The adaptive motor model estimates the motor torque and stator flux, providing feedback to the torque and flux comparators. This allows the torque and flux control loop to be established, [1]-[4]. The torque comparator is a three-level hysteresis controller and the flux comparator is a two-level hysteresis controller. The inverter switching output, used to control the induction machine, depends on the torque status signals and flux status signals from the torque and flux comparators.

Whereas using torque and flux status signals, along with the knowledge of the calculated position feedback of the space vector representing the flux linkage (i.e. determined in real time from the adaptive model of the induction motor), an appropriate voltage vector results from inside the optimum pulses selector. There is a different process subjecting the errors between torque/flux set points and their feedbacks in DTC in comparison to the vector control drives. In vector control, these errors are as inputs to the PI controllers. The outputs provided by the DTC controller are the set points for the *d* and *q* axis currents, sent to the inputs to the current controllers. However, DTC applies the error signals directly to the optimum pulse selector to control the inverter without any intermediate current control loops or involving transformation of coordinates.

The torque expression of induction motor in terms of stator flux / rotor flux [1] is:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\psi_r||\psi_s|\sin\varepsilon \tag{1}$$

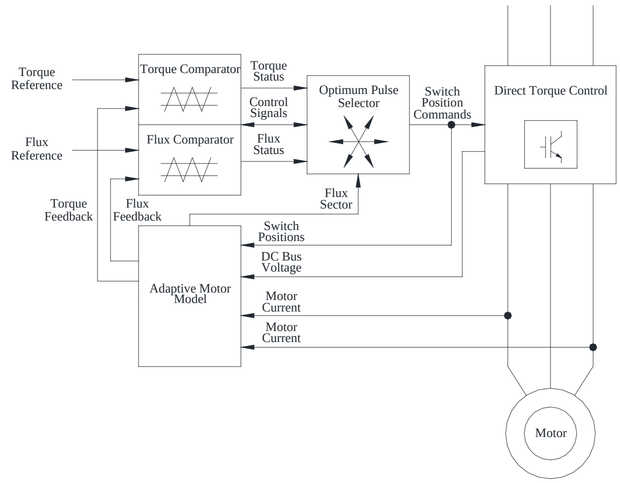

Figure 1: Block Diagram of a regular DTC Drive

The change of rotor flux is slow due to its relatively large rotor time constant, which means that, for short intervals, the rotor flux is relatively constant. The stator flux amplitude is relatively constant in a DTC scheme as well, whereas using a two-level hysteresis controller. Therefore, both space vectors (stator flux, respectively rotor flux) have constant amplitudes, according to relationship (1). If the instantaneous position of the space vector representing the stator flux varies rapidly, such that angle ε changes rapidly, the electromagnetic torque has a very rapid rate of change itself. Consequently, a fast torque response results. This is the core concept of DTC. The instantaneous electromagnetic torque expressed in terms of the stator current and the stator flux is:

$$T_e = \frac{3}{2}\frac{P}{2}|\psi_s||i_s|\sin\alpha \tag{2}$$

Whereas maintaining the stator flux constant, the output torque depends on the magnitude of stator current and the position between stator flux and stator current, considered as space vectors. Therefore, in general, if the output torque demand is higher, the motor will draw higher current.

4 Crop Cobble Shear DTC Control

A Crop Cobble Shear (CCS) is a system designated for cutting steel bar being an essential component in a steel rolling mill. In normal operation, the CCS performs a single cut to chop each end of the bar. One of the alternative but significant functions of the CCS occurs when cobble is required. In this mode, the shear will chop the bar into small lengths. This operation, namely cobble-cutting mode is a process of continuous cutting, applied to the steel bars. In the normal cutting mode, accurately cutting the bar to a specific length is crucial. This means that high performance control is required. Since it is a high dynamic control application, it is well suited to a torque control drive. In this case, the DTC drive is a proper alternative. However, during the cobble cutting mode, depending on the bar length, it has been observed that the DTC drive experiences frequent overcurrent faults, resulting in tripping out the drive. If the drive trips out during cobble cutting, the faults and subsequent repercussions may be serious and dangerous. It could potentially damage other equipment and create safety concerns. These facts required to carry out a study for identifying the source(s) for overcurrent.

By conducting field measurements, one determined that, during cobble cutting mode, the speed reference ramped up in a similar way to the normal cutting mode, as shown in figure 2. When the speed reference ramps up in a short time, two initialized signals, one representing the speed error, the other a "high torque" reference will act in order to minimize the speed error. This causes current spikes during the acceleration and deceleration during short periods. Because the accuracy of bar length and the quality of the bar is not as important as the normal cutting, the position control is not necessary during cobble cutting. If not within required range of lengths, in the chopped bar will be scrapped after cobble cut, and resent to the steel making as raw material. By controlling the drive with a constant speed reference, in cobble cutting mode, the torque reference will not be as high because the speed error will be much less. This results in the current being lower, according to equation (2), conducting to less heat generation.

The numerical simulations (see figure 3), performed using the MATLAB/SIMSCAPE software system [4], [5] and it show similar results compared to the actual steel mill system shown (see figure 2). The stator current trend (added as trend #4, in figure 3) clearly shows that during the speed ramp up/down, there are some current pulses generated. These current pulses created the excessive heat and exceeded the drive thermal limit, causing the fault condition in the DTC.

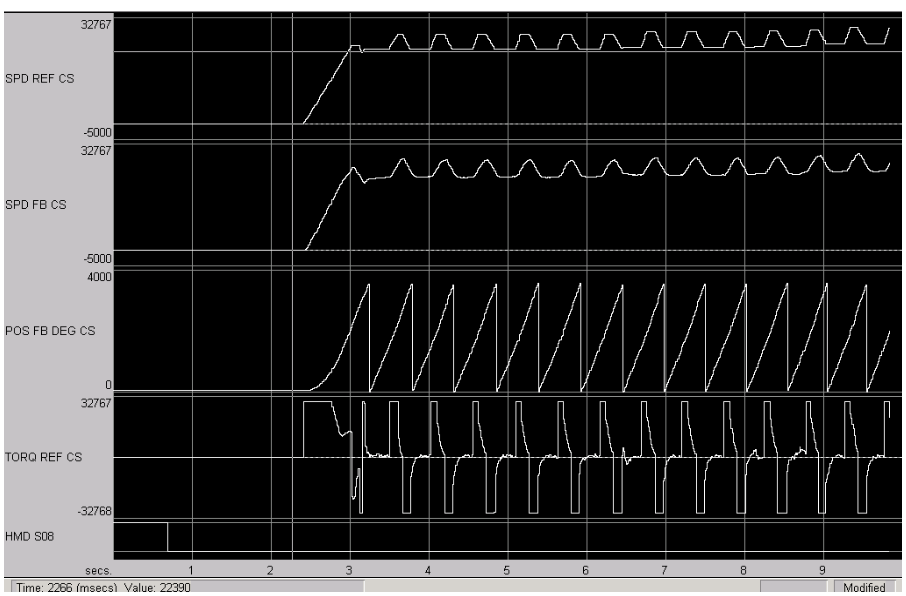

Figure 2: Real system results before modifications

The DTC drive provides an overload protection dependent on the square of the current and time, based on a thermal model [6]. Figure 4 shows how the system provides overload protection [5]–[8]. In this case, the CCS motor full load current (rated/nominal) is equal to 549A.

The drive allows for overload conditions for a short time defined for two situations as following:

- 150% Overload – allow 1 min every 5 minutes
- 200% Overload – allow 10sec every 60sec

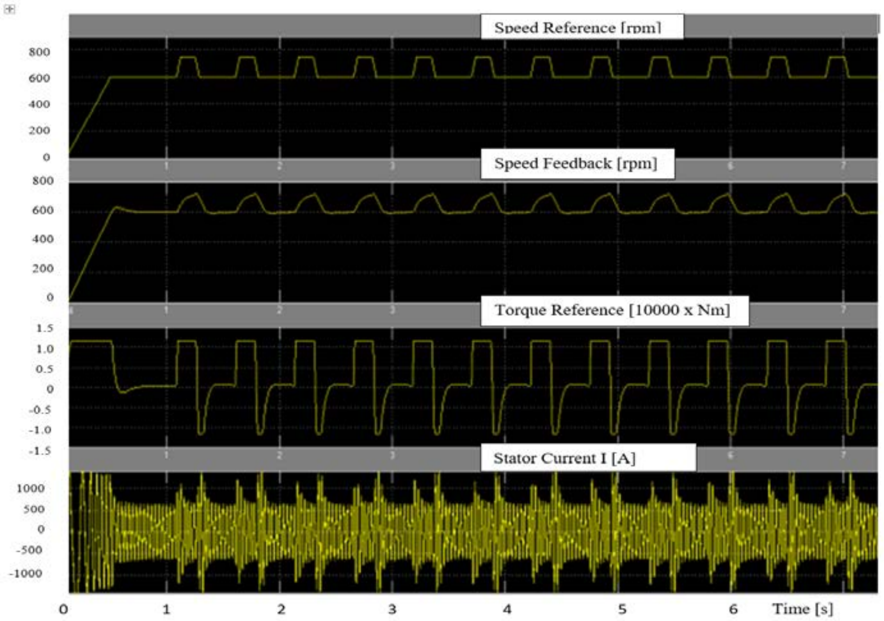

Figure 3. Simulation results before system modification

The CCS DTC system, considered a heavy-duty application, during the acceleration period, the developed torque will go up to 300% of rated torque and current will go up to close to 200% of rated current, as shown in figure 2 and figure 3. Therefore, in this case a 200% overload is enough to cover the value of the encountered current.

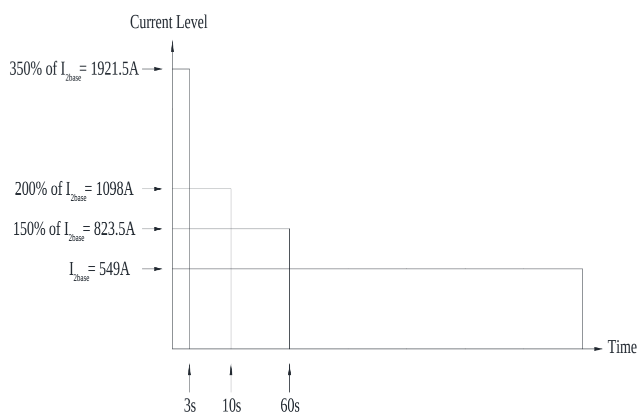

Figure 4: Output Current Overload Characteristic Graph

As shown in figure 5, $I_{2base} = 549\ A$, whereas $I_{2max} = 1098\ A$ for a duty cycle 10s/60s.

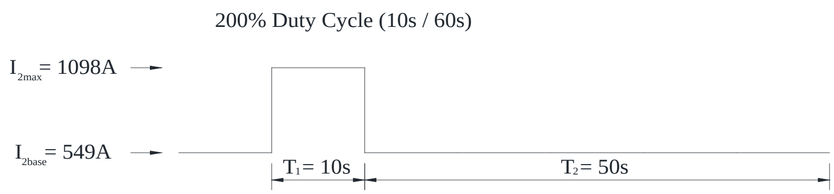

Figure 5. DTC Drive 200% Duty Cycle

The approximate average thermal limit of the DTC Inverter section with 60 seconds interval requires an estimation as following:

$$\begin{aligned}\text{Average Thermal Limit} &= I_{2\max}^2 (T_1) + I_{2base}^2 (T_2) \\ &= (1098A)^2 (10s) + (549A)^2 (50s) = 27.13\times 10^6 A^2 \cdot \sec\end{aligned} \tag{3}$$

An approximation for the average thermal dissipation of the DTC drive during cobble cutting is:

$$\begin{aligned}\text{Average Thermal Limit} &= I_{ramp}^2 (T_1) + I_{const}^2 (T_2) \\ &= (920A)^2 (24s) + (450A)^2 (36s) = 27.60\times 10^6 A^2 \cdot \sec\end{aligned} \tag{4}$$

The above calculations show that, during cobble cutting, the thermal dissipation exceeds the thermal limit of the DTC drive and causes the drive faults due to an overcurrent. The proposed solution is to reduce the width of the torque pulses or even eliminate them. This will result in a lower current drawn, accompanied by the current spikes elimination. It follows that the thermal dissipation will be lower and should be below the thermal limit of the DTC drive.

The simulation shows that, following the speed reference changing into a constant, illustrated in figure 6, the torque pulses disappear, except for the initial acceleration and the minimum torque that is required to maintain the CCS rotation. One can observe from figure 6 (Trend #4) the elimination of the current spikes, as well.

After these modifications, the estimated average thermal dissipation of the drive during cobble cutting becomes:

$$\begin{aligned}\text{Average Thermal Dissipation} &= I_{acc\_dec}^2 (T_1) + I_{consst}^2 (T_2) \\ &= (0A)^2 (0s) + (450A)^2 (60s) = 12.15\times 10^6 A^2 \cdot \sec\end{aligned} \tag{5}$$

The calculation shows the heat dissipation reduction from $27.60\times 10^6 A^2 \cdot \sec$ to $12.15\times 10^6 A^2 \cdot \sec$ after the implementation of the changes. The new calculated value is well below the thermal limit $27.13\times 10^6 A^2 \cdot \sec$ of the DTC drive. Analyzing figure 6, one can conclude that the constant speed operation of CCS works very well in terms of simulation. The main beneficiary of these modifications, performed to the actual steel mill system was DTC drive controller. Figure 7 gives complete information regarding the results following the tests performed with the modified system. Moreover, the results from the operational system show a complete elimination of the torque pulses. This compares well with the simulation result provided in figure 6. Once the tests subjecting the modified system became conclusive, the implementation of the changes became permanent, ensuring the elimination of the DTC drive overcurrent issue, previously encountered during the cobble cutting.

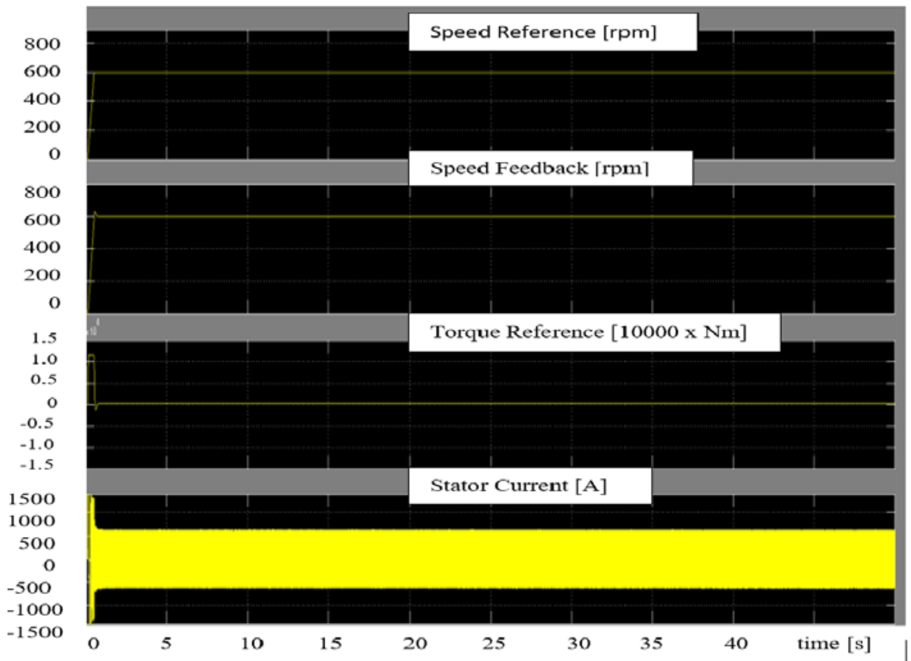

Figure 6. Simulation results after system modification

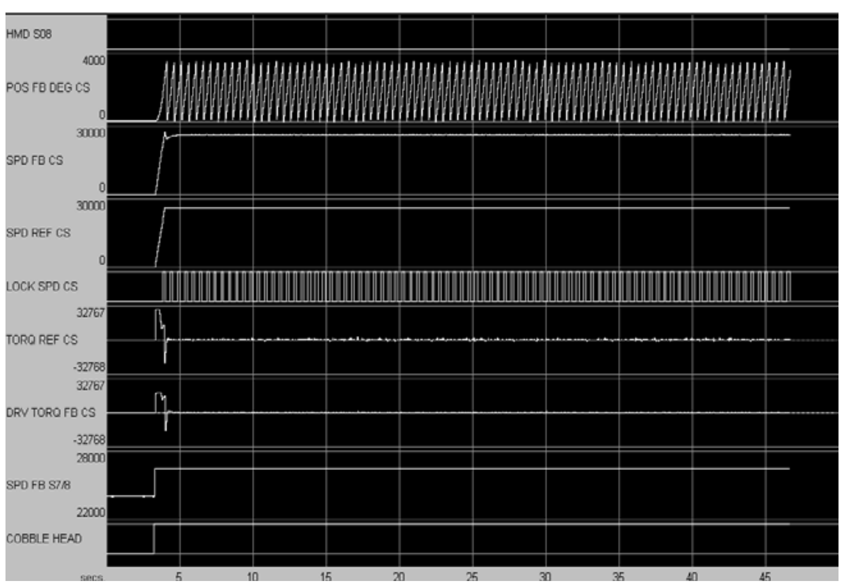

Figure 7. Real system results after modification

5 Conclusions

The speed ramping up/down during CCS cobble cutting caused the overcurrent faults in the DTC drive. This speed ramp is not required since the length of the bar and the bar head quality is not important. The improvement to the cobble cutting control consists in the generation of a constant speed reference signal. Following the gathering of practical data, shown in figure 2, the performed simulation (see figure 3) provided a better understanding of the fault current occurrence. In general, experimental data from measurements on the system in the steel mill favorably compares to the simulation results. The comparison shows a successful simulation of the system in order to determine a suitable approach for required by the necessity of CCS DTC drive operation improvement. Figure 6 displays a simulation example involving the constant speed reference, with relevance to the current spikes elimination. Following the system modifications, the measurements carried out verified the improvement. The final implementation regarding the reference torque profile shows the torque pulses elimination, as shown in figure 7. This achievement significantly reduces the thermal dissipation within the DTC drive. The calculation shows that the thermal dissipation of the modified system is below the thermal limit of the DTC drive. Therefore, the modification of the CCS operation eliminated the frequent faults previously encountered. Obtaining motor parameters in conditions of accuracy becomes extremely useful, whereas modeling the assembly motor-drive system for the purpose of simulation. Such simulations allow for an understanding of how drive systems operate and provide an opportunity to develop alternative strategies to overcome motor-drive issues.

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