Increasing Mill Production Using Medium-Voltage AC Drive and Active VAR Compensation

In 2011, Nucor Steel Tuscaloosa replaced its Steckel drums and upcoiler DC motors with new 1,500-kW AC induction machines fed from new voltage source inverters. As a result, the voltage variations were reduced during heavy load from the DC drives, and additional overload torque was available for the main stand DC motors. This paper describes the control strategy used in the converter and the improvement of the power system performance.

Nucor Steel Tuscaloosa Inc. has a Steckel mill with three coupled 4,700-hp DC motors for the single-stand, two 1,500-hp DC motors for the Steckel furnace drums and another 1,500-hp DC motor for the upcoiler. The mill configuration is shown in Figure 1.

Overload torque of the three 4,700-hp motors was limited to 180% due to weakness of the power system. In 2011, to increase production, Nucor was looking for alternatives that would allow the overload torque to be increased to the 225% maximum available from the stand DC motors and drives. Finally, Nucor decided to replace the Steckel drums and upcoiler DC motors with new 1,500-kW AC induction machines fed from new voltage source inverters. These inverters are fed from a three-level, neutral-point clamped voltage source converter that is also capable of injecting reactive current to partially compensate for the lagging 33 MVAR demanded by the DC drives. The control strategy used in the converter to maintain the DC bus voltage balanced under the injection of 14 MVAR leading or lagging, and the improvement of the power system performance by reducing the voltage fluctuations from 8 to 4%.

Background

The stand DC drives demand high lagging reactive power, especially during acceleration and deceleration, and also at constant speed during the first passes, when rolling torques are high. This is due to the fact that the thyristor converters retard the firing angle in order to produce the proper DC bus voltage and, as a side effect, the line current is always lagging the voltage. These high reactive power demands introduce voltage drops in the system.

Equation 1, equivalent to the expression shown in Reference 1, corresponds to the output voltage of an ideal thyristor convert-

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where

- \( a \) is the thyristor firing angle,
- \( q \) is the number of pulses of the converter and
- \( V_{LL} \) is the AC side line-to-line root mean square (rms) voltage.

The current in each phase will be lagging the phase to neutral voltage by the angle \( a \). As a result, the DC drives present to the system a low power factor with a minimum value when the motor speed and armature voltage are close to zero.

Figure 2 shows a simplified one-line circuit and two vector diagrams, including the corresponding phase to neutral voltage at a point upstream of the plant transformer impedance \( (V_{utility}) \) and at the DC drive transformer primary terminals \( (V_{drive}) \), as well as the line currents. The vector diagram on the left represents the condition when the mill DC drives are motoring and the current lags the voltage; the drops in the plant transformer impedance and feeders reduce the voltage at the drive terminals. On the right side, the mill is idling and the overcompensation due to the capacitor banks connected at the 13.8-kV bus produces a leading current. As a result, the voltage at the DC drive transformer primary terminals rises.

The voltage at the 13.8-kV bus rises and drops and has a total excursion of approximately 8–10%. Alabama Power connected a power quality (PQ) analyzer and trended the voltage during mill operation. The results are shown in Figure 3. The trend also shows the daily voltage fluctuations (from 14.4 to 14.7 kV when the mill is idling). The maximum
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In order to reduce the voltage variation and possibly increase the mill stand motors’ overload, a reduction in the net reactive power and total voltage fluctuation is recommended by injecting lagging VARs during mill idling and leading VARs when the mill is in operation. Table 1 summarizes the reactive power demand before the retrofit and the targeted values after the retrofit. An alternative solution was to replace the existing DC drives and motors with new AC voltage source inverters and AC motors. The new AC drives would operate with a high power factor. But after evaluation, Nucor Steel Tuscaloosa Inc. decided to implement VAR compensation, keeping the mill DC motors and replacing the upcoiler and the furnace drums’ DC motors with new AC induction machines.

Figure 4 depicts a simplified one-line diagram showing the final configuration. The left side shows the existing DC drives and mill motors. The new dual-bank converter, inverters and AC induction motors for the upcoiler, left and right furnace drums appear on the right side of the figure in blue. The new system also has the capability of feeding one 4.5-MW motor that would eventually replace one of the mill DC motors in a future retrofit.

The converter is a dual-bank voltage source, three-level, neutral-point clamped type. It was configured with a normal pulse

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Total Reactive Power Demand Before and After the Retrofit</th>
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<tbody>
<tr>
<td></td>
<td>Before retrofit (MVAR)</td>
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<tr>
<td></td>
<td>No load</td>
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<tr>
<td>Capacitors</td>
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</tr>
<tr>
<td>Misc. plant loads</td>
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<td>DC main drive</td>
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<tr>
<td>VAR compensation</td>
<td>6</td>
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</table>
These effects are well described and discussed in Reference 2. The worst operating condition corresponds to a high leading current because the converter will operate at a low power factor and high modulation index. The neutral current introduces voltage fluctuation on the two sections of the DC bus and also increases the possibility of voltage unbalance between them.

Figure 5 shows the converter capability curves considering the converter rated current and being at 150% overload for 60 seconds. The present operating point corresponds to the upcoiler and one of the furnace drum motors at 200% overload. The future operating point adds the active power demand of one mill motor at 200% overload, and a reduction of the maximum leading reactive power demand to approximately 8 MVAR.
Implementation

Figure 6 shows the topology of the three-level, neutral-point clamped voltage source converter. Each converter phase voltage is produced by the commutation of a single-pole triple-throw switch. The DC bus is divided in two sections, one between the positive bus and the neutral point, and the other between the negative bus and the neutral point.

Figure 7 corresponds to the actual converter where each switch is implemented with four injection enhanced gate transistors (IEGT), the corresponding anti-parallel diodes and two additional diodes for the neutral-point clamped effect. In this particular case, the neutral current tends to discharge the capacitors of the positive side of the DC bus and charge the ones on the negative side. This creates unbalanced DC bus voltages that need to be maintained under control.

Figure 8 shows the fundamental components of the line currents, voltage references and the expected converter neutral-point current, as calculated in Reference 2, considering a 1,500-A rms leading line current.

Several papers and publications discuss the implementation of different strategies to minimize the possible voltage unbalance between the two DC bus sections. The one used in this particular converter is described in Reference 3, where a DC offset is added to each of the phases’ voltage reference in such a way that more or less power is injected (or extracted) from
the positive or negative side of the DC bus capacitors. The value of the DC offset is calculated based on the measured converter neutral-point voltage and the value (including the sign) of the active power handled by the converter. This strategy requires the converter to handle active current; otherwise the DC offset added to the voltage references would not produce the desired effect.

Because the reactive power compensation requirements demanded a dual-bank converter, it was decided to circulate a small active current between the banks when the reactive current reference exceeds 5% of the converter rated current. By doing this, the small active component and the DC offset added to the voltage references are enough to keep the voltage balanced on the two sections’ DC bus.

Equation 2 represents an approximation of the reactive power demanded by the DC drive (12-pulse thyristor converter). The first factor on the right side of the equation is the rms current on the AC side of the converter, as shown in Reference 1. The reactive power demanded by the DC drives is proportional to the armature current on the DC motors and the sine of the firing angle, the armature current and the AC side line-to-line rms voltage.

\[
\text{VAR}_{\text{DC, Drive}} (I_{\text{DC}, a}) = \frac{\sqrt{3} + 1}{2 \cdot \sqrt{3}} \cdot I_{\text{DC}} \cdot \sqrt{3} \cdot V_{\text{LL}} \cdot \sin(a)
\]

(Eq. 2)
where

\( \text{VAR}_{\text{DC\_Drive}} \) is the DC drive reactive power demand, 
\( \alpha \) is the firing angle, 
\( I_{\text{DC}} \) is the armature current and 
\( V_{\text{LL}} \) is the AC side line-to-line rms voltage.

Because the system was sized to partially compensate for the lagging reactive power demanded by the DC drives (as shown in Table 1), it was decided to use just the absolute value of the DC drive armature current reference as a rough reactive current reference for the new converters. A more elaborate calculation

the utility voltage represented by the vector \( V_d^e \). The superindex “e” indicates that the vector is in the synchronous reference frame. The d-axis is 90° lagging the q-axis. As described in Reference 4, the d-axis is the negative of the imaginary axis in a complex plane. The diagram shows the converter current \( i_{dq}^e \) (in a motoring condition); \( i_d^e \) in the negative side of the d-axis represents a leading current. The component \( e_{dq}^e \) of the converter voltage has greater amplitude than \( V_{dq}^e \) in order to support the leading current. The component \( e_d^e \) is in the negative side of the d-axis. The total converter voltage \( e_{dq}^e \) is lagging the utility voltage; this condition is required for an operation in

Figure 8

Voltage references — line and converter neutral currents (fundamental components only).
bank A (bank B) active current reference ($I_{a_q}$) in order to create the circulating active component mentioned earlier. This reference, minus the corresponding feedback, is processed by a proportional plus integral (PI) current regulator, and its output added to other terms to compensate for the cross-coupling introduced by the transformer impedance. The result is the q-axis converter voltage reference ($e_{e_q}$).

The voltage saturation control (VSC), not included in the simplified diagram,
voltage ($V_c$) and finally the DC bus system, including the capacitor bank and the resistance ($R_L$), which represent the inverter’s equivalent loads. Because there is a common DC bus for the banks, only one capacitor bank and equivalent load are shown.

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Figure 12 shows a trend with several system variables to evaluate the performance of the VAR compensation during rolling. The system variables included in the trend are listed in the Table 2.

On the left part of the trend, the reactive power compensator was inactive (variable DI_DATA1_EXT at zero), and during rolling the voltage feedback ($V_{AC_F}$) experiences an important excursion of approximately 1,080 V (7.8% of the system voltage). On the right side, the reactive power compensator was active, a second piece was rolled and the voltage fluctuation was reduced to 540 V (3.9% of the system voltage).

When the reactive power compensator is active and before rolling, the system voltage feedback is reduced when compared with the idle periods with no reactive power compensation. This is because the reactive power compensator injects approximately 6.4 MVAR lagging to cancel the extra leading VARs introduced by the capacitor bank connected at the 13.8-kV bus. Now, during idle periods, the system operates at unity power factor. The reduction of the leading VARs during idle periods also helps in minimizing the voltage fluctuation.

The trend shows that the maximum value of the converter voltage reference ($E1_R$) during rolling reaches 103% (3,065 V), while injecting 11.3 MVAR leading. These values are within the capability of the converter (3,250 V and 14 MVAR leading).
The reactive power compensator has reduced the voltage fluctuation at the 13.8-kV distribution bus of the mill. This reduction will allow a future increase in the DC drives’ overload that will help increase mill production.

The new converter and inverters were installed in a new electrical room, with some additional equipment. Figure 13 shows the electrical room. Between the converter and inverter control panels (on the left) and the corresponding power bridges (on the right), an overhead cable tray can be seen where control wires and fiber optics for the IEGT gate signals were laid for the proper interconnection. Figure 14 shows the back side of the power bridge panels and the corresponding de-ionized cooling water inlets and outlets. The water-to-water heat exchanger was installed outside the electrical room.

The new electrical room has space for a future inverter. Also the de-ionized water cooling system has extra capacity for that inverter.
Summary

TMEIC achieved the goals set out in this reactive power compensation project. The voltage fluctuation during rolling (which was limiting the maximum overload capability of the DC drive system) has been reduced to approximately 50% of the original values.

In addition, new upcoiler and furnace drum AC inverters and induction motors are being fed from the same converters. These new drives and motors also help in reducing the maintenance cost when compared to the old DC motors fed from synchronous motor-DC generator sets.

Acknowledgment

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References
