Upgrade Legacy DC Drives to AC Now and Worry About the Motors Later

Chip Sondek[1], Benjamin Rudolph[2], Ronald Tessendorf[3], Christopher Uliana[4]

[1]Steel Dynamics Inc.
4500 Country Road 59
Butler, IN 47621
Phone: +1.260.868.8379
Email: Chip.Sondek@stld.com

[2,3,4]TMEIC Corporation
Mailing: 2080 Cook Drive, Salem, VA, 24153
Office: 1325 Electric Road, Roanoke, VA, 24018
Phone: +1.540.283.2293

[2]Email: Ben.Rudolph@TMEIC.com
Phone: +1.540.283.2109

[3]Email: Ronald.Tessendorf@TMEIC.com
Phone: +1.540.283.2093

[4]Email: Christopher.Uliana@TMEIC.com

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INTRODUCTION

When it came to deciding on upgrading your drive system you used to have little choice; stay with DC drives and motors or upgrade to AC drives and motors. This made for some very interesting phased installations, all-or-nothing choices, less-than-optimal decisions and general procrastination. Now there is a dual-purpose drive capable of powering AC or DC motors and shortening outage times. Converting all of your drives but only half of your DC motors to AC can result in roughly half the typical outage time. This paper will reveal how this is possible.

DC DRIVES

The basic 3-phase, 6-pulse, full-wave, full-reversing thyristor bridge power converter circuit is illustrated in Figure 1. In IEEE 444 terminology, this is a Form D Converter in which direct current can flow in either direction, and energy can be inverted from the motor to the AC power system. This converter consists of two anti-parallel Form C converters, each of which can invert energy but whose direct current can flow in only one direction. The combination of anti-parallel Form C converters therefore provides all combinations of DC voltage and current flow, or four quadrant operation.[1]

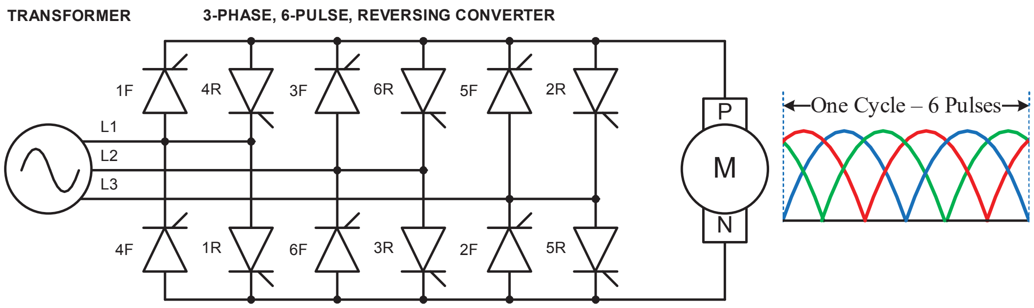


Figure 1. Basic 3-phase, 6-pulse, full reversing converter

The thyristor, also known as a Silicon Controlled Rectifier (SCR), conducts current when it receives a signal to its gate lead from a controller and the AC voltage across its terminals is the proper polarity to allow current conduction. Conduction of current by the thyristor stops when voltage polarity is reversed.

The thyristors in Figure 1 are labeled by normal firing sequence in the forward and reverse converter. For example, thyristor 1F is the first thyristor gated in the forward converter and is connected to the P or positive DC bus. Gating thyristor 2F, which is connected to the N or negative DC bus, completes the normal DC current path.

The ideal rectified DC voltage in Figure 1 is for the maximum condition with no allowance for average DC voltage reduction due to practical limits of thyristor operation. This is known as Edo, the average DC voltage under no load conditions, and is calculated as 1.35 times the incoming 3-phase line voltage.

Power Quadrants

Drive systems capable of 4-quadrant operation require the motor voltage and currents be capable of operating in positive or negative voltage and current. Figure 2 uses a simple hoist example to identify these modes or quadrants.

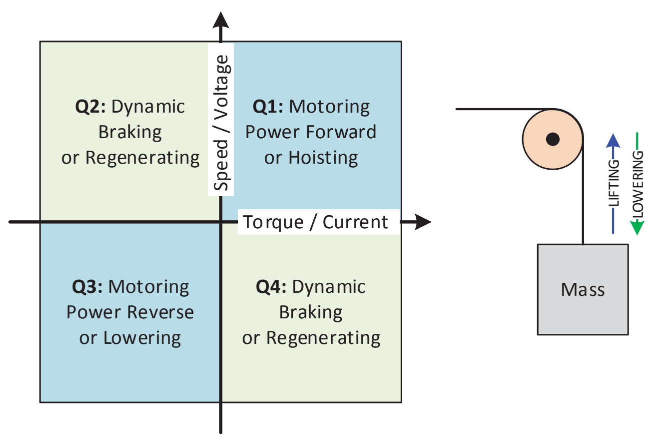


Figure 2. Power quadrant diagram

Q1. + *Speed and* + *Torque* provides power from the source to lift the load, or driven in the forward direction

Q2. + *Speed and* - *Torque* is a transient condition where the load is slowing down by regenerating power into the source or into a load bank (dynamic braking) when the source cannot accept power

Q3. - *Speed and* - *Torque* is a transient condition where the load is being accelerated in reverse in the case of a hoisting operation, or where the load is being driven in the opposite direction

Q4. - *Speed and* + *Torque* provides torque to control the lowering speed and is the equivalent of Q2 in the reverse direction

AC DRIVES

A basic Pulse Width modulated (PWM) inverter implemented with Insulated-Gate Bipolar Transistor (IGBT) devices is illustrated in Figure 3. IGBT conduction begins when the gate lead receives the proper signal and ceases when that signal is removed. The waveforms of Figure 3 consists of a series of positive and negative voltage pulses which, when applied to the inductance of an AC motor, results in an equivalent AC sinusoidal current as shown in red.

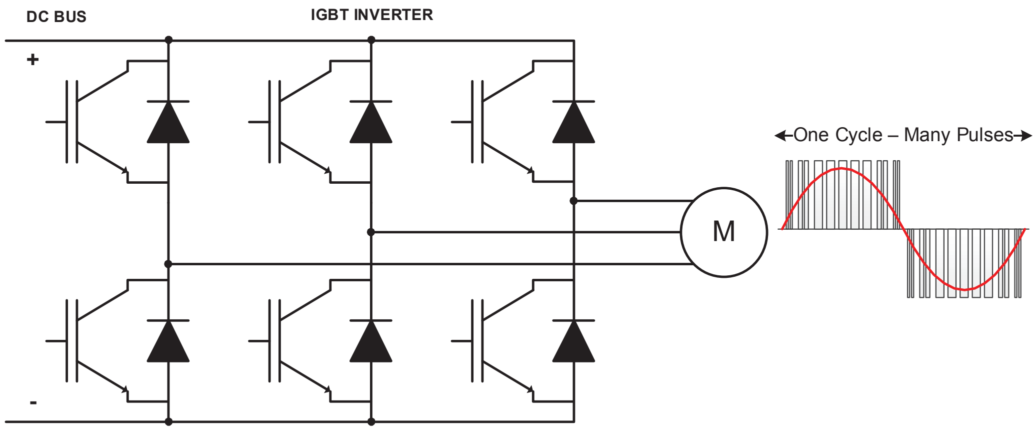


Figure 3. Basic PWM full reversing inverter

Upon initial inspection, the PWM Circuit of Figure 3 appears to consist of only half as many power devices as that of the converter shown in Figure 1. However, considering that each of the 6 IGBT's is paired with a matching blocking diode, as depicted to its right, the total number of devices is the same. Consider the case where the rightmost phase module is not gating such that no current flows through it and motor current is flowing as shown in Figure 4. Figure 4 illustrates the conduction path for the positive half cycle of voltage and current. The blue (solid) line path represent current flow when the DC bus voltage is applied to the motor. The green (dotted) line path represent current flow when the bottom IGBT is off and the diode shorts motor terminals through the upper DC bus rail (alternatively, shorting can occur through the lower DC rail as well). The average of the positive and zero voltages represents the effective line-to-line voltage, shown in red, applied to the motor.

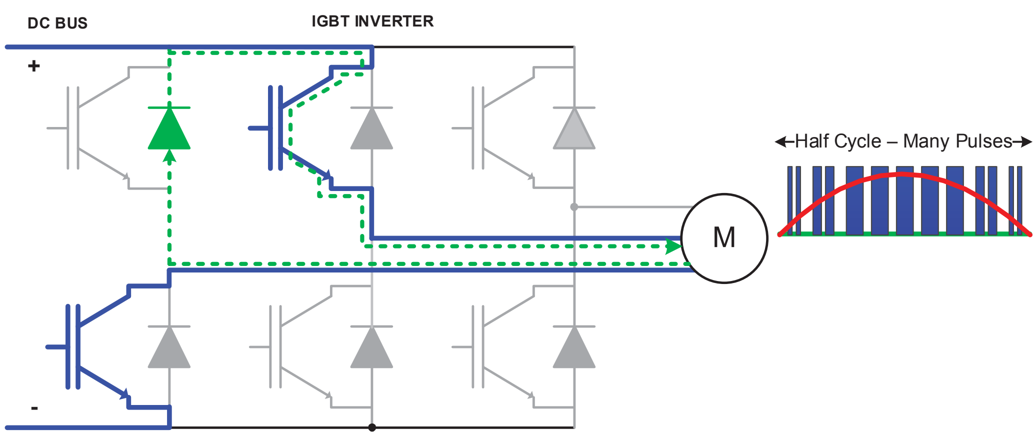


Figure 4. Positive half cycle PWM inverter conduction path

HYBRID AC OR DC DRIVES

Forward Motor Voltage

The Figure 5 diagram replaces the AC motor in Figure 4 with a DC motor. The same set of IGBTs that was used to make an AC waveform is used to make the DC output. The positive DC Bus is connected to the positive P set of commutator brushes using the upper IGBT while the negative DC Bus is connected using the opposing set of commutator brushes N using the lower IGBT. The inverter output pulse train has changed from the representation in Figure 4, which is configured to produce a sinusoidal waveform, to one with an average positive DC output. Figure 5 visualizes current flow during motoring conditions. When motor CEMF exceeds average applied voltage, regeneration occurs by reversing current flow and transferring power to the DC bus through diodes when DC bus voltage is applied to the motor (this behavior is possible due to loop inductance).

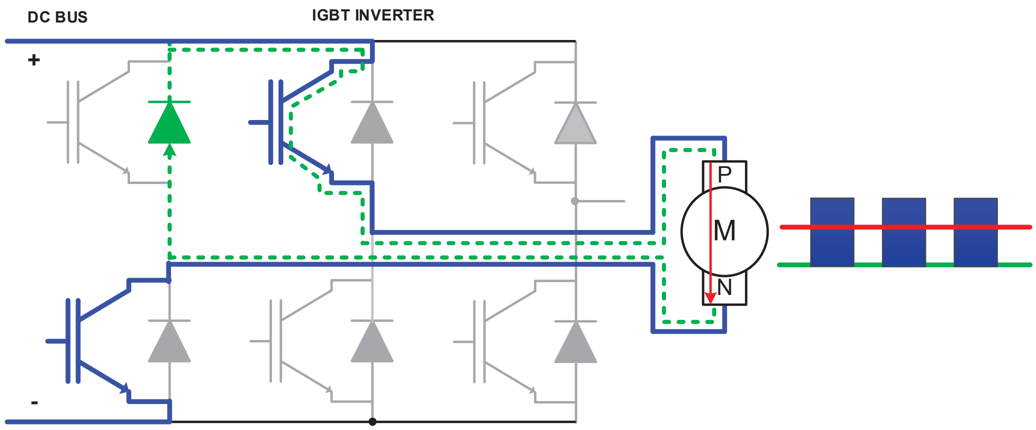


Figure 5. PWM inverter positive voltage applied to a DC motor

Several basic issues and questions are apparent in Figure 5 including:

1. Can I reverse the motor voltage?
2. How do I control the IGBT to get the average DC voltage needed?
3. The DC motor was designed to operate on the waveform shown in Figure 1 and now we are hitting it with fast rising voltage pulses. How long will the motor survive?
4. What do you do with the third lead?

Reverse Motor Voltage

Motor voltage is reversed from positive to negative using a different pair of IGBTs. The negative DC Bus is connected to the positive P set of commutator brushes using the lower IGBT while the positive DC Bus is connected to the opposing N set of commutator brushes using the upper IGBT.

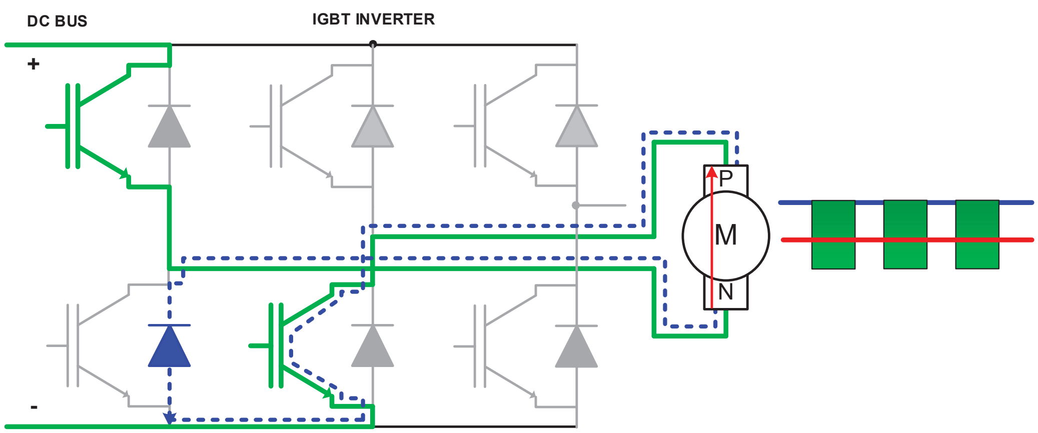


Figure 6. PWM inverter negative voltage applied to a DC motor

Two Quadrant Circuit

Many applications do not require four quadrant operation. The circuit of Figure 7 can operate in Q1 and Q2 (or Q3 and Q4 for reversed field) at twice the current of Figures 5 and 6 by applying two IGBTs and two diodes in parallel.

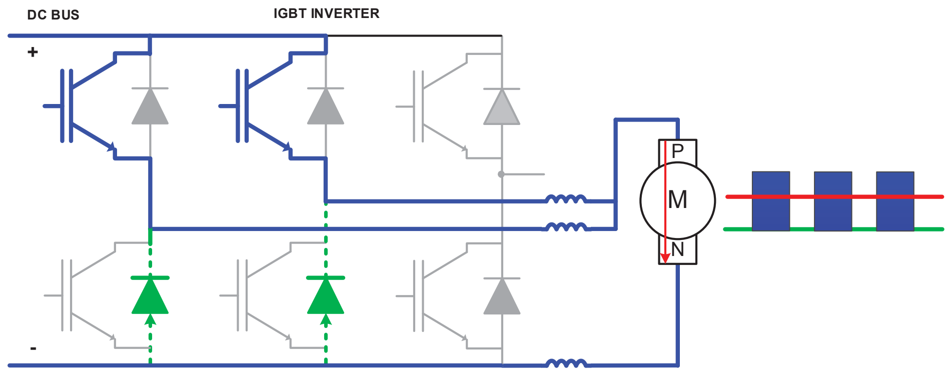


Figure 7. Two quadrant PWM drive

This circuit is only limited when attempting to regenerate near zero CEMF. Note also that parallel operation requires the use of external combining reactors since the internal bus work of the AC drive will not be modified. The philosophy of externally adding all hardware components required to make the AC drive suitable for use with a DC motor makes the later conversion of the DC application to AC easier and faster.

Average DC Voltage

The average DC voltage applied to the motor is controlled by the amount of time the positive or negative DC output voltage is applied to the motor armature. For maximum DC output, the IGBTs of Figures 4 and 5 can be continuously conducting since they are connected to a DC Bus. They are shown at approximately 60% of maximum output in an ON-OFF duty cycle.

DC Motor Survival

Existing DC motors were designed for operation from a DC generator or the thyristor converter waveform of Figure 1. These motor armatures will survive transient peak voltages no higher than twice the rated motor voltage and are high-potential tested at twice the rated voltage plus 1000V[2]. However, excessive peak voltage, typical of a PWM waveform, can contribute to motor insulation failure[3]. Also, the transition from DC generator to rectifier power demonstrated that increasing harmonic currents degrade motor commutation and increase motor heating[4,5].

These motors were not designed for the square wave pulses of Figures 4 and 5. Major areas of user concern when applying an IGBT AC drive to a DC motor include:

1. Will the motor insulation fail prematurely?
2. Will the motor commutate the current from bar-bar without excessive sparking?
3. Will the motor overheat due to additional harmonic currents?

These questions are addressed by comparing the motor armature voltage and current applied to a test DC motor by a thyristor drive versus a dual purpose PWM drive. Both the test DC thyristor drive and the test PWM converter are powered from a 460 VAC, 60 Hz feeder while the test PWM drive operates from a 680 VDC bus and a 3kHz gating frequency with the standard 4 quadrant control. The test industrial DC motor is rated for 25 HP at 500V and 43A. Voltage and current are measured at the motor terminals. The PWM "filtered" traces benefit from a dV/dt filter placed at the output of the PWM drive. One such filter configuration is shown in Figure 8.

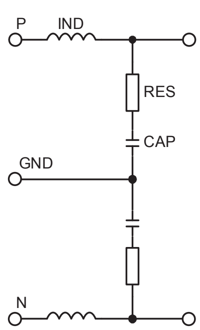
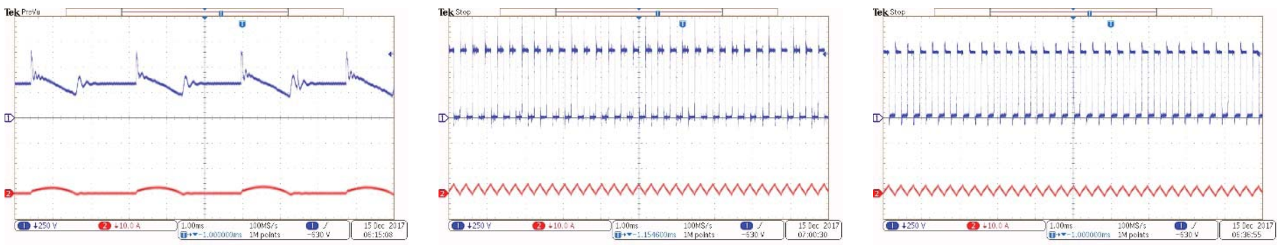


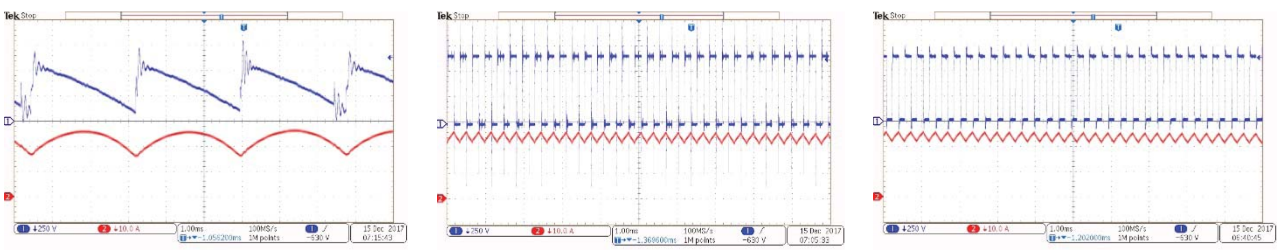
Figure 8. Drive output filter for use with DC motor windings

The scope traces in Figures 9 and 10 reflect typical applied voltage and current for both a thyristor-based power supply and a PWM drive, as measured at the motor terminals. Voltage (250V/div, blue) is displayed above current (10A/div, red). Measurements are taken at 68% speed, exposing the worst-case current ripple, at both no-load and 100% load conditions.



Thyristor PWM Unfiltered PWM Filtered

Figure 9. No-load motor armature terminals for thyristor and PWM unfiltered and filtered waveforms (1 msec/div)



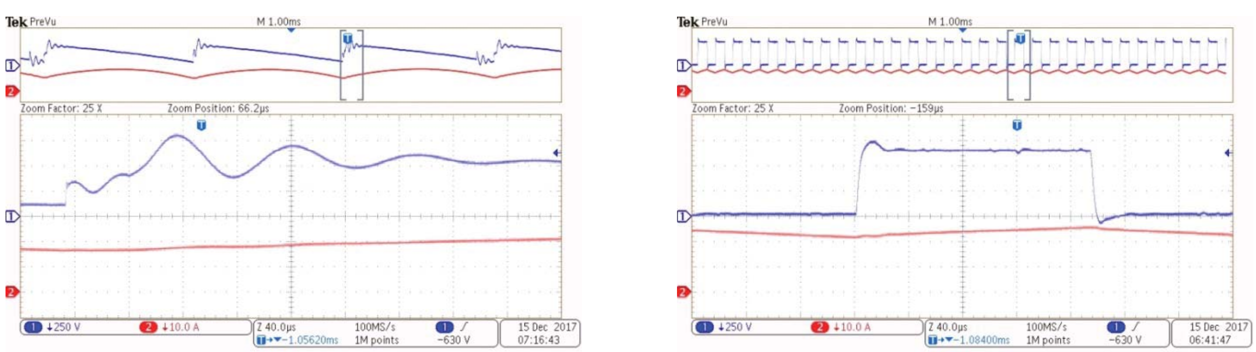
Thyristor PWM Unfiltered PWM Filtered

Figure 10. Loaded motor armature terminals for thyristor and PWM unfiltered and filtered waveforms (1 msec/div)

Peak Voltage Considerations

Comparison of the PWM traces in Figures 9 and 10 demonstrates substantial peak voltage reduction when applying the filter. Detailed analysis indicates a 20:1 dV/dt reduction and a 40% peak voltage reduction. The filtered output is drastically improved (versus a traditional PWM voltage signal), but how do these improved characteristics compare to a traditional thyristor drive?

Figure 11 explores the thyristor versus PWM transient voltage performance. The transient motor terminal voltage captured in the thyristor-based scope traces reflect a peak voltage of about 800V. DV/dt is about 600 V/usec at the beginning of the commutation notch and 25 V/usec elsewhere. The transient motor terminal voltage captured in the filtered PWM scope traces reflect a peak voltage of about 750V. Worst-case dV/dt is 200 V/usec.



Thyristor PWM

Figure 11. Transient voltage of thyristor and PWM waveforms (40 usec/div)

The comparison confirms that the filtered PWM drive does not apply any more voltage to the motor terminals than was already applied by the thyristor power supply. While this filtered PWM peak voltage is experienced more often than the thyristor peak voltage, the absolute peak voltage value is still well within the guidelines of the motor (2X rated motor voltage = 1000V). Thus, it is concluded that the filtered PWM signal will not accelerate insulation degradation.

Harmonic Current Considerations

When transitioning from DC generator control to thyristor converter control, industry discovered that DC motor commutation substantially degraded as RMS ripple current increased. This ripple current is the primary contribution of the drive system to commutation failure[6]. If the PWM drive does not increase the ripple current versus the thyristor drive, there will be no degradation in commutation.

Analysis of the current waveforms in Figure 10 yield thyristor RMS current of about 3A while the PWM RMS current is less than 1A. Thus, the PWM drive reduces RMS current by a factor of 3:1. This improvement should increase commutation margin similarly.

Since DC motor heating increases with harmonic current, the reduced harmonics associated with the PWM drive will result in a cooler running motor. Therefore, harmonic current analysis greatly favors the PWM drive over the thyristor drive.

The Third Lead

One of the three IGBT pairs is still available, the other two having been applied in our full reversing 4-quadrant DC drive. Figure 12 shows how we can use this pair as a non-reversing DC motor field exciter. The IGBT rating for the armature and field circuits are the same. However, the field current rating is much less than the armature current rating resulting in the field circuit being very lightly loaded.

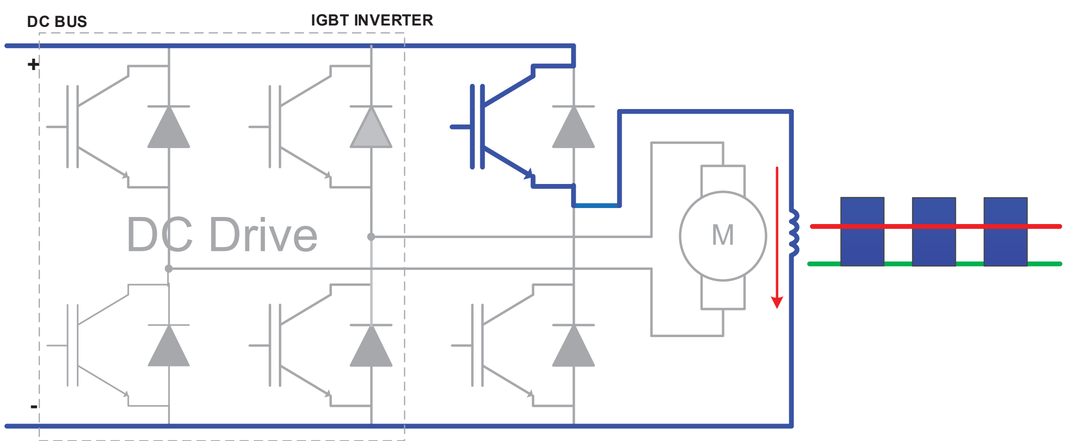


Figure 12. DC motor field exciter

The DC motor armature survival discussion also applies to the motor field and has the same solution. A dV/dt filter similar to that of Figure 8 can also be applied to the motor field circuit. A standard filter design is used for all field circuits, varied only to account for field current magnitude.

Motor field voltage and current waveforms are similar to the armature waveforms shown in Figures 9 and 10. Since only one IGBT leg is used to power the field, the effective switching frequency (1.5kHz) is half the armature switching frequency, doubling the current ripple. This harmonic current performance is still better than a typical thyristor drive. In fact, due to the very long time constant of the field circuit, RMS field current is very small (with both types of drives).

Ratings

Referring back to Figure 3 it is clear that each IGBT pair conducts current only part of the time, depending upon the voltage and current output, but never continuously. On the other hand, it is implied from Figure 4 that for maximum DC output the application requires continuous conduction of an IGBT pair. In addition to the power device rating, the current rating of a particular drive is dependent upon the manufacturer's design criteria. Furthermore, motor efficiency and power factor determine the motor shaft power rating. Therefore Table 1, which represents changing out a 500V DC motor to a 460V AC motor, only serves as a guide to understanding the drive rating methodology.

Table 1. Ratings comparison

Case	Formula	Volts	Amps	Power Out
AC (3-phase)	1.732 x Volts x Amps	460	>100	>80 KW
DC (1-phase)	Volts x Amps	500	100	50 KW

The conclusion is that when a particular AC drive is applied to a DC motor, the DC motor may later be replaced with a larger AC motor.

Packaging

The design philosophy employed uses a common AC-DC converter in a DC Bus lineup of standard IGBT PWM inverter packages. The auxiliary equipment, consisting of filters, contactors and whatever else a particular DC application may require, is included in a separate cabinet mounted in a convenient location. Figure 13 illustrates a typical arrangement. The Inverter package indicates normal AC motor application while the DP (Dual Purpose) Converter designation indicates the drive firmware is configured for DC motor control. The DC Aux block contains the necessary auxiliary equipment for use with the particular DC motor in question.

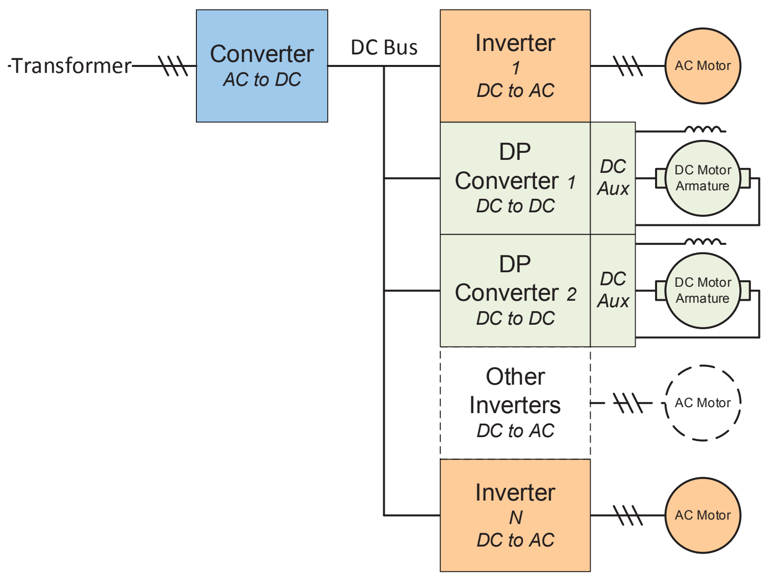


Figure 13. Common DC Bus lineup of AC and DC drives

When the DC motor is replaced with an AC motor, the external auxiliary cabinet is de-commissioned. The DP Converter only requires the proper motor cabling terminations and a firmware change from DC to Inverter AC motor control.

Example Installation

There are many possible Dual Purpose drive applications. One installation is on a Steel Dynamics (SDI) process line in Butler, Indiana USA. The General Electric DC2000 drives had been discontinued with parts no longer available from the manufacturer and spare components in short supply. Based on the maintenance situation, SDI decided to upgrade the line and evaluated a DC replacement in kind versus the more efficient, but costly, conversion to AC motors and drives.

During the evaluation period SDI became aware of the third possibility of an all new drive lineup configured for AC but with only some of the motors initially being upgraded from DC to AC. SDI decided on the TMEIC Corporation mixed use solution using TMdrive-10e2 drives configured in a combination of AC and DC drives.

For purposes of illustration, only one section of drives is shown in Figure 14.

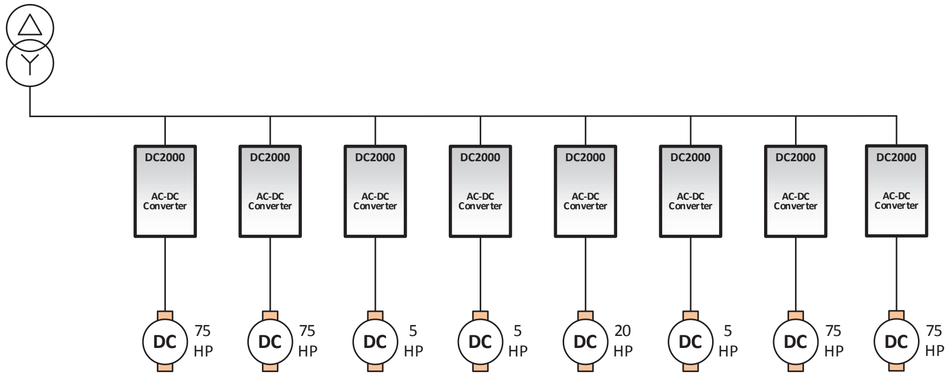


Figure 14. Existing DC drive lineup

Available floor space was not an issue. Therefore SDI decided to maximize pre-outage work and minimize outage time by including a new separate feed for the new drive lineup. The new transformer, AC-DC converter plus control power to all connected inverters and converters were able to be commissioned prior to the outage. The initial outage changed out the smaller 5 HP and 20 HP drives from DC to AC as shown in Figure 15. Converting small DC motors to AC was also implemented in the other drive lineups as well.

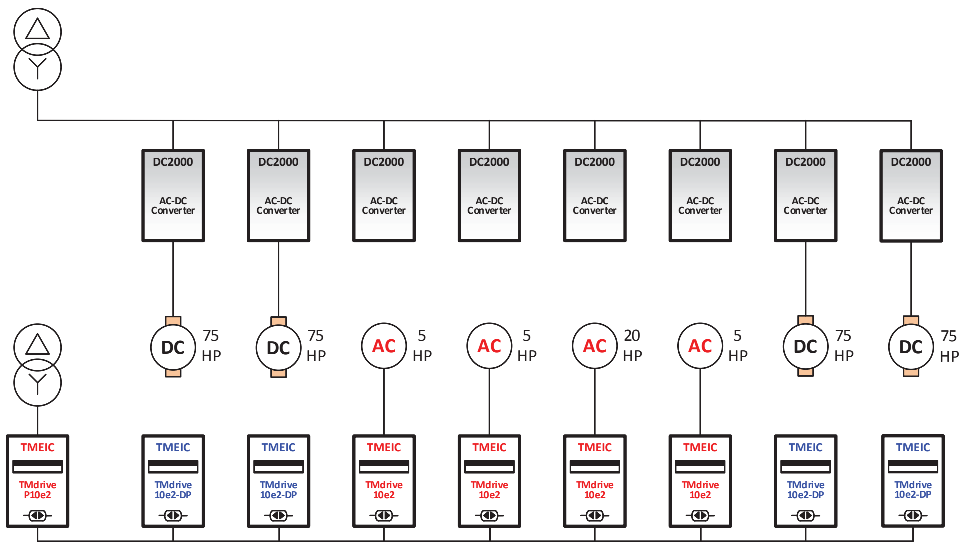


Figure 15. Initial AC and DC drive lineup

While four of the eight motors were upgraded from DC to AC in the initial phase, the intention is to eventually replace all of the DC motors with AC motors. In the meantime the remaining DC motors were switched over to the new Dual Purpose drives as time permitted. The first conversion is shown in Figure 16 where the two bridle motors were switched to the new Dual Purpose drive format.

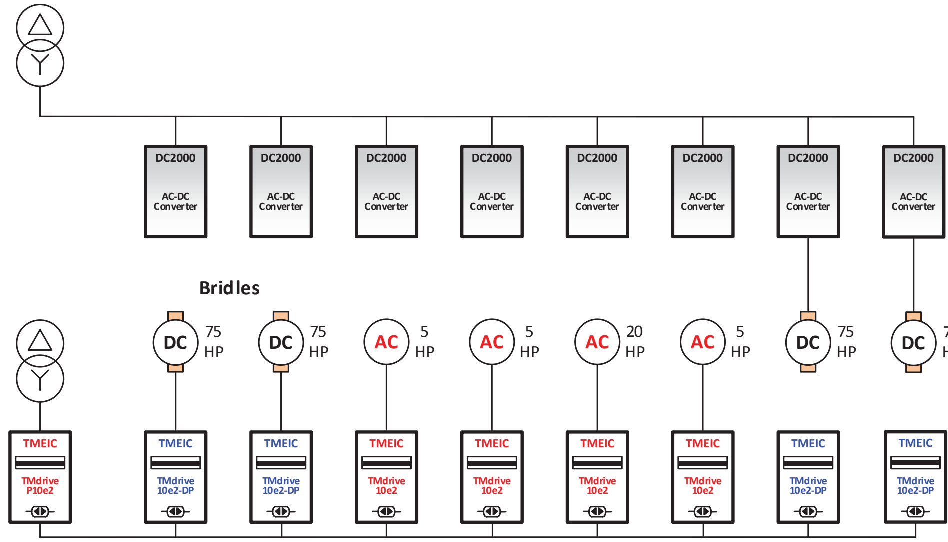


Figure 16. Conversion 1

The final conversion from the existing drive lineup to the new drive lineup was moving the Payoff Reel to the new drive lineup as shown in Figure 17. This allowed the existing DC2000s to be retired and become available as a source of spare parts for other locations.

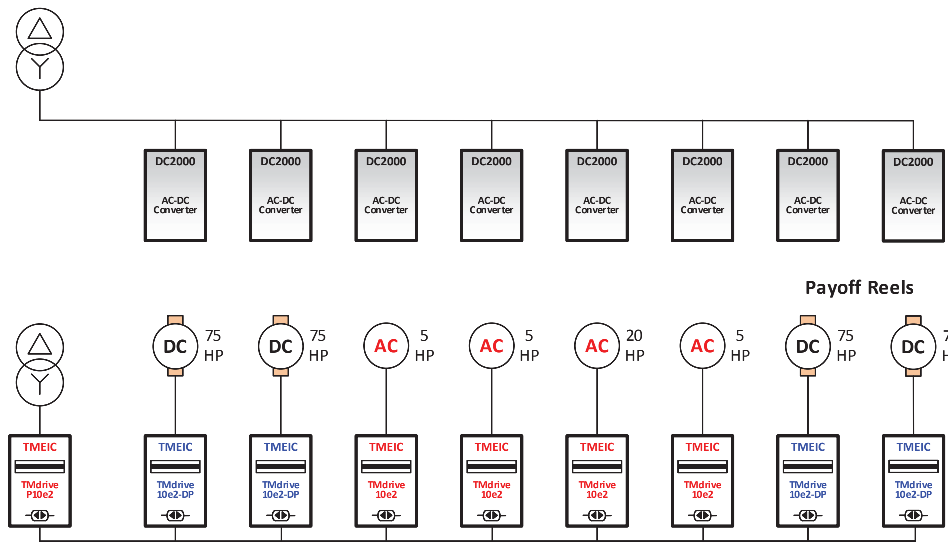


Figure 17. Conversion 2

Over time the intention is to replace the DC motors with AC motors. The conversion requires:

1. Changing the firmware from the DC converter version to the AC inverter version.
2. Removing or bypassing the DC Auxiliary panel shown in Figure 13.
3. Installing proper VVVF cabling to the AC motor (if the old DC cable was reused).
4. Installing the new AC motor.
5. Tuning the inverter.

With proper planning and preparation it is anticipated the conversion can be accomplished within one regular maintenance downturn. The final complete AC arrangement is shown in Figure 18.

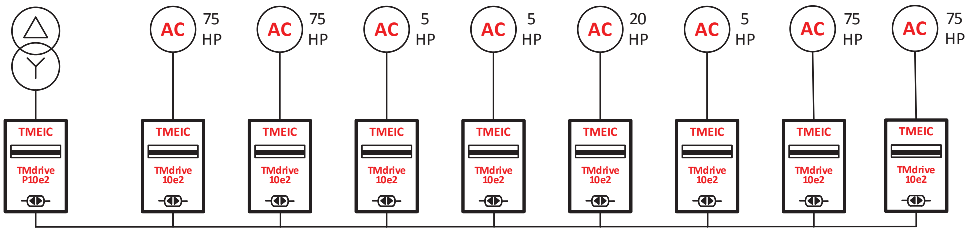


Figure 18. Final all AC arrangement

CONCLUSIONS

It has been demonstrated that a new AC drive system can be deployed to power and control a combination of existing DC motors and new AC motors. This arrangement reduces the initial investment in new AC motors and can significantly reduce the changeover outage time, while providing a future upgrade path to AC for the remaining DC motors. In addition, the new AC motor has the option of being higher power.

REFERENCES

1. AC Stevenson, *Power Converter Handbook 5th Edition,* General Electric Canada Inc., 2009.
2. "NEMA MG 1-2016", National Electrical Manufacturers Association, © 2016, pp. 12-2, 23-18.
3. S. Moriyasu and Y. Okuyama, "Surge propagation and overvoltages for PWM-inverter-driven motors,"*Electrical Engineering in Japan*, vol. 132, no. 2, pp. 65–72, 2000.
4. A. Schmidt and W. P. Smith, "Operation of Large D-C Motors From Controlled Rectifiers,"*Transactions of the American Institute of Electrical Engineers*, vol. 67, no. 1, pp. 679–683, 1948.
5. R. Hall and W. Konstanty, "Commutation of DC Motors," *IEEE Industry Applications Magazine*, vol. 16, no. 6, pp. 56–62, Nov. 2010.
6. N. Kaufman, "An Application Guide for the Use of D-C Motors on Rectified Power,"*IEEE Transactions on Power Apparatus and Systems*, vol. 83, no. 10, pp. 1006–1009, Oct. 1964.