Medium Voltage VFD’s can exacerbate problems with motor neutral voltages.

The following paper by Toshiba is a great explanation, and we appreciate Toshiba allowing us to use it.

For all of your medium voltage drive needs, including service on existing units, please call us at 800-848-2504.


Eddie Mayfield
President, EMA Inc.
Neutral Point Shift

To fully understand the solutions that Toshiba employs in the T300MVi to address the neutral point shift issue, we first need to define exactly what neutral point shift is, what causes it, why we need to be concerned with it and under what conditions does it actually present a problem. Neutral shift is a term used to describe a phenomenon that occurs when an AC motor drive causes the voltage potential of the motor’s neutral point to vary in respect to system neutral, which ideally, should be very close to zero volts in respect to true earth ground potential.

When a motor is fed directly from 3-phase utility power, the voltage applied to the motor windings and the current flowing through them are both sinusoidal in nature and in-phase with one another at the motor inputs. Assuming all three power phases coming into the motor windings are balanced, (equal in voltage and 120° out of phase with one another) the neutral point, (common, star, center point, etc.) of a wye-wound motor will be at, (or very near) the same zero volt potential as the earth ground connection to the motor chassis. This is good, as the winding insulation within the critical slot area of the motor is subjected only to the expected amount of phase-to-ground and phase-to-phase voltage stresses.

If for some reason the neutral point in the motor were to somehow be shifted to some voltage level other than zero, then the winding insulation would be subjected to an increase in overall voltage stress, as this new neutral-to-ground voltage level is additive to the normal phase-to-ground and phase-to-phase voltage stress levels. This additional stress is of special concern in the critical slot area of the motor due to the tight phase-to-chassis proximities.

Common Mode Voltage

The primary cause of a voltage shift at a motor's neutral point is common mode voltage created by AC motor drives. Common mode voltage is generally defined as any voltage that is common to both sides of a differential pair. In any differential pair, the differential voltage across the pair is the desired signal, whereas any voltage signal common to both sides is an unwanted signal that may have been unintentionally created due to circuit imbalances. When the pair is perfectly balanced, common mode voltages are canceled out. The degree of cancellation is called the common mode rejection ratio, or CMRR of the circuit.
For example:

![Diagram of 3-Phase AC/DC Converter]

Suppose we have a 460V, three-phase, fullwave bridge circuit feeding into a capacitive filter to create a 650Vdc power supply. The peak voltage of a 460V\text{RMS} AC voltage is:

\[ \text{Vac}_\text{PK} = \sqrt{2} \times \text{Vac}_\text{RMS} = 1.414 \times 460 = 650\text{Vac}_\text{PK} \]

The DC output of the rectified 460Vac is therefore 650Vdc, measured between the positive and negative outputs of the circuit which can be thought of as a differential pair, as the output voltage is the difference in voltage potential between them. No common mode voltage exists in this circuit because both the positive and negative sides of this differential circuit are perfectly balanced within the single filter cap.

But, a single capacitor will rarely be used as a filter in a circuit like this, as the capacitor would have to be rated at 800 volts and would therefore become cost prohibitive. Significant cost savings can be obtained by using two, 400 volt, electrolytic capacitors, (of equal value) in series to achieve the desired capacitance to filter the rectified AC power, as shown below:

![Diagram of 3-Phase AC/DC Converter with two capacitors]

The two capacitors form a voltage divider and theoretically, as the two filter capacitors are of equal value, they should each drop exactly half of the applied voltage with the mid-point between them at zero volts, in respect to ground, (assuming the 3-phase AC inputs are balanced).

Unfortunately, there is no such thing as a "precision" capacitor and capacitor tolerances are often ±20% at best. Assuming the worst case scenario where one cap is at +20%, (or 120%) of its rated value and the other is at -20%, (80%) of its rated value, the voltage drops across them are no longer equal. One will drop 60% of the applied voltage, while the other drops only 40%.
The cap tied to the positive buss is now dropping 390 volts, while the cap tied to the negative buss is dropping only 260 volts. The output voltage is still 650Vdc between the positive and negative outputs, but while the center point between the two capacitors is still acting as the circuit's "zero reference", it is now "shifted" (offset) from true earth ground potential by +65Vdc.

In this illustration, the desired values of ±325Vdc across the two caps are now both offset by +65Vdc. Therefore, this +65Vdc that is common to both sides of the DC buss can be thought of as a common mode voltage.

One problem that could arise from a voltage imbalance between the DC buss capacitors in the example, is that one of the caps is normally being subjected to a voltage level that is very close to its maximum rated voltage potential of 400 volts. If the circuit were to experience an input voltage surge, then it's very possible that the cap dropping 390V would then be subjected to a voltage level higher than its rating, which could cause catastrophic component failure. Therefore, it is imperative that something be done to eliminate the common mode voltage.

This is easily accomplished by adding a pair of equal value DC balancing resistors in parallel to the capacitors, as shown below:

Resistors normally have value tolerances that are much tighter than those of capacitors and can come much closer to actually being equal value, creating a voltage divider that will come very close to dropping exactly the same amount of voltage across each side. As the caps are in parallel with the balancing resistors, (and the voltage drops across parallel circuits are equal) the voltage across the caps is equalized very near the desired ±325Vdc value. In this instance, the addition of DC balancing resistors has equalized the voltage on both sides of our differential DC buss circuit and greatly reduced, (if not totally eliminated) the common mode voltage that existed without them.
This way, we have solved the *common mode voltage* problem, while still enjoying most of the cost savings over employing a single 800V cap.

**Current Source AC Motor Drives**

As stated previously, the primary cause of a voltage shift at a motor's neutral point is *common mode voltage* generated by an AC motor drive. Of the various types of AC drive methodologies currently employed, the first models that came to market were *current source* drives. As a general rule, *current source* AC drives generate a greater level of *neutral shift* than the more modern voltage source drives. Current source drives generally utilized active thyristor or GTO converters on both ends. Those having a grounded power transformer secondary as their input were generally worst case. Therefore, to illustrate the problem, drawn below is the schematic for a generic, (yet typical) *current source* AC drive with a grounded secondary on its input power transformer: (Circuit breakers and contactors normally employed between the power transformer and the input line reactor are not shown, for simplicity.)

![Schematic of a generic current source AC drive](image)

**Typical Current Source AC Motor Drive with a Grounded-Wye Power Feed**

The drive illustrated above consists of two, six thyristor converters, with their DC terminals coupled together across a pair of inductive filters. The input converter changes the incoming AC into positive and negative DC buss voltages through phase-angle control of the firing of the thyristors. The waveform diagram, (below the schematic) shows the $V_P$ and $V_N$ outputs of the input converter during one cycle of utility power, with the firing angle of the thyristors delayed by 20°, as this is typical of full-speed, full-load operation.

The key to understanding why the neutral point potential of the motor varies, (as shown in the waveform diagram above) in respect to chassis (earth) ground potential is twofold:

1) In a current source VFD, because of commutation requirements to ensure the thyristors "turn off" at the proper times, (except for the commutation interval) only two of the motor's three inputs will be conducting at any one time.

Because of this, the center point between the two windings within the motor that are in conduction at any one time is, in effect, the center point of a voltage divider, (between the conducting phases) which will always be at the same voltage potential as the mean voltage between the positive and negative DC buss potentials.
2) The mean value of the two DC buss voltages must be equal for both converters. Whenever there are two motor windings conducting, as outlined in item #1, (on the previous page) the firing of the thyristors in the output converter forms a series circuit, (through two phases of the motor windings) between the positive and negative DC buss. As all points in a series circuit have equal amounts of current flowing through them and the DC link inductors are of equal value, (they are often identical coils wound on the same ferrite core) then the voltage drop across both inductors will be equal as well.

The operation of each of the two converters causes the mean value of its DC system to vary in respect to the neutral of the AC system connected to that converter. If the AC neutral of the input converter is grounded, (as shown in the illustration on the previous page) then the AC neutral connected to the output converter, (motor neutral) will be shifted by the sum of these differences.

The DC mean voltage generally varies at three times the motor frequency, with the DC mean peak voltage value reaching 38% to 50% of the phase-to-neutral voltage. The output frequency is generally a bit different from the input frequency, so their respective peaks will periodically coincide. As either can reach 50% of the phase-to-neutral voltage, their sum can reach 100%, effectively doubling the nominal phase-to-neutral voltage stress on the winding insulation in the critical slot area of the motor.

In low voltage motors, this additional voltage stress does not present a problem, but in medium voltage drives, (especially 4160 Vac and higher) this can become problematic. The additional voltage stress created by neutral point shift will generally not cause an immediate motor insulation failure, but the effective life of the motor can be significantly shortened due to it's winding insulation being gradually degraded by ozone, which is generated by corona due to increased voltage stressing.

Solving the Neutral Shift Problem with an Isolation Transformer

In current source AC drives, the neutral shift problem of voltage stressing the motor windings was generally solved by installing an isolation transformer on the input of the drive. The neutral of the isolation transformer secondary is ungrounded, so any common mode voltage generated by the drive is now "shared" between the isolation transformer secondary neutral and the motor neutral. But as motors generally have as much as 150 times the coupling capacitance of an isolation transformer, the relatively high coupling capacitance of the motor tends to hold the motor's neutral point very near the earth ground potential on its chassis, while the low coupling capacitance within the transformer prevents this with the transformer.
In essence, the gross disparity in the relative coupling capacitance's between the motor and the transformer forces almost all of the common mode voltage to be felt on the isolation transformer secondary neutral. Unlike motor windings, a transformer's secondary insulation is normally well able to handle this additional stress without difficulty, as it is generally rated much higher than those of motor windings. Also, unlike a motor, a transformer has no slots to create a close tolerance between phase and ground.

In summation, the use of an isolation transformer does not actually eliminate neutral point shift, but instead transfers the effect away from the motor, (where it could eventually cause motor insulation failure) and applies it to the transformer, which can handle the additional stress without creating problems.

**Motor Windings as a Voltage Divider**

The drawing below illustrates the phase-to-phase-to-phase relationship between the phases of three phase power. By drawing a vertical line to represent a single instant in time, we can see that except for where one phase is exactly at it's zero crossing point, (as illustrated by Time-2) the phases will always be either two positive and one negative, (as illustrated by Time-1) or two negative and one positive, (as illustrated by Time-3). As previously stated, in a balanced system the instantaneous sum of all three phases is zero.

When 3-phase AC is applied into the motor leads of a wye-wound motor, the impedance of the motor windings will act as a type of voltage divider. When one phase is exactly at it's zero crossing point, (Time-2 in the illustration above) the two remaining phases will be at voltages equal in value, but in opposite polarity and the equivalent circuit formed could be illustrated as:
When all three phases are conducting, the voltage divider formed by the impedance of the windings can be represented by an equivalent circuit like the one below:

The two winding impedance's are equal, but the voltages feeding into them are not, therefore the voltage drops are across them are proportional to the voltage applied.

The voltage drop across the winding with the negative voltage input is equal to the drop across the two positive fed windings combined.

The sum of the two positive voltages is equal to the negative voltage applied to the third leg, therefore the center point remains at zero volts.

Equivalent Circuit: Wye Wound 3-Phase AC Motor when no Phases are at Zero Crossing Point

The circuit works the same way whenever two inputs are negative and only one is positive; only the polarities are different. Again, when fed by balanced 3-phase power from the utility, the sum of the voltage drops across the windings are polarity balanced at all times, holding the motor neutral at zero, in respect to the motor chassis.

But when fed by a voltage source, PWM VFD, (variable frequency drive) the voltage drops across the windings are unbalanced. To see why this happens, we need to discuss how the PWM voltage signal output is created in a voltage source VFD.

**Voltage Source AC Motor Drives**

Today, except for older installations the use of current source AC drives is generally limited to only the largest horsepower applications. Almost all low voltage AC drives, (up to 1200hp) and most medium voltage AC drives, (generally up to 5,000hp) are a type of voltage source design. Illustrated below is a schematic diagram for a "generic" low voltage, voltage source AC drive:
A voltage source VFD, (variable frequency drive) consists of three main power components; the rectifier, filter and inverter. Incoming 460Vac, 3-phase power from the utility is full-wave rectified into ~650 Vdc, ($\sqrt{2} \times V_{\text{Vac\,RMS}}$) DC buss voltage, which is ±325Vdc in respect to a zero volt reference at the center point between two, series filter capacitors across the 650 volt DC buss. (This capacitive filter smoothes the DC by dampening the ripple.) The inverter section of the VFD normally consists of six IGBT’s (insulated gate bipolar transistors) that fire in pairs to momentarily short the DC buss through the motor windings creating current flow within the windings.

An algorithm in the drive's memory controls the firing pattern of the IGBT's, (which simply act as high speed switches) to create a 2-level, PWM (pulse-width modulated) voltage signal output to the three inputs to the motor, resulting in a rotating voltage vector that moves in respect to switching states of the six IGBT’s. The "average" voltage of this rotating PWM signal causes a relatively sinusoidal current flow within the motor windings.

Ideally, the neutral point of the motor wye connection should always be at the same "zero" volt potential as the center point reference between the two filter caps across the DC buss within the drive, but generally this is not the case.

**Voltage Source AC Motor Drives with Corner Grounded, Delta-Connected Input Source**

Illustrated below is a voltage source VFD fed by a corner grounded, delta-connected input source, which is commonly found in low voltage power systems industrial and commercial usage.

Note that one phase of the secondary side of the input transformer is grounded and, (for safety reasons) the motor chassis is connected to the same ground. For this discussion $V_{DG}$ is defined as the voltage difference between the drive neutral between the DC buss caps ($V_D$) and ground. $V_{DW}$ is the voltage difference between the motor (winding) neutral ($V_W$) and the drive neutral, ($V_D$). $V_{WG}$ is the voltage difference between the motor neutral ($V_W$) and ground.

$$V_{WG} = V_{DG} + V_{DW}$$

The voltage difference between the motor neutral and ground is equal to the sum of the voltage differences between the drive neutral-to-ground and the drive neutral-to-motor neutral.
An equivalent circuit for the inverter stage feeding a motor is drawn below:

As the six IGBT's making up the inverter section of the VFD act as high speed switches, they can be represented in an equivalent circuit drawing using simple switches, while the impedance of the motor windings is represented by resistors. To create AC within the motor windings, the IGBT's must be able to cause current to flow within the windings in both directions.

**Equivalent Circuit: Inverter Section**

**Creating AC with Switches**

As shown in the illustrations below, we can see how by simply varying the switching pattern, it is possible to create current flow in either direction through the same set of windings, which by definition is "alternating current." A third switch, (either +buss or -buss) would also be closed to produce current flow in the desired direction within third motor leg. (Not shown, for simplicity.)

**Current Flowing Through Windings in Both Directions by Varying Switch Pattern**

Just as the phases of 3-phase utility power will always have either two positive phases and one negative phase, or two negative phases and one positive phase, so too will the 3-phase PWM signals on the outputs of a voltage source VFD.

Because of this, the six switches, (IGBT's) used to create the 3-phase PWM output will have two switches, (IGBT's) tied to the positive buss and one tied to the negative buss conducting, (or vise versa) whenever there is current flow through the motor windings.

**3-Phase PWM Waveforms**
There are six different combinations, (switching states) actively used to create the PWM waveform. As we've seen, the IGBT's are fired in pairs to short the DC buss through the motor windings. As the IGBT's in line with one another vertically will NEVER be fired at the same time, (because this would short out the DC buss) we can think of three vertical rows of switches and define their switching condition with a "X" when only the upper (+buss) switch is conducting and an "O" when only the lower (-buss) switch is conducting.

<table>
<thead>
<tr>
<th>Switching State</th>
<th>Firing Pattern</th>
<th>U-Phase to Drive Neutral</th>
<th>V-Phase to Drive Neutral</th>
<th>W-Phase to Drive Neutral</th>
<th>U-Phase to V-Phase</th>
<th>U-Phase to W-Phase</th>
<th>V-Phase to W-Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>X-O-O</td>
<td>+325</td>
<td>-325</td>
<td>-325</td>
<td>+650</td>
<td>+650</td>
<td>0</td>
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<tr>
<td>K2</td>
<td>X-X-O</td>
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<td>+325</td>
<td>-325</td>
<td>0</td>
<td>+650</td>
<td>+650</td>
</tr>
<tr>
<td>K3</td>
<td>O-X-O</td>
<td>-325</td>
<td>+325</td>
<td>-325</td>
<td>-650</td>
<td>0</td>
<td>+650</td>
</tr>
<tr>
<td>K4</td>
<td>O-X-X</td>
<td>-325</td>
<td>+325</td>
<td>+325</td>
<td>-650</td>
<td>-650</td>
<td>0</td>
</tr>
<tr>
<td>K5</td>
<td>O-O-X</td>
<td>-325</td>
<td>-325</td>
<td>+325</td>
<td>0</td>
<td>-650</td>
<td>-650</td>
</tr>
<tr>
<td>K6</td>
<td>X-O-X</td>
<td>+325</td>
<td>-325</td>
<td>+325</td>
<td>+650</td>
<td>0</td>
<td>-650</td>
</tr>
</tbody>
</table>

Earlier, we stated that the PWM waveform produces a rotating voltage vector within the motor windings. The six vector-generating IGBT switching states relate directly to the angle of the voltage vector:

- K1 = 0º
- K2 = 60º
- K3 = 120º
- K4 = 180º
- K5 = 240º
- K6 = 300º

As previously discussed, whenever a motor is driven by a VFD, the motor neutral should ideally be at the same potential as the drive neutral, but unfortunately this is not the case. Like current source drives, voltage source drives inherently generate some amount of neutral point shift within the motor windings.

Although the "average" voltage of the PWM output of a voltage source VFD creates a very sinusoidal current flow within the motor windings, we need to remember that the motor windings still form a voltage divider, (as discussed earlier) and the drive signal feeding the motor windings is NOT sinusoidal. At any given instant in time, each fired IGBT is connecting the full voltage of one side of the DC buss, (positive or negative) to the motor windings.

As seen before, the six active switching states used to create the 3-phase PWM output will cause two IGBT's tied to the positive buss and one tied to the negative buss to be conducting, or two IGBT's tied to the negative buss and one tied to the positive buss to be conducting whenever there is current flow through the motor windings.
As the impedance of all three windings are equal for a given frequency, \((X_L = 2\pi fL)\) the two windings in parallel will (together) produce a combined impedance exactly half that of their individual value. This means that the two parallel windings that are both tied to the +buss make up only 1/3 of the total circuit impedance during these three switching states, while the single winding tied to the -buss makes up the other 2/3. As the impedance the two parallel windings tied to the +buss only make up 1/3 of the total circuit impedance, they will correspondingly drop only 1/3 of the total 650Vdc applied to the circuit, while the single winding tied to the -buss will drop the other 2/3 of the 650Vdc applied voltage.

Illustrated below, is an equivalent circuit during the even switching states, K2, K4 and K6:

![Equivalent Circuit Diagram]

\[ Z_T = \frac{Z_1 \times Z_2}{Z_1 + Z_2} \]

**Equivalent Circuit: Motor Windings During Even Numbered Switching States**

The two parallel windings that are both tied to the +buss will only drop \(\sim 216\) Vdc (1/3) of the applied 650Vdc, while the single winding drops the remaining \(\sim 434\) Vdc. The unbalanced voltage drops cause the center point of the voltage divider, (motor neutral) to assume a common mode voltage of \(\sim +108\) Vdc in respect to the system neutral, (the center point between the DC buss caps). Thus, during the even numbered switching states, the motor neutral is shifted to \(\sim +108\) Vdc. During the odd numbered switching states, just the opposite condition exists. Two IGBT’s tied to the -buss while only one tied to the +buss are conducting. The amount of voltage dropped across the single and parallel windings remains the same, but the polarity is reversed. Thus, during the odd numbered switching states, the motor neutral is shifted to \(\sim -108\) Vdc.

In general, the motor neutral will be shifted by \(\sim \pm 1/6\) the total DC buss level whenever there is current flowing in the motor windings.

### Six Active Firing States of a Three Phase, 460Vac / Two-Level Inverter

<table>
<thead>
<tr>
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<th>Firing Pattern</th>
<th>U-Phase to Drive Neutral</th>
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<th>W-Phase to Drive Neutral</th>
<th>U-Phase to Motor Neutral</th>
<th>V-Phase to Motor Neutral</th>
<th>W-Phase to Motor Neutral</th>
<th>Motor Neutral to Drive Neutral</th>
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</thead>
<tbody>
<tr>
<td>K1</td>
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<td>X-X-O</td>
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<td>+325</td>
<td>-325</td>
<td>+216</td>
<td>+216</td>
<td>+434</td>
<td>+108</td>
</tr>
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<td>K3</td>
<td>O-X-O</td>
<td>-325</td>
<td>+325</td>
<td>+325</td>
<td>-216</td>
<td>+434</td>
<td>-216</td>
<td>-108</td>
</tr>
<tr>
<td>K4</td>
<td>O-X-X</td>
<td>-325</td>
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<td>+325</td>
<td>-434</td>
<td>+216</td>
<td>+214</td>
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</tr>
<tr>
<td>K5</td>
<td>O-O-X</td>
<td>-325</td>
<td>+325</td>
<td>+325</td>
<td>-216</td>
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<td>+108</td>
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The neutral point shift issue is further acerbated by the fact that there are two additional IGBT switching states that occur during output polarity reversal when there is no buss-to-buss current flowing through the motor windings, called K0 and K7.
During the K0 switching state, all three IGBT’s connected to the negative buss are fired, but none of the three IGBT’s connected to the positive buss are fired. During the K7 switching state, the opposite condition exists; all three IGBT’s connected to the positive buss are fired, while none of the three IGBT’s connected to the negative buss are fired.

During both switching states K0 and K7, the full potential of one side of the DC buss, (positive or negative) is applied to all three motor windings simultaneously. With the same voltage potential applied to all three phases, there is no difference in voltage potential between them and thus, no current flow through them. Therefore, with no current flow to drop any voltage, the motor neutral sees the same voltage potential as that applied to all the windings.

Illustrated below, is an equivalent circuit during switching state K7:

![Equivalent Circuit: Motor Windings During K0 and K7 Switching States]

In general, while switching state K7 causes the motor neutral to be shifted to full positive buss voltage, (+325Vdc) switching state K0 causes the motor neutral to be shifted to full negative buss voltage, (-325Vdc). Although the neutral shift in the motor is 3 times as bad during the K0 and K7 states, these two switching states are necessary in two-level inverters to provide a current path which will allow the magnetic flux around the windings to collapse during polarity transitions, without incurring a high inductive voltage spike which could be developed if they were not present in the firing sequence.

As the K0 and K7 switching states occur whenever the PWM waveform is transitioning between its positive and negative polarities, (at the "zero" crossings) the additional neutral shift incurred during these transitions (K0 and K7) is thus, often referred to as zero sequence voltage.

<p>| Eight Actual Firing States of a Three Phase, 460Vac / Two-Level Inverter |
|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|</p>
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<td>0</td>
<td>0</td>
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<td>+325</td>
</tr>
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</table>
Voltage Source AC Motor Drives with a Wye-Connected Input Source

Illustrated below is a voltage source VFD fed by a wye-connected 460Vac input source:

In this input configuration, there are two additional neutral relationships that need to be considered. As before, $V_{DG}$ is defined as the voltage difference between the drive neutral between the DC buss caps ($V_D$) and ground. $V_{DW}$ is the voltage difference between the motor (winding) neutral ($V_W$) and the drive neutral, ($V_D$). $V_{WG}$ is the voltage difference between the motor neutral ($V_W$) and ground. But now, we also need to be aware of $V_{TG}$, which is the voltage difference between the transformer secondary neutral ($V_T$) and ground and also $V_{TD}$ which is the voltage difference between the transformer secondary neutral ($V_T$) and the drive neutral, ($V_D$).

In this configuration, the voltage difference between the drive neutral between the DC buss caps ($V_D$) and ground, ($V_{DG}$) will be the difference between the transformer secondary neutral-to-drive neutral voltage, ($V_{TD}$) and the transformer secondary neutral-to-ground voltage, ($V_{TG}$).

$$V_{DG} = V_{TD} - V_{TG}$$

Due to the discontinuous conduction of the input rectifiers, the variations in the drive's zero reference ($V_D$) will occur in respect to the transformer neutral ($V_T$) at approximately three times the frequency of the source voltage. Therefore, the frequency of $V_{DT} = \sim 180\text{Hz} \ (3 \times V_{IN})$. 

'Scope Settings:
- 5msec/div
- 100V/div

Behavior of Drive Neutral-to-Ground with 3-Phase Input During PWM Output Operation
As the voltage difference between the motor neutral and ground is still equal to the sum of the voltage differences between the drive neutral-to-ground and the drive neutral-to-motor neutral, \( V_{WG} = V_{DG} + V_{DW} \) the switching states of the IGBT's will cause the motor neutral-to-ground to appear on an oscilloscope to behave as illustrated below:

The voltage waveform illustrated above is the resultant sum of the variations caused by the IGBT switching states added to the variations in the DC buss neutral-to-ground, illustrated on the previous page.

So, just exactly how much of a problem is this neutral shift phenomenon causing in low voltage motors being driven by voltage source, two-level PWM AC motor drives?
Low Voltage Motor Insulation Stress When Driven by a Voltage Source VFD

When a motor is operated directly by sinusoidal utility power, the motor’s nominal phase-to-neutral voltage \( V_{acRMS} \div \sqrt{3} \approx 265.6 \text{Vac} \), therefore the peak phase-to-neutral voltage \( (\sqrt{2} \times V_{acRMS}) \div \sqrt{3} = 375.3 \text{Vac} \), which is \(~81.6\%\) of the applied 460 \text{VacRMS} voltage.

As previously discussed, the DC buss voltage of a low voltage VFD is \( \sqrt{2} \times V_{acRMS} \). With the motor’s neutral point voltage level shifting, (as discussed) the instantaneous peak voltage from phase-to-ground can be the peak phase-to-ground voltage plus the neutral point shift voltage where:

\[
\text{The peak phase-to-ground voltage} = (\sqrt{2} \times V_{acRMS}) \div \sqrt{3}.
\]

Generally, the maximum neutral point shift voltage in a voltage source VFD is one half of the total DC buss voltage, \( (\sqrt{2} \times V_{acRMS}) \div 2 \). So the instantaneous peak voltage from phase-to-ground can be \( [ (\sqrt{2} \times V_{acRMS}) \div \sqrt{3} ] + (\sqrt{2} \times V_{acRMS}) \div 2 = 650 \div 1.732 + 325 = \approx 700 \text{volts} \), which is \(~1.52 \times V_{acRMS} \), as compared to \(~375 \text{volts} \) \(~81.6\% \) of 460 \text{VacRMS} for utility power.

\[
1.52 \div 0.816 = 1.86,
\]
therefore motors powered by low voltage, voltage source VFD's can consequently subject the motor phase-to-ground insulation to \(~1.86 \) times the voltage stress the insulation would normally be subjected to, as compared to a utility fed motor. On low voltage motors, the phase-to-ground insulation, (slot liner) is normally well capable of withstanding this additional voltage stress and therefore neutral shift poses no problems in most applications. But on medium voltage motors, the higher voltage levels involved (especially 4160V applications) can cause the additional voltage stresses placed on the slot liner insulation by neutral point shift to become problematic, especially when older, existing motors are being retrofitted to be driven with a medium voltage AC drive.

Medium Voltage

Just what is meant by the term medium voltage? The term is not uniformly defined, as it's definition tends to vary by both industry and application. In AC motor drives, the range from above 600 volts up to 15,000 volts generally represents some consensus. In Europe, 1,000 volts is generally considered the lower MV threshold. On a practical level, current MV drive products generally have a narrower range of 2,300 volts to 7,200 volts. Standard North American medium voltages are 2,300 volts and 4,160 volts, while Europe and the rest of the world predominately utilize 3,300 volts and 6,600 volt medium voltage levels.

Large industrial applications often require electric motors rated in thousands of horsepower to meet a variety of needs. To keep energy costs within tolerable levels, medium voltage motors have been utilized for many years, to meet these high power requirements. To soft-start these large medium voltage motors (reducing current inrush on start-up) and to control motor speed, Medium Voltage AC drives (MV drives) are often employed. Today's spiraling energy rates and the need for enhanced power quality have spurred the demand for new MV drive designs and technology to unprecedented levels.

The single most important factor driving all the recent activity in the MV drive market is savings in energy costs. So, how does using a medium voltage drive produce energy savings? To fully understand how medium voltage drives can result in significant energy savings, we need to discuss the nuances of energy and power.
Work

Energy is generally defined as “the ability to do work.” Physicists define work as a force applied to some form of matter (an object) multiplied by the distance that this object travels:

\[ \text{Work} = \text{Force} \times \text{Distance} \quad (W = F \times D) \]

Energy exists in various forms and is measured in various units of measurement, depending upon which form being utilized. One newton is defined as the force needed to accelerate (or move) a mass weighting one kilogram, one meter in one second, (in a vacuum with no friction). The amount of energy (work) required to move an object with the force of one newton over a distance of one meter is called a joule. In physics, work is defined as the product of force and distance and is measured in foot-pounds.

For example:

If one pound were lifted one foot, then one foot-pound of work has been performed. By adding the element of time into this scenario, then we could measure the rate at which the work is being performed:

If the weight were being raised one foot once each second, the rate at which the work would performed would be "one foot-pound per second”.

Power

In electrical circuits the measurement of the rate that work is being performed is called power.

Power is measured in units called watts and is generally represented with the letter “P” in mathematical expressions. (One watt is equal to one joule of energy being expended every second.)

Power is calculated by multiplying the applied voltage times the current:

\[ P = I \times E \]

For example, if the circuit was pulling 2.5 amps at 110 volts the power consumed would be:

\[ 2.5 \text{ amps} \times 110 \text{ volts} = 275 \text{ watts of power} \]

In the above example, the 275 watts represents the amount of power being expended every second. To find the total amount of energy being expended by an electrical circuit, the wattage (or rate of expenditure) must be multiplied by the time that the circuit is expending this amount of power:

\[ 275 \text{ watts} \times 6 \text{ hours} = 1,650 \text{ watt} / \text{hours of energy} \]

This is why electric bills show usage in terms of kilowatt/hours, (the prefix “kilo” meaning “thousand.”) So, for the example shown above, we can say that over a period of 6 hours, a 110v circuit, drawing 2.5A of current will expend 1.65 kilowatt/hours of energy.

A commonly used memory jogger for remembering how to calculate power is to remember the word “PIE,” (\( P = I \times E \)). There are other ways to calculate power if one of these two values is unknown. By transposing the equation we can also say that:

\[ P = I^2 \times R \quad \text{and} \quad P = \frac{E^2}{R} \]

Using any of these three equations will result in the same answer, when calculating power.
The resistance (R) within the circuit (or impedance in AC circuits) is generally a fixed value at a given frequency. So, examining the formulas above, it is easy to see that power is directly proportional to both the current and the voltage.

Assuming a fixed impedance for a given AC voltage and frequency, power is generally calculated as:

\[ P = I \times E \]

As voltage and current are inversely proportional for any given amount of power, by utilizing higher voltage levels, the same amount of power can be generated using proportionally lower amounts of current.

Heat Losses

As stated previously, there is no such thing as a “perfect” (zero ohms) conductor of electricity. All conductors will have some amount of inherent resistance to current flow. Although the internal resistance within a conductor (like copper wire) is usually quite small, it plays the predominate role in determining how much current a given conductor can safely carry.

When considering the internal resistance of a wire, there are two things we need to keep in mind. As stated previously:

1. The greater the length of the wire, the more internal resistance it has.
2. The greater the diameter of the wire, the less internal resistance it has.

The internal resistance of wires is important because it relates directly to the amount of heat that will be built up within a wire when electric current flows through it. As electrons flow through any material which is “resisting” the current flow, a certain amount of heat will begin building up within the material. Within any given material, the greater the current (or the greater the resistance) the greater the amount of heat.

As previously noted, \[ P = I^2 \times R \], so the higher the internal resistance of a component or a piece of wire, the more power that will be lost and dissipated in the form of heat as a constant level of current flows through it. This heat within the conductive material is generally shed (dissipated) into the air by thermal conduction due to the heated surface area of the material being in physical contact with the air. The larger the surface area of the conductor, the more heat it can dissipate and the cooler it will be for any given amount of current.

Example: Most everyone can relate to about how much heat that a 100-watt light bulb gives off. Suppose this same 100-watt light bulb was the size of a water tower. Do you think it would even feel warm to the touch? -- No!

Now, suppose we tried dissipating that same amount of heat in an object the size of a thimble. How hot do you think it would get? -- Red hot!

For this reason, wires that are intended to carry larger amounts of current are physically larger in diameter than those intended for smaller amounts of current flow. (The larger diameter also helps reduce the amount of heat generated for a given amount of current flow, in that the larger wire will also have a smaller internal resistance.)
This is also why high wattage components (i.e., resistors) are generally larger in physical size, to maximize their surface area to maximize their ability to dissipate heat.

By utilizing medium voltages, (2300-4160V) any specific amount of power can be generated using lower current levels, allowing for physically smaller components and wiring (yielding a smaller footprint and significant cost savings) as compared to equipment required to produce the same amount of power at low voltage levels (460-600V). As there is less current flowing in the conductors of medium voltage circuits, there is less power lost in the form of heat dissipated to the atmosphere, so more of the energy usage is available to the load to perform work. In this way, medium voltage equipment is much more energy efficient than low voltage equipment, (to produce a given amount of power) and can generate significant savings in energy costs.

**Medium Voltage AC Motor Drives**

Large industrial applications often require electric motors rated in thousands of horsepower to meet a variety of needs. To reduce energy costs, medium voltage motors have been utilized for many years, to meet these high power requirements.

To soft-start these large medium voltage motors (reducing current inrush on start-up) and control motor speed, Medium Voltage AC drives (MV drives) are often employed. Like low voltage drives, the first models of MV drives to came to market were current source drives, utilizing active thyristor or GTO converters on both ends. These drives were generally simple, relatively economical and highly reliable.

Currently, the highest power medium voltage drives are still current source drives, (as previously discussed) whose thyristor based (SCR and GTO) circuitry has become the standard technology in these current source, medium voltage drives for induction motors. They are found in widespread usage in centrifugal load applications, where they generally offer the advantage of higher efficiency than other types of controls.

But in spite of all their virtues, medium voltage current source drives do have their drawbacks when compared to their more modern voltage source cousins. They are known for inducing significant harmonic currents in supply lines and their power factor tends to deteriorate as motor speed is decreased. Low order harmonics on their outputs can induce torosional resonances within the motor and as noted previously, without a dedicated isolation transformer on their input, they create rather large common mode voltages (neutral point shift) that necessitate special motor insulation in the 10kV to 12kV range.

Current source drives also tend to cost more than voltage source drives, (in terms of dollars per horsepower) simply because voltage source drives generally utilize parts manufactured in much higher volumes than those utilized in current source designs. The relatively recent introduction of IGBT’s with higher inverse voltage ratings have allowed voltage source drives broach the medium voltage market.

Today's spiraling energy rates and the need for enhanced power quality has spurred the demand for new MV drive designs and technology to unprecedented levels. While the largest, (highest power) MV drives are still of the current source variety, voltage source MV drives have started making significant inroads into the low and medium power MV drive market. This is due not only to their lower cost vs. horsepower ratio, but also because of their inherent advantages in terms of power factor, torque pulsations, harmonics and neutral point shift.
The newer voltage source MV drives utilize a variety of topologies, but due to limitations in the voltage ratings of available switching devices, they do not use single-bridge converters to create a medium voltage signal to drive the motor. Instead, they generally they use multiple low voltage PWM power cells to create cascaded, multilevel PWM signals to reach the medium voltage levels required by the motor.

All of the neutral point shift issues previously discussed for low voltage drives also apply to medium voltage drives, only more so due to the higher voltages involved. One obvious answer to the neutral point shift problem would be to always utilize a motor having at least 6KV class insulation, (10KV-12KV on current source 4160V drives) which can withstand the additional voltage stress placed on the slot liner, but this would mean using a special type motor that could not always be easily replaced in the event of a failure. In addition, the relatively high coupling capacitance between the motor neutral-to-ground could still cause common mode voltages to appear between the motor neutral and ground that could induce shaft voltages, bearing currents or circulating bearing currents, which could cause premature motor bearing failures.

While a significant concern in any medium voltage application, how a voltage source medium voltage drive deals with it's inherent neutral point shift (or fails to) is of paramount importance in retrofit applications where an existing MV motor is to be used.

**Toshiba T300Mvi Medium Voltage Drive**

The Toshiba T300MVi is the newest generation of Toshiba medium voltage, voltage source AC motor drives, designed for applications from 300 to 5,000 horsepower. The unique T300MVi design offers a significantly smaller footprint and a low component count. Instead of requiring a 6kVA insulated motor, existing MV motors can easily be accommodated in retrofit applications because neutral point shift issues are addressed in a number of different ways that do not require special high voltage motor insulation:

1. Input transformer provides for isolation as well as harmonic cancellation
2. PWM algorithm designed to avoid the problematic “zero sequence” states
3. Neutral point clamping diode design

All of these features provide the Toshiba T300MVi some unique advantages in today's highly competitive MV drive market.
Input Transformer

Instead of requiring special 6KV class motor insulation, one of the ways the T300MV*i* addresses the neutral point shift problem inherent to voltage source drives, is utilization of an integral dual-purpose input isolation transformer. Motors generally have a much higher amount of inherent coupling capacitance (secondary neutral-to-ground) than does an isolation transformer, (as much as 150 times more). As explained earlier, when an input transformer is utilized (and the secondary neutral is not grounded), the vast majority of any common mode voltage produced, (neutral point shift) will be imposed (felt) on the transformer (instead of the motor) due to it's much lower secondary neutral-to-ground coupling capacitance.

This additional voltage stress imposed on the transformer is generally not problematic for two reasons; unlike a motor, transformers do not have slots (where the neutral point shift problem is most critical) and transformer winding insulation is generally rated for at least twice the normal voltage stress to ground.

IEEE-519-1992 Compliant

In addition to providing isolation to shift common mode voltage stresses away from the motor neutral, the T300MV*i*’s integral input transformer has multiple phase-shifted secondaries that provide a 24-pulse, (multipulse) input to the passive input rectifier section of it's main power circuit. The unique 24-pulse front end on the T300MV*i* creates harmonic cancellation which greatly reduces the amount of total harmonic distortion (THD) reflected back to the input power lines. Currently, the Toshiba T300MV*i* the only medium voltage drive on the market that is fully IEEE-519-1992 compliant, without additional optional equipment installed.
No Zero Sequence Voltage States

The phase-to-phase output of the Toshiba T300MVi is a cascaded, multi-step (5-step) PWM waveform that produces a very sinusoidal motor current, as shown below:

The T300MVi utilizes three power cells (one for each output phase) all having simplified schematics like the one illustrated below:
The output voltage signal of each of the three power cells (connecting to the three motor phases) are all referenced to the same power cell neutral, as illustrated below:

The output voltage signal of each of the three power cells, in respect to the power cell common is a 3-step, PWM waveform, as shown on the right:
As the output of each power cell is in itself, a multi-step PWM waveform (unlike the 2-step PWM utilized in low voltage drives), the problematic zero sequence firing states (K0 and K7) previously discussed, are unnecessary to allow the output PWM waveform to transition between its positive and negative polarities. Therefore, the T300MV i the algorithm utilized to create the PWM firing signal for the IGBT's is designed to avoid these states and thereby elude subjecting the motor neutral to the additional zero sequence voltage (neutral shift) they inherently create.

**Neutral Point Clamping**

In a cascaded power cell design, it necessary for all of the power cells to share a common reference that is in some way relative to their respective DC Buss neutrals. Therefore, in the T300MV i, each of the three main power cells are designed with a bridge circuit of neutral point clamping diodes, as shown below:

At any given point in time, one (or more) of the clamping diodes in at least one of the three power cells will be forward biased, "clamping" the power cell common line to within 0.7 volts of at least one of the power cell neutral (zero volt) references. As the power cell common (drive neutral) line (the voltage reference for all three output phases) is "clamped" to within 0.7 volts to one or more of the power cell neutrals by one (or more) of the clamping diodes, the phase reference for all three power cells remains consistent.

Therefore, by combining the attributes of an integral input isolation transformer a PWM algorithm that avoids zero sequence states and cascaded power cells whose neutrals are clamped together, the T300MV i minimizes neutral point shift within the motor to a point where it's effect is negligible, making it an ideal platform for retrofit applications.