Measuring Reflected Voltage Spikes in VFD Motor Applications

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Abstract: This article discusses the low voltage AC induction motor, when configured with modern adjustable speed/variable frequency drives. The article is focused on those that operate at or less than 600 volts. The widespread proliferation of adjustable speed/variable frequency drives has resulted in many process control improvements for industrial applications. These drives are generally used to very precisely control the rotational speed and direction of electric motors. In VFD applications, certain critical items such as cable length may not be allowed to vary, by the very nature of the plant, marine, or industrial layout. Therefore, testing for the existence of (and measurement of) these spikes typically requires deployment of an oscilloscope, with properly rated probes. An oscilloscope allows accurate measurement of any voltage spikes, and can help determine the effectiveness of any steps taken to mitigate them.

1. Introduction:

How many times have you been scratching your head, wondering why there are still electric motor failures at your facility? You might be seeing electrical failures, where the windings inside the motor burn out. You might be seeing bearing failures, where the bearings burn out. You might be seeing cable failures, where the insulation on a motor feeder cable goes bad. You have noticed that these problems seem to have one common item: they are occurring more often on your motors that are being controlled with ASD or Variable Frequency Drives.

You may not be seeing many problems in your motors in direct across the line applications. What could some of the differences be?

Having heard about reflected voltage spikes, and thinking your voltages may be too high, you have used your latest, high quality digital multi meter to make measurements of the voltages on your motors, and the meter displays them as in spec.

You have been periodically testing, using a nice, high quality Meg ohm meter to check the quality of the electric motor insulation, and have not noted any major insulation resistance anomalies. Yet, suddenly “Out of the blue” a motor may trip offline. The smoke tells the tale; another winding burned. Sometimes, during the trouble shooting, the drive appears to have gone down too. So it is pulled and sent out for repair. Now, you are down a VFD, the motor, and the time to get things running again.

You have been thinking about investing in a nice, high quality vibration analyzer, and thermal imaging camera, but know budgeting for that kind of expense takes time and politicking.

But you had to ask, even though you knew it would happen: Management asked you to look again at all your options, because they said “Money is tight”.

Is there any other way you can determine what is going on?

You start doing some research. You find some articles that talk about reflected waves. In these articles it sort of talks about using an oscilloscope to make measurements that can determine if reflected voltage spikes exist. They say an oscilloscope is the best way to do it.

So, now you realize that you had been doing at least a couple things wrong.

The first thing you were doing wrong was checking your voltage at the output of your drive. (Best to be checking it right at the motor terminals)

The second thing was that you were using your trusty digital multi meter. Even though it is one of the latest models, it simply is not designed to make measurements of the high frequencies that exist in the reflected waves. In fact it has a parameter on it called “Low pass filter” that helps it suppress the high frequency voltages. (You will need to make the measurements with a higher bandwidth device)

Maybe you already have some equipment in your tool inventory that will get the information you need. This article is intended to help you determine if you do, and how to proceed.

To understand a bit about the reflected wave phenomenon that contributes to these hidden surges, we will discus it next. Then, we will discuss proper methods and test equipment needed to make safe, successful, and accurate measurements of them.

2. The nature of the reflected voltage wave.

The phenomenon of electric wave reflection is nothing new. It is documented in the literature for electric motors, at least 80 years ago. In those days there were no VFD drives. But, there certainly were switching surges, bus transfers and lightning strikes. During early studies of high voltage transmission lines in the early 1900’s direct measurements were made for the first time of these electric surges. Observation of voltage reflections was then observed. They used oscillograph’s (early ancestor of the oscilloscope) to capture the waves. Steps for mitigating the most deleterious effects were invented and implemented. Examples of this would be surge arrestors and lightning rods or specifying an intermediate transformer between the AC mains and the motor.

When a very fast electrical transient occurs (i.e. VFD spikes, or lightning - for example) on a feeder cable to an electric motor or generator, it will travel along very, very rapidly, in the form of an electric wave front. When this wave front suddenly meets the phase terminals of an electric motor, something very different happens. A discontinuity occurs, i.e. an impedance mismatch. No longer is the voltage wave simply speeding forward down a transmission line. It now ‘sees’ the motor winding as a high impedance, approximating an open circuit. As the ‘bulk’ of the energy wave continues to move toward the motor coils, the first, leading edge bounces backward - towards the feeder cable. It is at this instant that the voltage ‘piles up’ and the resulting ringing reaches a much, much higher level. It could reach a crest of 2 x times higher than when it left the VFD output.

Analogy: think of an ocean wave approaching a sea wall. As the wave comes in, it strikes the wall. What happens? Some of the wave splashes high up in the air. The height of the splash (in some ways) is similar to the crest of the reflected voltage.

A significant difference between VFD and direct across the AC line applications is the relative amount and magnitude of surges. We all understand that lighting storms do not occur every day. We know bus transfers may not happen every day, and we know that direct across the line electric motor breakers are not switched on and off 1000’s of times per second. Lightning strikes, bus transfers and switching surges may have much, much higher magnitudes than VFD spikes.
But, they tend to occur a lot less often.

These days VFD use a technique called PWM (Pulse width modulation) to generate a series of current pulses several thousand times per second. These current pulses will approximate a sine wave if you measure them with a current transformer. The frequency of the current sine wave will directly determine the rotational speed of the induction motor shaft. This is known as the *fundamental* frequency. Your VFD control panel will generally indicate this for you, say 55Hz (as an example)

Each current pulse has a voltage spike associated with it. These voltage spikes travel down the power cables to the motor and in a similar way to the above examples – they may pile up across the motor terminals. These spikes occur at what is known as the *carrier* frequency. This could 5,000 or more spikes per second. The effect of VFD surges could be likened to the old example of “death of a thousand cuts” No single VFD effect instantly zaps a motor, cable or bearing. It is the cumulative wear effects of the carrier surges and associated phenomena we are concerned with. How do we actually measure them safely using an oscilloscope?

3. Measuring VFD spikes using an oscilloscope.

Now that we have some understanding of the high speed and high frequencies of the VFD spikes, we know that our digital multi meter will simply not be able to make an adequate measurement. It is the technician’s right hand, but just not designed to do that. So, we will use an oscilloscope, as they have the very good high frequency response needed.

There are several critical items we need to consider for making accurate, and most importantly – *SAFE* measurements of reflected voltage wave transients.

A) What is the voltage rating of your oscilloscope probes? They must carry a rating of at least 1000V and even better, CAT II or III or IV. Look for these ratings in the tech specs. Fluke®, Tektronix® and other vendors have acceptable probes. If you do not see acceptable ratings, do not use the probes, period.

B) How many channels does our scope have? The most capability would be if your scope has 4 input channels. This would allow true, simultaneous measurements of all 3 phase to phase voltages in a typical VFD drive applications. It is possible to make measurements using a lower amount of channels, (say 2 channel) if that is all you have.

C) Is our scope safe to “float” without a chassis ground? Remember, we are making measurements of signals that could approximate 1000V. It is important that we make the measurements safely. If the scope is plugged into 115 V AC mains, the scope will be ground referenced to 115V AC mains ground. This could contribute certain measurement errors, as the VFD output is actually synthesizing 480V three phase power. What to do?

We could “float” the scope using a cheater plug…If you have an oscilloscope with a metal chassis, this has some important considerations. For example, you could find that full mains voltage appears on the metal chassis of your scope. This is not recommended by this author. If you do this and make a mistake, you won’t like what happens…

Or, leaving the oscilloscope plugged into proper earth ground, we can use a special type of oscilloscope probe called a “Differential high voltage probe” to cancel this effect. (The downside of using a differential probe is that they generally are expensive, and much larger than optimal.)

Or, we can use an oscilloscope that is rated for use without a chassis ground. This type of scope chassis and all controls are generally made of plastic, rubber, or other insulating material. Inside, it is designed with special high levels of voltage isolation. This way, the operator of the scope is protected from voltages being measured. Fluke®, and certain other vendors have acceptable Oscilloscopes for this type of measurement. Check the ratings carefully.

D) We need to make a phase to phase measurement. The reason is that the greatest peak to peak electric stress from reflected wave voltage generally occurs between phases.
As far as the motor insulation is concerned – this voltage stress really matters.

E) We can also make a phase to ground measurement. The phase to ground measurement is important as well. In this measurement, we simply measure from the 3 phases of the motor, directly to the motor frame.

4. Go to the motor, and prepare to make safe measurements of reflected waves.

While you may be tempted to try and make your measurements of the reflected voltage waves at the output of your VFD, it is likely that you will not get the information you need. The pulses that are leaving your VFD output transistors are probably going to be quite square, with sharp edges. It might be good to learn for training purposes, but you need to get information about exactly what is going on at the motor terminals.

By the time the pulses from the VFD propagate all the way down the feed cables to the motor, the reflections will alter their pulse shapes, and 'pile up' voltage against the motor phase terminals. This effect has been known to develop a non linear voltage drop across the turn to turn insulation system. This distortion and voltage distribution is from the reflection phenomena.

Being sure to follow your plant safety procedures, don your PPE gear as well.
You will need to make you way to the motor terminals. When you get there, you will need to get access to the motor terminal leads. This will probably mean you will need to remove the cover of the motor connection box. It's likely you will need to arrange to power off the motor and drive, depending on your company policies.

If you find that you have IEC type connectors, the measurements may be relatively straightforward to implement. The terminal posts can make convenient connection points for the oscilloscope probes. If screened or shielded cables have been implemented as part of the VFD installation, take care to avoid damaging them. Pay attention to the grounding around the cable screens. It is important they are as short as reasonably possible.

If instead, you find a monster ball of tape wrapped around each of the phase terminals, you will be facing a bit more work. After doing your best to remove a reasonable amount of tape, you might be able to make some measurements. Care must be taken to prevent inadvertently causing a short circuit. For example; you might need to temporarily set up the connections with some nice 3M™ Motor Lead Connectors. Then, when done you will be able to finish off the work with the 3M™ covers, - and without the tape balls.

Anyway, what will be done is a group of differential measurements. With your properly rated "floating" scope in hand, connect the 3 x floating clips as shown in the example drawing.

You should be able to capture traces on your O'scope that show the differential voltages across Phase 1-2, 2-3 and 3-1. This is what will get the voltage measurements you need. Do not be surprised if you measure 1000 volts peak to peak (or more) across your motor terminals! This is the effect you were trying to confirm.

Now that you found it, and it is real, what to do?

Make records of the waves, and the peak-peak voltages if possible. Repeat for phases to ground. You will need them later, to determine the effect of any mitigation steps. You will have to be able to connect both the probe inputs, and the grounds to each other.

The illustrations below might help you if you have any questions.

5. Summary.

The technical steps that are discussed in this article are needed for verification of the existence, and voltage level of reflected voltage spikes. Once they are verified, the best plan is to keep copies of these high frequency waves, and the phase-phase and phase-ground voltages. These copies can be used for later reference. Modern storage oscilloscopes make short work of the once tedious process of saving your test data.

Reasonable steps that might be implemented to mitigate ill effects of reflected voltage surges could include installing line reactors, sine filters, cable terminators, placement of an isolating transformer, shaft grounding brushes, insulated bearings, or simply making sure that electric motors exposed to VFD control carry a manufacturer's *inverter* rating.

It was not the intent of this particular article to describe the many different possibilities for low voltage motor reflected wave mitigation. That may be in a future article. However, it was the intent to provide guidance towards safely and accurately being able to verify the existence of reflected voltage waves.

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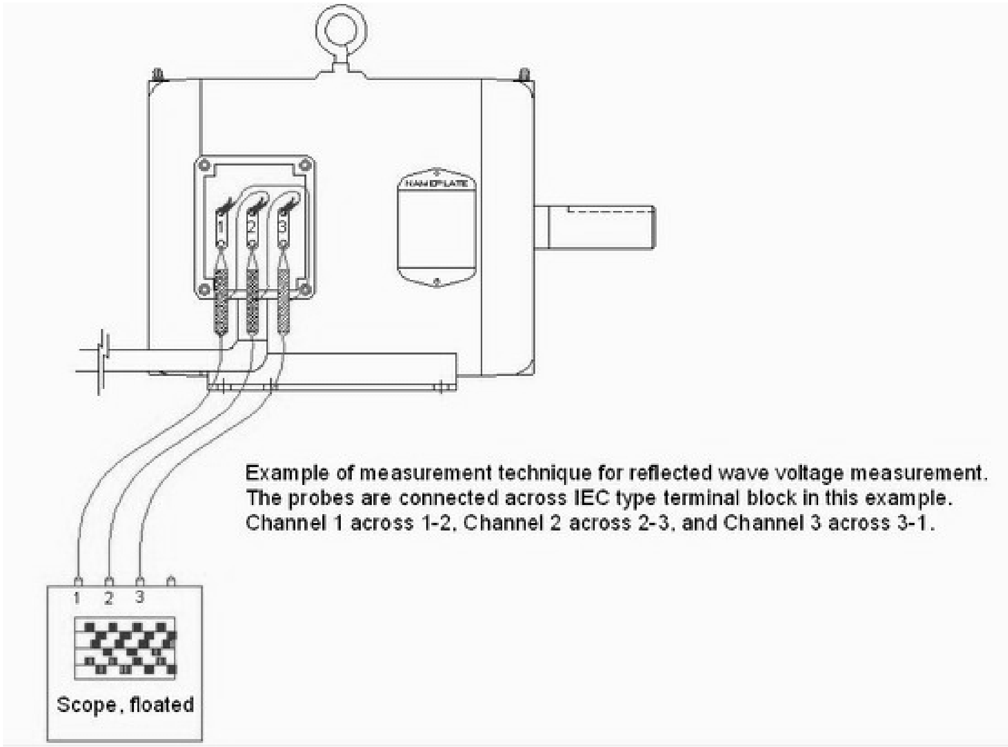
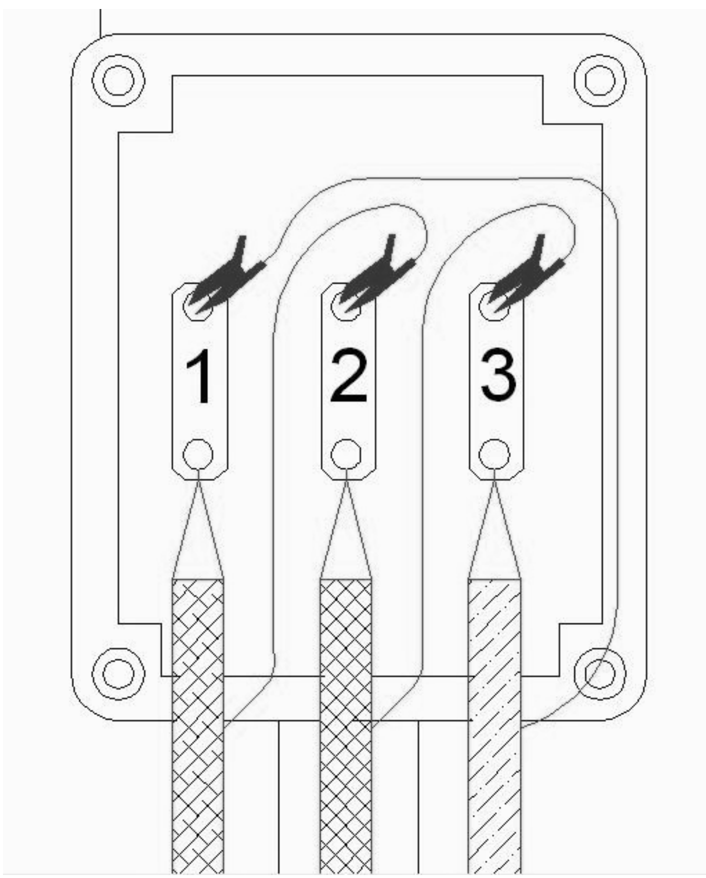

NAMEPLATE
1
2
3
Example of measurement technique for reflected wave voltage measurement.
The probes are connected across IEC type terminal block in this example.
Channel 1 across 1-2, Channel 2 across 2-3, and Channel 3 across 3-1.
1 2 3
Scope, floated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