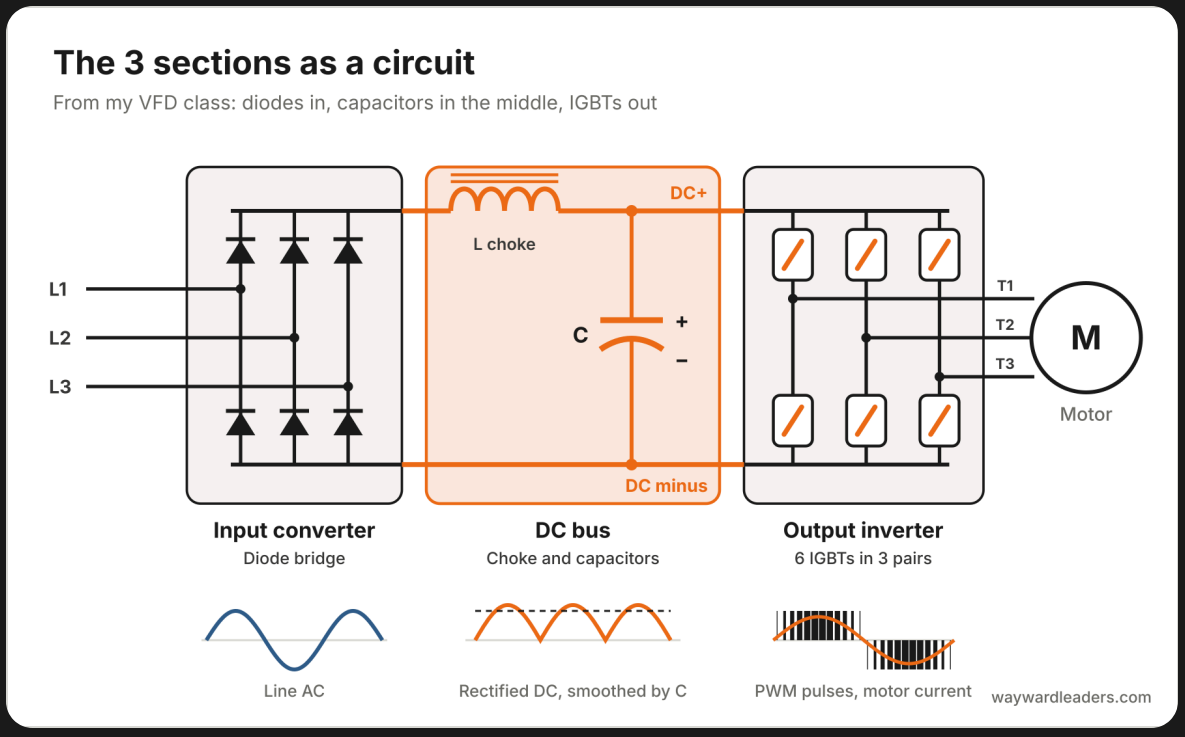
Wayward Leaders®
VFD Training & Reliability

FREE FIELD GUIDE

What Is a VFD?

The basics from my VFD class: what a drive does, what is inside it, how it makes speed, and when the motor in front of you needs one.



Dr. Carl Lee Tolbert
Wayward Leaders | waywardleaders.com

Before you start

This guide is the opening of my in-person VFD class, written down. It covers the same ground in the same order, so you can read it before a class, after one, or in place of one.

What is in it

1. Get your motor running: 3 common ways
2. All the names, and a definition
3. What every VFD does
4. Volts per hertz
5. The 3 sections inside every drive
6. How the drive makes speed: slice, squeeze, squirt
7. Only 4 kinds of load
8. Control arrangements
9. Parts of a VFD, the panel and the system
10. Checking the 3 sections with a meter
11. What a drive costs the motor and the building

Safety first

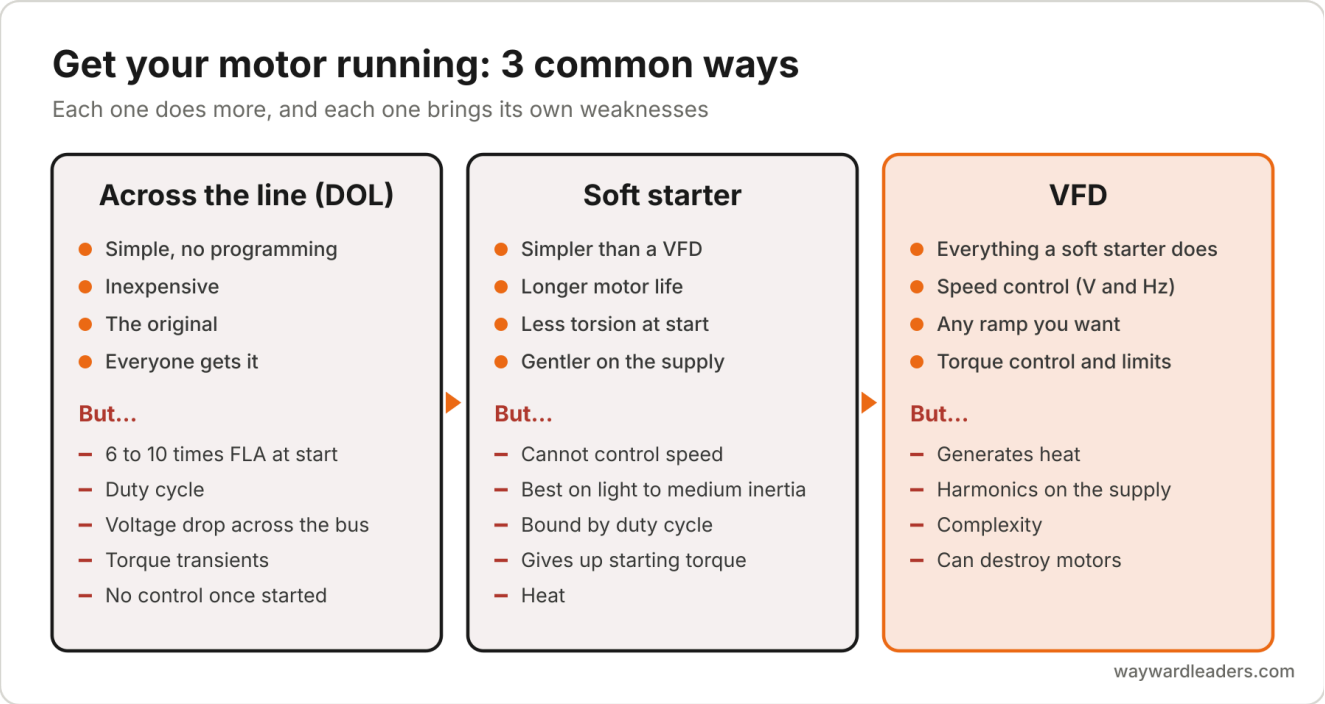
Construction trades and installation, maintenance and repair workers are the 2 groups that suffer the most fatal electrocutions at work. Electrical hazards kill more than 300 and injure about 4,000 U.S. workers every year.

Drive work is for a qualified person: someone with the skills and knowledge to work on the equipment and the safety training to recognize and avoid its hazards. Before you touch a drive:

- Disconnect every power source and verify it visually where you can.
- Follow your approved lockout and tagout procedure.
- Identify all power sources from the drawings and documents.
- Wear the PPE your arc flash study calls for.
- Wait the discharge time on the drive's label, then prove it dead with a meter. A drive's DC bus capacitors hold a charge after the power is off.
- Follow NFPA 70E.

1 Get your motor running: 3 common ways

There are 3 common ways to start an AC motor. Each one does more than the last, and each one brings its own weaknesses.



Across the line (DOL)

The original. A contactor and an overload, simple, inexpensive, no programming, and everyone gets it. The weaknesses show up at start: the motor pulls 6 to 10 times its full load amps, the voltage sags across the bus, the motor slams the load with full torque, and once it is running there is no control at all. It is also bound by how many starts an hour the motor can take.

Soft starter

Ramps the voltage up at start so the motor and the machine see less shock. Simpler than a drive, easier on the motor and the coupling, and gentler on the supply. It cannot control speed, it works best on light to medium inertia, it is bound by a duty cycle, it gives up torque at start, and it makes heat while it ramps. Once the motor is up to speed it runs on the line.

VFD

Everything a soft starter does, plus control of voltage and frequency the whole time the motor runs. That means speed control, any ramp you want, and torque control and limits. The bill that comes with it: drives make heat, put harmonics on the supply, add complexity, and can destroy motors when the install is wrong.

2 All the names, and a definition

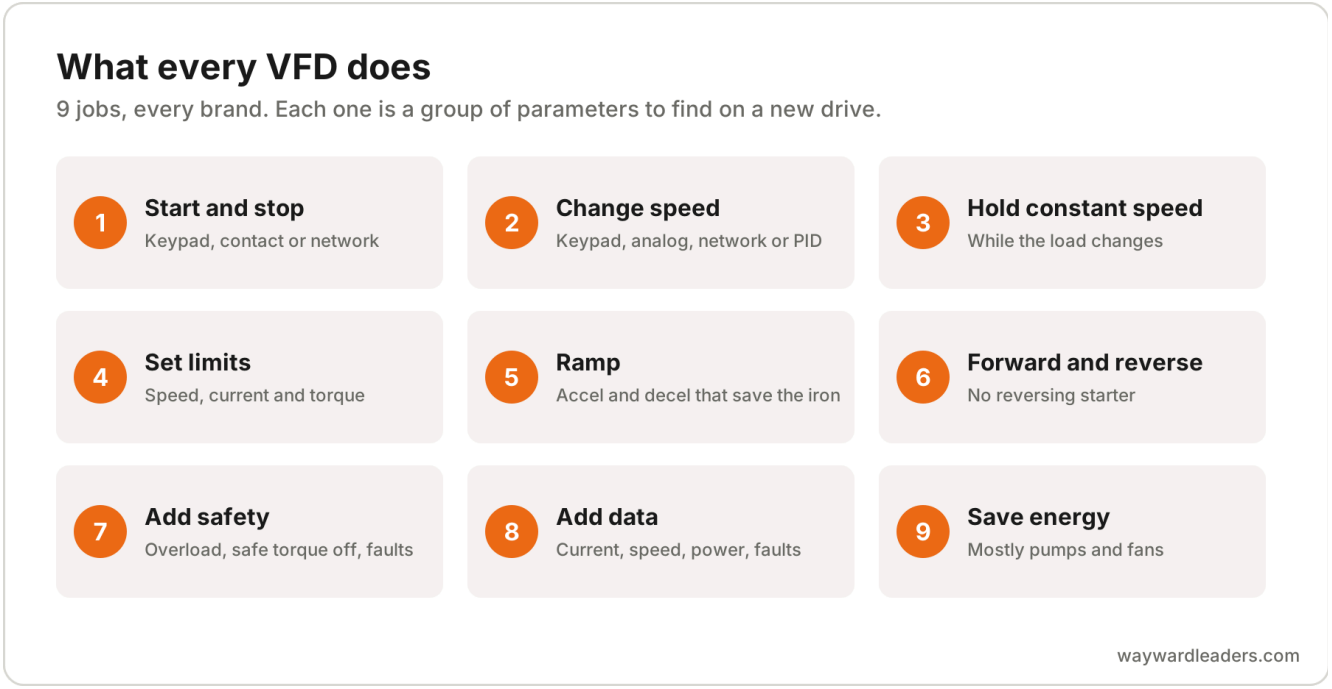
You will hear this box called an adjustable frequency drive (AFD), an adjustable speed drive (ASD), a variable speed drive (VSD), a frequency converter or an inverter. In the U.S. the industry settled on variable frequency drive, or VFD, and that is the name this guide uses.

> **Very simply stated, the variable frequency drive controls the motor so that it may be run at very low speeds, very high speeds or anywhere in between.**
>
> LARRY STANLEY

It is the definition I use in class. It holds up because it says what the drive is for before it says what is inside it. The drive does that by changing 2 things the motor sees: the frequency, which sets the speed, and the voltage, which goes up and down with it.

3 What every VFD does

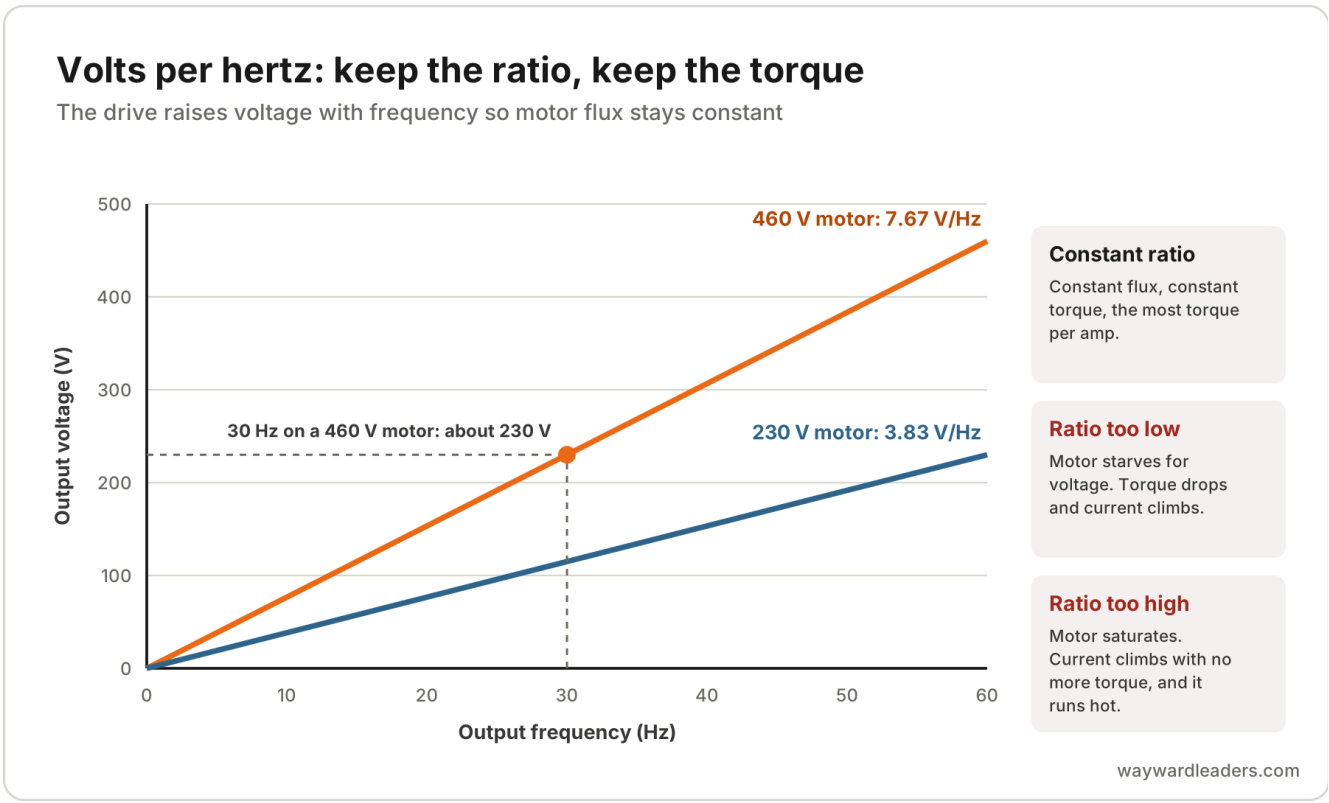
Strip away the brand, the keypad and the menu tree, and every drive does the same short list of jobs. Each one is a group of parameters you will go looking for, which is how you learn a new drive fast.



Function	What it means on the job
Start and stop	From a keypad, a hardwired contact or a network command.
Change speed	From a keypad, an analog signal, a network or a PID loop.
Constant speed	Holds the speed while the load changes around it.
Limits	Minimum and maximum speed, current limit, torque limit.
Ramping	How fast it speeds up and slows down. This is what saves the coupling, the belts and the pipe.
Forward and reverse	Changes direction with no reversing starter.
Add safety	Motor overload protection, safe torque off, and a long list of faults that stop the motor before something breaks.
Add data	Current, voltage, speed, power and a fault history. Often more information about the motor than the plant has anywhere else.
Save energy	On loads where the power falls with speed, mostly centrifugal pumps and fans.

4 Volts per hertz

The drive moves voltage and frequency together so the motor's magnetic flux stays right. The ratio comes straight off the nameplate.



- **460 V, 60 Hz motor:** 460 divided by 60 is about 7.67 V/Hz. At 30 Hz the drive gives it about 230 V.
- **230 V, 60 Hz motor:** 230 divided by 60 is about 3.83 V/Hz.
- **Frequency sets speed:** a 4 pole motor runs about 1,800 rpm at 60 Hz and about 900 rpm at 30 Hz, a little less for slip.

Why the ratio stays constant

1. A constant V/Hz ratio gives constant motor flux.
2. Constant flux gives constant torque.
3. That gives the most motor torque per amp.

Too low a ratio

Flux drops, so torque drops. The motor starves for voltage, and the current climbs trying to make up for it.

Too high a ratio

The motor saturates. Current climbs with no more torque to show for it, and the motor overheats.

What you will see with a meter

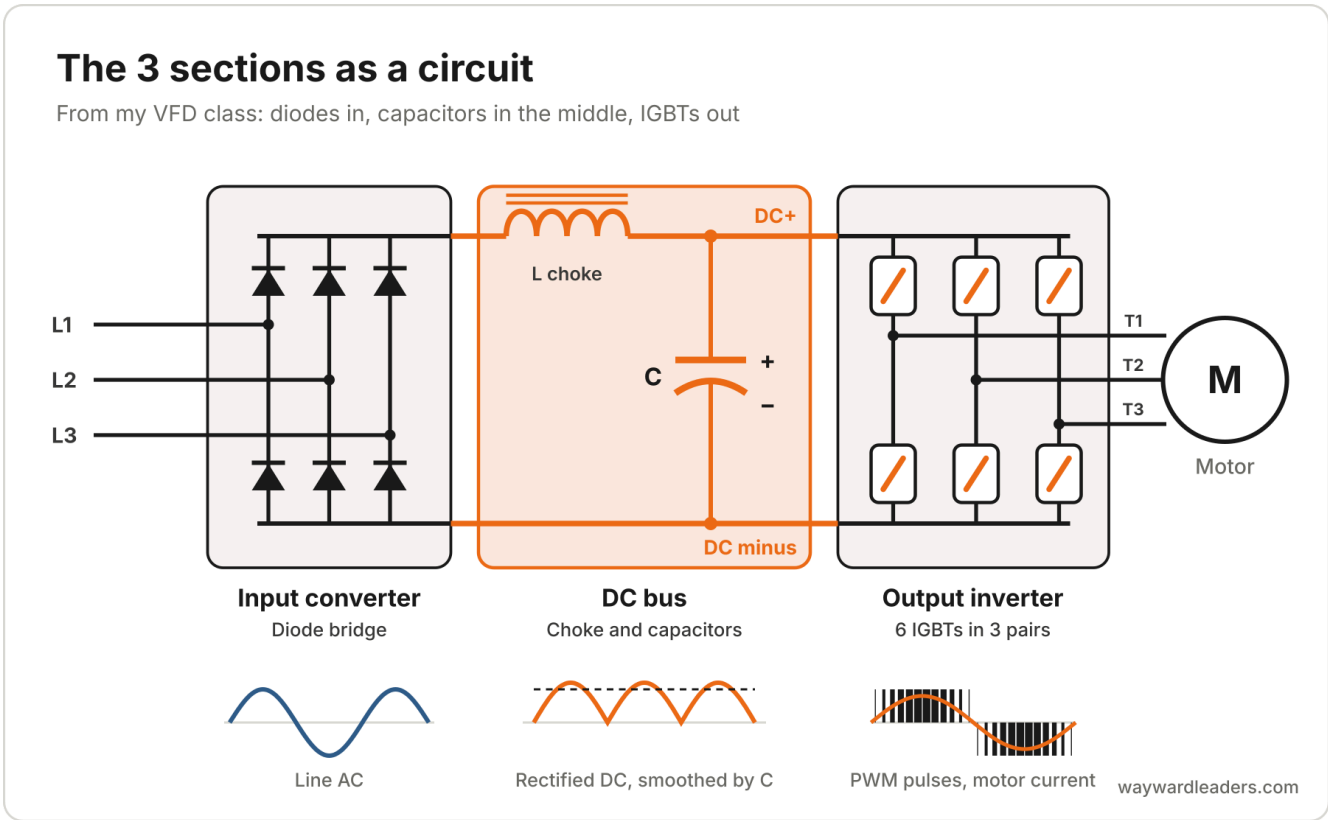
The line on the chart is the idea. Real drives bend it at both ends.

- **Below about 1.5 Hz,** the drive adds extra voltage, called boost, so the ratio climbs to about 5 to 15 V/Hz. That lets the motor make torque near zero speed.
- **At 60 Hz on a 460 V motor,** a meter made for drive outputs may read about 448 V, or about 7.46 V/Hz, a little under the nameplate. A regular meter can read a PWM output wrong.

Sensorless vector and closed loop vector modes do the same job with a motor model, plus an encoder for closed loop, and they hold torque better at low speed. Every mode depends on accurate nameplate data going into the drive.

5 The 3 sections inside every drive

Open any standard 6 pulse drive from any maker and you will find the same 3 sections in the power circuit: AC to DC to AC. Knowing them is what lets you troubleshoot a drive you have never seen before.



The 3 sections as a circuit, from my VFD class. Under each section is what the voltage looks like there: line AC, rectified DC before the capacitor smooths it, and PWM pulses to the motor. L is the DC choke, C the capacitor bank.

1. Input converter

A diode bridge on the input terminals, marked L1, L2 and L3 or R, S and T. It turns incoming AC into pulsing DC. Most drives use a 6 pulse bridge, which is also where a drive's harmonics come from: it pulls current from the line in short, sharp gulps.

2. DC bus

A bank of capacitors that smooths the DC and stores it. On a 480 V supply the bus sits at about 650 VDC with the drive running, roughly 1.35 times the line voltage, and a little higher at light load. On a 230 V supply it is about 310 VDC. Many drives also carry a DC choke here to soften the input current.

3. Output inverter

Six IGBTs on the output terminals, marked T1, T2 and T3 or U, V and W. The circuit shows how they are wired: 3 pairs, one pair for each motor lead. The top IGBT in a pair connects its lead to DC+, and the bottom one connects it to DC minus. The control board never turns on both in the same pair at once, because that would short the bus.

The inverter switches each lead between DC+ and DC minus thousands of times a second, with the 3 pairs timed apart, and that builds 3 phases of new AC at whatever frequency the drive is told to make. What leaves the drive is a train of full bus voltage pulses, the waveform at the bottom right. The motor's windings smooth the current into something close to a sine wave. Those sharp pulse edges are why a meter can read the output oddly, and why the cable and the motor insulation see stress a line started motor never sees.

The control board watches all 3 sections and trips the drive when something goes outside its limits. Most fault codes you will ever read are that board telling you which section it was protecting.

6 How the drive makes speed

The inverter makes square pulses of full bus voltage and varies how wide they are. In the motor's windings those pulses add up to a current that looks close to a sine wave. That is pulse width modulation, PWM, and I teach its 3 settings as slice, squeeze and squirt.

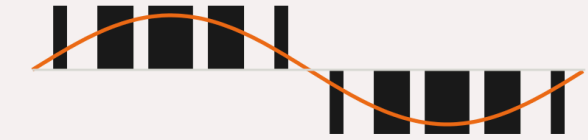
Slice, squeeze, squirt: how a VFD builds AC from DC

Black bars are the switch pulses. The orange line is the AC the motor feels.

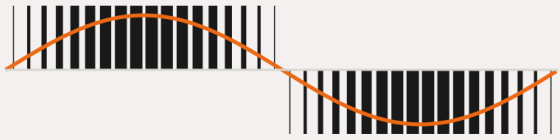
Slice

Carrier frequency

How many times a second the IGBTs slice the DC bus. More slices, smoother wave.



Few slices: rough wave

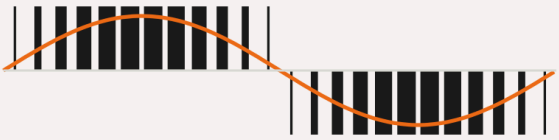


More slices: smoother wave

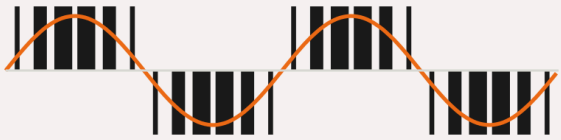
Squeeze or stretch

Fundamental frequency

Squeeze the pattern and frequency (speed) goes up. Stretch it and it comes down.



Stretched: lower frequency

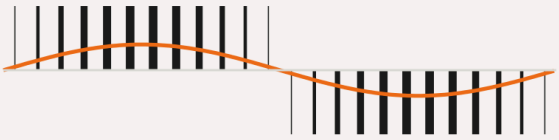


Squeezed: higher frequency

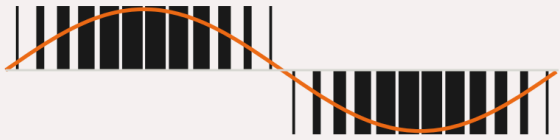
Squirt

Modulation index

How long the switch stays on in each slice, like a hose on or off. Longer squirt, more voltage.



Short squirts: lower voltage



Long squirts: higher voltage

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Slice

Carrier or switching frequency, commonly 2 to 16 kHz. Sets the quality of the waveform. More slices run smoother and quieter at the motor, and hotter in the drive, with more noise into the cable and bearings.

Squeeze

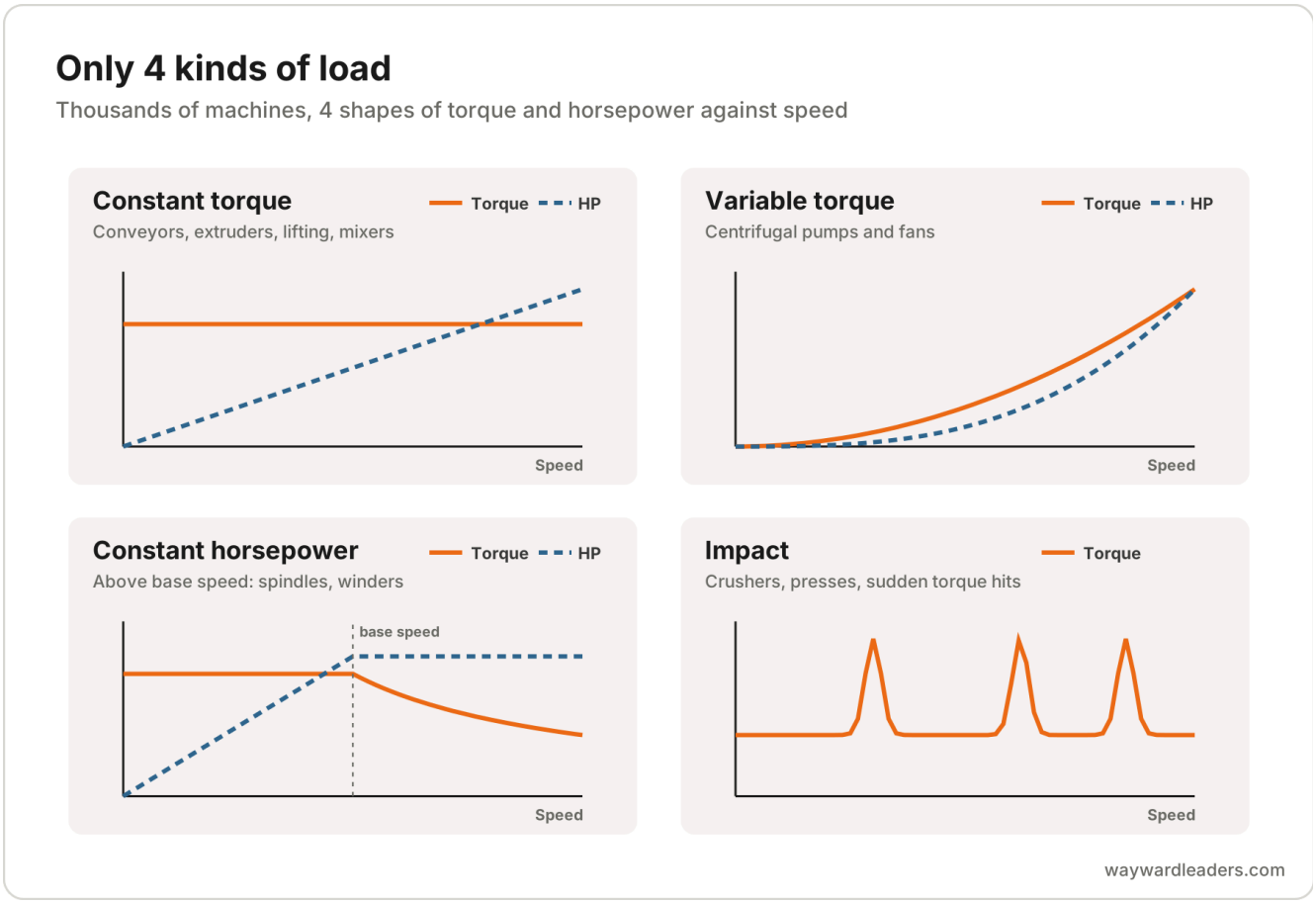
Fundamental frequency. Squeeze the pulse pattern together and the output frequency goes up. Stretch it out and it comes down. This sets motor speed.

Squirt

Modulation index. How long the switch stays on in each slice, like a hose that is on or off. A longer squirt puts out more voltage.

7 Only 4 kinds of load

There are thousands of versions of driven equipment, over 2,000 by my count, and only 4 kinds of load. The kind decides what the drive has to do.



Load	How it behaves	Examples
Constant torque	Same torque at every speed. Horsepower rises in a straight line with speed. Drives earn their place on control, ramps and starting torque.	Conveyors, extruders, lifting equipment, rolling mills, planers
Variable torque	Torque rises with the square of speed, horsepower with the cube. 80 percent speed needs about half the power. This is where drives pay for themselves.	Centrifugal pumps, fans, blowers, centrifuges
Constant horsepower	Above base speed, in field weakening, torque must fall as speed climbs. The motor decides how fast you can go.	Spindles, grinders, routers, winders, test stands
Impact	Sudden torque spikes. On a punch press the drive and motor must bring the flywheel back to speed before the next stroke. Size for the peaks.	Presses, crushers

A drive is the wrong call when the motor runs at full speed all the time and only needs a gentler start. A soft starter does that job with less money and complexity.

8 Control arrangements

The same drive can be wired and set up to take orders in several ways. Knowing which one you are looking at is half of troubleshooting a speed problem.

Local or hand
Run from the keypad on the drive.

Remote or auto
Run from a PLC, a switch, an analog signal or a network.

Multi-motor
One drive running more than one motor. These run in scalar (V/Hz) mode.

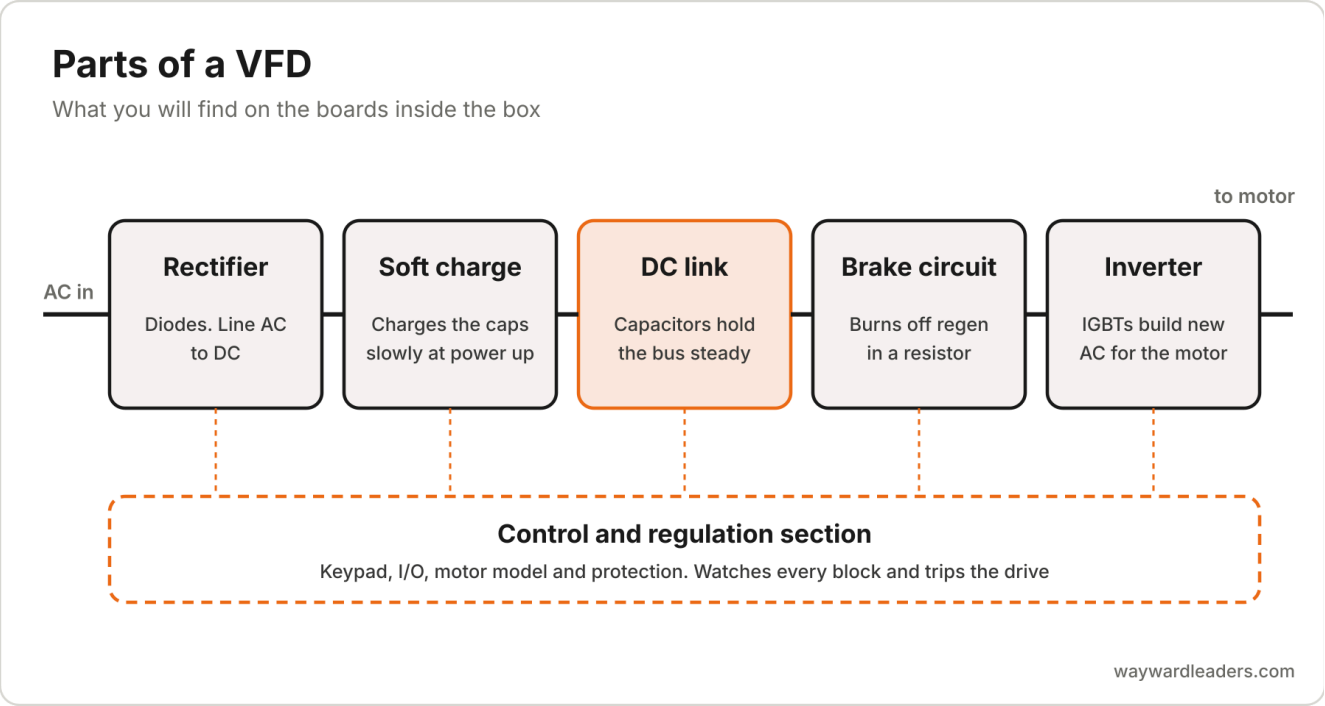
Lead and follower
One drive sets the speed or torque and others follow it, as on a line with several sections.

Closed loop or PID
The drive holds a process value, such as pressure or level, by changing speed.

Cascade
One drive and its loop controlling more pumps or fans, bringing them on and off as demand changes.

9 Parts of a VFD, the panel and the system

The 3 sections are the power path. On the boards you will find a few more parts.



- **Rectifier:** the diodes of the input converter.
- **Soft charge circuit:** charges the bus capacitors slowly at power up so the inrush does not take out the diodes or the fuses.
- **Intermediate circuit (DC link):** the capacitors, and the choke where there is one.
- **Brake circuit:** where fitted, dumps regenerated energy into a resistor when the load drives the motor, such as a fast stop on a heavy fan.
- **Inverter:** the IGBTs that build new AC.
- **Control and regulation section:** the keypad, the I/O, the motor model and the protection.

The drive is part of a control panel

In the field the drive sits in a panel, and the panel decides much of how long it lasts. Expect to find pilot devices, grounding and bonding, cooling, control power, a main surge protective device (SPD), main fuses and, on many jobs, a bypass.

The panel is part of a larger system

And the panel serves a machine. On an extruder line the drive works with the operator panel, the main controls, the safety system, the motor and gearbox, the screw, the barrel heaters, the cooling blowers and the batch feeder. When the drive faults, the cause can be anywhere in that system.

Why this matters

We expect 3 things from a drive install: reliable performance, a long life (published drive life runs 100,000 to 200,000 hours), and safe operation. Installations have cumulative effects. Small misses add up, and they show up later as faults.

10 Checking the 3 sections with a meter

When a drive is dead or won't come out of a power fault, the 3 sections give you an order to work in. Lock out and tag out first, and treat the bus as live until you have measured it.

1. **Prove the bus is dead.** Wait the discharge time on the drive's label, then measure DC volts across DC+ and DC minus. Open nothing else until that reads near zero.
2. **Check the input converter.** On diode test, read from each input terminal to DC+ and to DC minus, both directions. A good diode reads a few tenths of a volt one way and open the other. All 3 phases should read alike. One that reads short or open is your failed diode.
3. **Check the output inverter.** Do the same from each output terminal. A shorted IGBT usually reads near zero both ways on one phase.
4. **Check the bus under power.** It should sit near 1.35 times the line voltage at idle. Low, or rippling badly under load, points at a missing input phase or tired capacitors.
5. **Check the output under load.** Output current on all 3 phases should balance within a few percent. Balanced output and still tripping usually points at the motor, the cable or the load.

The manual for the drive in front of you wins over anything general. The order above stays the same from brand to brand.

11 What a drive costs the motor and the building

A drive does all the good a soft starter does and a lot more, and it brings a bill: it can destroy motors, it makes heat, it puts harmonics on the supply, and it adds complexity. None of those are reasons to avoid drives. They are reasons the install matters more than the brand.

- **Motor windings.** The fast pulses put voltage spikes on the windings that a line started motor never saw. Buy motors rated for drive duty.
- **Bearings.** The same pulses push common mode current through the motor bearings when the cable and grounding give it no way home.
- **Cable.** The cable between drive and motor stops being ordinary wire. Use VFD cable and land the shield right.
- **Heat.** Every drive gives off heat that the enclosure has to get rid of.

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Where to go next

This guide is the start. Here is the rest, most of it free.

Watch the video

The same lesson, narrated, on the Wayward Leaders YouTube channel.
youtube.com/watch?v=4G2Lf8KTaLs

Take the free class

What Is a VFD, with short quizzes, on The Tolbert School.
tolbertschool.com/vfds

First Power, No Surprises

Free class on installing a drive right before the first power up.
tolbertschool.com/vfds

Read the field note

What Is a VFD and How Does a VFD Work, with links to cable, bearings and motors.
waywardleaders.com/field-notes/f/what-is-a-vfd-and-how-does-a-vfd-work

Before the First Fault

My book on drive installation and commissioning, free inside every paid VFD course.
waywardcarl.gumroad.com/l/before-the-first-fault

VFD Undercurrents

My biweekly VFD newsletter. Sign up at the site.
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This guide is general training material. It does not replace the drive maker's manual, your site's electrical safety program, NFPA 70E or the NEC. Work on drives only if you are qualified and authorized to do so. Figures are teaching drawings. Pulse counts and widths show the idea, not a real carrier frequency.

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