AC loads controlled via digital circuits

On/off, also known colloquially as "bang-bang" control.
This is like driving a car with the requirement that your foot is all the way down or all the way up on one of the peddles, never in the middle. This works pretty well for things that have long time constants such as a heating load.

This type of control is usually achieved with some type of relay or contactor, maybe a series of them.
Relays operate asynchronously to the AC current. They may switch at any time in relation to the current.
There is a need for fly-back suppression, but diodes don't work because it is an AC situation. Usually a series RC network is put across the switching device. https://www.illinoiscapacitor.com/pdf/Papers/RC_snubber.pdf

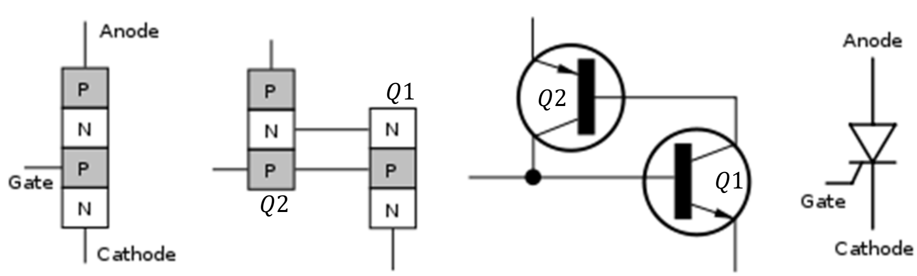
In order to get more sophisticated switching we need to first investigate solid-state switching devices. We start with. . .

Silicon controlled rectifier

1

AC loads controlled via digital circuits

Silicon controlled rectifier (SCR)
This is a single crystal of silicon (actually, any semiconductor) with four layers built into it, npnp.
It acts like two transistors that trigger each other.
Suppose both $Q1$ and $Q2$ are off. Then $Q1$ will keep $Q2$ off and, unless current is injected at the gate, $Q2$ will keep $Q1$ off.
Suppose a little gate current is provided. That turns $Q1$ on and $Q1$ turns $Q2$ on which latches $Q1$ on, etc.
The SCR will stay on until Anode-Cathode current is stopped by some other process.
In AC circuits, the reversal of the powerline current means that every 1/120'th of a second the SCR will switch off.
The goal of operation becomes control of the RMS voltage (and current) via wave shaping.

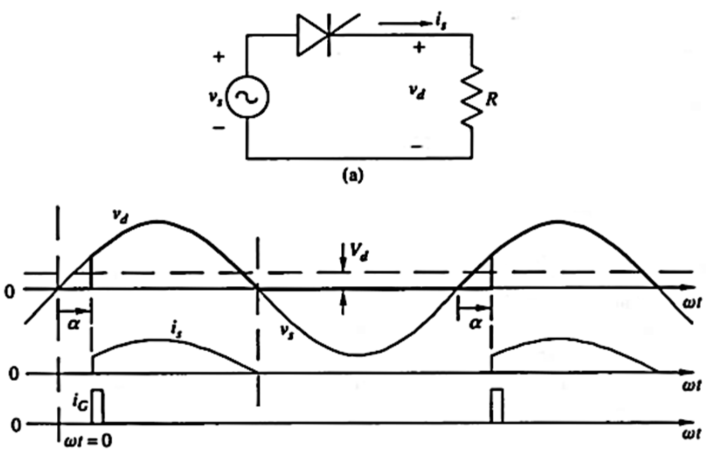


https://commons.wikimedia.org/wiki/File:Thyristor.svg

2

AC loads controlled via digital circuits

The goal of operation becomes control of the RMS voltage (and current) via wave shaping.
The SCR needs to be triggered on once per cycle at a particular angle through the cycle.
As shown, 0 to 50% of the AC voltage (or current) can be obtained by wave shaping.

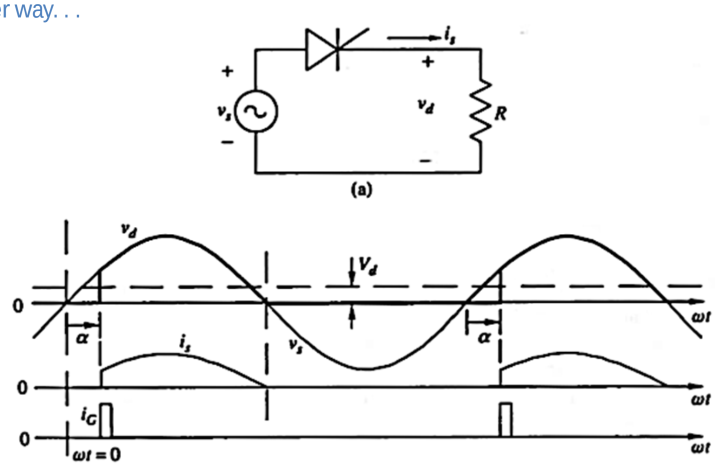


https://commons.wikimedia.org/wiki/File:Simple_scr_circuit.png

3

AC loads controlled via digital circuits

The goal of operation becomes control of the RMS voltage (and current) via wave shaping.
The SCR needs to be triggered on once per cycle at a particular angle through the cycle.
As shown, 0 to 50% of the AC voltage (or current) can be obtained by wave shaping.
One may add a second SCR to control the other half of the wave, thus obtaining 0 to 100% range of control.
But there is a better way. . .

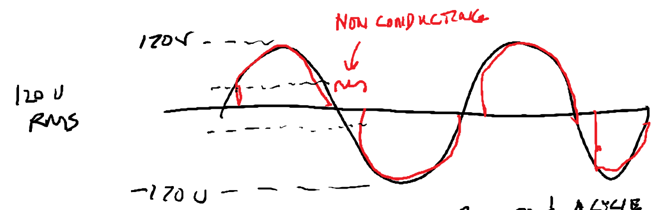


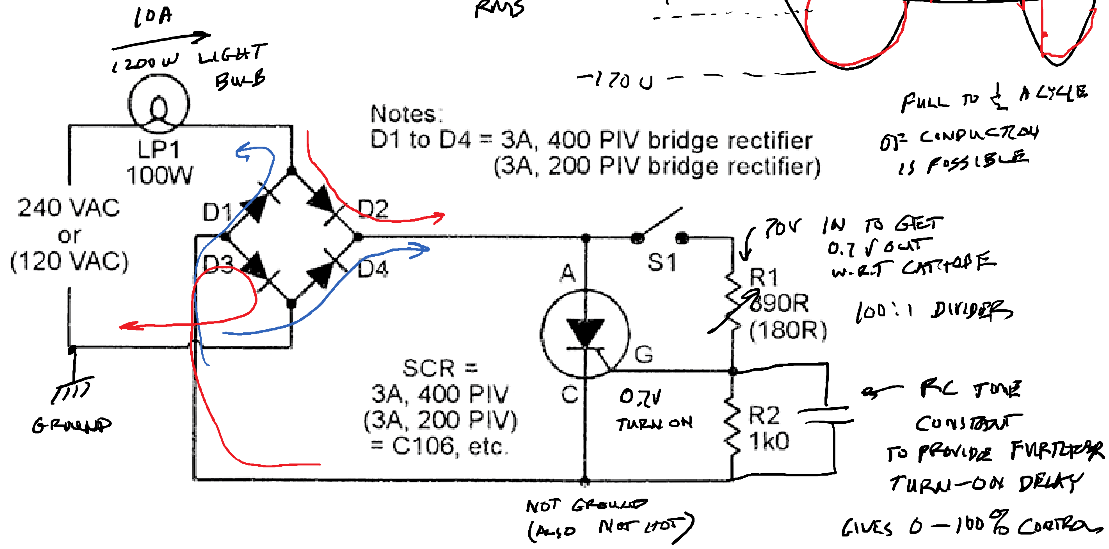
https://commons.wikimedia.org/wiki/File:Simple_scr_circuit.png

4

AC loads controlled via digital circuits

A bridge rectifier can extend one SCRs control to both halves of the waveform.

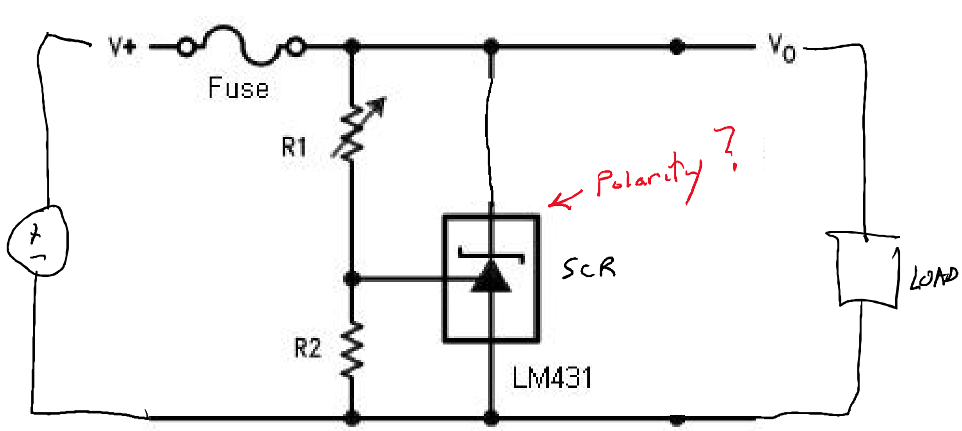




http://www.nutsvolts.com/uploads/wygwam/NV_0102_Marston_FIG4.jpg

5

Sort of unrelated. . . ***Crowbar protection*** of a power device. (Another application of an SCR)
Protection from high voltage. When tripped it causes the fuse to blow.



https://commons.wikimedia.org/wiki/File:Crowbar_Circuit.jpg

6

<u>AC loads controlled via digital circuits</u>
The idea of an SCR can be extended to a device that by itself can control both halves of an AC waveform.

The “super SCR” is actually called a. . .

Triac

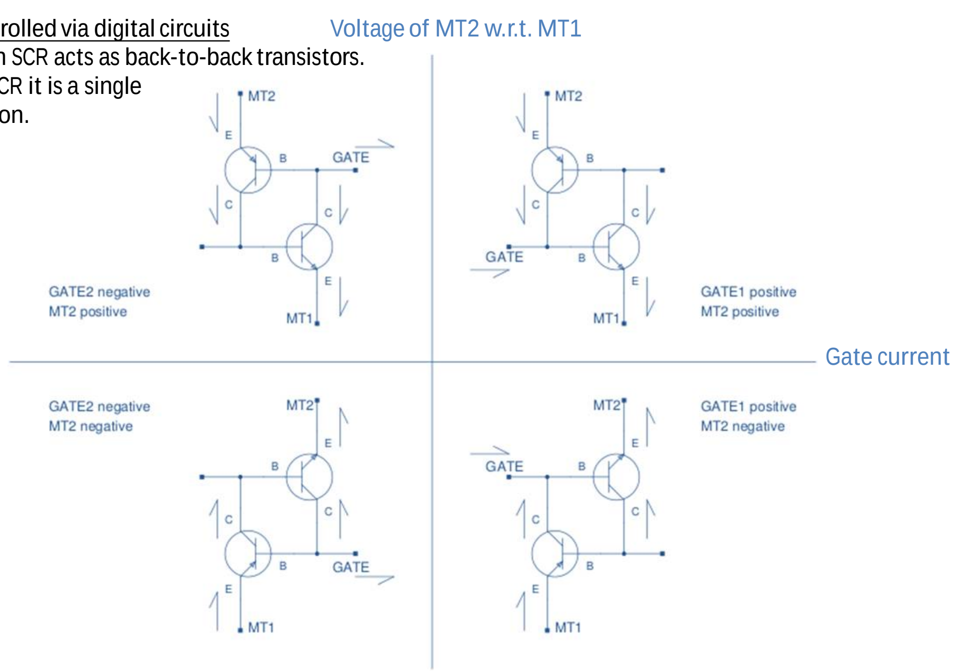
Two back-to-back SCR’s if you will, but actually it is more complicated than that.
Used for switching AC loads under the control of a DC logic pulse.

See Wikipedia
https://en.wikipedia.org/wiki/TRIAC

See also Teccor Application Note 1001
http://www.littelfuse.com/~/media/electronics/application_notes/switching_thyristors/littelfuse_thyristor_fundamental_characteristics_of_thyristors_application_note.pdf.pdf

7

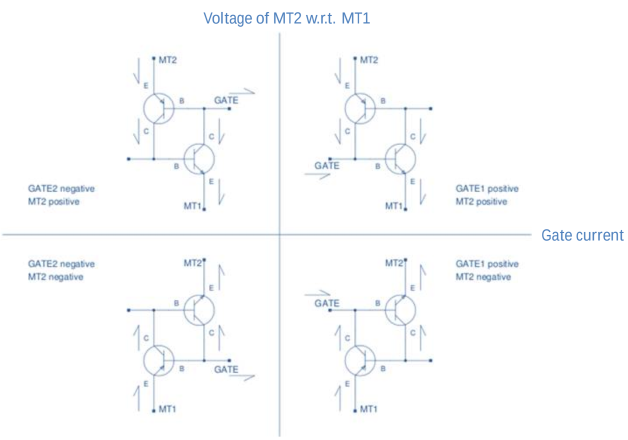
<u>AC loads controlled via digital circuits</u>
A Triac, like an SCR acts as back-to-back transistors.
And, like an SCR it is a single crystal of silicon.

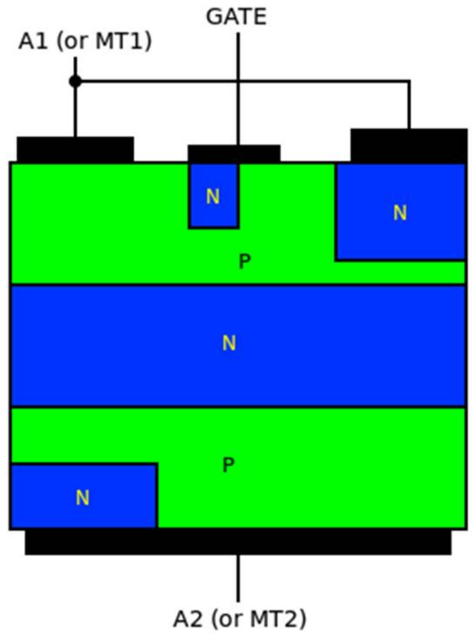


https://commons.wikimedia.org/wiki/File:TRIAC_Equivalent_Circuit.png

8

<u>AC loads controlled via digital circuits</u>
A Triac, like an SCR acts as back-to-back transistors.
And, like an SCR it is a single crystal of silicon.
Here is the physical structure.
It operates in *4-quadrants.*
It is similar to two SCRs but has only one gate—easy to control.





https://commons.wikimedia.org/wiki/File:Triac_structure.svg
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9

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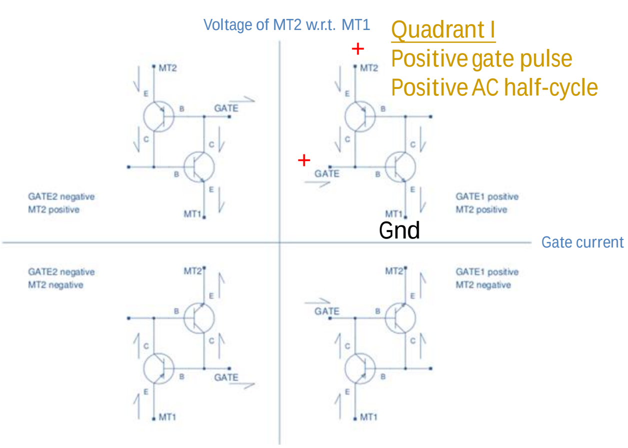

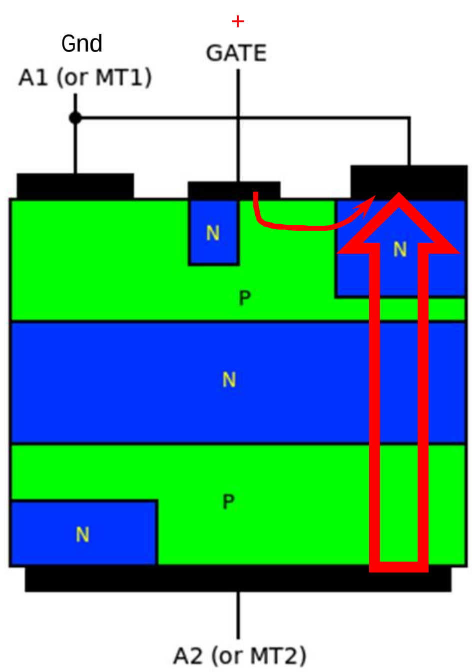

https://commons.wikimedia.org/wiki/File:Triac_structure.svg
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10

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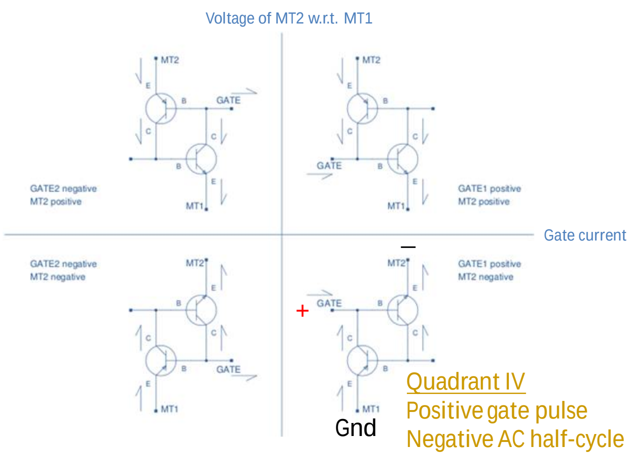

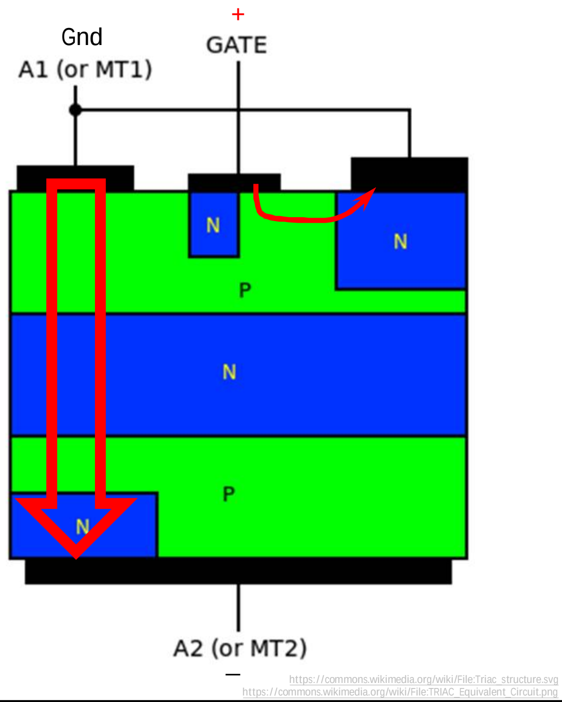

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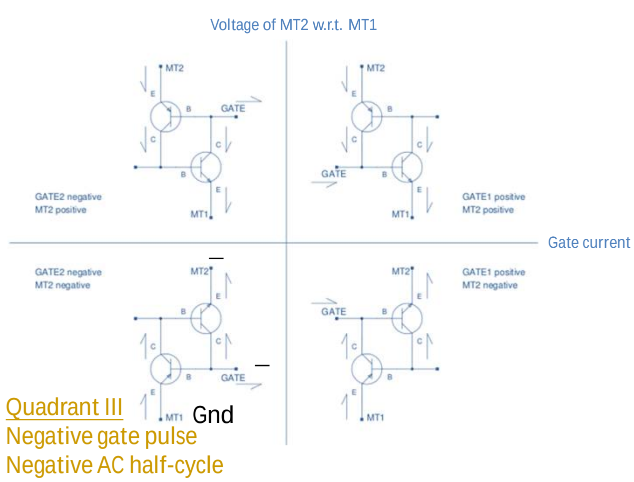

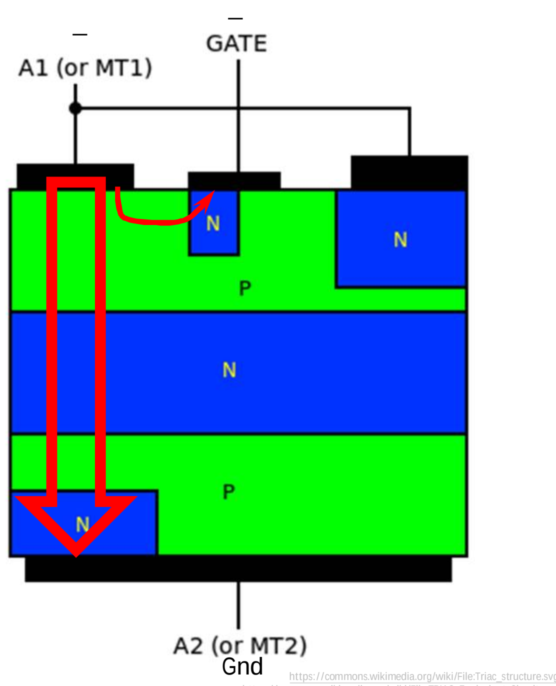

12

AC loads controlled via digital circuits

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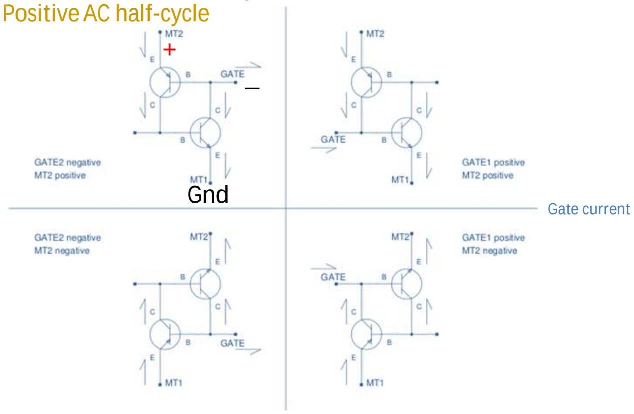
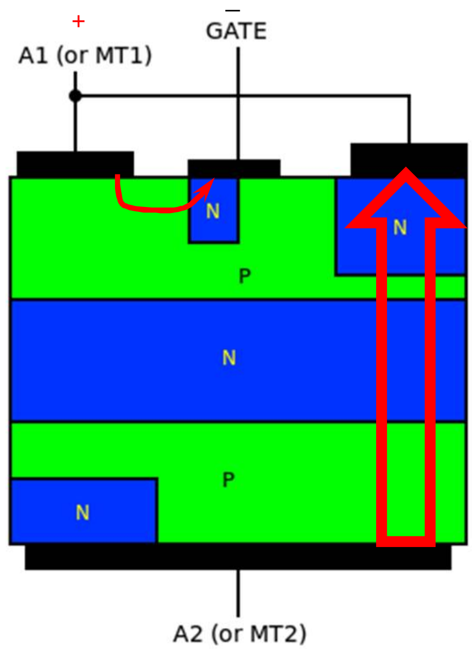
And, like an SCR it is a single crystal of silicon.
Here is the physical structure.
It operates in *4-quadrants.*
It is similar to two SCRs but has only one gate—easy to control.

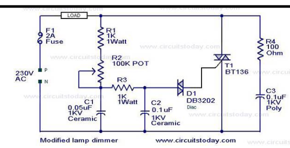
Quadrant II
Negative gate pulse
Positive AC half-cycle





https://commons.wikimedia.org/wiki/File:Triac_structure.svg
https://commons.wikimedia.org/wiki/File:TRIAC_Equivalent_Circuit.png

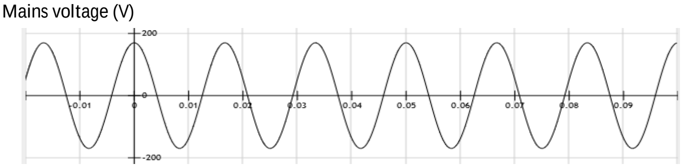
AC Motors, e.g. induction motors, shaded pole motors, etc.
Efficient speed control requires frequency control.
Simple and efficient speed control—remove cycles from the power line.



Inefficient speed control can be achieved with RMS voltage control via a triac.

This is sometimes done for low-power motors where wasted power (heat) is not such an issue.
Reducing voltage in these motors varies the amount of *slip*. Speed is continuously variable.
In other words, the magnetic field in the rotor is weakened so the related currents start sliding sideways allowing the metal of the rotor to turn slower than the magnetic field of the stator. This slipping of the field in the rotor causes heat. Some motors can tolerate it, some can't. Due to harmonics from switching and magnetostriction, this type of control also causes a characteristic electrical buzzing (raspy humming).

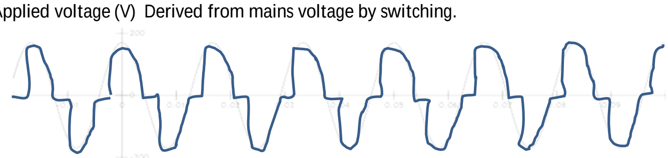
Mains voltage (V)



Time (sec)

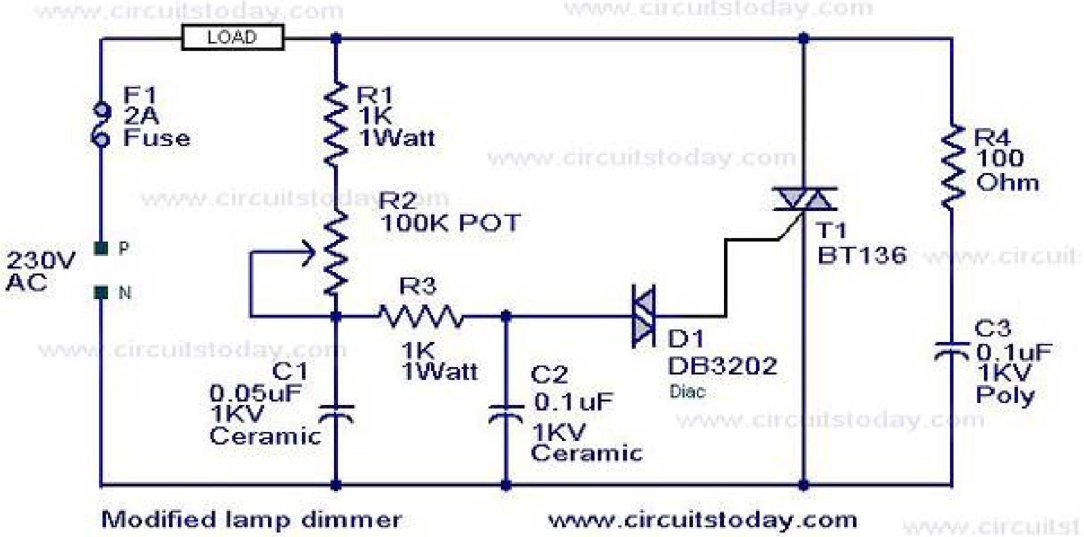
60 Hz, ~1750 RPM typical (4 poles)
(1800 – 1750)/1800 = 3% slip

Applied voltage (V) Derived from mains voltage by switching.



Time (sec)

Lower RMS voltage
speed ~1500 RPM (4 poles)
(1800 – 1500)/1800 = 17% slip



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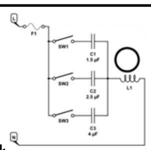
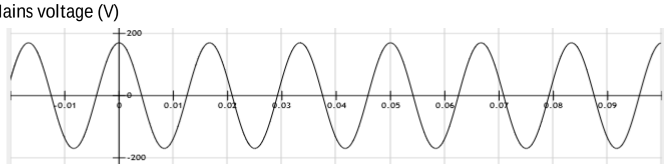


AC Motors, e.g. induction motors, shaded pole motors, etc.
Efficient speed control requires frequency control.
Simple and efficient speed control—remove cycles from the power line.

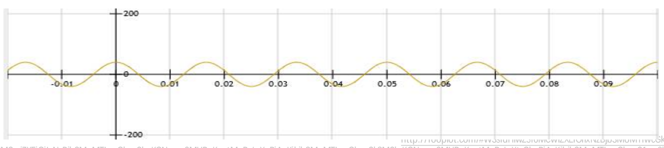
Inefficient speed control can be achieved with RMS voltage control via capacitors in series with the motor.
This is sometimes done for low-power motors where wasted power (heat) is not such an issue.
Reducing voltage in these motors causes *slip*. Capacitors are switched, not variable. About 3 to 5 speeds.
In other words, the magnetic field in the rotor is weakened so the related currents start sliding sideways allowing the metal of the rotor to turn slower than the magnetic field of the stator. This slipping of the field in the rotor causes heat. Some motors can tolerate it, some can't. Very popular for fan motors.
Operation is nearly silent—very slight mellow hum.

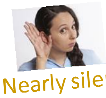
Mains voltage (V)



60 Hz, ~1750 RPM typical (4 poles)

Applied voltage (V) Derived from mains voltage by a series capacitor.





Nearly silent

Lower RMS voltage
speed ~600 RPM (4 poles)
67% slip!
(Heating, but not much power input.)

https://www.overstock.com/Lighting-Ceiling-Fans/HomeSelects-Contempo-52-Ceiling-Fan-with-Wall-Switch-Silver/18701830/product.html https://electronics.stackexchange.com/questions/217828/calculating-the-capacitor-values-to-control-ceiling-fan-speed https://pixabay.com/photos/listening-listen-upset-3079065/

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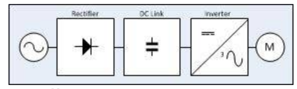
AC Motors, e.g. induction motors, shaded pole motors, etc.
Efficient speed control requires frequency control.
Simple and efficient speed control—remove cycles from the power line.



Optimal speed control can be achieved with sinusoidal signal generation and amplification—called a VFD drive.

- This is almost always the technique used for high-power motors. **OPTIMAL!**
- *Slip* is very low—certainly less that 5% reduction from synchronous speed.
- The motor runs nearly silently. For three-phase motors, theoretically zero vibration.
- Efficiency is high.
- Usually the VFD drive hardware is purchased and the computer talks to it via Ethernet, CAN-bus, RS-232, etc.

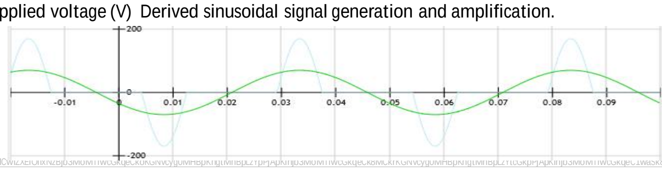
Mains voltage (V)

Time (sec)

60 Hz, ~1750 RPM typical (4 poles)

OPTIMAL!

Applied voltage (V) Derived sinusoidal signal generation and amplification.



Time (sec)

OPTIMAL! **Choose This!**

20 Hz, 582 RPM (4 poles)
3% slip, very quiet.

https://commons.wikimedia.org/wiki/File:Small_variable-frequency_drive.jpg https://commons.wikimedia.org/wiki/File:VSI_Topology.jpg

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