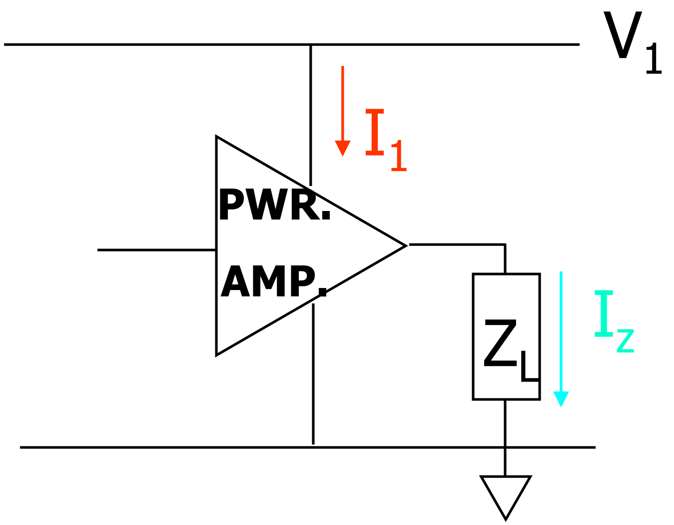
ACTUATORS

INTRODUCTION

Actuators = they transform the control signal provided by the controller into electric power and then in other kinds of power/energy (mechanical, chemical, thermal, kinetic …) accordingly to the nature of the process.

A first intuitive solution to provide electrical power to the process is to employ a *power* operational amplifier.



The amplifier will provide a power $W_1=I_1V_1$ generally > than W_z consumed by the process, since $I_1>I_z$ and $V_1>V_z$

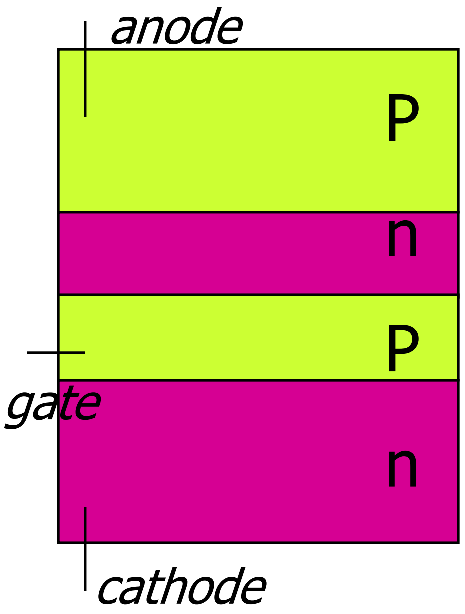
The power not delivered to the load is lost on the amplifier as heat and thus can limit the yield of the supply. This is acceptable if we are working with low powers.

On the contrary it is possible to adopt a PWM approach i. e. a strong power amount for a limited interval of time: in this case the load must be sensible to the average of the applied signal as if a smaller voltage has been applied constantly (*chopper*). Otherwise a solution featuring a new type of rectifier can be devised ...

SCR - SILICON CONTROLLED RECTIFIER

A transistor can switch quickly. When the power provided is high, however, the transistor dissipates a lot passing from interdiction to saturation (and vice-versa) in long times.

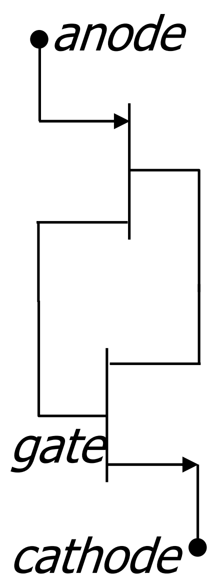
The SCR (thyristors) are semiconductor based devices that rectify the voltage in controlled mode so assuring a quite fast commutation.

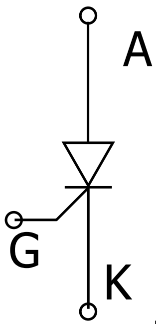


4 layers, 2 thick and 2 thin with p/n polarization. The situation is similar to have two triads (transistors) *pnp* and *npn* 'embedded' (interspersed).

The thin layers feature a thickness < charge diffusion length: it is what commonly happens in the base of a transistor.

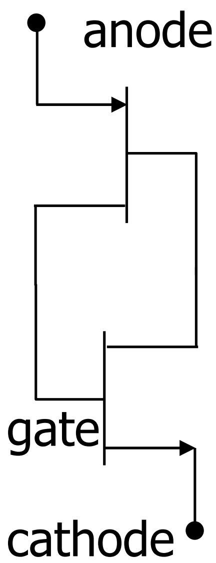
The base of the *npn* is the collector of the *pnp* and vice-versa.





The device works when a positive voltage difference between anode and catode and when a positive pulse is given to the gate so as to activate the *npn* of the circuit.

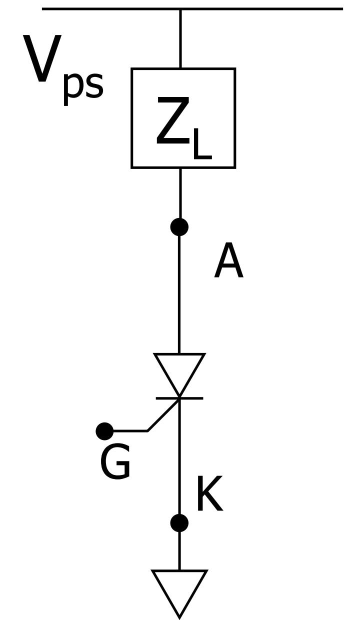
SCR – how it works



It is necessary to apply a load otherwise the gate current is amplified by the *npn* part, that 'extracts' it from the basis of the *pnp* that, on turn, amplifies it further and sends it again to the base of the *npn*.

The situation is similar to a 'loop' whose amplification factor is β^2 (100^2 ex.), so as in few steps the current augments and can burn down the SCR.

A load prevents this since it limits the current.

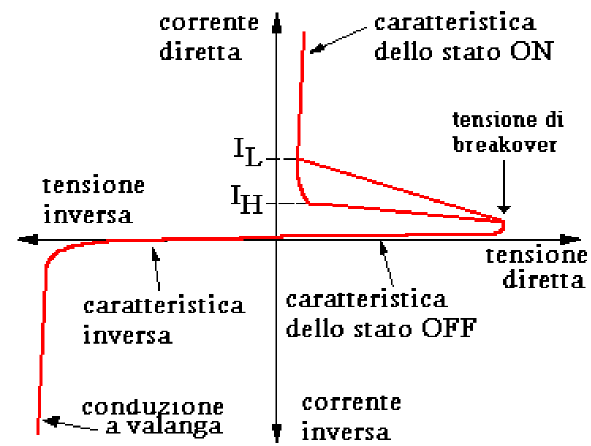


The voltage drop on the SCR is nearly 1 V.

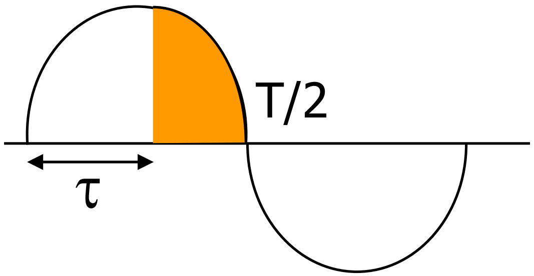
It (V_{ps}) can be applied to the load in two ways:

1) Partialization of the line (mains) voltage;

2) Selection of the line voltage periods

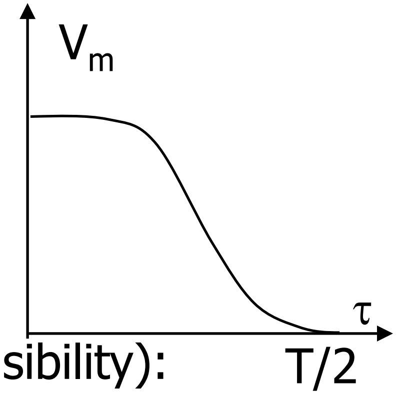


SCR – partialising with resistive load



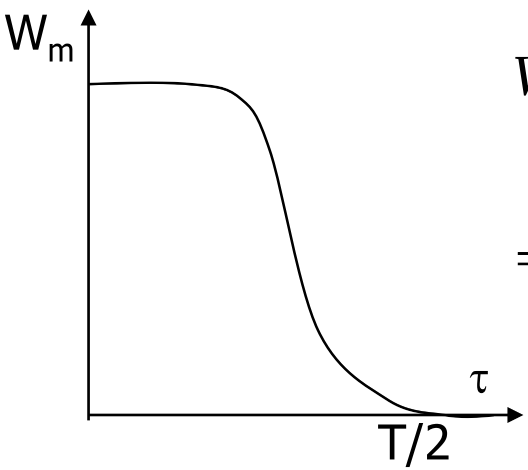
Let's suppose to apply an alternate voltage to a *resistive* load: in the negative wave the SCR is not active and if τ is the delay with which the pulse is sent to the SCR gate, the power provided to the load corresponds to the orange area.

The average applied voltage is:



$$V_m = \frac{1}{T}\int_{\tau}^{T/2} V_P \operatorname{sen}\omega t\, dt = \frac{V_P}{\omega T}\left[\cos\omega\tau - \cos\omega\frac{T}{2}\right] = \frac{V_P}{2\pi}\left[\cos\omega\tau + 1\right]$$

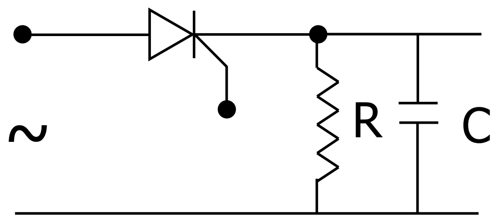
The applied average power instead is (depending on the load sensibility):

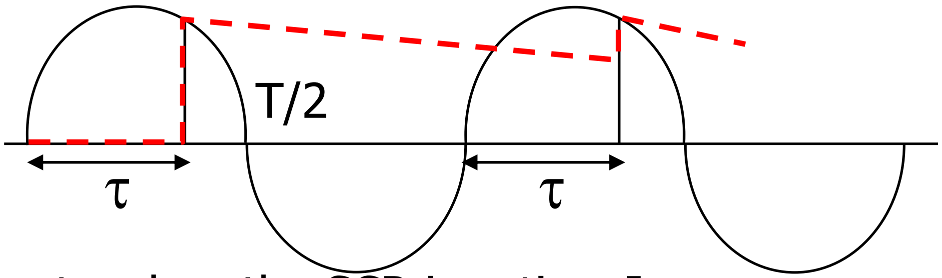


$$W_m = \frac{1}{T}\int_{\tau}^{T/2} \frac{V^2(\mathrm{t})}{\mathrm{R}}\, dt = \frac{1}{T}\int_{\tau}^{T/2} \frac{V_P^2 sen^2\omega t}{\mathrm{R}}\, dt = \frac{V_P^2}{R\omega T}\int_{\omega\tau}^{\omega T/2} sen^2 x\, dx =$$

$$= \frac{V_P^2}{4\pi R}\left[x - sen x \cos x\right]_{\omega\tau}^{\omega T/2} = \frac{V_P^2}{4\pi R}\left[\pi - \omega\tau + sen\omega\tau\cos\omega\tau\right]$$

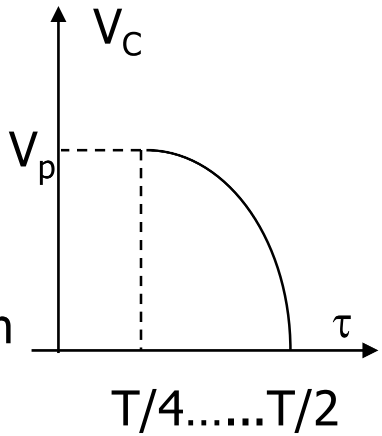
SCR – partialising with capacitive load





The voltage on the capacitor is null up to when the SCR is active. In that moment C is charged instantaneously (depending on the charge current provided by the SCR).

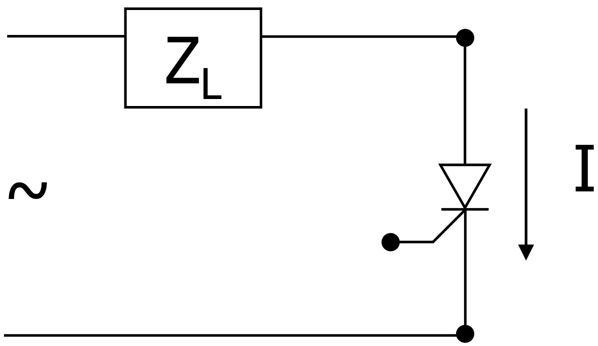
If τ is i the second half-period ($T/4<\tau<T/2$) the SCR goes immediately off since its cathode has a voltage nearly fixed (it diminishes with a velocity established by the RC constant) while the anode decreases really faster.

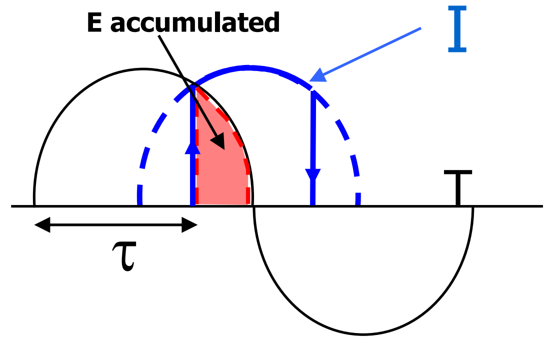


When the SCR is off the capacitor discharges through the RC circuit. In practice $V_C = V_p$ sen $\omega\tau$.

If instead τ is in the first half-period ($0<\tau<T/4$) the SCR is always active and the capacitor charges at the peak value (the power provided to the load cannot be regulated) and here it remains since then the SCR gets off.

SCR - partialising with inductive load





$$I = \int_{\tau}^{t_{spegnim}} \frac{V_p}{L}\, sen\, \omega t \, dt$$

On τ the pulse is given to the SCR gate and this turns on.

The current features a 90° phase shift compared to the voltage supply and reaches the maximum when the voltage becomes zero.

In case of negative values of the power supply the SCR remains active (direct polarization), only until when a current exists that flows in the anode-cathode direction (the inverted voltage “drains” the charge cumulated in the coil).

This happens (negative half-wave) for the necessary time to eliminate the current. If the inductive load can be considered ideal this time is always equal to $T/2-\tau$, since the inductor (if ideal) must return the same energy cumulated during the positive half-wave.

Unlike the resistive load, the inductive one keeps the current flowing in the SCR even in the negative half-wave. The SCR, however, cannot be turned on in the negative half-wave.

SCR- Observations

•Quick current or voltages transitions when the SCR turns on ⇒ disturbances for other devices or in the mains.

•Instead partializing of the voltage, it is possible to select the half-wave of the signal (es. 1 half-wave 3 ⇒ the power will be equal to the 30% of the one available). This a slow solution since the necessary number of periods must be waited.

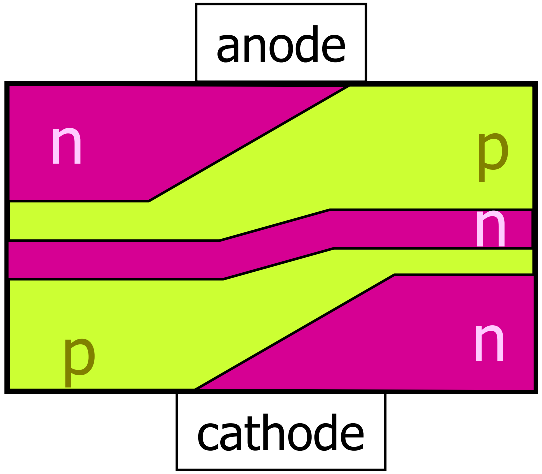
•The load can have the capacity to average or integrate the applied signal: if these capacities can be developed in short times the first approach can be used, as an alternative the last one.

•For a motor it is better to partialize. For an oven better 1 wave on N.

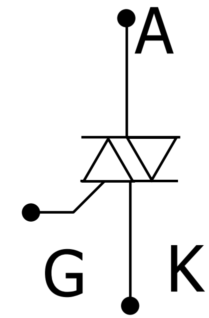
•They are also called thyristors.

•A typical usage is as controlled rectifier in the inverters.

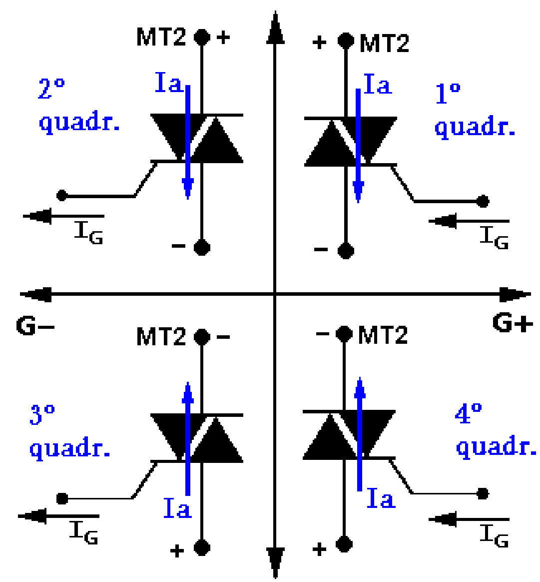
TRIAC



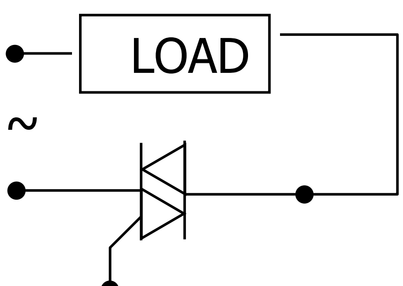
It is similar to 2 complementary SCR joined side by side (complementary means the gate is applied on the thin *n* layer or on the *p* thin one)

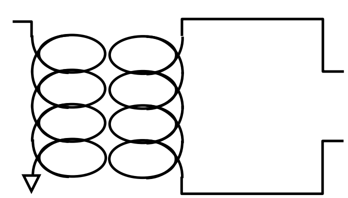


The input gate is unique and allows to turn on the device with voltages +/-; usually a positive pulse is applied if V_{ak} >0 or a negative one if V_{ak} <0. This allows therefore a passage of current in both the directions. The load is usually applied in series and the TRIAC turns off whenever the voltage crosses the zero point.



Typically, the TRIAC is supplied with a galvanic coupling that avoids dangerous 'ground loop'.



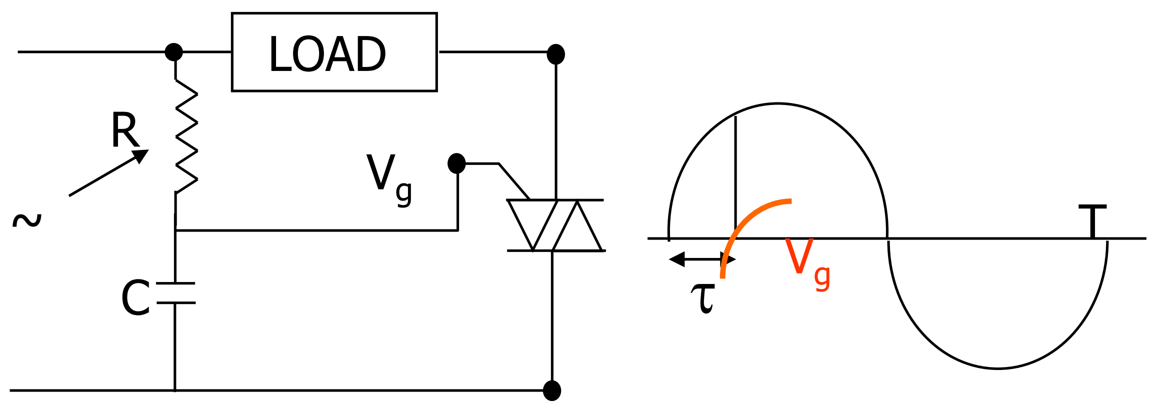


TRIAC/SCR – delay tuning

A suitable RC circuit can be used to generate a gate pulse with a fixed delay.

However it will be necessary to apply to the TRIAC 2 pulses every period of the AC signal.

This circuit makes Vg to follow the AC signal with a delay near to RC (<<T).



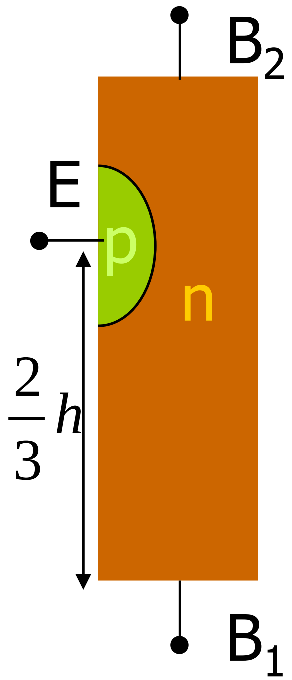
If RC is chosen greater a 90° phase shift can be obtained so as to apply half the available power.

It is also possible to 'program' the delay with a μP if it is possible to establish the zero crossing instant in the voltage. the temporization can be set through a timer that notifies the processor when to exit the pulse for turning on.

When this is not possible, a new approach based on the unijunction (UJT) transistor can be introduced.

The RIAC is used as a relay, and as a voltage regulator in small domestic appliances (chandeliers) or electric motors. The power is exploited better compared to SCR but they need also dissipating sinks.

UNIJUNCTION TRANSISTOR



A silicon bar features a weak n-type dopant ⇒ a few free charge carriers ⇒ the bar is equivalent to a big resistor.

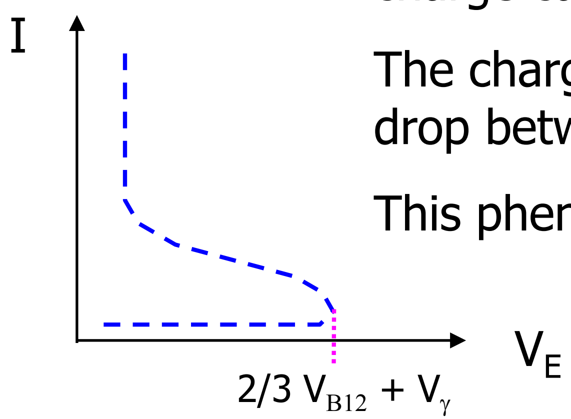
A layer with strong p-type dopant is instead located at a 2/3 of the bar length (nearly).

If a positive voltage is applied between the two basis (B1-B2), a weak current takes place and the voltage is distributed proportionally to the length ⇒ V_E=2/3 V_{B12}.

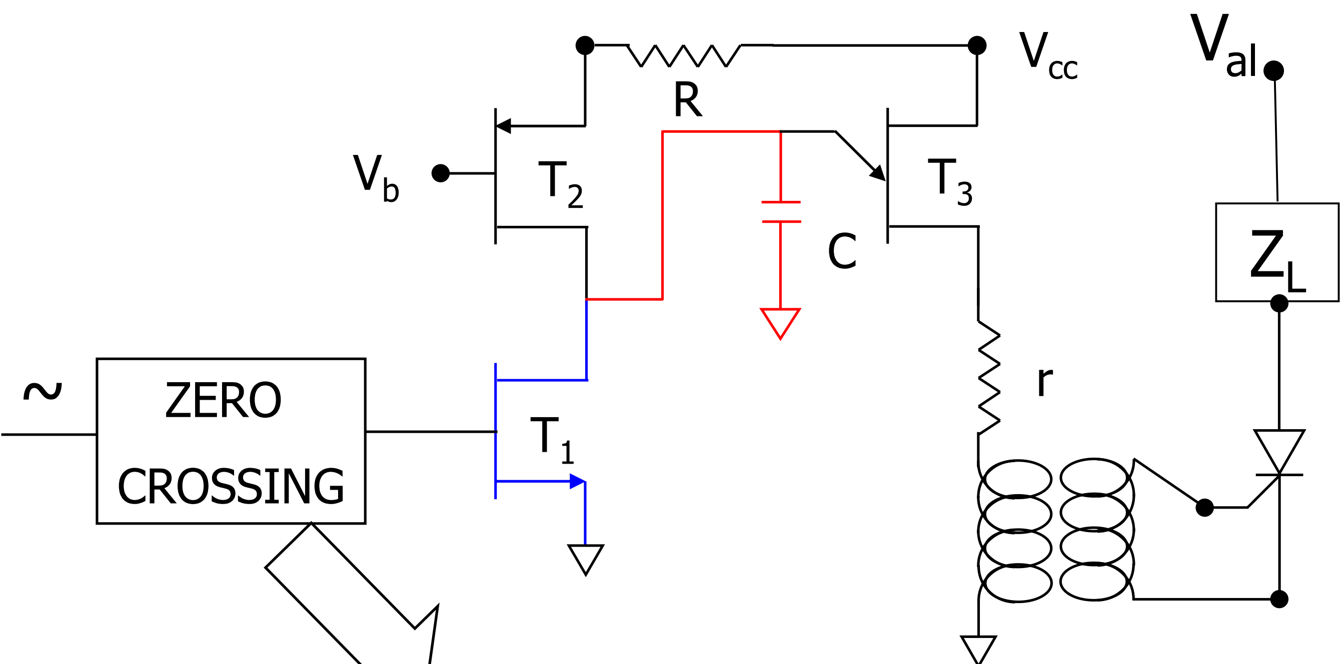
By applying to the E point a voltage > 2/3 V_{B12} a lot of positive charges will be expelled to the p-type area towards the lower voltage point (B_1). The lower part of the bar will get rich with charge carriers and the resistivity diminishes.

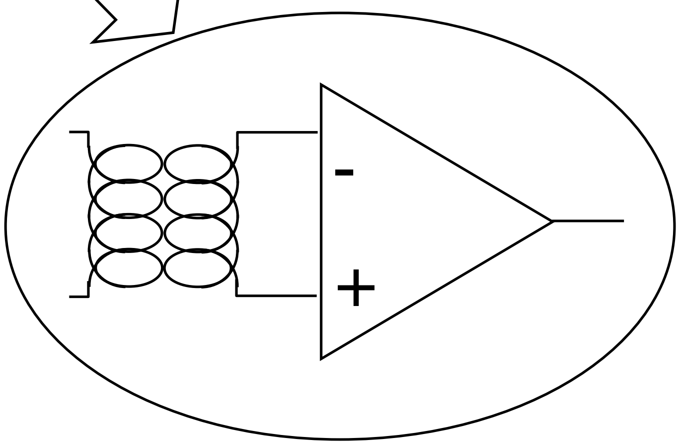
The charge accumulation across the junction EB_1 lowers the voltage drop between E and B_1 and accelerates the charge passage.

This phenomenon self-regenerates within certain physical limits.



UJT TRANSISTOR control of the SCR activation



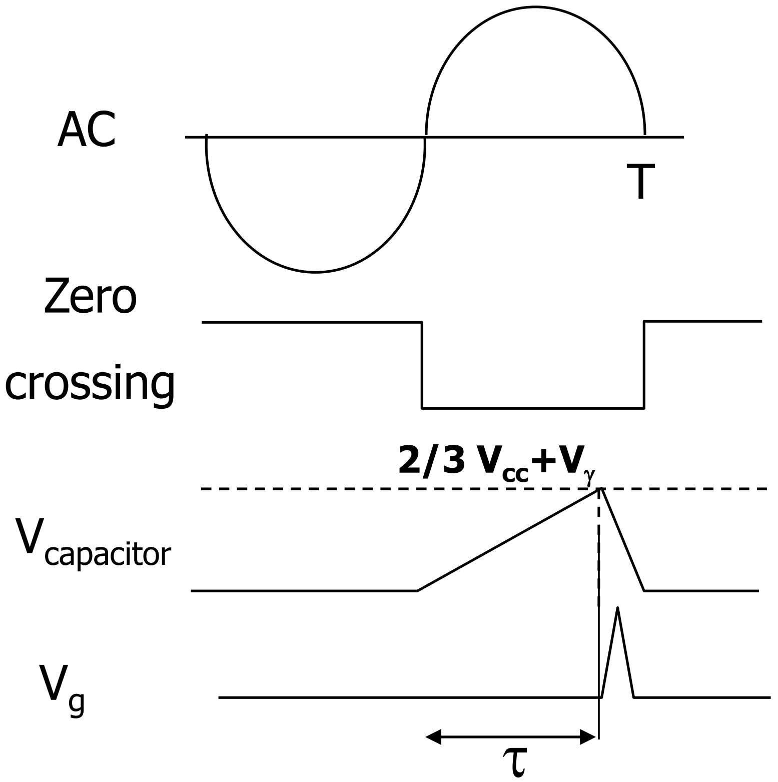


The charge is accumulated in C during the positive half-wave and then discharged by the UJT so as to have high short pulse that turns on the SCR

When V_{cond} reaches $2/3V_{cc}$ (+Vg) the UJT transistor is active for a short time. The it is off because the transistor T_1 keeps empty the capacitor C.

If the AC voltage is <0, the comparator will turn on the transistor preventing the capacity from charging, if the voltage is >0, the transistor is open (off) and the capacity will be charged.

UJT TRANSISTOR control of the SCR activation



$$\tau = \frac{\frac{2}{3} C \cdot V_{cc}}{I_c}$$

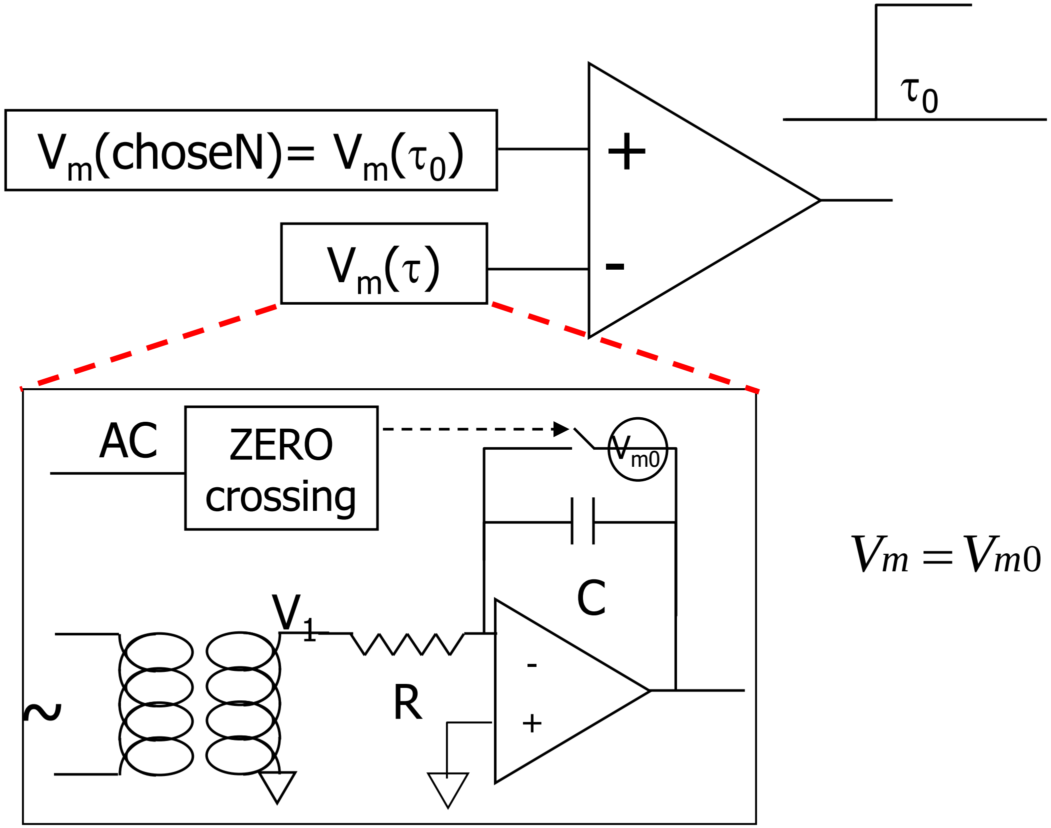
$$I_c = \frac{V_{cc} - V_b}{R}$$

$$\tau = \frac{2}{3} \frac{RC \cdot V_{cc}}{V_{cc} - V_b}$$

V_b allows to regulate the charge velocity of the capacitor so to establish when the SCR should be turned on (that is the supplied power amount).

This circuit features a strong not linearity between the delay and the power applied to the load

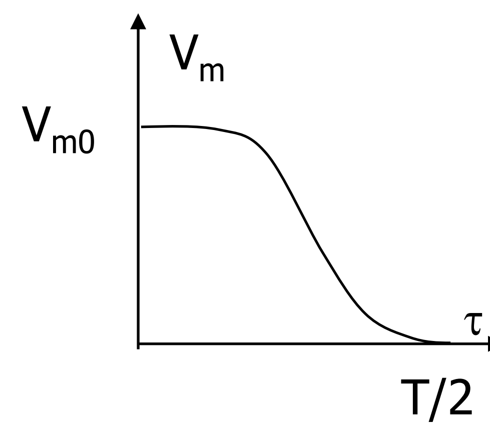
A FURTHER SOLUTION: SCR EMULATOR



We fix the V_m average voltage (equal to the desired power), so as when the corresponding τ is reached the comparator exits a pulse for turning on the SCR.

How it is possible to generate $V_m(\tau)$?

$$V_m = V_{m0} - \int_0^{\tau} \frac{V_1}{RC} dt \qquad V_{m0} = \int_0^{T/2} \frac{V_1}{RC} dt$$



Now by changing the $V_m(\tau_0)$ voltage the average voltage given to the load can be regulated (if 0 no power supply is given, if V_{m0} the maximum power is provided)

As an alternative to this approach, a table (on the μP) can be implemented with the correspondence between a fixed delay and the relative average voltage that is supplied to the load).

DC MOTORS

A DC motor can be considered as a «reversed» tachometric dynamo since it exploits the rotation of conductive materials merged in a magnetic field that develop a electromotive force proportional to the rotation velocity. This allows to suppose that:

$$V=k\omega$$

This force gives origin to a current that is transformed into a mechanical torque as expressed by

$$\Gamma=k'I$$

The electrical power absorbed by the motor is thus

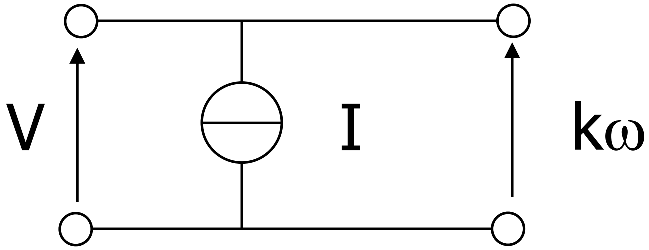
$$W_{ele}=VI=k/k'\ W_{mech}$$

where $W_{mech}=\omega\Gamma$ (rotation pulsation * mechanical torque)

If k=k' no losses are present and all the electrical power is converted in the mechanical one. Conversely *electrical losses* (power dissipation on resistors and coils), *mechanical coils* (friction), *electrical shifts* (inductive effects in the coils) and *mechanical* (motor inertia) can take place.

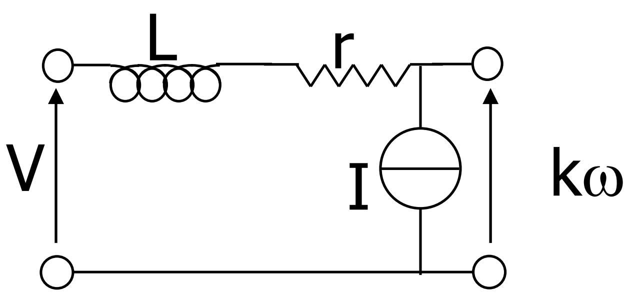
DC MOTORS: electrical model

IDEAL CASE



$$I = \frac{\Gamma}{k}$$

REAL CASE



In this case kω does not correspond to the applied voltage, due to the presence of parasite components (inductive and resistive).

A relationship exists between the generated torque and the angular velocity into which also friction and inertial losses must be taken into account :

$$\Gamma = \Gamma_0 + \gamma\omega + J\dot{\omega}$$

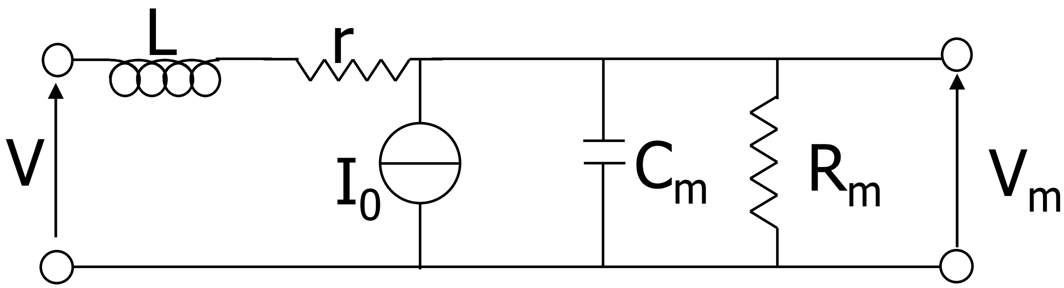
Γ_0 effective torque, γ friction coefficient, J inertial moment

DC MOTORS: electrical model

Therefore $I = \dfrac{\Gamma_0 + \gamma\omega + J\dot{\omega}}{k'} = \dfrac{1}{k'}\left[\Gamma_0 + \dfrac{\gamma}{k}V_m + \dfrac{J}{k}\dot{V}_m\right]$

If we set $I_0 = \dfrac{\Gamma_0}{k'}$ $\quad \mathrm{R_m} = \dfrac{kk'}{\gamma}$ $\quad \mathrm{C_m} = \dfrac{J}{kk'}$

We have (L-transform) $\quad I = I_0 + \dfrac{V_m}{R_m} + sC_mV_m$



Real model used to characterize the behavior of the motor (V applied voltage, V_m=kω part of this voltage that arrives to the motor)

DC MOTORS: electrical model

The electrical parameters depend on mechanical factors:

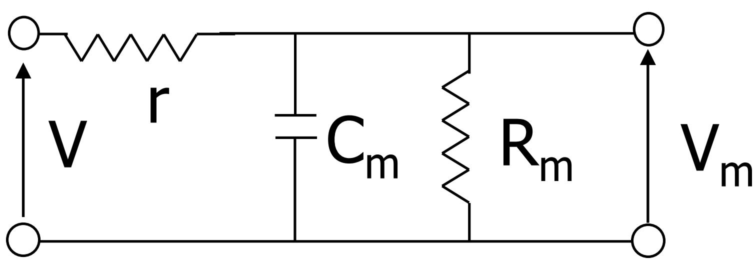
- R_m inversely proportional to the friction coefficient
- C_m proportional to the inertia
- I_0 effective torque (i. e. necessary to win a friction or to lift up a weight)

The characteristic of the motor is an expression V_m/*input* where the *input* can be a current or a voltage

1) VOLTAGE INPUT (DRIVING)

The motor features 2 time constants $\tau_m = R_m C_m$ e $\tau_{el} = L/r$ con $\tau_m >> \tau_{el}$.

Inductive effect L and I_0 generator not affecting frequency response can be neglected



$$\frac{V_m}{V} = \frac{1/r}{\frac{1}{r} + \frac{1}{R_m} + sC_m} = \frac{1}{1 + \frac{r}{R_m}} \frac{1}{1 + s\tau_v}$$

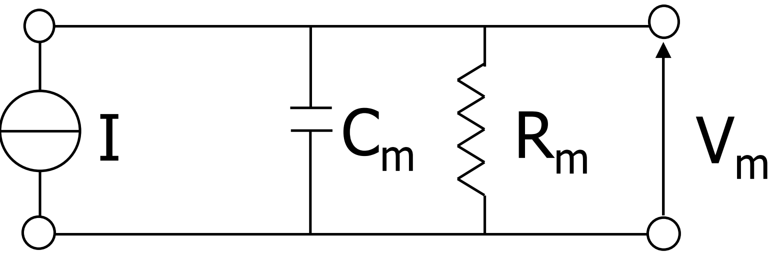
If $t \to \infty$ $V_m \approx V$ since $R_m >> r$

with $\tau_v = \frac{rR_m}{r + R_m} C_m$

DC MOTORS: electrical model

2) CURRENT INPUT

r can be neglected (beyond L e I_0) since it is in series with the ∞ generator resistance.



$$\frac{V_m}{I} = \frac{R_m}{1 + s\tau_m} \quad \text{con } \tau_m = R_m C_m$$

When the transient expires the rotation velocity depends only on the friction.

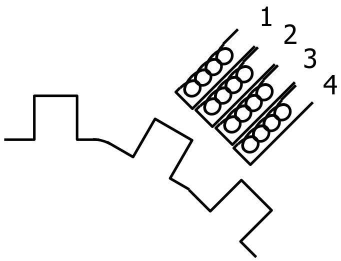
τ_m is directly proportional to the inertia and inversely proportional to the friction. A 'braked' motor reaches earlier its operative velocity.

How to brake the motor?

1) Turning off the voltage: the C_m capacity will discharge on $r || R_m$

2) Turning off the current: the C_m capacity will discharge only on R_m (slower)

STEPPER MOTORS



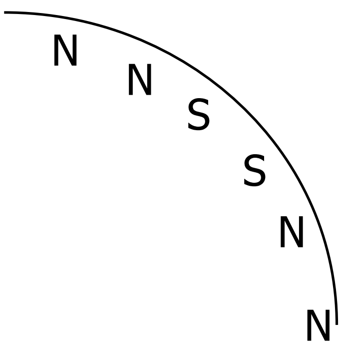
It is an actuator that answers to the input signal with a position variation. It is different from the DC motor since it is used for controlling angular rotations and their velocities but not forces or torques. It consists on a moulded and contoured rotor with ferromagnetic expansions and a 4 winding/wrapping stator.

Every 'tooth' will be attracted by the field developed by the wrapping coils, supplied alternatively in pairs (1-2, 2-3, 3-4).

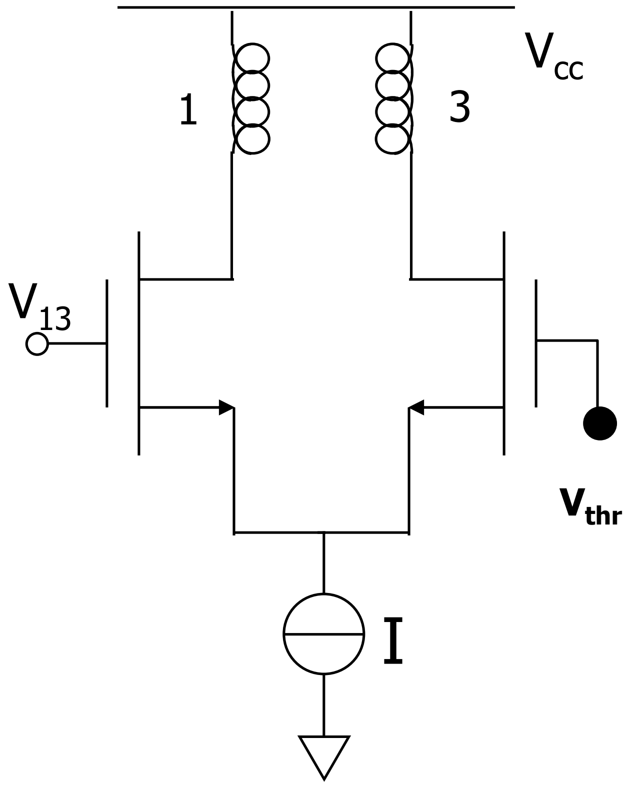
1	2	3	4
ON	ON	OFF	OFF
OFF	ON	ON	OFF
OFF	OFF	ON	ON
ON	OFF	OFF	ON
ON	ON	OFF	OFF

Since the coils lie within 1/4 of the angular step of a tooth, the rotor will cover in 4 steps all the tract below them.

The rotor, can be, actually, carried out with positive/negative polarities (SOUTH/NORTH) able to cause attractions and repulsions.



STEPPER MOTORS: driving circuit



Every time only one of the wrapping coils 1-3 e 2-4 is active, and a 'balanced stage' can be used for driving them, in fact if

$V_{13} > \mathbf{V_{thr}}$ the coil 1 is active

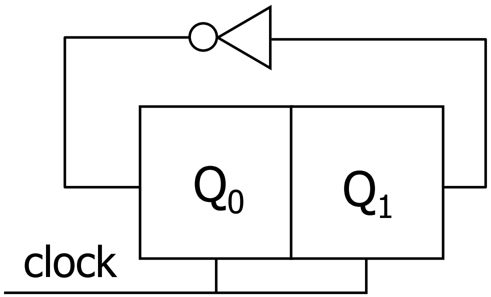
$V_{13} < \mathbf{V_{thr}}$ the coil 3 is active

The same to control the 2-4 pair.

It is necessary to generate the control voltages V_{13} e V_{24} so as to respect the following table

1	2	3	4	V_{13}	V_{24}
ON	ON	OFF	OFF	+	+
OFF	ON	ON	OFF	-	+
OFF	OFF	ON	ON	-	-
ON	OFF	OFF	ON	+	-
ON	ON	OFF	OFF	+	+

STEPPER MOTORS: FF driving circuit



Q_0 drives V_{13}, Q_1 drives V_{24}: the FF based shift register inverts Q_1 and sends it, in the next clock cycle, to Q_0 as foreseen in the table.

To achieve an opposite rotation it is necessary to run across the table from the bottom and to use a reversible shift register.

1	2	3	4	V_{13}	V_{24}
ON	ON	OFF	OFF	+	+
OFF	ON	ON	OFF	-	+
OFF	OFF	ON	ON	-	-
ON	OFF	OFF	ON	+	-
ON	ON	OFF	OFF	+	+

It is not a good idea to use a μP since sometimes emission frequencies of the pulses are high and this causes a CPU overhead.

Amplifiers are used to make the shift register able to drive in current the logic port.

PFM PULSE EMISSION: STEPPER MOTORS

1	2	3	4
ON	OFF	OFF	OFF
OFF	ON	OFF	OFF
OFF	OFF	ON	OFF
OFF	OFF	OFF	ON
ON	OFF	OFF	OFF

Wave: less torque with respect two phase (1vs1.4)

Half step: the step number is twice (precision) but the torque is irregular and the power consumption not constant

1	2	3	4
ON	OFF	OFF	ON
ON	OFF	OFF	OFF
ON	ON	OFF	OFF
OFF	ON	OFF	OFF
OFF	ON	ON	OFF
OFF	OFF	ON	OFF

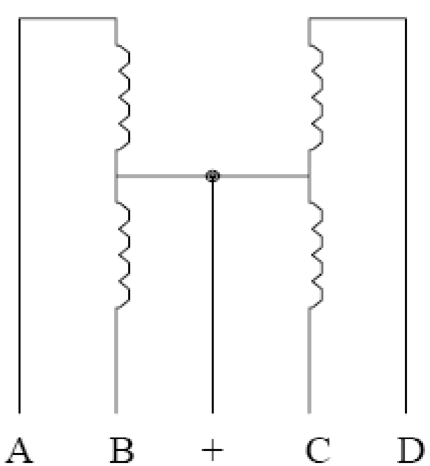


Fig 1. Five-wire stepper motor

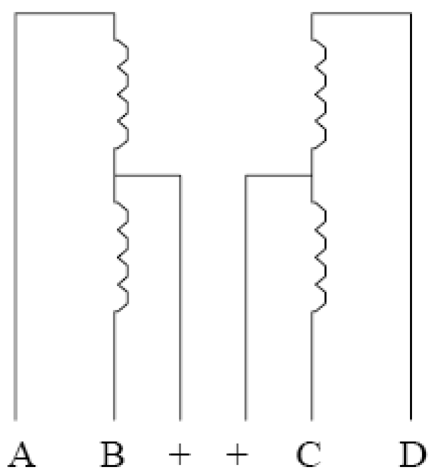


Fig 2. Six-wire stepper motor

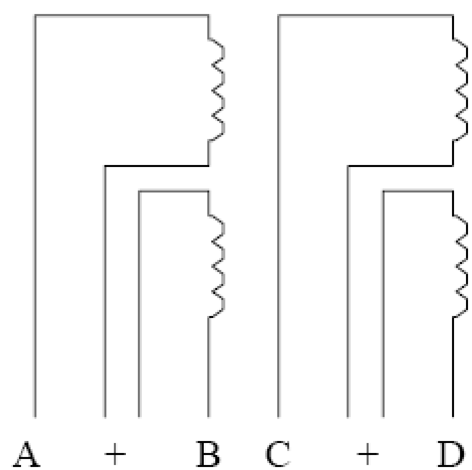
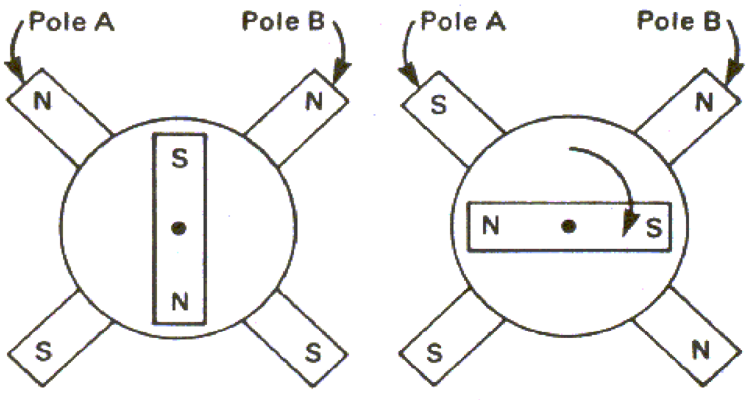
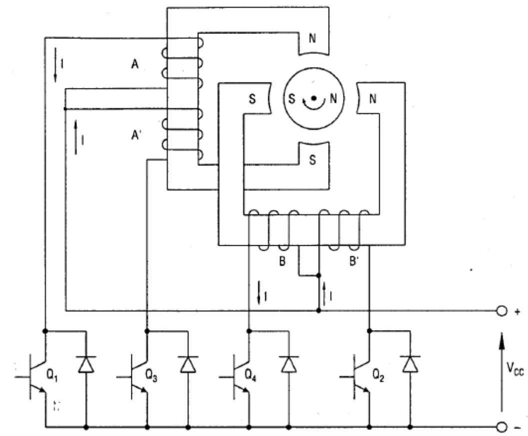
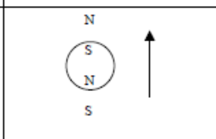
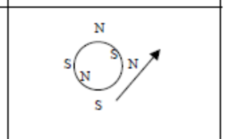
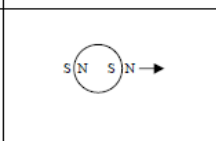
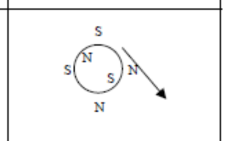
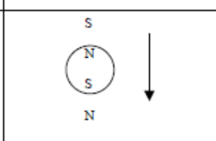
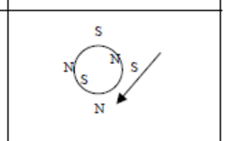
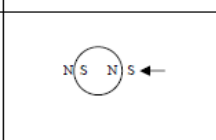
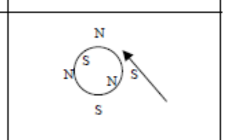


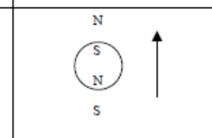
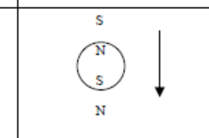
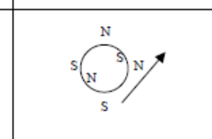
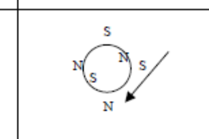
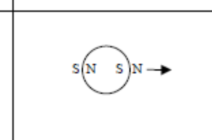
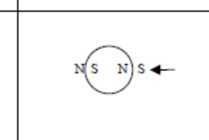
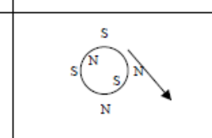
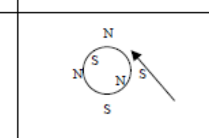
Fig 3. Eight-wire stepper motor

PFM PULSE EMISSION: STEPPER MOTORS





1a. WAVE DRIVE MODE		1b. NORMAL DRIVE MODE	
Transistor Accesi	Posizione Rotore	Transistor Accesi	Posizione Rotore
Q1		Q1 e Q2	
Q2		Q2 e Q3	
Q3		Q3 e Q4	
Q4		Q4 e Q1	

1c. HALF STEP MODE			
Transistor Accesi	Posizione Rotore	Transistor Accesi	Posizione Rotore
Q1		Q3	
Q1 e Q2		Q3 e Q4	
Q2		Q4	
Q2 e Q3		Q4 e Q1	

STEPPER MOTORS: how to power supply

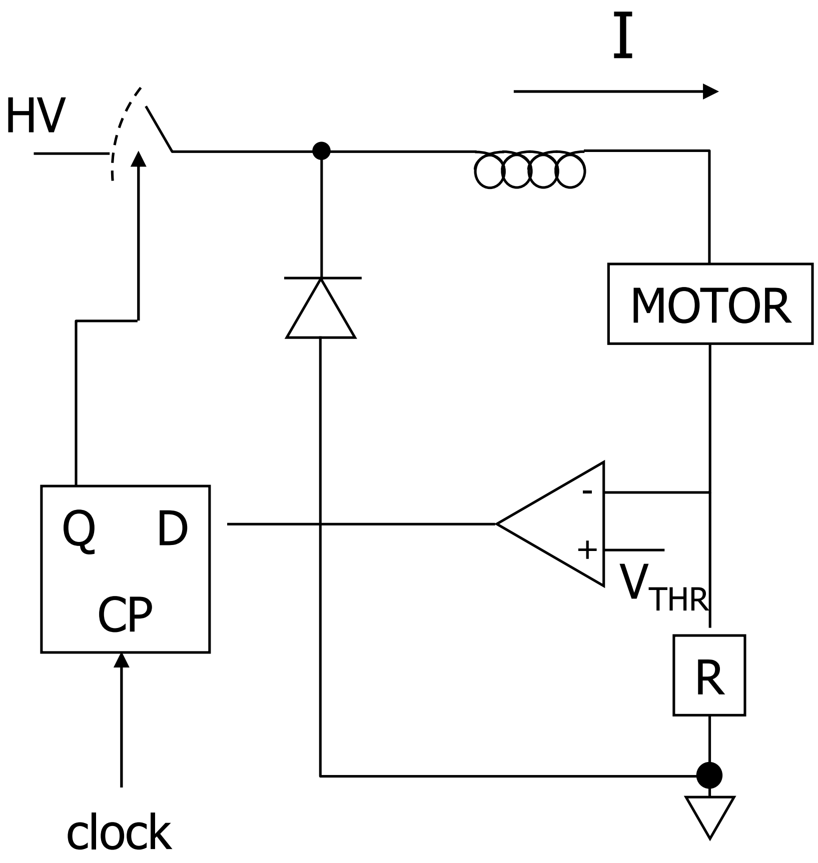
- This actuator responds with a velocity to the control input variable, allowing to determine the new position without any need of a position transducer (i. e. if we fix a 100 pulses/sec velocity, this corresponds to half a round in a second, if the sensibility of the transducer is 1 round after 200 pulses). Sometimes a limit switch is necessary.

- These motors require power supply in the order of few V, with currents in the order of the A ⇒ r in the coils must be relatively low; since the delay is L/r in an inductor, time constants can be high. L moreover can be high if the coils windings are high.

For example if the command voltage is applied to the coil 1, this one due to the initial ‘resistance’ will inhibit the, at least at the beginning, the current flow. This means that in the MOS drain V_{cc} is nearly present and that the MOS will employ further time to exit from the interdiction towards saturation ⇒ this is acceptable if the working frequency is not so high.

It is better to provide higher voltages (⇒ > resistors, < time constants): however this brings to a strong power dispersion on the MOS (heat). Thus a *PWM* solution is employed with suitable on-off intervals (tunable duty cycle).

STEPPER MOTORS: PWM POWER SUPPLY



The motor receives a constant current, obtained through a HV voltage necessary to provide fast commutations (time constant L/r)

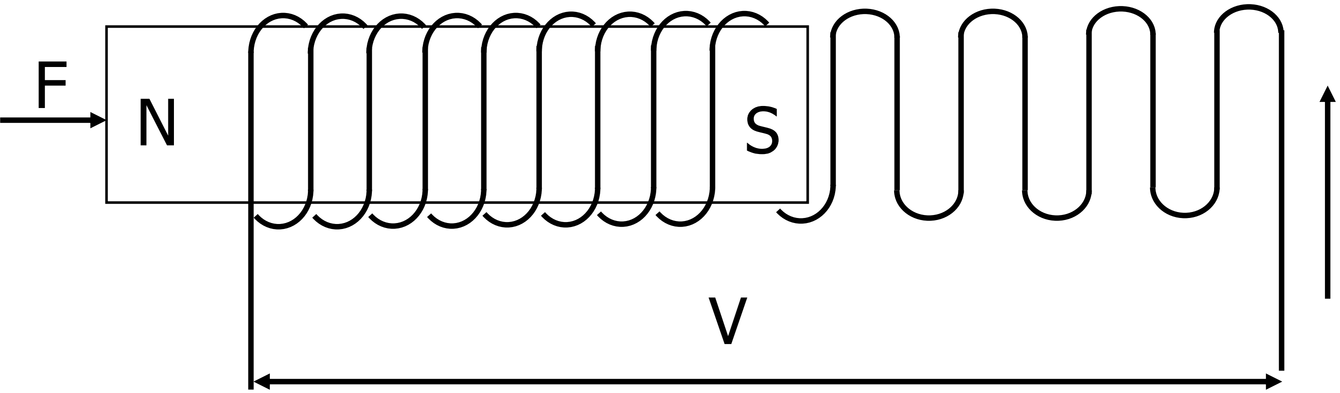
If current is < V_{rif}/R the flip flop close the switch so supplying the motor with a 100 V voltage. Alternatively (open switch), the circuit is grounded through a diode.

The flip flop closes the switch depending on a clock period that allows to regulate the opening and closing intervals (that means the duty cycle).

The inductor serves as “regulation maker” allowing a smooth passage among the levels of the current (high low high low) without shocking the motor.

ON OFF control.

ELECTROMAGNETIC ACTUATOR



It works in dual mode compared to the linear velocity transducer and converts the provided current in a proportional force.

A rod of magnetized ferromagnetic material partially inserted in a current supplied solenoid.

The magnet will be attracted inside the solenoid or made to exit with a force F that can be determined in this way:

V (electromotive force induced in the solenoid)= $\mathbf{n\Phi_B} \boldsymbol{v}$ *Faraday-Neumann law*

Let's apply the power conservation $\Rightarrow$ $\mathbf{VI=F}\boldsymbol{v}$ so $\mathbf{F= n\Phi_B I}$

i. e. it is possible to control with the current the amount and the direction of the force applied to the rod.

If the rod is not magnetized, the current I in the solenoid will magnetize it, determining a magnetic flux dependent on the current itself. The consequent force that acts on the rod is so proportional to I^2 $\Rightarrow$ unidirectional traction.