CONTROLLERS FOR SPEED CONTROL OF DC MOTOR DRIVES: MODELING & SIMULATIONS

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Abstract: The thyristor DC drive remains an important speed-controlled industrial drive, especially where the higher maintenance cost associated with the DC motor brushes compared with induction motor is acceptable. The controlled rectifier provides a low-impedance adjustable DC voltage for the motor armature, thereby providing speed control. The DC Motor Drives are increasingly applied in many recent industrial applications that require excellent transient performance of drives. In general, the role of controller is very crucial in the control of drive for transient and dynamic conditions. This paper has been attempted to present the Comparative study of Proportional (P), Proportional Integral (PI), and Proportional Integral Derivative (PID) controller for speed control of DC Motor Drive. The performance of P, PI and PID controllers are considered and compared. A proposed DC Motor Drive have a precise speed control, stable operation in complete range of speed and good transient behavior with smooth and step less control.

I. INTRODUCTION

UNTILL the 1960s, the way of obtaining the variable - voltage DC supply needed for speed control of an industrial DC motor was to generate with a DC Generator.The generator was driven at fixed speed by an induction motor, and the field of the generator was varied in order to vary the generated voltage. The motor/generator (MG) set could be sited remote from the DC motor, and multi-drive sites (e.g. steelworks) would have large rooms full of MG sets, one for each variable-speed motor on the plant. Three machines (all of the same power rating) were required for each of these 'Ward Leonard' drives, which was good business for the motor manufacturer. For a brief period in the 1960s they were superseded by grid-controlled mercury arc rectifiers, but these were soon replaced by thyristor converters having low cost, higher efficiency (typically over 95%), smaller size, reduced maintenance, and faster response to changes in set speed [9], [12], [14]. The disadvantages of rectified supplies are that the waveforms are not pure DC which limits the overload capacity of the converterand that a single converter is not capable of regeneration. Though no longer pre-eminent, study of the DC drive is valuable for several reasons:

- The structure and operation of the DC drive are reflected in almost all other drives, and lessons learned from the study of the DC drive therefore have close parallels to other types [20], [21].

- The DC drive tends to remain the yardstick by which other drives are judged [21].
- Under constant-flux conditions the behaviour is governed by a relatively simple set of linear equations, so predicting both steady-state and transient behaviour is not difficult. When we turn to the successors of the DC drive, notably the induction motor drive, we will find that things are much more complex, and that in order to overcome the poor transient behaviour, the strategies adopted are based on emulating the DC drive [17].

II. DC MOTOR DRIVE

Direct current (DC) motor has already become an important drive configuration for many applications across a wide range of powers and speeds. The ease of control and excellent performance of the DC motors will ensure that the number of applications using them will continue to grow for the foreseeable future.

An Electrical Motor Drive is defined as a form of machine equipment consist of Electric Motor together with its electronic control equipment &energy transmitting links design to convert electrical energy into mechanical energy and provide electronics control of this process.
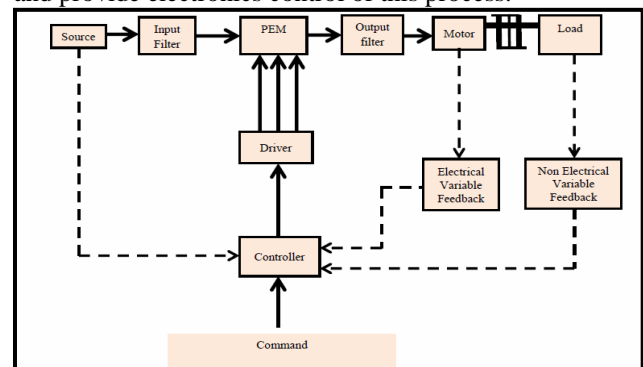

Fig. 1. Block Diagram of DC Motor Drives

The arrangement shown in Fig.1 is typical of the majority of DC drives and provides for closed-loop speed control [5].

The main power circuit consists of a six-thyristor bridge circuit which rectifies the incoming AC supply to produce a DC supply to the motor armature. The assembly of thyristors, mounted on a heat sink, is usually referred to as the 'stack'. By altering the firing angle of the thyristors the mean value of the rectified voltage can be varied, thereby allowing the motor speed to be controlled. The controlled rectifier produces a crude form of DC with a pronounced ripple in the output voltage. This ripple component gives rise

to pulsating currents and fluxes in the motor, and in order to avoid excessive eddy-current losses and commutation problems, the poles and frame should be of laminated construction [18], [19].

We know that motors supplied through thyristor drives have laminated construction, but older motors often have solid poles and/or frames, and these will not always work satisfactorily with a rectifier supply. It is also the norm for drive motors to be supplied with an attached 'blower' motor as standard. This provides continuous through ventilation and allows the motor to operate continuously at full torque even down to the lowest speeds without overheating [3], [20].

Low power control circuits are used to monitor the principal variables of interest (usually motor current and speed), and to generate appropriate firing pulses so that the motor maintains constant speed despite variations in the load. The 'speed reference' is typically an analogue voltage varying from 0 to 10 V, and obtained from a manual speed-setting potentiometer or from elsewhere in the plant.

The combination of power, control, and protective circuits constitutes the converter. Standard modular converters are available as off-the-shelf items in sizes from 0.5 kW up to several hundred kW, while larger drives will be tailored to individual requirements. Individual converters may be mounted in enclosures with isolators, fuses etc., or groups of converters may be mounted together to form a multi-motor drive [3], [7], [9], [13].

Parts of DC Motor Drive

*1)Input Source:*For motors up to a few kilowatts the armature converter can be supplied from either single-phase or three-phase mains, but for larger motors three-phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor: the power is much less than the armature power, so the supply is often single-phase is used.

Very low power drives are generally fed from single-phase sources; low and medium power motors are fed from three-phase 400 V supply, large motors may be rated at 3.3 KV, 6.6 KV and 11 KV.

Some drives are powered from a battery voltage may be 24 V, 48 V or 110 V dc. For the aircraft and space application 115 V, 400 HZ supply is used. For line traction application 65 KV, 50 HZ supply is used and for underground traction application 500 to 759 KV DC supply is utilized [3].

*2) Input and Output Filters:*The electronic filters are circuits which perform signal processing functions, specifically to remove unwanted frequency component from the signal, A power supply must provide ripple free source of power from an AC line. But the output of a rectifier circuit contains ripple components in addition to a DC term.

It is necessary to include a filter between the rectifier and the loads in order to eliminate these ripple components. Ripple components are high frequency A.C. Signals in the D.C output of the rectifier. These are not desirable, so they must be filtered through filter circuits.

*3) Power Electronics Modulator (PEM):*A Power Electronics Modulator (PEM) is a heart of Power Electronics System which modulates the power available from the source as required by the load with the command input given by

controller [21].

The power modulator performs the following functions:

i. It modulates the flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.

ii. It restricts source and motor current to permissible limits during transient operations, such as starting, braking and speed reversal.

iii. It converts the electrical energy of the source in the form suitable to the motor. If the source is dc and an induction motor is to be employed, then the power modulator is required to convert DC in to a variable frequency AC.

iv. It selects the mode of operation of the motor i.e. motoring and braking.

*4) Controller:*The controls for a power modulator are provides in the control unit. The nature of the control unit for a particular drive depends on the power modulator that used.

When semiconductor converters are used, the control unit consists of firing circuits which employ linear and Digital Integrated Circuits, transistors and microprocessor are used when sophisticated control is required.

Control for power electronics modulator is built in control unit which usually operates at much lower voltage and power levels.In addition to operating the power electronics modulator it may also generate commands for the protection of power electronic modulators and motors. Input command signal which adjusting the operating point of the drive by analyzing the feedback signal in the controller.

The controller is realized with analog and integrated circuits. The present trend is to use microprocessors, single chip modulators, Digital Signal Processors (DSP), VLSI and special custom chips known as Application Specifics ICs (ASIC) to embody a set of functions in the controller [1], [4].

*5) Sensors:*Speed sensing is required for implementation of closed loop speed control schemes. Speed is usually sensed by using tachometers.

Two commonly used methods of sensing the current are: (i) using current sensors employing Hall Effect, and (ii) Using a non-inductive resistance shunt in conjunction with an isolation amplifier, which has an arrangement for amplification and isolation between the power and control circuits.

*6) Energy Transmitting Link:*The energy transmitting link is placed between motor / equipment and load. It provides speed and torque conversions from a rotating power source to another device.

There are basically four different methods for energy transmitting links like:

i. Direct coupling method
ii. Using chain
iii. Using belt coupling
iv. Gear Drives

III. CONTROL SYSTEM DESIGN

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PID controllers use three basic behavior types of modes: P - proportional, I-integral and D-derivative. While Proportional and integrativemodesare also used as signal control modesa derivative mode is rarely used on its ownincontrolsystems.CombinationssuchasPIandPIDcontroller areveryoften usedin practicalsystems [6].

A. Proportional (P)Controller
A Proportional controller system is a type of linear feedback control system. The Pcontrollersystemismorecomplexthanon-offcontrol systemslike abi-metallicdomesticthermostat,but simplerthana PID controlsystemusedin somethinglike an automobile cruise control. Ingeneral, it can be said that Pcontrollercannotstabilizehigherorderprocesses [32], [33].
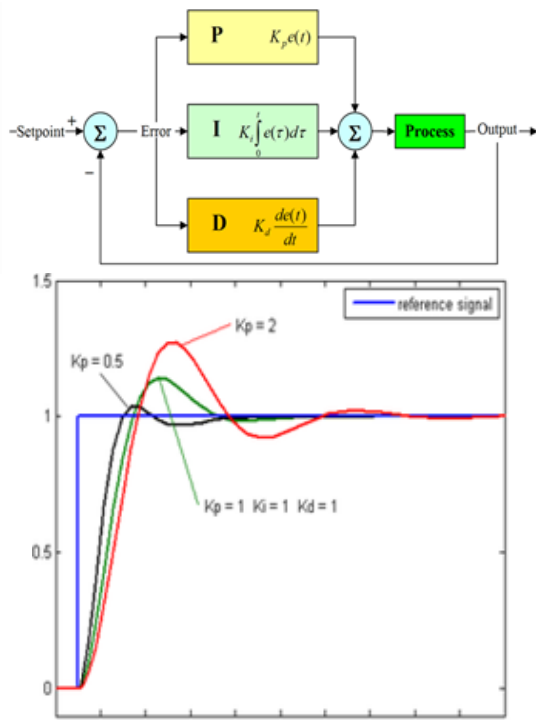

Fig. 2. Block Diagram and Response of P Controller
Forthe1storderprocesses,meaningtheprocesseswithone energy storage, a large increaseingaincanbetolerated.
Proportional controller can stabilize only 1 storderunstable process.ChangingcontrollergainK canchangeclosedloop dynamics.Alargecontrollergainwillresultincontrolsystemwith:
a) Smaller steady state error, i.e. better reference follower
b) Faster dynamics, i.e.broader signal frequency band of the closed loop system and larger sensitivity with respect to measuring noise
c) Smaller amplitude and phase margin. In the P controller algorithm, the controller output is proportional to the error signal, which is the difference between the set point and the process variable. In P controller the actuating signal

forthecontrolactioninacontrol system is proportionaltothe errorsignal.Theerrorsignalbeingthedifferencebetweentherefer enceinputsignalandfeedbacksignalobtainedfromthe output. Forthesystemconsideredasshowninthe Fig.2.Theactuatingsign al isproportionaltotheerrorsignal therefore; thesystem iscalledPcontrollersystem.Theerrorofsignalgivenas follows:

$$e(t)= k[r(t)-h(t)] \qquad (1)$$

Itisdesirablethatthecontrolsystembeunderdampedforthepointo fview ofquickresponse. Anunderdamped controlsystem exhibitsexponentiallydecayingintheoutputtimeresponsedurin gthetransientperiod [22].Proportional Integral (PI) Controller Atpresent,thePIcontrollerismostwidelyadoptedinindustrialap plicationdue toits simplestructure,easyto designandlow cost.Despitetheseadvantages,thePIcontrollerfailswhenthecont rolledobjectishighlynonlinearanduncertain.PIcontrollerwilleli minateforcedoscillationsandsteadystateerrorresultinginoperat ionofonoffcontrollerandPcontrollerrespectively.However,intr oducingintegralmodehasanegativeeffectonspeedoftherespons eandoverallstabilityofthesystem.Thus,PIcontrollerwillnotincr easethespeedofresponse.ItcanbeexpectedsincePIcontrollerdoe snothavemeansto predictwhatwill happen withtheerrorin near future.Thisproblemcanbesolvedbyintroducingderivativemode whichhasabilityto predictwhat will happenwiththeerrorinnear futureandthustodecreaseareactiontimeofthecontroller.PIcontr ollersareveryoftenusedinindustry,especiallywhenspeedofther esponseisnotanissue.Acontrol withoutDmodeis used when
1.Fastresponseofthesystemisnotrequired
2.Largedisturbancesandnoisearepresentduringoperationofthe process
3.Thereisonlyoneenergystorageinprocess(capacitiveorinducti ve)
4.Therearelargetransportdelaysinthesystem.Therefore,wewou ldliketokeeptheadvantagesofthePIcontroller.Thisleadstoprop oseaPIcontrollershownin Fig.3.Thiscontrollerusesofthepropor tionaltermwhiletheintegraltermiskept,unchanged.Thecontroll eroutputinthiscaseis

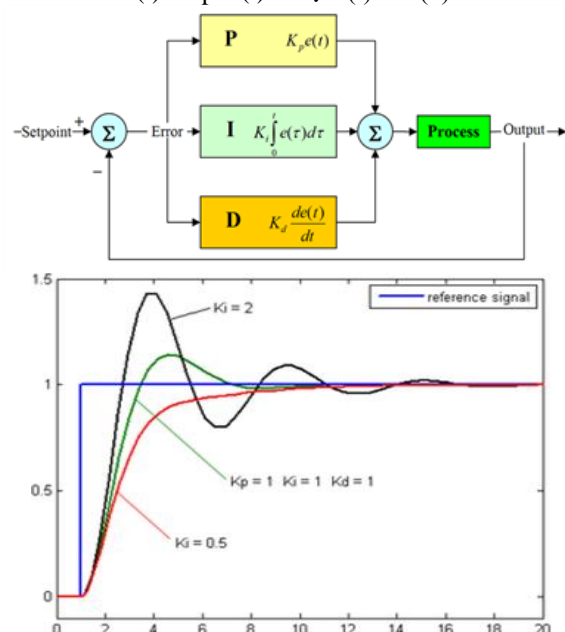$$u(t)= Kp.e(t)+ Ki\int e(t)\, dt \quad (2)$$

Fig. 3. Block Diagram and Response of PI Controller

Fig.3. block diagram of PI controller for an integral error compensation scheme, the output response depends in some manner upon the integral of the actuating signal. This type of compensation is introduced by using a controller which produces an output signal consisting of two terms, oneproportionaltotheactuatingsignalandtheotherproportionaltoitsintegral.SuchacontrolleriscalledproportionalplusintegralcontrollerorPIcontroller [23].

B. Proportional Integral Derivative (PID) Controller

Manyindustrialcontrollersemployaproportional, integral plus differential PID regulator arrangementthatcanbetailoredto optimize a particular control system. PID controller is most commonly used algorithm for controller design and it is most widely used controller in industry. The controllers used in industry are either PID controlleror its improve version.Thebasictypes of PID controller areparallelcontroller, serialcontroller, andmixedcontroller. The PID controller algorithmutilizedforisdesignvelocityalgorithm,itisalsocalledincrementalalgorithm. In the industry, PID controllers are themostcommoncontrol methodologyto useinrealapplications [25], [34].

PID controllerhasall the necessary dynamics:fastreaction onchange ofthecontrollerinput(Dmode),increase incontrol signaltoleaderrortowardszero(Imode)andsuitableactioninsidecontrolerrorareatoeliminateoscillations(Pmode)DerivativemodeimprovesstabilityofthesystemandenablesincreaseingainKand decreaseinintegraltimeconstantT$_i$,whichincreasesspeedofthecontrollerresponse. PID controllers are the most often used controllers in the process industry. The majority ofcontrolsystemsintheworldareoperatedPIDcontrollers.Ithasbeenreportedthat98%ofthecontrolloopsinthe pulp and paper industries are controlled by single-input single output PI controllers and that in process control applications, more than 95%ofthecontrollersareofthePIDtypecontroller.PIDcontroller combinestheadvantageofproportional,derivativeandintegral controlaction [26].
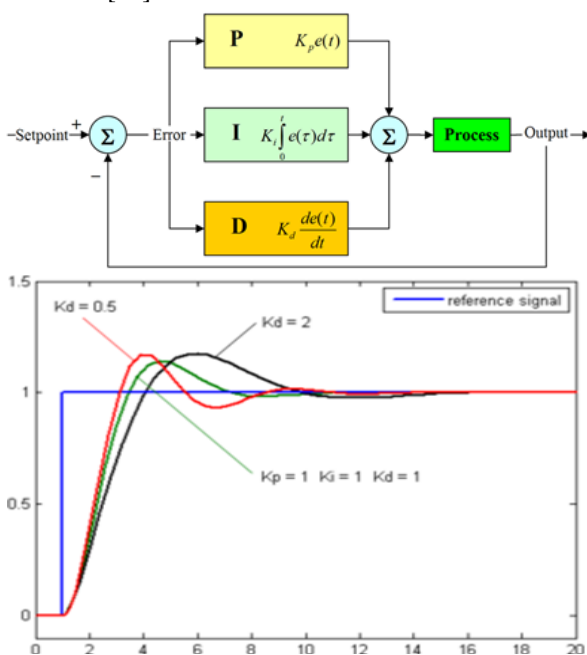

Fig. 4. Block Diagram and Response of PID Controller

ThecontrolsignalisproportionaltotheerrorsignalandtheproportionalgainKp.Aproportionalcontrollerwillhavetheeffectofreducingtherisetime and will reduce, but never eliminate. If an integrator is added, the controlsignalisproportionaltotheintegraloferrorandtheintegralgainKi.Integralcontrolwillhavetheeffectofreducedtheerror,inprinciple,tozerovalue.Thein principlemustbeadded,becausetherearealwayslimitsonaccuracy in any system. Derivative control is used to anticipatethefuturebehavioroftheerrorsignalbyusingcorrective actionsbasedontherateofchangeintheerrorsignal.ThecontrolsignalisproportionaltothederivativeoftheerrorandKdisthederivativegain.

$$u(t) = K_p . e(t) + K_i \int e(t) \, dt + K_d \frac{de(t)}{dt} \quad (3)$$

Derivativecontrol will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response.Derivativecontrolactioncan never be used alone because thiscontrolaction is effective onlyduringtransientperiods.ThePIDcontrollermakesacontrollooprespondfasterwithlessovershootandmostpopularmethodof controlbyagreatmargin.Thecombinedactionhastheadvantages ofeachofthethreeindividualcontrolactions [24], [27].

C. Selection of Controller

The control system should beanalyzedand suitablecontroller should be selected and designed. Few important propertiesofthewidelyusedP,PI,and PID controllers are:

a) Mode of Action
b) Process lag.
c) Speed of the error correction.
d) Acceptability of steady-state error.

According to the above information controllers and systems can be assigned to each other as:

- For easy-to-control systems where steady-state errors are acceptable, P controllers are used.
- In systems with great lag where off set is to lerable, PD controllers are used.
- For applications with low requirement to control dynamics, where the system does notexhibitgreat lags; Icontrollersare used.
- For a dynamic control response without exhibiting the steady state error, PI controllers are used.
- If it is required that the speed of the response is as high as possible, regard less of the greater lag; PID controllers are used [29].

IV.   DC MOTOR DRIVE COMBINED WITH CONTROLLER

Fig. 5 shows a closed loop speed control scheme which is widely used in electrical drives [30]. It employs an inner current loop within an outer speed loop. Inner current control loop is provided to limit the converter and motor current or motor torque below a safe limit. In some schemes the current is controlled directly [8].
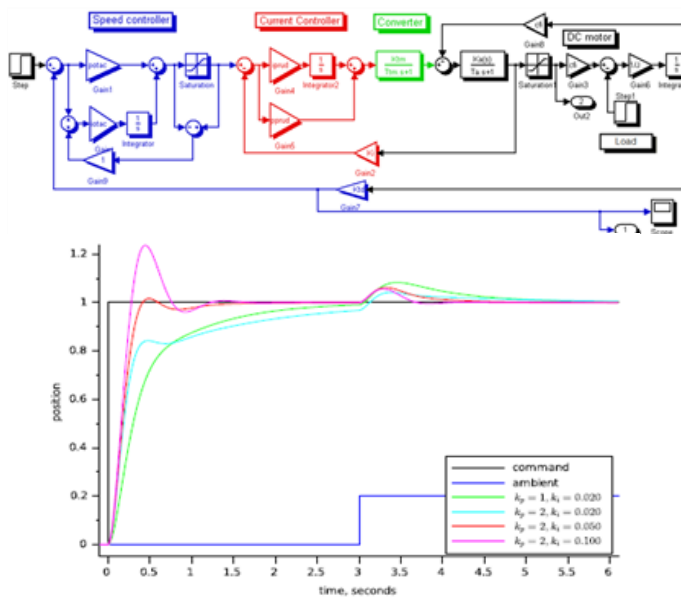
Fig. 5. Closed loop control and response of DC Motor Drives

Inner current loop is also beneficial in reducing the effect on drive performance of any non-linearity present in converter-motor system.

An increase in reference speed ωm* produces a positive error Δωm, speed error is processed through a speed controller and applied to a current limiter which saturates even for a small speed error. Consequently, limiter sets current reference for inner current control loop at a value corresponding to the maximum allowable current. Drive accelerates at maximum allowable current [10].

When close to the desired speed, limiter desaturates. Steady state is reached at the desired speed and at current for which motor toque is equal to the load torque.

A decrease in reference speed ωm* produces a negative speed error. Current limiter saturates and sets current reference for inner current loop at a value corresponding to the maximum allowable current. When close to the required speed, current limiter desaturates [11].

The operation is transferred from braking to motoring Drives, when settles at a desired speed and at current for which motor torque equals to load torque [15]. In those drives where the current I,do not have to reverse for braking operation; current limiter will have input / output characteristics as normal. In those drive applications where the load torque is able to provide enough decelerating torque; electric braking need not be used [16], [28], [31]. Table 1 and 2 shows the effects of coefficients and effects of changing control parameters respectively [29].

TABLE 1: COMPARASION OF GAIN RESPONSE OF P, PI AND PID CONTROLLERS

Parameter	SpeedofResponse	Stability	Accuracy
Increasingk	Increase	Deteriorate	Improves
Increasingki	Decrease	Deteriorate	Improves
Increasingk	**Increase**	**Improves**	**Noimpac**

TABLE2: EFFECTS ON VARIOUS O/P PARAMETER OF P, PI AND PID CONTROLLER WITH RESPECT TO VARIATION IN RISE TIME

Parameter	P Controller	PI Controller	PID Controller
Risetime	Decrease	Decrease	MinorDecrease
Overshoot	Increase	Increase	MinorDecrease
Settlingtime	Smallchange	Increase	MinorDecrease
Steadystateerror	Decrease	Significantchange	Nochange
Stability	Worse	Worse	IfK_dSmall,Better.

V. CONCLUSION

Pcontrollercanstabilizeonly1storderunstableprocess.PIcontrollercanbeusedtoavoidlargedisturbancesandnoise presents during operation process. Whereas PID controller can be used when dealing with higher order capacitive processes. The comparative study of P, PI and PID Controller is carried out, in which PID controller gives good response than any other controller. Further output response of DC Motor Drive will be evaluated by using different P, PI and PID controllers. Based on different industrial application of DC motor, appropriate controllers are chosen. DC motors are used extensively in industrial variable speed applications because of most demanding speed-torque characteristics and are simple in controlling aspects. The linear system model of separately excited DC motor with Torque-variation is designed using PID controller. A MATLAB simulation of proposed system with no-Load and full-load condition is performed on Simulink platform to observe the system response. The motor speed is kept constant in this experiment. The simulation result of the experiment shows that a motor is running approximately at a constant speed regardless of a motor load. The Simulink results show that the speed of the motor is slow down only for about 270 rpm (9%) in 980 milliseconds under the effect of full load. However, the motor speed is hunting about 200 rpm (6.66%) in 900 milliseconds on no-load condition. It is concluded that a PID controller is an effective tool for controlling the motor speed in presence of load disturbances.

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