Application Guidance Notes: Technical Information from STAMFORD | AvK

AGN 090 – Motor Starting Fundamentals

INTRODUCTION

There are a number of aspects to be considered regarding the electrical supply required for starting a motor. Guidance is offered for Motor Starting applications, because 'Motor Starting' continues to create technical problems for Generating Set manufacturers. This guidance is intended to assist Generating Set manufacturers when they discuss with their customers, the characteristics of the motor or motors to be started. The information on the motor will determine the type and size of alternator that is nominated and assist in the selection of a suitable Generating Set.

MOTOR DESIGN FUNDAMENTALS

To help with identifying the information required for alternator sizing purposes, it is necessary to understand the basic design of an induction motor.

Induction Motor Basics

Motors are part of the family of Rotating Electrical Machines (REMs). The industry standard for REM's is IEC 60034. This international standard consists of many parts covering all aspects of performance from efficiency through to Duty Type and includes sections on ratings, protection, noise, vibration etc.

Enclosure protection design can be from IP22 through to a totally enclosed design rated at IP55. For further information, refer to AGN066 – Alternator IP Protection.

Rotor

The cylindrical rotor has a cast-in aluminum 'squirrel-cage' with round /oval bars running axially just below the surface of the cylindrically shaped, laminated steel constructed rotor core assembly. The aluminum cage-bars are circumferentially equi-spaced around the rotor, with the number of such bars being decided by a design relationship with stator winding's number of poles. This winding configuration being related to the required motor starting torque and required level of rated running torque; all being a complex function considered by the electro-magnetic design engineer at the design stage of the motor, based on performance specification requirements. At each end of the rotor these Squirrel-cage-bars are shorted together by either a process part of the way the aluminum cage is cast into the steel rotor assembly, or by some form of machine press/crimp/rivet process.

Stator

To keep it simple, the following description is just for a 3-phase motor. The stator has a symmetrical, equi-distributed 3-phase winding within a laminated steel, stator core assembly. When a 3-phase ac voltage is applied to the stator winding, current will flow through' this winding, and this will create an electro-magnetic flux within the stator core, which actually spills out in a controlled manner and crosses the air-gap between stator and rotor. This electromagnetic flux will induce a voltage (electrical pressure) in the rotor's squirrel cage-bars. If a 3-phase ac voltage of 50Hz is applied to the stator winding, then a resultant circumferentially 'rotating' magnetic field can be reasoned to be traversing around the stator bore at 1500 rpm.

As the ends of the Squirrel-cage-bars are shorted together, therefore making a closed electrical circuit, electrical current will flow through the cage-bars, and thereby an electromagnetic flux is now created by the Squirrel-cage 'winding' of the rotor core assy.

The fixed speed 50Hz flux in the stator winding generates its constantly changing N.S.N.S.N.S magnetic fields in each of the four pole regions (remember that in a 3-phase machine each of the 4 poles is actually a complex 'mix' of rising and falling U-V-W phase influences). The magnetic fields created within the rotor's Squirrel-cage are attracted by the stators N.S.N.S.N.S magnetic fields, and chase them - magnetic attraction - thereby developing a rotational torque and so a rotary movement of the motors rotor and shaft.

MOTOR STARTING METHODS

Here we consider the moment at which the ac voltage is switched onto the stator. We know that motors have a large inrush current at 'start'. We also know there are various types of motor starting systems, and these are briefing described as follows:

- Direct on Line: resulting in the highest levels of inrush currents (actually technically described as Locked Rotor currents).

- Star-Delta being a traditional way to reduce the inrush current by making the stator have a higher Impedance (Impedance: electrical symbol is Z, and consider Z is actually a term for resistance in an ac circuit, whereas resistance R is resistance associated with a dc circuit, the unit for both is Ohms) and so less willing to allow the applied voltage to force current into the stator windings.

- Power Electronics are more often the most cost-effective ways of controlling the starting related inrush current, achieved by using an Electronic Soft Start system. Of course, power electronics can be used to change the actual level of applied frequency (Hz), by changing the actual running speed of the motor. This is done by modifying the mains 50Hz to a lower or higher level of Hz at an appropriate voltage level. These systems being known as Variable Speed Drives (VSDs) or Variable Frequency Drives (VFDs).

Under a start condition with lots of current flowing in the motor's stator winding, a very strong electromagnetic field is developed within the stator and this is imposed onto the rotor assembly. This induces a high voltage, and so high current, in the Squirrel-cage, resulting in a high strength magnetic field in the rotor. These 'strong' magnetic fields in the stator and rotor result in a high rotational torque, and so the motor is able to overcome the 'stiction' of a coupled load and begin its acceleration to speed.

Using a start method that results in reduced inrush current will limit the motors ability to develop starting torque, making it important to ensure the start method will allow the motor to develop sufficient torque to start and not held in a locked rotor 'stalled' condition.

From this variation of motor starting methods, it is clear that, when asked to nominate a suitable alternator for starting a motor, the following must be established:

- Supply system voltage and frequency.
- Motor designed running kVA.
- Motors actual run kVA when driving its coupled load.
- The characteristics of the coupled load.

In the information gathering process, problems can start at the very first stage, where the information relating to the motor will almost always be provided as unqualified kW. Now, if this data has been taken from the motor nameplate it almost certainly will relate to the **kWm [mechanical]** that the motor is designed to develop as shaft power.

Sometimes the data for the motor has been taken from the motor control centre, and this often relates to the **kWe [electrical].** This situation needs to be clarified as part of the exercise to quantify the motor impact kVA during motor starting and to establish the continuous rating associated with the run kVA.

For alternator sizing purposes, we have a dilemma; should the motor efficiency be taken into account, or not? When it involves the combined running of a number of relatively small motors, the efficiency is often relatively low and so the issue becomes quite significant in quantifying the impact and run kVA levels. The next area for clarification is to identify the motor start method, this being crucial in identifying the impact kVA, which in turn will determine the size the alternator, especially if a maximum level of Transient Voltage Dip [TVD] has been specified.

Starting power requirements for typical starting methods

Direct on Line. This presents a high impact kVA, but does allow the motor to develop a high starting torque and so often a necessity to overcome the motors coupled load static inertia requirements. Typical applications being, a loaded conveyor belt, or a stone crusher with a jammed stone. Impact kVA levels will vary with different motor design characteristics, from 4 times run kVA up to 9 times the run kVA. As a general Rule of Thumb:

- *Use **7** times for motors < 250 kWm.*
- *Use **6** times for motors >250kWm.*

The starting power factor for these DOL motors will be low, at 0.1 to 0.2 lagging.

Star Delta. This starting method is a cost-effective system to reduce start 'impact kVA levels' and is still very commonly employed in applications where there is no demand for the motor to develop a high starting torque, for example, [water] pumps, or fans with relatively low mass impellers. It should not be forgotten that at the transition from star to delta, there will be a second impact kVA condition, which could be as high as 5 x run kVA and unless the point of transition is carefully set during equipment commissioning, it may well result in a level of transient voltage dip that causes the start process to fail. As a general Rule of Thumb:

- *Use an initial 'star' impact factor of 2.5 times run kVA and, with a 'good' transitional impact 3 times run kVA.*

The starting power factor for these Star Delta motors will be 0.4 lagging.

Auto Transformer. If an auto transformer is used with various tapping points available, it offers the opportunity to set the lowest possible impact kVA, with the idealised starting torque, sufficient to ensure the motor's coupled load is accelerated to speed, after the lowest possible 'start' impact onto the electrical power system. In most cases the situation is a compromise; as there is only one transformer tapping point available and the impact kVA has to be calculated around this. In most cases it is quoted as 80%. It should be remembered that there will be a second 'impact' when full working voltage is applied. As a general Rule of Thumb:

- *The impact kVA will be based on the normal DOL value (see previous page) times the applied percentage Voltage^2. For example, assuming a DOL factor of 7 and an auto transformer tapping point of 80%. The impact kVA will therefore be: $7 \times 0.8^2 = 4.5$ times the run kVA.*

The starting power factor for these Auto Transformer motors will be between 0.2 and 0.25 lagging.

Electronic Soft Start. Motors with Electronic Soft Start systems could be considered to be the absolute, ideal, start system. They have Auto Transformer characteristics refined to simulate multi-adjustable tapping for the initially applied 'pedestal' voltage and a step-less progression to full working supply voltage, over an adjustable controlled, ramped time period. With all this offered within a cost effective, solid-state, electronics package.

Unfortunately, these units introduce **harmonic distortion** onto the electrical supply system and whilst still offering benefits for motor starting on a mains supply, the harmonics can become a critical factor for both the 'Soft Starter' and the Generating-Set that are to operate together. This is unless sufficient guidance is provided during the engineering stage for the total electrical system.

It is possible to get the motor to start with a 40% pedestal voltage, which will result in an impact kVA of 0.16 x the DOL factor of 7. This will result in an impact of only 1.1 times the normal run kVA.

However; when the harmonic distortion is present, the critical factor is: will the distortion levels adversely affect the control circuits in both the 'soft starter', and/or the AVR of the alternator? The harmonic current distortion levels are decided by the characteristics of the power electronics employed within the 'soft starter'. The effects of this current distortion will cause harmonic distortion to the supply voltage waveform and the resulting level of voltage distortion being a product of the 'source impedance of the supply'.

For an alternator, the 'source impedance' is most directly controlled by the value of the sub-transient reactance (X"d). So, the critical situation is that the source impedance of the supply should be as **low** as possible, such that the resulting level of harmonic voltage distortion is kept as low as possible. As a general Rule of Thumb:

- *Where solid state 'soft starters' are employed, any quick 'rule' will result in a very expensive, and oversized, standard alternator being nominated. It is better to gather the motor and starter data, for accurate alternator sizing calculations.*

A cautionary note on terminology: Americans will often use the term 'Soft Start' for Star Delta systems.

Variable Speed Drive (VSD). As with the Electronic Soft Start, these units introduce **harmonic distortion** onto the electrical supply system. They work by ramping the voltage, which results in an impact kVA in the order of 1.1 times the normal run kVA.
The actual start method, and so multiplying factor, will depend on the required motor torque to overcome its coupled load's static friction, in order to ensure the motor is never held in a stalled condition.

It should always be remembered that motor designs are available for specific motor-powered applications; therefore, motor designs with a high starting torque are available for which a DOL situation may take 10 x designed kVA. Similarly, for a low torque pump requirement, a special motor design with only 3.5 x designed kVA for a DOL start are also available. It is important to know as much about the motor design as possible.

When considering Electronic Soft Start systems, where the start current or start kVA has not been advised, it is important to request details of the 'set level' of pedestal voltage, in terms of %, of supply voltage. Then use this V%, in per unit terms, in the same way as with the Auto Transformer system.

Having identified the Start Impact kVA, establish: what other loads are being supported by the Generating Set, as this provides guidance about acceptable levels of transient voltage dip % or acceptable levels of harmonic voltage distortion for the electrical system.

The harmonic voltage distortion on the system will be just short term with Electronic Soft Start systems and continuous as with VSD motors.

It is also important to establish if more than one motor is to be supplied and then, will those motors be started simultaneously or sequentially?

Fundamentals Considerations for Specific to Generating Sets

Accept that the most significant problem associated with motor starting is the ‘impact kVA’ and the magnitude of this starting problem is due to the motors characteristics, as a result of a suddenly applied standard voltage and frequency; this characteristic being the result of the motor’s internal ‘slip frequency’.

So, if a scheme could be devised to apply a very low voltage and perhaps a low frequency to reduce the slip frequency, it should be possible to start the motor and run it up to speed at the lowest possible motor start kVA level.

Before going any further it must be stated that if the motor to be started must develop a high starting torque and maintain a high torque during the run-up period, the required [high] motor shaft power will be developed as a result of the [high] input power, therefore related to the [high] input kVA, to the motor.

For all the reasons associated with characteristics of induction motors, a high starting torque is related to a high input kVA during the run-up period. For exactly the same reason that choosing a motor start method, DOL or Star-Delta etc. is always based on the motor’s required torque level. Therefore, the following start method should only be used for low torque start applications.

The scheme involves an alternator with an excitation system that can support a steady state short circuit current, therefore an alternator with a separately excited type of system. The motor is connected to the terminals of the Generating Set, but with the Generating Set not running.

Option 1.

- Start the Generating Set.
- As it runs up to speed, the excitation system will ‘see’ the motor as a ‘short circuit’, therefore current will flow through the motor windings and result in the motor developing torque and therefore, will start to rotate.
- As the motor speed rises, the short circuit condition on the alternator will change, resulting in a gradual reducing current, in conjunction with a rising alternator output voltage.

- If it is possible to arrange for the running speed of the engine to be controlled, therefore holding the system frequency as low as is possible, [engine minimum speeds vary] to keep the slip frequency situation as low as possible.
- The ideal run-up would be to engineer a system whereby some reduced, but relative frequency, voltage and current stability are achieved and the motor and Generating Set finish the run-up to rated speed, in relative synchronism.

Option 2.

- Same condition of motor connected to Generating Set, with the system at rest. The alternator excitation system is disabled by a switch. The Generating Set is started and allowed to run up to speed. The excitation switch is closed. In line with the above [Option 1] described process, the alternator excitation system goes 'flat-out' in an attempt to establish the required system voltage and in so doing allows the Generating Set to push the motor up to speed, with a rising voltage.

- The difference here is that there is no attempt to reduce the slip frequency situation. It has to be said that this may be of marginal benefit, when the speed at which an engine reaches speed; there is little chance for the motor to stay 'locked' with the generated frequency.

Both the above procedures are used to start motors where there is a dedicated one motor to one Generating Set situation and the motor control system is powered from an independent source and of a design that will allow that 'permanent connection' between motor and Generating Set with the Generating Set at rest.

It must be emphasised that the motor to be started must be coupled to a very low inertia load, otherwise the motor will just stall. Typical applications are; ship bow-thrusters, where the impeller can be set to zero pitch, and pumps where there is no standing 'head pressure' of water.

Prolonged Run up Times.

Some applications, such as large fan drive applications, involve a motor running up to speed over a time period that may well extend to 30seconds (or more). The motor has been designed with this level of overload capability, although it may well be specified that the motor should not be subjected to this situation more than say, once per hour. Due consideration must be given to the capabilities of the Generating Set that must support the motor during this prolonged overload / run up period.

Consideration must obviously be given to the motor impact kVA, the resulting transient voltage dip [TVD] and then for the duration of the run up period. Some attempt must be made to calculate the input kVA to the motor compared with time, right up to the point that the motor reaches nominal speed, at designed run kVA.

This information will give guidance regarding the alternator's output current, allowing consideration to be given to the heating effect upon the stator windings and also the level of excitation under which the Generating Set will be operating over the run up period. This excitation situation must be quantified to identify the risk of the AVR unit detecting a prolonged period of ‘over excitation’ and deciding to safeguard the alternator by switching off the excitation.

A well-engineered system will have included all considerations to ensure that after commissioning this will not happen, it being a real problem if it happens, especially if just seconds before the motor ‘run up’ is completed.

Running at speed

As the rotor speed increases, the effects of the rotor’s magnetic flux is one of changing the motor’s 'willingness' to accept having current forced into its stator winding by the applied 3-phase ac supply voltage.

This situation is often referred to as the motor developing a 'back emf' (Electro-Motive Force). But this again is a complex situation of the closer the rotor speed is the stator’s rotating electro-magnetic field speed (remember 4-pole winding, 50Hz supply = 1500rpm rotating flux speed) the lower the level of induced voltage and current into the Squirrel-cage.

In fact, when the rotor gets close to 1500rpm the level of induced voltage/current in the Squirrel-cage is much reduced and so for this reason, induction motors actually run with a 'slip-frequency' of something like 2Hz. This is why a 4-pole motor’s rated speed is typically 1440 rpm under a very light load or no-load condition.

When load is applied to the motor’s shaft, which tries to slow the rotor's speed, the current in both stator and rotor increase, because of increased 'slip-frequency’ and this is the motor’s inherent design method of developing more shaft power.

Of course, if too much load is applied it is possible to exceed the motor's designed limits and take it in to a 'pull-out' torque situation, which effectively means it goes into a stall condition, pulling high current from the supply, because the rotor speed is too low to create the required back emf. Hopefully the motor's circuit breaker will trip and stop a 'burn-out'.

IDENTIFYING A SUITABLE TYPE OF ALTERNATOR AND EXCITATION SYSTEM

We know, it is the power demand on the impact of starting the motor that determines the size of alternator required for supplying power to that motor. It is usual to consider that a motor is capable of developing its required starting torque, providing that the applied voltage to the motor and its starter, does not have a Transient Voltage Dip (TVD) greater than 35%. It is important to take into account, that this motor and its starter are connected to the Generating Set via cabling that also has a TVD contribution. Therefore, throughout the industry it is usual to allow 10% of the TVD for the cabling, which then effectively leaves 25% for the Generating Set.

Transient Voltage Dip on Motor Starting

This 25% for the Generating Set will have to take into account the effect of the speed droop, of the engine. So realistically, the alternator technical data sheet Locked Rotor Curves - which are based on a constant speed - are used and perhaps the most that can be allowed, just for the alternator, is now considered to be <25%.

It is also important to consider a situation where the Generating Set is supplying other loads and these loads may well be critical to such levels of TVD, or indeed a transient frequency dip on the system. In such circumstances the above TVD values may have to be further reduced. Some loads can be quite intolerant of sudden voltage or frequency changes. Here, the critical factor is the 'slew rate' of the change.

A well-designed alternator working at a good flux level will have a TVD of around the 25% level with an impact of around 175% of its Class H temperature rise rated kVA. A separately excited alternator, consisting of auxiliary winding excitation or PMG excitation, can be almost 200% and the self-excited alternators, using an SX type or AS type AVR, may be only 160% of the Class H temperature rise rating for a 25% TVD.

If the motor instantly demands torque; therefore, subjecting the Generating Set to an instant demand for power, or the motor has a high inertia load and so will have a slow rate of acceleration to rated speed, therefore demanding higher than normal run kVA for a prolonged period, then the separately excited alternator is the only alternator worth offering.

Transient Voltage Rise

One further point that must always be considered, is the Transient Voltage Rise (TVR) when a given rated load is suddenly rejected. Many specifications state a TVR of no more than 120% voltage at rejection of a high proportion of rated load. This is achievable, but does need clarification of the rated load and careful consideration for the nominated alternator.

Locked Rotor Condition and Power Factor

With consideration of the above points, alternator technical data sheets, specifically the Locked Rotor Curves, are used to provide guidance regarding each alternator’s performance against an impact load with a low power factor. The following established values of power factor against the identified levels of Locked Rotor kVA are used:

For DOL start use:	0.1pf to 0.15pf.
For Star/Delta use;	0.4pf.

For other start methods the value of power factor will need to be chosen as appropriate to the Impact kVA multiplier.

For instance, a VSD will probably start at 0.8 to 0.85 pf. In fact, for these ‘other’ methods a power factor is used that will suggest a realistic demand for engine power over the motor’s acceleration period as set by the motor controller, or Soft Starter’s ramp rate of voltage rise.

The commissioning procedure should optimise the 'starter' settings, especially for the transition point from Star to Delta. For many start considerations, experience about the motors rate of acceleration from a Locked Rotor situation is known to be a much-reduced slip frequency per unit speed and the fact that this may now be related to a demand for the motor to develop a high percentage of its designed shaft power.

DEMAND FOR ENGINE POWER

Often, the Impact kVA looks high, so therefore does the instantaneous demand for engine power. But experience suggests the kinetic energy of the engine/alternator’s spinning mass will satisfy a high proportion of this momentary energy demand, to help offset the short delay whilst the engine fuelling system can produce real shaft kWm.

The old-fashioned way of relating Generating Sets to a performance of kW of Motor to kVA of Generating Set, is no longer considered to be reliable for a cost-effective nomination and so are rarely used and should be discouraged.

Under the conditions at the moment the supply is applied to the motor, the rotor is at rest, termed “Locked Rotor” and the electrical situation is described as an “impact kVA”. The power factor of the impact kVA will be such that the kWe will be very similar to the normal run kWe and from the kWe/kVA relationship and a typical power factor for this impact condition, can be established.

Under impact kVA conditions the Generating Set is usually operating under an overload situation and this combined with the very low power factor, which incurs high excitation levels, results in a Generating Set that is operating at an efficiency level considerably below its ‘rated’, normal published figure.

This therefore, demands of the engine more kWm than may well at first have been considered and so available engine power can become an issue. However, if the motor coupled load is easily accelerated to speed, this momentary demand for engine power at the locked rotor condition is of a very short duration, and may well be easily satisfied by the kinetic energy associated with the engine crankshaft / flywheel, combined with the alternator rotor assembly.

If a prolonged run up time is involved, or high torque demanding load is coupled to the motor, then the engine will be called upon to develop some level of sustained power [kWm] that may well push it into an overload [fuel stop] condition.

If this results in the engine speed falling and it usually does, then it may well activate the AVR’s ‘Under Frequency Roll Off’ circuit, which is designed to reduce the output voltage in relation to the operating speed. This circuit is incorporated into AVR’s to act as protection for the alternator’s excitation windings and an aside benefit is that by reducing the output voltage, it reduces the load on the alternator, therefore the load on the engine, therefore tends to help the engine overcome this sudden demand for power.

The level of impact kVA, of the motor that is being started, is also reduced by this reduction in voltage and frequency. The reduction in applied voltage will affect a reduction in the current and the reduction in frequency will affect a reduction in the slip frequency, further reducing the current.

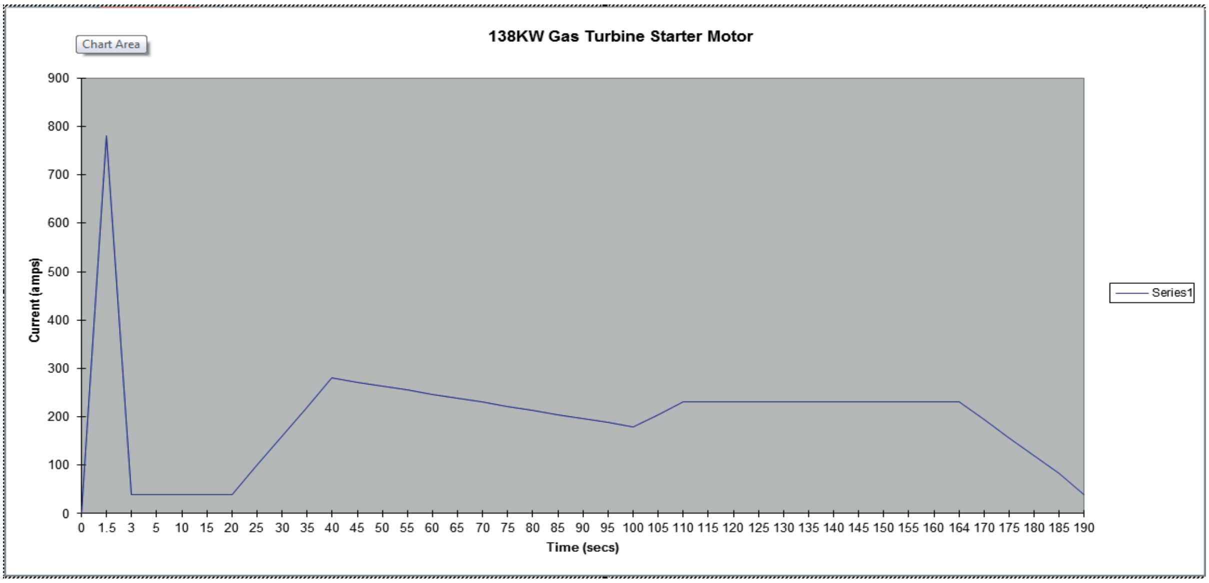
So, now a point is reached where the motor is demanding less power of the engine, equilibrium exists in the ‘power demanded’ and ‘power available’ stakes and then [hopefully] the engine turbocharger tips the balance in favour of the engine and rated speed and voltage are achieved, supporting a motor and load at rated duty.

Application Engineering can provide guidance regarding the required engine power (kWm) required during the motor impact and during motor run-up to speed. The engine power is based on the above established information. It is possible to make assumptions and use typical data when relevant data is not known, but the customer will be made aware of the real information shortfall.

GAS TURBINE STARTER MOTORS

The following guidance is taken from information supplied from Natural Gas Corporation and is based on a 138KW Gas Turbine Starter Motor.

A Direct-on-Line start peak reaches approximately 780 amps and settles down to approximately 40 amps within 3 seconds. This is followed by a load ramp from 40 amps at 20 seconds to approximately 280 amps at 40 seconds and gradually decreasing to 180 amps at 100 seconds, then rising to 230 amps at 110 seconds, holding until 164 seconds, then dropping to approximately 40 amps again until 190 seconds. All times are given in seconds from the start initiated at zero.



This 138KW Gas Turbine Starter Motor stands as a typical example of the starting pattern for such motors.

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