Enhanced Features of DFIG Wind Energy Converters regarding new Grid Code Requirements

Roman Bluhm, Jens Fortmann
Repower España S.L., P° Castellana 141 - pta 20, 28046 Madrid, Tel.: 0034917893463
E-mail: R.Bluhm@repower.de, J.Fortmann@repower.de

Abstract – **Wind Power is going to cover a major part of the electrical energy supply of many countries. The increasing development of wind power is causing higher demands on grid compatibility of Wind Energy Converters (WEC).**

Manufacturers like REpower are optimising the wind turbines and control strategies to cope with new requirements and to support grid integration.

Techniques of controllable reactive current infeed and voltage control with benefit for grid stability will be described and visualised by simulations performed with a validated model of a modern Multi-Megawatt-WEC, equipped with Doubly Fed Induction Generator (DFIG). The results will be compared to field test measurements.

Index Terms – **Grid fault ride through, continous voltage control, wind farm controller, Doubly Fed Induction Generator**

I. Introduction

There is a common political agreement that the fast growth of wind energy installations will continue during the next decade. The European Commission agreed to cover 20% of the European energy consumption by renewable energy sources in the year 2020. A great part of this percentage will be coverd by wind energy. Following a study of the German Energy Agency [1], there will be up to 52.3 GW wind power connected to the German grid in the year 2020. In Spain, the wind industry sector estimates an installed capacity of 40 GW by 2020 [2]. Following these prognoses, wind power is no longer negligible in any respect.

To manage the system integration of wind energy, Transmission System Operators (TSO) published special requirements (Grid Codes) which all newly installed wind farms have to fulfill. Most Grid Codes focus on the behaviour of Wind Energy Converters (WEC) during grid faults like voltage dips. In the past, immediate disconnection was required in this case. At present WEC have to guarantee to stay connected during different kinds of faults and have to supply reactive current during the fault. Grid Codes also adress the support of grid stability during normal operation. Different kinds of reactive power supply or voltage control are demanded by TSOs.

This paper shows results of continous voltage control, using the same control characteristic during grid fault and normal operation in a wind farm of wind turbines with doubly fed induction generator (DFIG). Three different kinds of implementation of voltage control in a wind farm are described and compared by simulation. Simulation results are compared to field test measurements.

II. Basic Design of a Windfarm with DFIG Windturbines

Many Wind Energy Converters use Doubly Fed Induction Generators (DFIG). The basic layout of a DFIG-System is shown in figure 1. The aerodynamic rotor of the turbine is coupled to an induction generator via a gear box. The stator windings of the generator are directly connected to the grid. The rotor windings are connected to a 4 quadrant converter system which consists of a rotor side converter (RSC), a DC link and a line side converter (LSC). The converter system is responsible for variable speed operation and reactive current control. Only a part of the produced active power has to pass the converter. For this reason a DFIG system is an advantageous cost- and energy-efficient option compared to full converter systems.

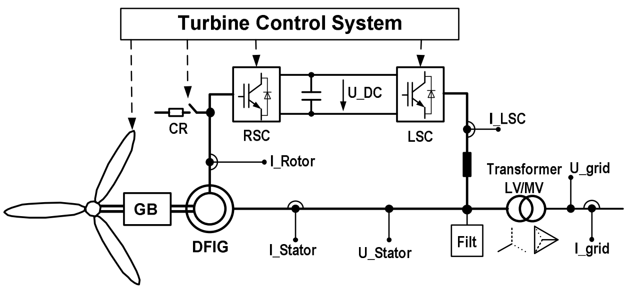

Figure 1 – Basic layout of a DFIG wind turbine

Active and reactive power can be controlled independently by decoupled control algorithms of the fast current control of the RSC. The LSC is mainly used to maintain the DC-link voltage and can supply additional reactive power. The turbine Control System also uses the pitch angle of the aerodynamic rotor to control generator speed at high wind speeds. A transformer connects the DFIG system, which operates at low voltage (LV, e.g. 690V), to the medium voltage (MV, e.g. 20 kV) grid. The turbine control system may control the active and reactive power output at LV or MV side of the transformer.

Most Grid Codes demand to control active and reactive power at the grid connection point or point of common coupling (PCC), which is usually located at medium or high voltage (HV, e.g. 110 kV) side of the HV transformer. For this task a wind farm controller can be installed at the PCC, as shown in figure 2. The wind farm controller can receive setpoints for active power reduction, reactive power or voltage control from the Control Centre of the TSO and control these setpoints at the PCC by sending control signals to all turbines of the windfarm.

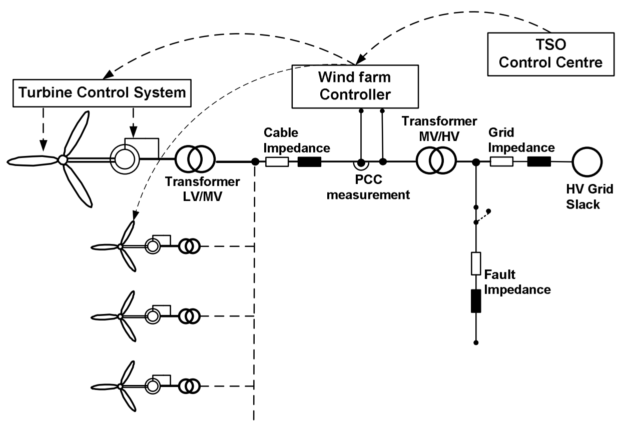

Figure 2 – Basic layout of wind farm and control signals

III. Grid Code Requirements for Voltage Control

The existing requirements of TSOs for voltage control are quite different. The German TSO Eon [3] and the VDN Transmission Code 2007 [4] demand reactive current infeed proportional to the voltage outside of the normal operation range of +- 10 percent of nominal voltage. The maximum required reactive current is equal to the nominal current:

$$Iq_{max} = I_{nominal} = 1\,\text{p.u.}$$

The characteristc is shown in figure 3 and can be described as voltage control with dead band.

The British TSO National Grid requires a continous voltage control as shown in figure 4. The control is continously acting inside the standard voltage range without dead band. Compared to the Eon requirement, the actuating variable is reactive power instead of reactive current. National Grid also defines the transient behaviour during a step response as shown in figure 5. 90 percent of the requiered reactive power should occur within 1 second. The maximum required reactive power (Qmax) is defined as a power factor of 0.95 at rated power, which is equivalent to about 0.33 p.u. (per unit) of nominal power:

$$Q_{max} = \tan(\text{acos}(0.95)) \cdot 1\,\text{p.u.} \approx 0.33\,\text{p.u.}$$

Considering these requirements, manufacturers of wind turbines are investigating enhanced control features to support the grid integration of large amounts of wind energy.

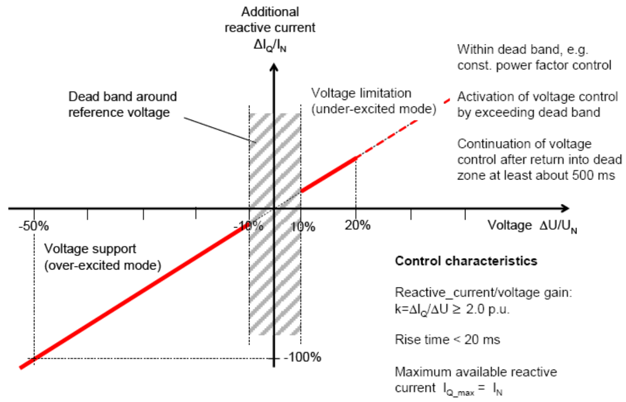

Figure 3 – Voltage Control characteristic with dead band, Eon [3]

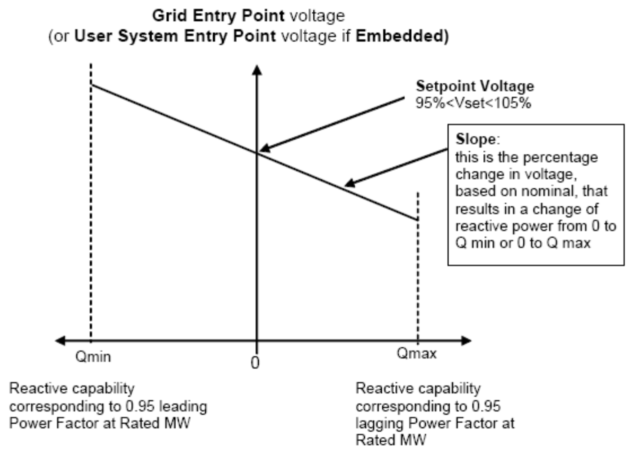

Figure 4 – Continous Voltage Control characteristic, National Grid [5]

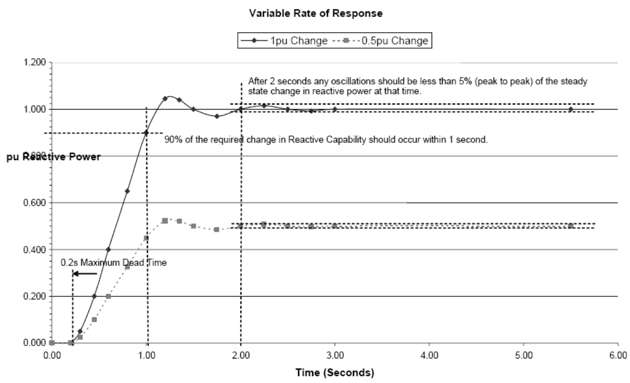

Figure 5 – Step response of Voltage Control, National Grid [6]

IV. Voltage Control Implementation

A. *General Layout*

The central point of a voltage controller is to calculate the setpoint for reactive power depending on the voltage. A general block diagram for a proportional characteristic is shown in figure 6. The voltage measurement (U_meas) is subtracted from the voltage setpoint (U_set) to calculate the voltage deviation (ΔU). This deviation is multiplied by the proportional control factor KVC to calculate the reactive power setpoint (Q_set). Depending on the desired control characteristic, a reactive current setpoint (Iq_set) can be used instead of the reactive power setpoint.

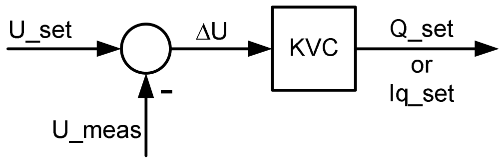

Figure 6 – Proportional Voltage Control block diagram

The control algorithm is usually set up in per unit values based on nominal voltage and nominal power or nominal current. The proportional control factor KVC represents the slope of the voltage control characteristic in figure 3 and figure 4 and is calculated as follows:

$$KVC_{Eon} = \frac{\Delta Iq}{\Delta U} = \frac{1.00\,p.u.}{0.5\,p.u.} = 2$$

$$KVC_{NG} = \frac{\Delta Q}{\Delta U} = \frac{0.33\,p.u.}{0.05\,p.u.} = 6.6$$

The slope definition of National Grid is not equivalent to the proportional control factor KVC, because it refers to the percentage change in voltage, which results in the maximum reactive power setpoint. In the example above of KVC_{NG} = 6.6, National Grid would talk about a slope of 5 percent.

The proportional voltage controller has no integral term and for this reason the voltage setpoint can not be adjusted exactly. Besides the availiable reactive power would not have sufficient influence on the grid voltage in most cases. Only the resulting reactive power or reactive current setpoint of the voltage controller can be adjusted exactly.

B. *Implementation on turbine level*

Grid fault voltage drops are transient events, which in most cases do not last longer than 300 ms. An effective voltage support during these events is only possible with very fast response times of few tens of miliseconds. To achieve such fast response times, voltage has to be controlled directly in the converter control, locally on turbine level. Power converters based on IGBT (Insulated Gate Bipolar Transistor) technology allow a reaction within miliseconds. Due to decoupled control algorithms, the reactive current can be controlled independently of the active current. The detailed implemention on turbine level with control equations has already been described in [7], [8] and [9].

The local voltage control is basically used to fulfil the fault ride through requirement with reactive current support as shown in the characteristic with dead band (figure 3). Instead of using a dead band with power factor control, it can be advantageous for grid stability to keep the local voltage control activated during normal operation. There will be no switching of the control strategy at the limits of the standard voltage range. A steady state limitation enables higher currents in case of grid faults but limits the reactive current during normal operation. During grid faults, the reactive current infeed can be temporarily increased up to approximately nominal current. When this limit is reached, the proportional voltage control characteristic remains constant (see figure 7). Due to the importance of reactive current infeed during grid faults, the priority of control may be changed from active to reactive current.

An additional advantage of the local voltage control is its inherent capability to reduce voltage differences between wind turbines within a wind farm. Voltage deviations within a wind farm can become a problem in wind farms located along a long distribution line. Using a power factor controller at the turbine and identical power factor setpoints for all turbines, the voltage would increase along the line with each turbine. In case of high grid voltages or high capacitive power factor setpoints, this could lead to an undesired shutdown of turbines at the end of the line. Using voltage control, all turbines can control their optimum voltage setpoint and remain within safe voltage operating limits.

C. *Implementation on wind farm level*

The steady state requirements for reactive power supply during undisturbed operation are usually defined at the grid connection point, see for example figure 4. Due to the reactive power losses of the medium and/or high voltage transformer and cable lines, a local voltage control can not exactly adjust the PCC reactive power setpoint. For this task, a wind farm controller is installed, like illustrated in figure 2. Based on measurement and control at the PCC, the wind farm controller calculates setpoints that have to be transferred to the individual turbines.

Because of the distance and communication delays between the controlled point (PCC) and the actuator (WEC) the time constant of this central voltage control is limited. The requirement of National Grid is to achieve 90 percent of the requiered reactive power within 1 second (see figure

5), which is already a challenging task for many wind farms. For this reason the central voltage control is only used to guarantee the exact steady state values at the PCC, but can not deliver very fast response during grid fault voltage drops.

D. Combined Implementation

A combination of both, central and local voltage control can combine their favorable characteristics with benefit for grid stability. The continous voltage control on turbine level delivers a very fast response to deep voltage drops and also to small voltage deviations inside the standard operation range. The combination with voltage control on wind farm level ensures an exact adjustment of the required reactive power value at the grid connection point. A stable control of the combined controller can be guaranteed because the time constant of the subordinate local control is more than 10 times faster than the time constant of the wind farm controller. The settings like slope or response time of the combined voltage control can be easily adapted to achieve the desired characteristics required at different connection points or in different countries.

V. SIMULATION STUDY

A. Simulation Setup

A simulation study is carried out to analyse the behaviour of the described implementation modes of voltage control. The simulation is performed with the software Matlab-Simulink with a model of a REpower MM turbine with a nominal power of two megawatt. The model was validated with measurements obtained by a field test measurement campaign. The wind farm layout is as shown in figure 2 with a ratio of windfarm nominal power to grid short circuit power of 1:20. The windfarm is running at rated active power output. The turbine control point is located at low voltage side of the LV/MV transformer and the proportional control factor KVC of turbine and wind farm voltage controller is set to 4:

$$KVC_{study} = \frac{1.00\,p.u.}{0.25\,p.u.} = 4$$

Figure 7 shows the resulting characteristic for a voltage setpoint of 1.0 per unit. The reactive power setpoint at a voltage of 1.0 per unit is zero and a voltage deviation of 0.25 per unit results in the maximum reactive current setpoint of 1.0 per unit. The reactive current setpoint stays constant for voltages lower than 0.75 per unit. Positive sign of reactive current stands for capacitive or overexcited operation which results in rising voltage.

B. Voltage deviation

The simulation case shows the control behaviour during a small step of the grid voltage of 5% inside the standard operating range.

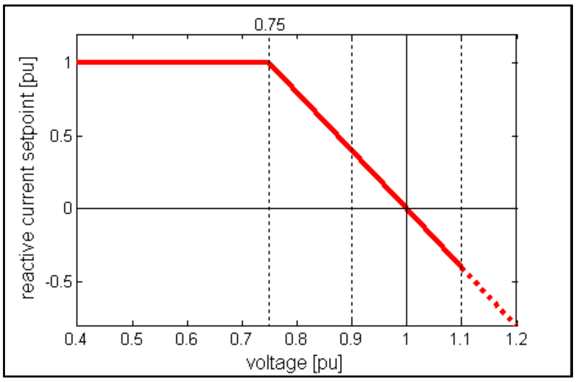

Figure 7 – Voltage control characteristic in simulation study

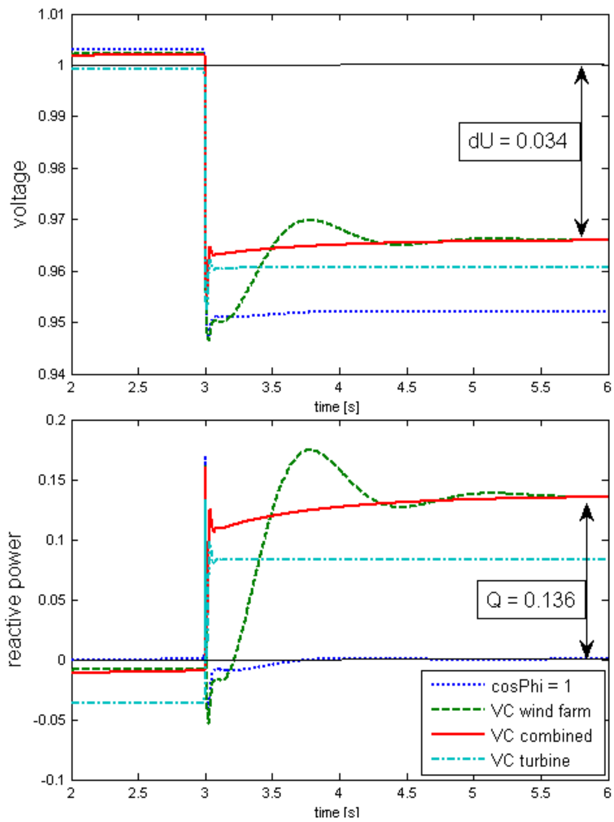

Figure 8 – Response of 4 different control modes to a 5% voltage step, values in per unit at PCC

Three modes of voltage control implementation, local ("VC turbine"), central ("VC wind farm") and combined ("VC combined") are compared to constant power factor operation ("cosPhi=1") in figure 8. This case represents a common situation in rural areas with a high percentage of wind power infeed and low short circuit power of the grid, where voltage deviations are a challenge that grid operators have to face. Such sudden voltage changes are due to far grid faults or switching actions. The alternating active power of the wind energy source and global settings for reactive power like a fixed power factor setpoint for a whole country can lead to additional voltage deviations. Voltage control can improve the situation by using the reactive power range of the wind turbines to minimise the voltage fluctuation and to keep the voltage inside the admissible range.

The simulation result in figure 8 shows that all modes of voltage control support the grid voltage after the voltage step. Without reactive power, the grid voltage would fall about 5%, like the blue dotted line with a cos Phi equal to one. The turbine voltage control (cyan dashdot line) delivers a very fast response, but does not reach the requiered steady state value for reactive power at the PCC, because the controlled point is at turbine low voltage side. The shown PCC values of the turbine voltage control are shifted due to the transformer and cable impedance.

The wind farm voltage control shows a slower response (green dashed line), but still fulfils the National grid requirement of figure 5. The required steady state value is reached after about 2 seconds.

The combined voltage control (red solid line) shows both very fast reaction time and exact steady state control at the PCC with a very favorable, less oscillating characteristic. The new steady state voltage of this control mode is about 0.966 per unit, corresponding to a voltage control deviation of 0.034 per unit, which results in reactive power delivery of 0.136 per unit. These values confirm the setting of the control factor KVC, because 0.136 is 4 times 0.034.

VI. MEASUREMENT RESULTS

A. *Small voltage drop*

Figure 9 shows a field test measurement result of combined voltage control that confirms the fast response time. The small voltage drop was generated by switching a serial impedance. In this case additional compensation terms for transformer and cable line were used in the turbine controller. For this reason the steady state value is reached even faster than in the simulation case and the transient behaviour is slightly different. The voltage setpoint was set to 0.93 per unit, which results in maximum inductive reactive power before the voltage drop. After the drop, the reactive power rises but stays inductive, because the measured voltage of 0.98 per unit is still higher than its setpoint.

B. *Deep voltage drop*

Figure 10 shows the performance of local voltage control during a 500 milisecond symmetrical voltage drop to 20 percent residual voltage. The measurement was done on medium voltage side of the turbine transformer. The local voltage control is essential for the fast reactive current response. The high reactive current of about 1 per unit only corresponds to reactive power of about 0.25 per unit, because of the low voltage.

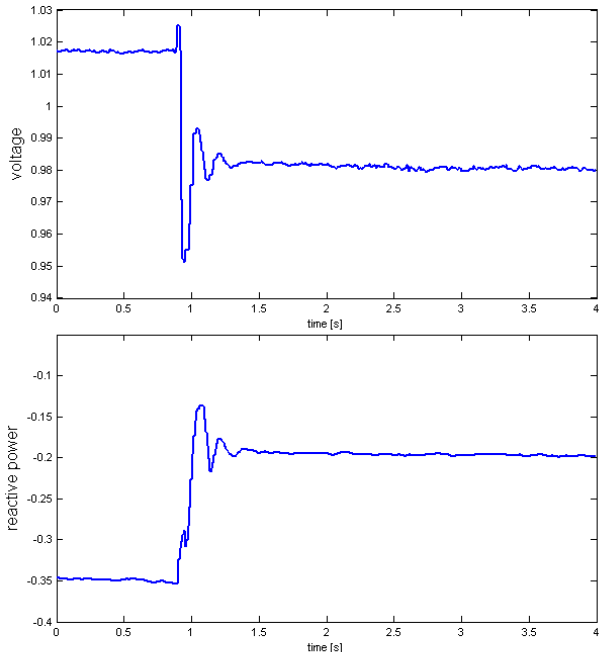

Figure 9 – Field test measurement of combined voltage control, response to small voltage step, values in per unit at PCC

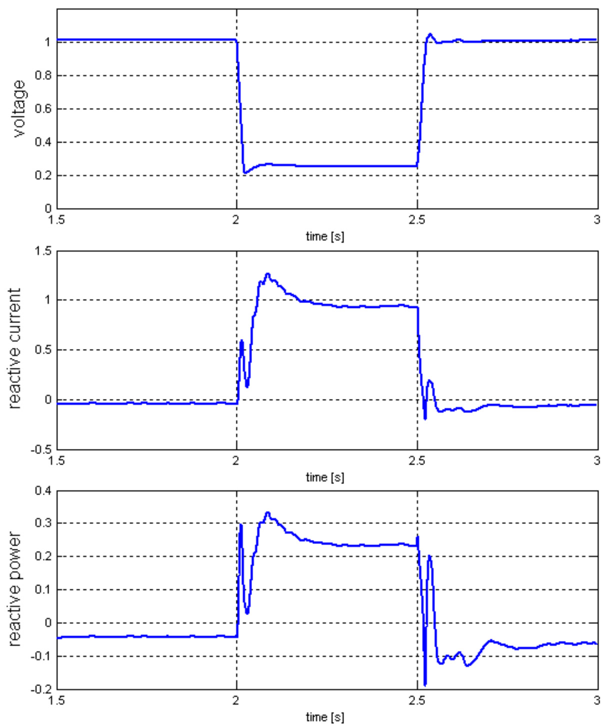

Figure 10 – Field test measurement of local voltage control, response to voltage drop to 20%, values in per unit, turbine MV-side

During such deep voltage drops, very high currents have to be managed by the DFIG system. Appropriate protection devices are necessary to withstand the overcurrents. Based on new techniques, modern WEC with DFIG ride through these grid faults without disconnection.

VII. Summary

High participation of wind power generation in European grids is a challenge that grid operators and the wind energy sector have to face during the next decade. Grid codes already require wind farms to contribute to stable network operation. Wind turbines with doubly fed induction generators can fulfil these requirements and supply even faster highly dynamic reactive current support.

A simulation study compared three modes of voltage control with a constant cos Phi operation. As a result, the combination of local and central implementation of voltage control in a windfarm shows the most favorable behaviour. Field test measurement results confirm the achievable fast response times and control characteristics.

With this kind of voltage control, wind farms are able to contribute to voltage stability in a similar way as conventional power plants. Together with other features like active power reduction on demand and frequency control, the planed integration of wind energy will become a manageable task.

VIII. Biographies

Roman Bluhm (1977) received his Dipl. Ing. degree in energy systems engineering from the University of Clausthal, Germany. In 2004 he joined the R&D department of REpower Systems AG, Germany with focus on grid connection and simulation. Since 2008 he is R&D engineer in REpower España S.L., Madrid.

Jens Fortmann (1966) received his Dipl.-Ing. degree in electrical engineering from the Technical University Berlin, Germany, in 1996. From 1995 to 2002 he worked for the wind turbine manufacturers Suedwind and Nordex Energy. Since 2002 he is with REpower Systems AG, Germany as project manager for the simulation and implementation of new technologies for improved grid compatibility of wind turbines.

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