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System-wide Inertial Response from Fixed Speed and Variable Speed Wind Turbines

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Abstract—As wind penetration levels on power systems increase worldwide, the dynamic characteristics of these systems are changing due to the displacement of synchronous generation. One issue, of particular concern, is the resulting reduction in system inertia. Modern, variable speed wind turbines are controlled by power electronics and so do not inherently contribute to the inertial response of the system. Such devices can however be fitted with a control loop which provides an active power response to significant frequency deviations, similar to the inertial response of fixed speed wind turbines and synchronous generation. However, the response of variable speed turbines is dependent on local wind speeds and so cannot be quantified deterministically by system operators. This paper examines the potential for wind generation to contribute to system inertial response and considers the aggregated inertial response capabilities of fixed speed and variable speed wind generation.

Index Terms— Active power, DFIG wind turbines, frequency control, inertia, grid code, wind power plants.

I. INTRODUCTION

IN addition to supplying energy many conventional generators are relied upon to provide support services such as contingency and regulating reserve, and reactive power. As wind penetration levels increase, conventional generators will be displaced while the requirement for support services will grow due to the increased variability on the system [1]. Consequently, transmission system operators (TSOs) and distribution system operators (DSOs) have modified their grid codes, with various functionalities specified for newer wind farms, such as inertial response and low voltage fault ride through. In this way, wind turbines can offer a partial solution to the variability and uncertainty they introduce [2]. One of the most prominent concerns regarding the increased penetration of wind power is its impact on frequency stability [3]. Following a generator forced outage, the system frequency will fall at a rate dependent on the combined inertia of connected generators and loads. Synchronous generators and fixed speed wind turbines (FSIGs) intrinsically increase power system inertia, however, this does not occur with the addition of variable

speed wind turbine generators due to their differing electromechanical characteristics [4]. The most widely employed variable speed wind turbine technology today is the doubly fed induction generator (DFIG). DFIGs are not electrically coupled to the system frequency due to their power electronic control mechanisms, and so do not inherently exhibit an inertial response to deviations in system frequency from nominal. In theory, however, their torque set-point can be modified by an input dependent on the rate of change of system frequency [5]. As a result, a number of wind turbine manufacturers are developing control systems which can be configured to emulate an inertial response similar to that expected from synchronous generation [6]. It is also possible for direct drive turbines to be fitted with such a control loop however, as they currently hold a limited market share, only the inertial response of DFIGs and FSIGs are considered in this study [7].

Large, interconnected power systems generally have considerable system inertia due to the large rotating masses associated with conventional generation. While many of the operational issues associated with increased wind penetration levels are likely to be first encountered by small, isolated systems with low system inertia, a reduction in system inertia can also affect large, interconnected systems. For example, where low inertia (i.e. wind rich) areas are connected to larger systems via a weak link, undesirable low frequency inter-area oscillations may result, which can lead to sub-optimal power flows and inefficient operation of the system [8]. Additionally, with wind farms increasingly moving off-shore, the impact of increasing dc connections must also be considered. Irrespective of turbine technology, a dc connection decouples the stored energy of the turbine rotor from the grid. With variable speed increasingly preferred over fixed speed wind generation, and dc (offshore) connections likely to be more common, conventional plant will be replaced by generation inherently lacking inertial capability.

A key consideration in assessing the reliability and performance of a power system, large or small, is the expected inertial contribution of its generation. Systems with low inertia will experience a greater rate of change of frequency (ROCOF) following a generation-load imbalance. As a result, the maximum acceptable frequency drop is more likely to be exceeded, thus increasing the likelihood of load shedding. In systems with significant wind penetration levels, the variable nature of wind, as well as its impact on factors such as conventional plant commitment, means that assessment of the system inertial response capability becomes more probabilistic. In addition, due to the geographical diversity of wind farm outputs, the stored rotational energy in DFIG wind turbines

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could potentially vary greatly with different regional weather patterns. For a given system-wide wind generation profile, power could be supplied by a small number of wind turbines operating at close to rated power or perhaps a large number of turbines at low output. This paper examines the inertial contribution that can be assumed to be available from DFIG and FSIG based wind turbines aggregated across a power system, with the Ireland system taken as an example.

The paper is structured as follows. Section II details the data that was used for this analysis, and Section III reviews the state of the art of the emulated inertial response of DFIGs today as well as examining the inertial response capability of FSIGs. Section IV describes the methodology employed and assumptions made in determining the inertial response available from wind turbines. Section V highlights the results of this study and illustrates the kinetic energy potentially available from wind turbines for frequency response. Section VI considers the implications of the results of this study on power system operation, while Section VII summarises the conclusions of this work.

II. IRELAND DATA ANALYSIS

The Ireland power system is taken as an example in this analysis due to the 10 year wealth of wind data available from individual wind farms. Due to the general trend towards a less carbon intensive energy future, Ireland is one of many countries experiencing a rapid increase in wind generation with a target of 40% penetration from renewable sources by 2020, the majority of which is expected to come from wind turbines. Today, the island has an installed wind capacity of approximately 1700 MW. Under the Gate 3 process, which determines how generation is added to the grid over the 18 month period starting December 2009, a total of 3,900 MW of renewable energy will be offered grid connection in 2010-2011. While the island is well positioned to exploit a strong natural wind resource and has already reached instantaneous wind penetrations exceeding 50%, operational impacts relating to the dynamic effects of such high wind penetration levels on a small isolated power system must be investigated if such significant investment is to be justified.

The Ireland system is operated in two regions, Northern Ireland (NI) and the Republic of Ireland (RoI) which are linked by a 220/275 kV line. The data set used to compile the model implemented in this paper spanned 1 year and was based on quarter-hourly wind power output data of 98 wind farms in the Republic of Ireland and half hourly wind power output from 23 wind farms in Northern Ireland. The NI data was interpolated to obtain a quarter hourly dataset compatible with that of RoI.

Information was not available from individual wind farms on the number of turbines that were offline due to maintenance at any one time. It was therefore assumed that all turbines in each farm were in operation. In reality, it is possible that a number of turbines were out of service in some wind farms at various stages throughout the year. However, with in excess of 1000 wind turbines on the system in total, the loss of a few turbines at various instances due to operational faults or maintenance issues was not deemed to pose significant risk to the integrity of the results of this study.

III. WIND TURBINE INERTIAL RESPONSE: STATE OF ART

The inertial response of FSIG turbines is similar to that of synchronous generators, as it is a function of the change in system frequency [9, 10]. If the system frequency falls, the machine decelerates at a rate determined by the inertia of the generator, the gear shaft stiffness and the inertia of all of the masses connected to the shaft of the machine, including the gearbox and blades. The kinetic energy contributed by the machine is then converted into electrical energy resulting in a power surge. For a change in steady state system frequency from f_0 to f_1 , the kinetic energy released by synchronous machines and FSIGs can be given by

$$\Delta E_k = E_{k0}(1 - \omega_1/\omega_0) \quad (1)$$

where ΔE_k is the kinetic energy supplied by the machine in response to such a change in frequency, E_{k0} is the total stored energy in the machine, ω_0 is the nominal rotor speed (coupled to system frequency in the case of synchronous generation, and operating at a certain slip for FSIGs and other induction generators) and ω_1 is the rotor speed following a change in system frequency.

Commercial fixed speed wind turbines rated above 1 MW have inertial constants of typically 3-5 s, i.e. the period of time a generator can provide rated output from its stored kinetic energy [11]. Dual-speed operation can be achieved by using an induction machine with two winding configurations. At high wind speeds, the rotor can switch to a higher speed to operate closer to the maximum C_p and extract more energy. FSIGs, dual-speed and similarly opti-slip turbines operate similar to synchronous machines in the provision of inertial response, although the response is slightly slower due to the rotor slip.

Despite the favorable inherent inertial response associated with FSIGs, DFIG based turbines represent the majority of grid-connected wind turbines today due to their superior energy capture and improved control capabilities. There is also interest in direct drive wind turbines which offer an alternative configuration of variable speed wind turbines and are growing in market share due to the advantages associated with the removal of the gearbox from a wind turbine. In both types of variable speed wind turbine power output is controlled by power electronics and is determined by the machine's optimal power tracking curve (OPT), whereby any change in wind speed results in a change in the torque set-point [12]. Although specifications vary between manufacturers, DFIGs generally operate at rotor speeds between 0.7 pu to 1.2 pu. Direct drive wind turbines follow a similar power-speed curve, however the range of operating speeds is even larger. The power electronic converters in both turbines decouple the rotor speed from system frequency. Consequently, variable speed wind turbines have not conventionally been capable of providing an inertial response.

In recent years, it has been proposed that DFIG wind turbines be fitted with a modified control loop to provide an emulated inertial response in the case of a significant frequency deviation from nominal [13, 14]. Essentially, it is viewed that

modern, variable speed wind turbines could act as programmable power plants and could potentially offer flexibility to ameliorate the effects of increased variability on the system, such as increased ramping capability and reactive power control. In the case of significant under-frequency excursions, pseudo inertial response controls can be implemented that cause the power output of a variable speed wind turbine to temporarily increase in the range of 5% to 10% of the rated turbine power [15]. The turbine provides an active power response by harnessing the stored energy of the rotor and increasing the power output of the generator. Below rated wind speed the response is followed by a period of recovery, meaning that the power output of the turbine is temporarily reduced below the original operating point. Above rated wind speed the captured wind power can be increased using pitch control and can temporarily exceed the rating of the turbine. During such operation the turbine is accessing previously untapped wind energy and so is not technically an inertial response. In the case of above rated wind speeds, the recovery period can thus be reduced using pitch control. While traditional DFIGs offer no inertial response, by using active controls, the rotor speed of DFIGs can be driven lower than a fixed speed wind turbine as the response is not constrained by physical inertia and can thus provide more active power. It should be noted, however, that the response of the turbine relies on active controls, unlike synchronous machines. Therefore, the response is not the same in all operating conditions [15]. If a turbine is operating close to its rated output, the limits of the power electronic converters may not permit as effective an inertial response as if it were operating at a lower output.

IV. QUANTIFYING THE INERTIAL RESPONSE CAPABILITIES OF FSIG AND DFIG WIND TURBINES

The inertial response capability of conventional generation is straightforward to define using the nameplate information. In the case of a power system with conventional synchronous generators only, a system dispatch is capable of determining the units that are connected, spinning and therefore contributing to the stored energy of the system. However, assuming wind generation has priority access, a system dispatch will not specify the exact number of wind units which are in a position to contribute to the system kinetic energy nor the potential stored resource available from online turbines. The methodology applied here quantifies the inertial response potentially available to a power system from wind generation, assuming that all variable speed wind turbines can provide an inertial response as required, with a view to identifying the potential impact of increased wind penetration levels on the dynamic frequency response.

As referred to in Section III, the combined inertial response capability of all variable speed wind generation will vary depending on the individual operating conditions of different turbines across the system. Fig. 1 illustrates the average power output of each wind farm on the Republic of Ireland system for various system wind generation levels over a 3 month period. For a given system generation output above 0.2 pu, the power output of individual wind turbines could vary from 0 to

1 pu, thus introducing considerable uncertainty into the potential inertial response capability of the system. Due to the variable nature of wind power, the geographical distribution and the differing operating characteristics of variable speed and fixed speed wind turbines, the process for determining the turbines that are connected, spinning and those capable of contributing to system kinetic energy becomes more probabilistic in nature.

Fig. 1. Individual wind turbine output as a function of RoI wind generation

Although there are a wide range of turbine sizes and manufacturer designs on the Ireland power system, for simplification purposes the inertial constant of the fixed speed wind turbines on the Irish system was assumed to be 4 s in this study. One of the primary objectives of a power system operator is to minimize the need for load shedding. In Ireland, load shedding takes place when the system frequency drops to 49.3 Hz (nominal frequency is 50 Hz), thus according to (1), the most stored kinetic energy a FSIG wind turbine or other conventional unit should need to provide to the system is approximately 0.03 pu.

The OPT characteristic of DFIG machines is not generally available for individual turbine models. Fig. 2 illustrates a generic OPT curve that shows how the rotor speed of a DFIG turbine varies for different power outputs [16]. The stored kinetic energy of each wind farm is calculated based on the rotor speed corresponding to the average power output of the turbines in each farm.

Fig. 2. Generic DFIG optimal power tracking curve (OPT)

The kinetic energy available to the system from wind generation is dependent on the number of wind turbine units capable of contributing energy from their rotors. At low wind farm outputs, assuming some wind speed variation across the wind farm, it is likely that all wind turbines will not come online coincidentally. It is assumed in this study that for any wind farm operating at or above 0.1 pu, all turbines are online and producing power equally. Where a wind farm is generating less than 0.1 pu, the number of turbines online is expected to increase linearly with generation output up to 0.1 pu at which point it is assumed all turbines are online.

The nature of the inertial response associated with FSIGs is different to the response that will result from the active controls in DFIG-based machines. While FSIGs inherently provide an inertial response dependent on the change in system frequency, the actual inertial response that can be provided by future DFIGs will be limited by operational limits such as their minimum rotor speed and maximum power output.

In the case of DFIGs, not all turbines which are producing power are capable of contributing to the kinetic energy of the system. If the rotor of an individual turbine is spinning at the minimum rotor speed, it cannot be expected to contribute to the kinetic energy of the system as to do so would mean driving the machine below its minimum operating speed. It is assumed that DFIG wind turbines producing less than 0.1 pu are operating at their minimum speed and so cannot be called upon for inertial response. This limit also acts as a constraint on the maximum possible kinetic energy that can be supplied by a wind turbine. Similarly, if a turbine is producing close to or at its rated power, the power surge that it can provide must be limited in respect to the limits of the power electronics. In this study, the maximum instantaneous power that DFIG turbines could provide has been limited to 1.1 pu, as shown in (2).

$$\text{Power Output} + \text{Inertial Response} \leq 1.1 \text{ pu} \quad (2)$$

It has been found that wind turbines can, in some cases, provide superior inertial response to conventional generators. In [15] it is shown that, for a certain initial disturbance, the frequency drop in a system with an emulated inertial response from wind turbines is about 12% better than that in a system with no wind generation. Two scenarios were investigated in this study with respect to the frequency response that could be expected from wind generators. Scenario I examines the maximum inertial response available to the system from wind generation assuming that all DFIG wind turbines can contribute a maximum of 10% of their rated power during a system imbalance. The only limitations that were put on this response were that the rotor speed could not drop below the machine's minimum operational speed and the output of an individual turbine could not exceed 1.1 pu. In Scenario II, the same limitations existed as in Scenario I, however it was also assumed that the response required from wind generators would not exceed that normally required of conventional generators. In the latter case the maximum inertial response required of a DFIG wind turbine is 0.03 pu of its rotor's kinetic energy. The inertial response capability in Scenario I is likely to be in excess of the

response required of wind generation on a real power system. It is presented in this study to determine the upper limits on the inertial response capability of wind generation on a power system.

V. AGGREGATED INERTIAL RESPONSE FROM WIND TURBINES

The number of wind turbines online is a key factor in determining the inertial response capabilities of wind generation. Fig. 3a illustrates the number of wind turbines capable of contributing an emulated inertial response to the system as a function of the system-wide wind generation, assuming all variable speed wind turbines are equipped with such a response capability. The set of turbines capable of contributing an inertial response comprises all FSIG wind turbines and DFIG wind turbines operating above 0.1 pu.

Fig. 3a. Number of wind turbines capable of contributing inertial response as a function of generation output.

Fig. 3b. Probability density function for system-wide generation output

While the number of turbines online is relatively deterministic at low and very high generation outputs, at mid range generation levels, the number of turbines online varies considerably. For example, at a generation level of 0.2 pu, the number of turbines online ranges from 0.6 pu to approximately 0.9 pu. If the wind generators on the island were comprised solely of FSIGs, the kinetic energy available to the system versus total generation would also adopt a shape similar to this as the stored energy in FSIGs is largely independent of wind speed and so increases with the number of turbines online [3]. The large variation in the number of turbines online in the low and mid generation region of 0.05 pu to 0.6 pu flags the issue of

uncertainty in the emulated inertial response potentially available to the system operator. In order to determine the aggregate inertial response capability of wind power, the system operator must be able to identify how many DFIG turbines are operating above their minimum operating speed and so are capable of contributing an inertial response. Fig. 3b illustrates the probability of various system wind generation output levels occurring over the year in question. It should be noted that the low and mid level output regions show the most common occurrence meaning that the most probable generation levels coincide with the greatest uncertainty in the available inertial capability of wind generation.

A. Scenario I - Maximum potential inertial response from wind generation.

It has been proposed that wind turbines can be expected to provide up to a maximum fraction of their rated power in the form of an emulated inertial response during a frequency event. The data points in Fig. 4 represent the aggregated kinetic energy available to the system from FSIG and DFIG wind turbines at various generation outputs over a one year period, assuming DFIG wind turbines can provide of 10% of their rated turbine power in inertial response. The shape of this plot is similar to that in Fig. 3a as the inertial response must plateau when all turbines are online and contributing 10% of their rated power. This scenario does not consider the variations in individual DFIG inertial response capability due to local wind speeds and assumes that turbines capable of contributing an inertial response can contribute 10% of their rated power. The variation in the kinetic energy available for a given wind generation output occurs as a result of the changing profile of wind turbines operating above rated speed and hence capable of contributing an inertial response.

As implied by Fig. 1, the power output of individual turbines and hence the store of kinetic energy available can vary considerably depending on regional wind profiles. At low generation output, up to 0.15 pu, many wind turbines are operating at low outputs, as illustrated in Fig.1. Similarly, at high generation output, many turbines are operating close to rated output, thus the kinetic energy available is reasonably deterministic. At generation levels between 0.2 pu and 0.8 pu, individual turbines across the island of Ireland are producing at various different outputs, thus the potential kinetic energy available varies greatly.

Fig. 4. Scenario I: Maximum kinetic energy available from wind generators in Ireland as a function of total wind generation output.

While the average kinetic energy available for a given total generation in Fig. 4 has a distinctive trend, the standard deviation of the potential resource available to a power system operator during a frequency event is large. For example, for a system generation level of 0.4 pu the stored energy could vary between 400 MJ and 700 MJ. While the absolute inertial response illustrated in this case is likely to exceed that expected from wind power on a real system, this scenario illustrates the absolute maximum aggregated inertial response that could be expected of wind generation on the system assuming the 10% limit and the uncertainty associated with it.

B. Scenario II- Inertial response limited to 0.03 pu of stored energy.

Unlike FSIGs, the kinetic energy available from variable speed turbines varies significantly with wind speed. The inertial response profile of wind generation changes somewhat when the response is limited to 0.03 pu of the stored energy of the individual DFIG wind turbines. Fig. 5 illustrates the kinetic energy available from wind generation assuming that wind turbines contribute an inertial response in proportion to that of conventional generators and which varies depending on their operating conditions. In this scenario the characteristic of the available kinetic energy does not plateau at mid-generation levels as the potential response continues to increase with increasing wind speeds. While the magnitude of the response is greatly reduced due to the 0.03 pu limit imposed in this scenario, there is still considerable variation in the inertial response capability, particularly at low and mid generation levels.

Fig. 5. Scenario II: Kinetic energy available from wind generation as a function of wind generation output, assuming 0.03 pu limit on kinetic energy contribution.

VI. DISCUSSION

Due to the differing characteristics of variable speed wind turbines to conventional generators, the kinetic energy available from variable speed wind generation exhibits nonlinearity with respect to the total generation output. This is in clear contrast to the inertial response of synchronous machines, which is not dependent on unit output. While it is unlikely that all wind turbines would be expected to contribute such a significant inertial response in reality, Scenario I is included here in order to illustrate the potential resource of stored rotor energy that is available, its limitations and the uncertainty of its provision. The implication is that even if wind turbines are capable

of providing an emulated inertial response, the inertial response capability of wind generation may vary greatly in magnitude in systems with high wind penetration levels. Should high wind generation levels coincide with periods of low demand there may be few synchronous generators online and the potential inertial response capability of wind generation online could vary significantly from that forecasted due to variations in regional winds. As a result, a risk exists that aggregate inertial response capability of the system may be below the minimum value required for secure system operation.

The profiles of the inertial response capability of system wind generation have significant implications on the potential for wind to contribute to power system stability. In Scenario II, when the inertial response capability of wind generation is limited to a level similar to the response expected from conventional generation, the magnitude of the response is significantly lower than that in Scenario I and the potential response does not plateau at a mid range generation. In this scenario an increase in system wind will tend to result in an increase in inertial capability. While certain distinct patterns emerge from Section V, for a given system wind generation output the actual kinetic energy available could vary across a broad spectrum of values. For example, for an overall generation output of 0.2 pu in Scenario II, as illustrated in Fig. 5, the stored energy available could lie anywhere between 60 MJ and 120 MJ, meaning that the actual inertial response can vary within a band of approximately 60 MJ. In [17], it was assumed that the minimum inertial requirement on the 2020 Ireland power system should be equivalent to that of 9 x 150 MW synchronous units, each with a H constant of 4 seconds. This equates to the generators providing approximately 160 MJ of combined inertial response capability if any reduction in system frequency were not to result in load shedding. Thus, the inertial response capability of the system, given only the present installed wind capacity could vary by almost 40% of the minimum inertial response requirement. Such uncertainty around the stored inertial response resource could lead to considerable economic implications resulting from the unnecessary commitment of conventional generation for regulation purposes. This issue is most likely to have an impact on system operation during periods of low demand as it will cause uncertainty regarding how many conventional generators should be brought online to meet system security concerns. This model considers data from a system with an installed wind capacity of 1200 MW. On a system with increased wind penetration, increased market share of direct drive turbines and more offshore wind farms, it is likely that this band of uncertainty will become greater due to the increased variability of system generation.

The differences between Fig. 4 and Fig. 5, both in magnitude and shape, highlight the need for more detailed studies in this area in order to quantify the maximum inertial response that can be harnessed by wind generation in the future. This paper also highlights that the accuracy of regional wind forecasts will be a key factor in forecasting the inertial response capability of power systems with significant wind generation. The system wind generation level alone does not convey the geographical diversity of the wind production, which is necessary for quantifying the inertial response as the inertial capability of DFIGs varies considerably with wind speed.

It should be noted that this paper assumes an inertial response capability from all variable speed wind turbines on the system. In reality, it is unlikely that an inertial response capability will be retrospectively applied to existing turbines and so will only be available from new turbines. Of course, the actual implementation of an emulated inertial response from wind turbines also presents a number of challenges to system operators which require further investigation. The need for, and benefit of, real-time SCADA systems to centrally control and monitor the number of turbines online, wind turbine outputs and hence the inertial response capability of wind turbines should be assessed. While a SCADA system could potentially provide information on the real-time status of turbines online, due to the stochastic nature of wind, uncertainty exists in the day ahead unit commitment of power systems with high wind penetration levels. Errors associated with regional wind forecasts will introduce further uncertainty into the inertial response capability of system wind generation, thus magnifying the issue.

Another crucial aspect not considered here is the impact of wind turbines' fault ride through capability on the inertial response capability of wind generation. In the case of a network fault, the local voltage may be depressed thus reducing the power capability of wind turbines in the neighbouring area. The reduction in wind power will lead to a generation-demand imbalance and hence a fall in system frequency. In such a case, wind turbines may not be capable of releasing stored rotational energy in the form of an emulated inertial response. It is indicated that this power imbalance may be much greater than that arising from the forced outage of a conventional generator [17]. Further work should consider the implications of this issue in detail if the reliability of the emulated inertial response is to be quantified.

VII. CONCLUSION

This paper presents the aggregated inertial response that could be provided by wind power generators in the case of a fall in system frequency, assuming variable speed wind turbines are capable of contributing an emulated inertial response. Two scenarios are considered in this study and both reveal that the stored energy available to the system could vary considerably for various system wind generation outputs. That is, for a given system-wide wind generation level, the potential inertial response available from wind generation could lie within a broad spectrum of values. Taking the minimum inertial response requirement for the 2020 Ireland system, this study shows that even at relatively low levels of installed wind generation, the estimated inertial response capability of the system could be in error by almost 40% of the minimum requirement, an inertial response equivalent to that of over 3 medium-sized conventional generating units. Confidence in the scheduled inertial response capability of the system is vital for the stable operation of the system. This study indicates that accurate regional wind forecasting, reinforced by real-time SCADA controls may need to play an important role in the sensible commitment and dispatch of conventional plant in power systems in which wind power contributes to the system inertial response.

VIII. ACKNOWLEDGEMENT

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X. BIOGRAPHIES

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