LOW POWER STAND-ALONE MICRO-GRID WITH WIND TURBINE

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***Abstract*—The energy demand around the world is increasing, the need for renewable energy source that will not harm the environment has been increased in which wind power is one among them. There are many loads that are away from the main grid. For isolated localities, one practical approach to self-sufficient power generation involves using a wind turbine with battery storage to create stand-alone systems. The power conversion system consists of Wind turbine driven Permanent Magnet Synchronous Generator (PMSG), a Diode Rectifier, a DC-DC boost converter to which the high voltage DC loads are connected. Battery is connected to store the excess power generated from wind turbine. The low voltage loads are connected to a system through a DC-DC buck converter, this entire system forms the DC micro grid. The proposed system is demonstrated using MATLAB/SIMULINK based simulations**.

***Keywords*—**Wind Energy, PMSG, Uncontrolled Diode Rectifier, DC-DC converters, DC link voltage.

I. INTRODUCTION

In recent years, the electrical power generation from renewable energy sources, such as solar and wind, is increasingly attracting interest because of environmental problems and shortage of the traditional energy like fossil fuels etc, in the near future. The two configurations used for wind energy conversion system are the stand-alone or autonomous systems and the grid or utility connected systems. Standalone systems directly supply electrical load especially in isolated areas which will eliminate the need for extensive transmission lines from the utility. However the wind is an ever changing energy source, continuous power generation is not possible without energy storage. Wind power mainly depends on geographic and weather conditions and varies with time. So it is necessary to construct a system that can generate maximum power for all operating conditions. Permanent Magnet Synchronous generator is used for stand-alone wind power generation because of its advantages such as reliability, low maintenance and high efficiency.

In order to achieve variable speed operation, power electronic converter interface is used to supply load. The converter consists of uncontrolled three-phase diode rectifier, and DC-DC converters.

In this paper, the modeling of generator and the power electronic interface is carried out in steady state condition [2].

Power electronic devices with variable speed system are very important, where AC–DC converter is used to convert AC voltage with variable amplitude and frequency at the generator side to DC voltage and that voltage is boosted to DC link voltage (380V) by boost converter. This in turn is connected to the loads which operate at higher voltages. The loads which operate at lower voltages are connected to the link through a DC-DC buck converter which bucks the DC link voltage to 24V. The reliability of the variable speed wind energy system can be improved significantly by using a direct drive permanent magnet synchronous generator (PMSG). PMSG has several advantages when compared to other types of generators which are used in wind energy conversion systems such as simple structure, can operate at slow speed, self excitation capability, leading to high power factor and high efficiency operation. When PMSG is used, there is no need of a gearbox which suffers many times from faults and requires regular maintenance, which makes the system inefficient.

Battery energy storage system is essential for a standalone system to meet the required load. As a variable speed wind system which has a fluctuating generated power due to the variability of wind speed. It can store the excess energy when the generated power from the wind is more than the required load power for a time. When the generated power from the wind is less than the required load, battery supplies the required power to maintain the power balance between generated and required load power. The varying power from wind energy system can be removed and the reliability of power to the load can be maximized with battery storage system.

Most residential households are currently supplied with 240V AC, requiring rectifiers for DC operated appliances to convert the AC voltage to usable DC, leading to power losses in the conversion. Standby power loss also factors into AC distribution for DC electronics and appliances, since the rectifiers will continue draw power even if the device is in standby. DC distribution in a building would require rectification only from the grid to the internal grid in the household, or micro-grid, and would use DC-DC converters for the rest.

With the interest in reducing dependency on foreign petroleum and CO_2 emissions, renewable energy has been a rapidly expanding area. Renewable energy generation helps strengthen the case for DC distribution since renewable energy sources generate DC power. With DC distribution, DC-DC conversion is all that is required to interface with the grid and battery storage to a micro-grid compared to AC, which would require AC-DC conversions in addition. By maximizing energy efficiency with renewable energy sources, the demand on the power grid is also reduced, which leads to less reliance on foreign petroleum and reduced CO_2 emissions.

In this paper, author derived and presented the following models: wind turbine, Permanent Magnet synchronous generator, rectifier, Boost converter and the buck converter. The simulink model was constructed and implemented using the power system simulation tools in MATLAB/SIMULINK. This model is used to predict the performance of the wind turbine generator system.

II. STAND-ALONE WIND ENERGY CONVERSION SYSTEM

The circuit topology for the variable speed stand-alone wind energy supply system is shown in fig. 1. The system consists of the following components: Wind turbine which is connected to Permanent Magnet Synchronous Generator of __kW. The Permanent Magnet Synchronous Generator is driven directly without using gearbox. Uncontrolled diode rectifier is used to convert AC output from generator to DC voltage and this voltage is fed to DC-DC boost converter which will boost the voltage to DC link voltage (380V). Battery bank is connected to the DC link of which the nominal voltage is maintained at 380V. The proposed model has been modeled and simulated using MATLAB/SIMULINK.

III. MODELLING OF THE SYSTEM

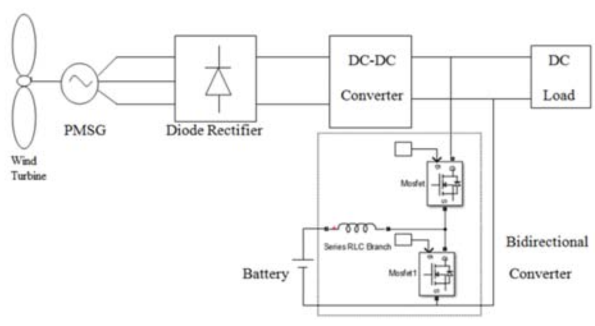

Fig 1: Power circuit topology of a stand-alone wind energy supply system

A. Modelling of Wind Turbine

The Wind Power is given by,

$$P_w = \frac{dW_w}{dt} \quad (1)$$

Energy drawn by wind turbine is,

$$W_w = V_a \frac{1}{2} \rho (V_1^2 - V_3^2) \quad (2)$$

Where,

, is Energy drawn by wind turbine, ρ is the Air density(kg/m^3) V_a is the air stream volume element, V_1 is undisturbed far upstream wind speed, V_2 is wind speed at turbine.

The power in the wind in an area is given by ,

$$P_w = 0.5\rho A V_w^3 \qquad (3)$$

Where, V_w is the wind velocity (m/s)

But the turbine captures only a fraction of this power. The power captured by the turbine (P_m) can be expressed as

$$P_m = P_W \times C_p \qquad (4)$$

Where, C_p is a fraction called the Power coefficient. The power coefficient represents a fraction of the power in the wind captured by the turbine and has a theoretical maximum of 0.55.

The power coefficient can be expressed by a typical empirical formula as,

$$Cp(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \qquad (5)$$

Where, β is the pitch angle of the blades in degrees

λ is the Tip speed ratio of the rotor blade tip speed to wind speed

$$\lambda = W_r \cdot R / V_w \qquad (6)$$

Where, W_r is the Turbine rotor speed

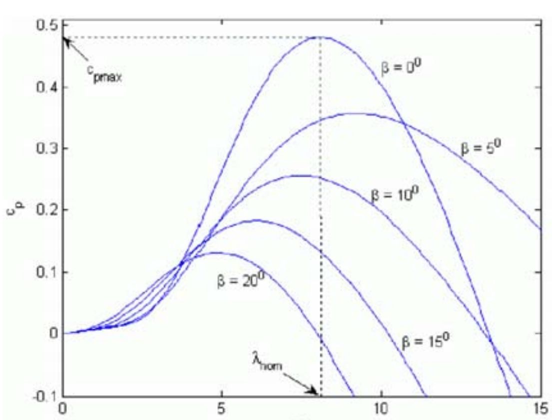

Fig 2: Cp verses lambda[4]

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (7)$$

Where, C1 = 0.5176, C2 = 116, C3 = 0.4, C4 = 5, C5 = 21, C6 = 0.0068

Substituting these values in equation 5, it becomes

$$Cp(\lambda) = 0.5176\left(\frac{116}{\lambda} - 9.06\right)e^{-\frac{21}{\lambda_i}+0.735} + 0.0068\lambda \qquad (8)$$

The power and torque characteristics of a wind turbine are governed by equations (4) and (5). With the power coefficient function given by (3), the mechanical power (P_m) of the turbine can now be represented as[3],

$$P_m = 0.5\rho A C_p V_w^3 \qquad (9)$$

$$P_m = 0.5\rho A(0.5176\left(\frac{116}{\lambda} - 9.06\right)e^{-\frac{21}{\lambda_i}+0.735} + 0.0068\lambda)V_w^3$$

(10)

The volume of aerodynamic torque T_w in N-m is given by the ratio between the power from the wind and the turbine rotor speed W_r in rad/s, as follows

$$Tw = Pm / Wr$$

(11)

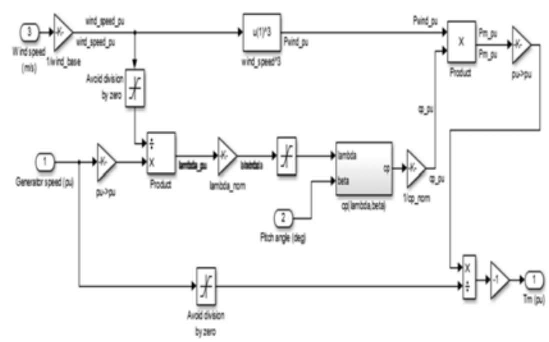

Fig 3: Matlab/SIMULINK model of Wind Turbine

B. Modeling of Permanent Magnet Synchronous Generator

A Permanent Magnet Synchronous generator is a generator in which the excitation coil, normally in the rotor, has been replaced by a system made up of permanent magnets which provide a constant excitation field, which eliminate the need of additional excitation system.[3]

It is used in those cases where small voltage drops by a certain degree or when power converters are connected to the output of the generator. The power converters can convert a voltage range into continuous voltage of a constant value. The operation of the PMSG is different from that of normal synchronous generator. In a normal generator, voltage is controlled by means of excitation, but in PMSG, excitation is constant that is why, when the generator is charged, voltage drops without the option to regulate.

The main advantage is its simplicity. The manufacturing and assembly of the rotor will be cheaper if the magnets are used. They do not have brushes, thus the maintenance is not required. The mechanical consistency of a PMSG is superior and it does not require additional systems for its excitation. By eliminating the excitation, energy savings of about 20% can be attained by simply using magnets.

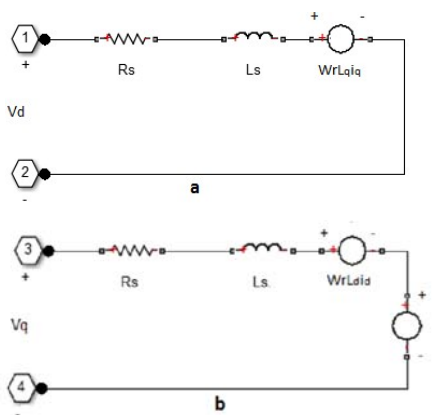

Fig 4: d-q-axis equivalent circuit model of the PMSM (a) d-axis (b) q-axis

The analysis of the PMSG can be made using quadrature equivalent circuit in which the damper windings are replaced with two equivalent windings in direct and quadrature axis respectively and permanent magnet is replaced with an equivalent superconductor winding placed in the direct-axis. The current through the equivalent winding of the permanent magnet (I_f) will be constant in all modes of operation.

The voltage equations of the PMSG can be derived from the voltage equations of the synchronous machine in *dqo* reference frame.

The voltage equations for the synchronous machine can be written as:

$$V_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_s \lambda_q$$
$$V_q = R_s i_q + \frac{d\lambda_q}{dt} - \omega_s \lambda_d \qquad (12)$$
$$V_o = R_s i_o + \frac{d\lambda_o}{dt}$$

The flux linkage in *d* direction can be written as:

$$\lambda_d = L_d i_d + \lambda_m$$

$$\lambda_q = L_q i_q \qquad (13)$$

When equations 13 are substituted in equations 12, we get,

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_s L_q i_q$$
$$V_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_s L_d i_d + \omega_r \lambda_m \qquad (14)$$

This is the standard current dynamics model of a PMSG where, R_s is the stator resistance, L_d and L_q are the *d*-axis and *q*-axis inductance, λ_m is the flux linkage due to permanent magnets, V_d and V_q are the *dq*-axis voltages, ω_r is the rotor speed, i_d and i_q are *dq*-axis current components.

The total input power into the machine when the rotor *dq* reference plane rotates at a speed of $\omega_r = d\theta_r$ /(θ_r is the rotor angular position), equation becomes,

$$P_{in} = \frac{3}{2}(V_q i_q + V_d i_d) \qquad (15)$$

Where, the zero sequence components are neglected.

The mechanical output power is given by[3],

$$P_{out} = \frac{3}{2}\left(\omega_r L_d i_d i_q + \omega_r \lambda_m i_q - \omega_r L_q i_q i_d\right) \qquad (16)$$

For a P pole machine, with $\omega_r = (P/2)_m$, where ω_{rm} is the rotor speed in mechanical radians per second.

$$P_{out} = \frac{3}{4} P \omega_{rm}\left(L_d i_d i_q + \lambda_m i_q - L_q i_q i_d\right) \qquad (17)$$

The equation for electromagnetic torque is obtained by,

$$T_e = \frac{P_{out}}{\omega_{rm}} = \frac{3}{4} P\left(L_d i_d i_q + \lambda_m i_q - L_q i_q i_d\right) \qquad (18)$$

If P is the number of pole pairs then electromagnetic torque becomes:

$$T_e = 1.5(\lambda_m i_q + (L_d - L)_q i_d) \qquad (19)$$

Mechanical system:

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m) \qquad (20)$$
$$\frac{d\theta}{dt} = \omega_r$$

Where, T_m is the shaft mechanical torque, θ is the rotor angular position, J is the combined inertia of rotor and the load.

C. Modeling of uncontrolled diode Rectifier

The diode rectifier is the most commonly used topology in converting AC to DC voltage output. The circuit of a uncontrolled diode rectifier is shown in figure 4. The AC power generated from the PMS generator is converted into DC power through diode bridge rectifier. The same system is modeled in Matlab/Simulink

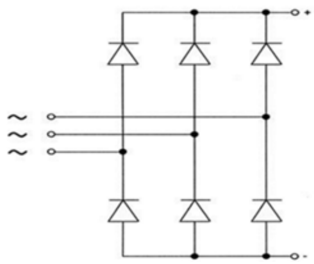

Fig 5: 3-Phase Uncontrolled diode Rectifier[10]

The DC output voltage (V_{dc}) from a rectifier is given by the expression:

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \sqrt{3}\, V_m \sin \omega t \; d\omega t = \frac{3\sqrt{3}V_m}{\pi} = \frac{3\sqrt{2}V_{LL}}{\pi} = 1.654V_m = 1.3505V_{LL}$$

(21)

Where, V_{dc} is the output voltage, V_m is maximum peak voltage, V_{LL} is line to line voltage, R is the load resistance.

The output DC current (I_{dc}) is given by the expression,

$$I_{dc} = \frac{3\sqrt{3}V_m}{\pi R} = \frac{3\sqrt{2}V_{LL}}{\pi R} = \frac{1.654V_m}{R} = \frac{1.3505V_{LL}}{R}$$

(22)

The RMS voltage (V_{rms}) is given by the expression,

$$V_{rms} = \sqrt{\frac{3}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (\sqrt{3}\, V_m \sin \omega t)^2 \; d\omega t} = \sqrt{\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}}\, V_m = 1.6554V_m = 1.3516V_{LL}$$

(23)

D. Modeling of DC-DC converters

Boost converter:

The voltage and current equations of dc-dc converter under steady state conditions can be found by using the two basic principles such as, the principle of volt-second balance and the principle of capacitor amp-second or charge balance. The principle of inductor volt-second balance says that the average value, or the dc component of the voltage applied across an ideal inductor winding must be zero and the principle of capacitor amp-second or the charge balance says that the average current that flows through an ideal capacitor must be zero. Thus, to determine the voltages and currents of dc-dc converters operating in periodic steady state, one averages the inductor current and capacitor voltage waveforms over one switching period, and equates the results to zero [1].

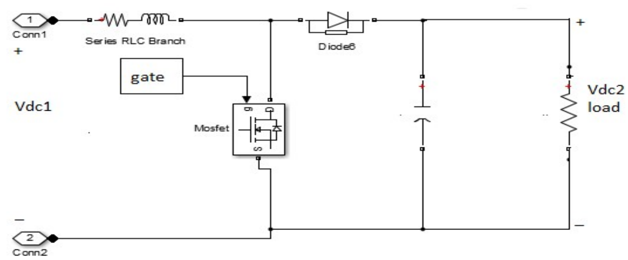

Fig 6: Simulink model of Boost converter

The expression for output Voltage and current is given by,

$$V_{dc2} = \frac{V_{dc1}}{(1-D)[1 + \frac{R_L}{(1-D)^2 R_{load}}]} \qquad (24)$$

Assuming a lossless circuit,

$$V_{dc1}I_{dc1} = V_{dc2}I_{dc2}$$

(25)

$$I_{dc2} = (1-D)\left[1 + \frac{R_L}{(1-D)^2 R_{load}}\right] \qquad (26)$$

E. Battery Energy storage:

In this proposed topology Battery bank is connected to the DC link through DC-DC bidirectional converter as shown in fig 1.

Bidirectional Buck-boost converter:

In this paper, the battery bank is connected to the DC link voltage through a bidirectional DC-DC buck-boost converter. In addition to, charge/discharge current to/from the batteries bank according to the generated power from the wind and the demanded load power, the DC-link voltage can be maintained constant as a reference value. This can be attained by controlling the bidirectional DC-DC buck-boost converter. The batteries bank voltage will be kept same as the DC- link voltage i.e. 380V.

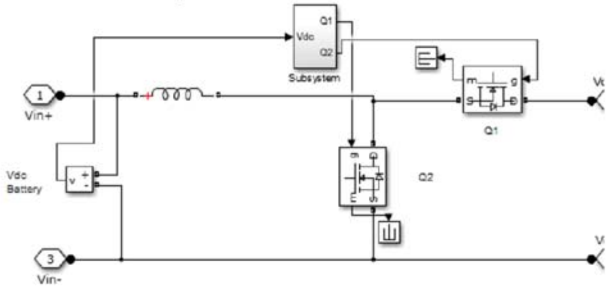

Fig 7: Birectional DC-DC converter

The control strategy is shown in the figure. To regulate the DC output voltage at a reference value, the control strategy of DC-DC bidirectional buck-boost converter uses a PI controller. In this control technique the DC voltage V_{dc} is sensed and compared with the reference DC voltage V_{ref}. The error signal is sent to the PI controller. The output signal is the duty cycle for the switches Q1 or Q2 according to the case of charging or discharging [2].

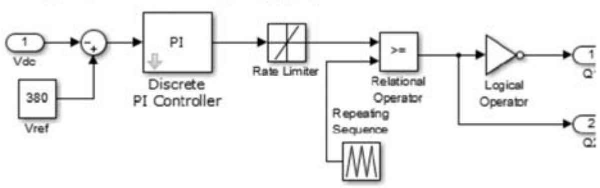

Fig 8: Control strategy for bidirectional DC-DC converter

During charging, the current flows from DC-link voltage to the battery bank. In this mode, Q1 is the active switch while Q2 is kept off. On the contrary, during discharging, the current transfers from battery bank to the DC-link voltage. In this mode, Q2 acts as a controlled switch and Q1 is kept off. Also, presence of the inductor at the batteries bank side results low ripple current which achieves higher efficiency and longer lifetime for the battery storage system.

IV SIMULATION RESULTS

The proposed topology for PMSG based variable speed stand alone wind turbine is simulated in MATLAB/SIMULINK. Fig. 9 shows the simulation circuit of the proposed topology. The value of the power coefficient Cp was kept at optimum value which is equal to 0.48 with varying wind speed.

The performance of bidirectional DC-DC buck-boost converter controller to achieve the main purpose of storing power is demonstrated. It has been able to charge current to the battery bank when the generated power is more than the demanded power and discharge the power when the generation is less than the demanded power. It also helps in maintaining the DC link voltage to 380V. Table 1 shows the wind turbine and PMSG parameters considered.

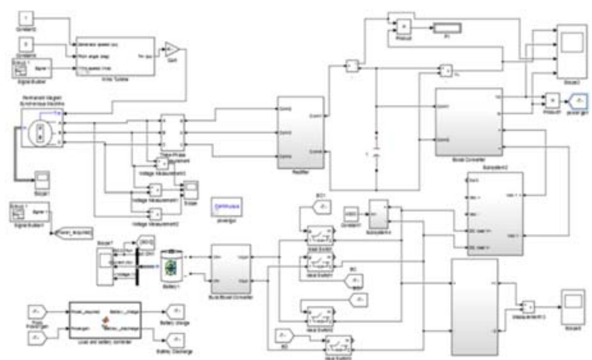

Fig 9: Simulation diagram of the proposed system

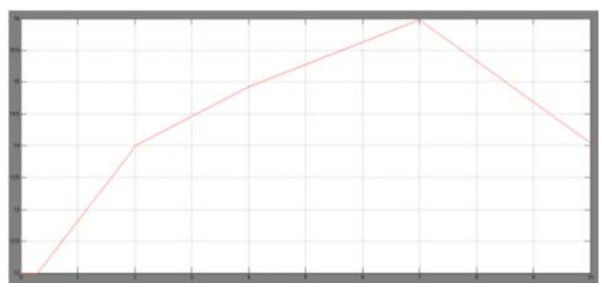

Fig 10: Wind speed

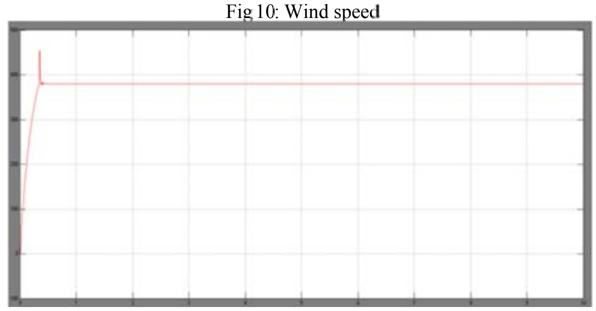

Fig 11: ConstantDC link voltage(380V)

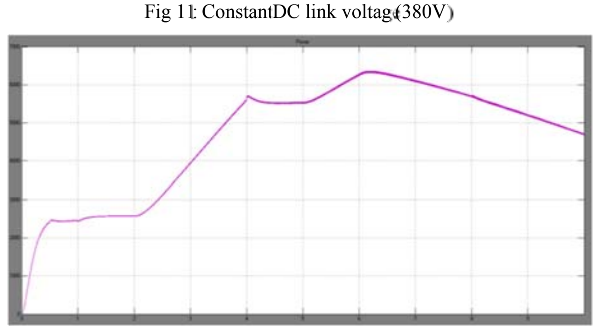

Fig 12 Power generated from the Boost Converter

Table 1: Wind Turbine and PMSG parameters

Wind Turbine	
Rating Air Density Blade Radius Rated Wind Speed Inertia constant	10KW 1.225Kg/m^3 3.7m 16m/s 0.6s
Permanent Mag net Synchronous Generato r(PMSG)	
Rating Rated phase voltage Pole number Inertia constant	12KVA 200V 42 0.4s

V CONCLUSION

The comprehensive and performance analysis of a variable speed stand-alone wind turbine with a PMSG using MATLAB/SIMULINK is presented in this paper. From the simulation results it can be seen that the control strategy used in the boost converter system helped in attaining 380V which is taken as a DC link voltage. The control used in the bidirectional converter which is connected between battery bank and DC-link voltage, is capable of maintaining the DC link voltage at a constant value, further it helps the battery to store surplus of wind energy and supply power to the load when the power generated from the wind turbine is less. With that the optimum value of the power coefficient is obtained which means that the maximum power is obtained from the available wind energy.

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