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Solar PV array Fed BLDC Motor using Buck-Boost Converter with Minimized Torque Ripple

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Abstract: Solar energy is an important renewable resource which is abundant in nature and free of running cost though its installation cost is higher. Trapped solar energy is used to run motors for different applications. Motors used for applications are dc motors, induction motors or BLDC motors of which BLDC motors are more advantageous. BLDC motor is fed from a voltage source inverter which has a dc link capacitor at the front end. The life time of dc link capacitor is affected by its operating temperature and cost increases with the use of dc link capacitor. Cost and bulkiness of motor drive is reduced by eliminating the dc link capacitor but it results arising torque ripple at the output of motor. Thus to minimize the torque ripple, a new method is proposed where the dc link capacitor is replaced by a ceramic capacitor and a switch. It reduces the torque ripple due to elimination of electrolytic capacitor and the compensation capacitor is only around 3 % of original dc link capacitor.

Keywords: BLDC motor, solar PV, Buck- Boost converter, P&O-MPPT, torque ripple compensation.

I. INTRODUCTION

Depletion and harmful effects of fossil fuels like carbon emission, global warming led to the utilization of renewable energies as they are a best alternative to the conventional energy resources. Renewable resources like solar energies and wind energies are receiving wide attention [1]. India was the first country to include a separate ministry under government for renewable sources. The advantages like pollution free generation, no running cost and large abundance in nature made increasing attraction towards the installation of solar PV generating system. The tracked energy can be used for a wide range of applications like water pumping, ventilators etc. Irrigation in remote areas is economical with the use of solar PV water pumping system where transmission of conventionally generated electricity is either costly or not possible [2]. The tracked energy from solar PV array is regulated to the required dc voltage by a dc-dc converter. Motors used for driving the water pumps can be DC motors or AC motors. DC motors can be directly connected to solar PV array. Hence the conversion stage can be avoided. But DC motors have the disadvantage of continuous wear and tear of brushes and frequent maintenance. Induction motors require complex control and hence they are also not preferred [3].

BLDC motors are preferred over DC motors and induction motors due to their advantages like long operating life, higher efficiency, low maintenance and better speed torque characteristics. Stator windings of BLDC motors are energized in a sequence from an inverter. A bulkier DC link capacitor is connected in between the dc-dc converter and inverter to get a constant voltage at the input of inverter, thus to make the voltage ripple free. But the DC link capacitor is bulkier in size and its life time is affected by operating temperature. Moreover the cost is about 5-15% of overall cost of BLDC motor drive. As an attempt to reduce the cost of motor, DC link capacitor can be eliminated at the expense of torque ripple. Thus a new torque ripple compensation technique is proposed to compensate for the torque ripple associated with the elimination of the DC link capacitor. In this method, torque ripple compensation technique is proposed to a solar PV array fed DC link capacitor free BLDC motor.

The paper is organized as follows: Concept of system configuration is explained in section II. The modeling of BLDC motor is detailed in section III. Modeling of photovoltaic system is discussed in section IV. Design of Buck-Boost converter is presented in section V. Torque ripple compensation technique in section VI and the results are shown in section VII. Finally the conclusion and future trends are mentioned in section VIII.

II. SYSTEM CONFIGURATION

The proposed system consists of a solar PV array, dc-dc converter, voltage source inverter, BLDC motor and a pump load. Solar energy is tracked by the solar PV array whose efficiency is maintained by an MPPT system. The unregulated dc voltage at the output of PV system is made a regulated dc voltage by means of a dc- dc converter. Duty ratio of switch in the converter is controlled by MPPT technique. Switching pulses for inverter is generated according to back emf using a truth table. Switching pulse for buck- boost converter is generated by MPPT algorithm. DC link capacitor replaces a ceramic

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capacitor and a switch with anti- parallel diode between converter and inverter. This is done as a method to reduce the overall cost of BLDC motor drive with dc link capacitor.

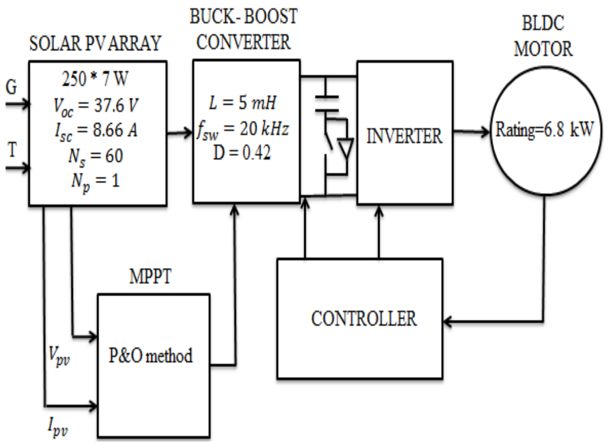

Fig.1. Configuration of the SPV-Buck boost converter fed BLDC motor with torque ripple compensation

III. MODELING OF BLDC MOTOR

BLDC motors are synchronous motors which consist of three phase stator windings connected in star fashion, rotor made of permanent magnets and a hall sensor. A 3 phase, star connected trapezoidal back emf type BLDC motor is used for the mathematical modeling. For simplifying equations and the model, the following assumptions are:

- Eddy current and hysteresis losses are neglected.
- Armature reaction is not considered.
- Stator windings are symmetrical and concentrated [4].

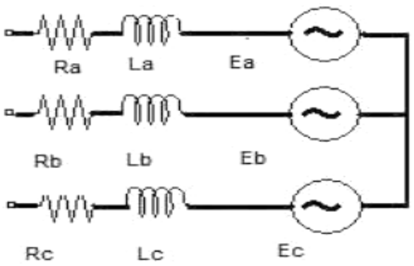

Fig.2. BLDC motor equivalent model

The matrix equation of phase voltages is:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

$$V_a = Ri_a + L\frac{d}{dt}(i_a) + e_a \quad (2)$$

$$V_b = Ri_b + L\frac{d}{dt}(i_b) + e_b \quad (3)$$

$$V_c = Ri_c + L\frac{d}{dt}(i_c) + e_c \quad (4)$$

where R is the resistance of each phase (Ω), L is the self-inductance of each phase (H), M is the mutual inductance between any two phases, V_a, V_b, $V_c$are the stator phase voltages (V), i_a, i_b, i_c are the stator phase currents in (A), e_a, e_b, e_c are the back emf signals (V) of BLDC motor and p is the differential operator.
In a three phase BLDC motor back emf is related to as a function of rotor position. Rotor position function is a unit function generator which has a maximum value of +1 or -1 which have a phase difference of 120° between each phase [5].

$$e_a = k_w f(\theta_e)\omega \quad (5)$$

$$e_b = k_w f(\theta_e - 2\pi/3)\omega \quad (6)$$

$$e_c = k_w f(\theta_e + 2\pi/3)\omega \quad (7)$$

Where k_w is back EMF constant per phase[V/rad.s^{-1}],θ_e is electrical rotor angle [° el.], ω is rotor speed [rad.s^{-1}].
The equation of electromagnetic torque is:

$$T_e = \frac{1}{\omega}(e_a i_a + e_b i_b + e_c i_c) \quad (8)$$

The mechanical torque is given by

$$T_m = J\frac{d\omega}{dt} + B\omega + T_L \quad (9)$$

Where J is the moment of inertia of drive [kgm^2], B is the damping constant [Nm.s.rad^{-1}], T_L is the load torque [Nm]. The parameters of a 6.14 kW BLDC motor is shown in Table I.

TABLE I 3 PHASE BLDC MOTOR SPECIFICATIONS

Motor value	Parameters
Stator inductance per phase	2.55 m H
Stator resistance per phase	0.43Ω
Moment of inertia, J	0.0689 kgm^2
Friction coefficient, B	0.05 Nm.s.rad^{-1}
Rated speed	2300 rpm
Rated power	6.14 Kw
Back emf constant	0.51 V/rad.s^{-1}

To make BLDC motor running, the rotor magnetic field should continuously catch stator magnetic field. Stator windings are energised in a sequence to make the rotor rotate. Thus information about the position of rotor is important to know which stator winding must be energised next. Sensing of rotor position is done by Hall Effect sensors which work on the principle of Hall effect. These rotor position sensors are mounted on the stator which continuously senses the rotor position and give right information to switch the right stator windings at the right time. This method is called position feedback control. Table II shows the function of rotor position of three phases for different sectors of angles from 0- 360°.

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TABLE II FUNCTIONS OF ROTOR POSITIONS BASED ON ANGLE

Theta_elec θ	$f_a(\theta)$	$f_b(\theta)$	$f_c(\theta)$
$0^0 - 60^0$	1	-1	$1-\frac{6}{\pi}\theta$
$60^0 - 120^0$	1	$-3+\frac{6}{\pi}\theta$	-1
$120^0 - 180^0$	$5-\frac{6}{\pi}\theta$	1	-1
$180^0 - 240^0$	-1	1	$-7+\frac{6}{\pi}\theta$
$240^0 - 300^0$	-1	$9-\frac{6}{\pi}\theta$	1
$300^0 - 360^0$	$-11+\frac{6}{\pi}\theta$	-1	1

IV. MODELING OF PV SYSTEM
V.

A PV cell is a p-n junction diode fabricated in a thin wafer of semiconductor which works on the principle of photo electric effect, electricity is generated when light falls on it. Current through output of a PV module is

$$I = N_p I_{ph} - N_p I_o \left(exp\left[\frac{q(V/Ns + IRs/Np)}{AKT}\right] - 1 \right) - \frac{V+IR_s}{R_p} \quad (10)$$

where V is the voltage of the PV module, $I_{ph}$is the photo-current, $I_0$is the reverse saturation current, $N_p$is the number of cells connected in parallel, $N_s$is the number of cells connected in series, q is the charge of an electron (1.6*10^{-19}C), k is Boltzmann's constant (1.38*10-23J/K), A is p-n junction ideality factor, (1 <a < 2, a = 1 being the ideal value), and T is the PV module temperature [6].Output of PV module varies with photo current which depends on solar irradiance and PV module temperature.

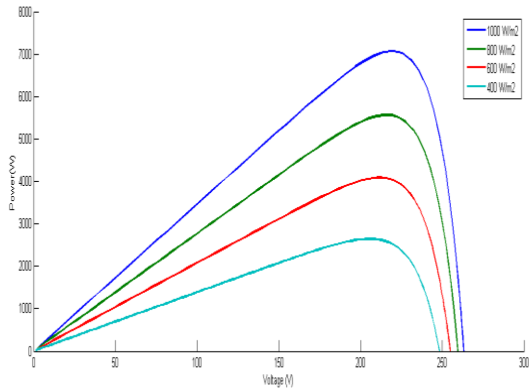
$$I_{ph} = G[I_{sc} + k_1(T - T_{ref})] \quad (11)$$

where I_{sc} is the short circuit current of the PV cell, k_1 is the temperature coefficient T is the current atmospheric temperature andT_{ref} is the temperature at nominal condition (25^{o}C and 1000W/m^2), G is the current irradiance level.

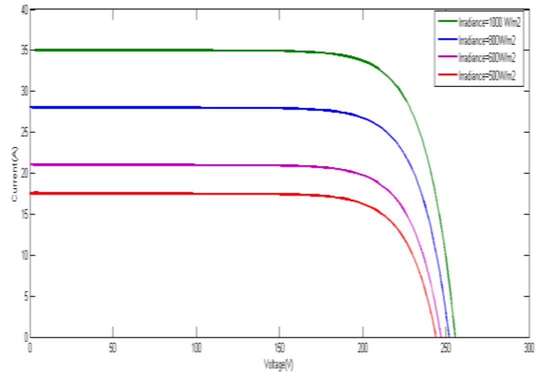
TABLE IIII PV MODULE PARAMETERS

Electrical parameters	Value
Maximum Power (P_{max})	250 W
Open Circuit Voltage (V_{oc})	37.6 V
Short Circuit Current (I_{sc})	8.66 A
Number of Series Cells (N_s)	60

Figure 3 (a) and (b) shows the P-V curve and I-V curve for different irradiation levels of a 7 kW PV array respectively. Infigure 3(a) the open circuit voltage decreases slightly when irradiation is reduced from 1000 W/m^2 to 600 W/m^2 whereas in figure 3(b), the short circuit current decreases largely when irradiation is reduced from 1000 W/m^2 to 500W/m^2.



(a)



(b)

Fig. 3 PV and IV characteristics for different irradiation levels

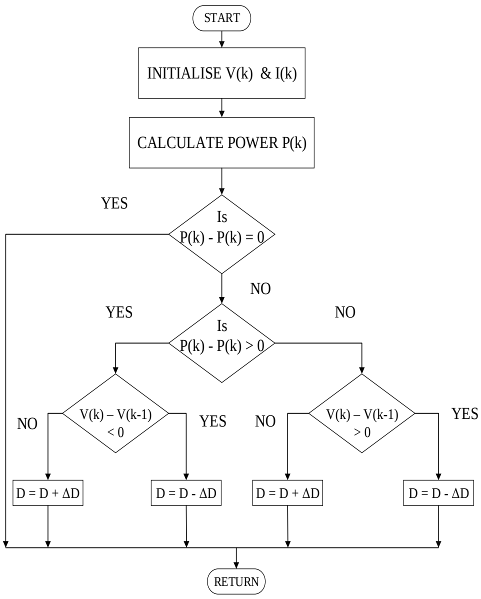


Fig.4. Perturb and Observe Algorithm

To utilize the trapped power from the available power, we make use of maximum power point techniquesMaximum power is extracted at the intersecting point of PV curve and IV curve. The operation of MPPT techniques is based on maximum power transfer theorem; maximum power is transferred when source impedance matches load impedance. Of the different MPPT techniques, P&O method is used here.

VI. BUCK – BOOST CONVERTER

Buck boost converter is a dc-dc converter which performs both buck and boost operation. It gives a regulated output from an unregulated input. When duty ratio is less than 50%, buck operation is performed whereas when duty ratio is greater than 50 %, boost operation is performed. When the switch is in ON state, inductor L is directly connected to the input and it charges. Capacitor supplies energy to load. When the switch is in OFF state, L is connected to load and capacitor [7]. The output voltage is given by

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \quad (12)$$

The rated DC voltage of the BLDC motor is $V_{dc} = 310$ V, the output of buck-boost converter and PV voltage at MPP is $V_{pv} = 286$ V, the input to buck-boost converter. Hence

$$D = \frac{V_{dc}}{V_{dc}+V_{pv}} = \frac{310}{310+286} = 0.52 \quad (13)$$

Current flowing through L is the output current of PV array at MPP.$I_L = I_{pv} = 24.02$ A. Allowing 6% current ripples, with a switching frequency of 20 kHz, input inductor

$$L = \frac{DV_{in}}{f\Delta I_L} = \frac{0.52*286}{20000*0.06*24.02} = 5.1 \text{ mH} \quad (14)$$

Allowing a 0.4 % voltage ripple,

$$C = \frac{I_O D}{\Delta V_C f} = \frac{24.02*0.52}{0.004*310*20000} = 503\mu F \quad (15)$$

Where D is the duty ratio of dc – dc converter, f is the switching frequency, ΔV_c is the voltage ripple across capacitor and ΔI_L is the current ripple of inductor.

VII. TORQUE RIPPLE COMPENSATION TECHNIQUE

The elimination of dc link capacitor introduces torque ripple at the output of motor. Hence a new method proposed is a low value inexpensive capacitor (ceramic capacitor) and aswitch connected between the converter and the inverter. The 503 µF capacitor in between the buck-boost converter is replaced by a ceramic of 25 µF. A switch with antiparallel diode is used to provide the required current to run the motor. The motor drive is fed with a voltage between 0 to 325 V without a dc link capacitor. The build-up of phase current is possible when rectified mains voltage is greater than back emf. Capacitor is charged when input voltage is less than back emf with the compensation technique. Energy stored in capacitor is discharged when $V_m < E$, so that current in motor is maintained at current reference [8]. By controlling the gating pulse applied to the switch discharge of capacitor is controlled. Controller is developed in such a way that gating pulse is generated based on value of back emf and rectified mains voltage.

$$T = \frac{1}{2\pi f}\sin^{-1}\frac{E}{V_m} \quad (16)$$

Where T is the time taken for $V_{in}(t)$ to reach E from 0 V.
V_m is peak value of voltage (V) .
fis the frequency of input supply voltage (Hz) .
At E =100 V,V_m=310 V,

$$T = \frac{1}{2*\pi*50}\sin^{-1}\frac{100}{310} = 1.23 \text{ ms} \quad (17)$$

The value of C_{DC} is selected such that it is capable to provide the required reference current when $V_m < E$ to maintain current at reference. The minimum value of capacitance that is required to provide current at reference is

$$C_{DC} = \frac{2TI_{avg}}{V_m - E} \quad (18)$$

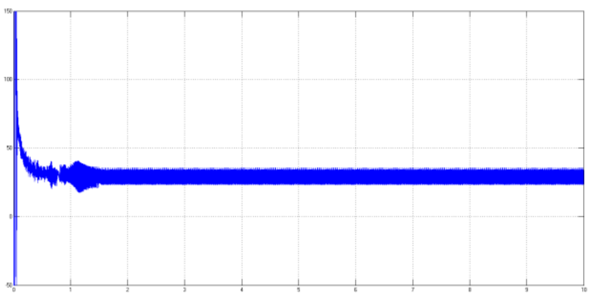
With$I_{avg} = 2$ A,C_{DC} is calculated as

$$C_{DC} = \frac{2*1.23*10^{-3}*2}{310-100} = 23\mu F \quad (19)$$

A ceramic capacitor of 25 µF with a switch thus replaces a 503 µF capacitor.

VIII. RESULTS AND DISCUSSIONS

The modelling of torque ripple compensation technique of BLDC motor with compensation capacitor is carried out in MATLAB™/SIMULINK™. To compare the torque ripple at the output of BLDC motor with and without a compensation capacitor the simulation is carried out for an irradiance of 1000 W/m^2.



(a)

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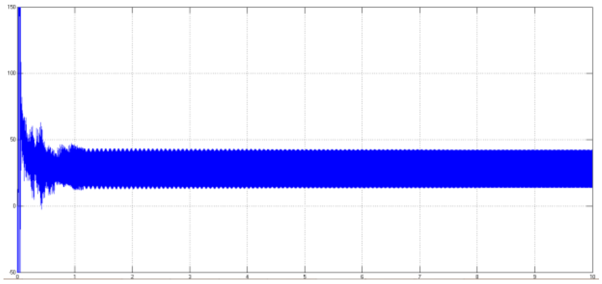


(b)

Fig.6. Electromagnetic torque output of a BLDC motor for a load torque of 20 N-m for G=1000 W/m^2 (a) with compensation capacitor (b) without compensation capacitor

Figure 6(a) shows the electromagnetic torque of a 6.8 kW BLDC motor with compensation capacitor. The result is compared with another BLDC motor of same rating without a compensation capacitor whose electromagnetic torque is as shown in Fig 6(b). At 1000 W/m^2, motor has a rated current of 25A at rated torque of 20 N-m.

Motor with a low value capacitor runs satisfactorily at G=1000W/m^2 with a rated dc voltage of 310 V at the output of buck-boost converter. This voltage appears across the compensation capacitor and switch. The low value capacitor along with switch is able to drive the motor at rated condition. Motor has a peak current of 30 A and a speed of 2200 rpm at this irradiance level. Figure 7 shows the motor current with the compensation capacitor and switch. As irradiance level is high, motor operates at the rated current. The rated voltage is applied to the motor using the compensation technique. It is able to drive the motor at rated dc link voltage with a reduced torque ripple as compared with a motor with no compensation capacitor.

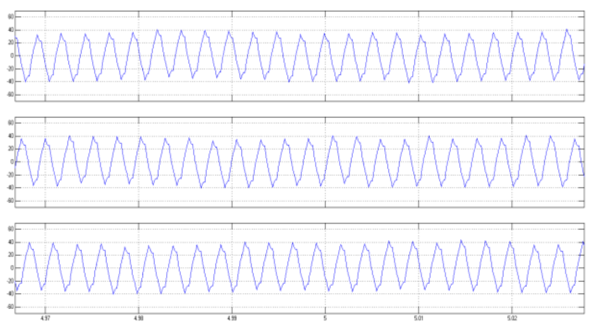
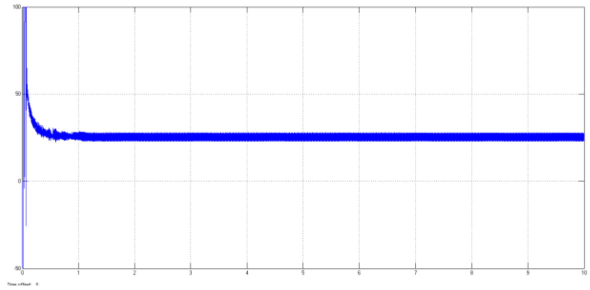
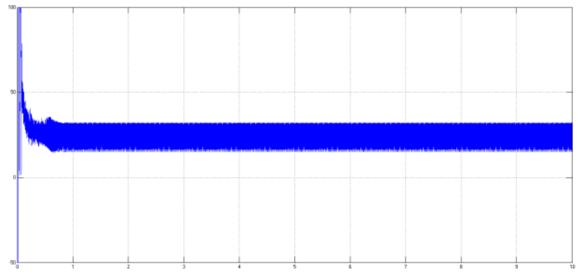


Fig.7. Motor current with compensation capacitor for G= 1000 W/m^2

Irradiation is changed from 1000 W/m^2 to 600 W/m^2 to demonstrate the performance of motor.When the solar irradiance is changed from 1000 W/m^2 to 600 W/m^2 , as amount of tracked energy is less, the converter output voltage is less due to which the electromagnetic torque and stator current decreases. Torque generated with 600 W/m^2 is less than that generated with 1000 W/m^2. There is a comparable reduction in ripple in the electromagnetic torque with compensation capacitor shown in figure 8(a) when comparing with the torque generated in a BLDC motor of same rating without compensation capacitor as shown in figure 8(b).



(a)



(b)

Fig.8. Electromagnetic torque output of a BLDC motor for 20 N-m for G=600 W/m^2 (a) with compensation capacitor (b) without compensation capacitor

As the solar irradiance level decreases, the dc link voltage, speed, stator current and back emf of motor reduces. The speed of motor reduces to 1900 rpm and the dc voltage at the output of converter is 230 V. Figure 9 shows the motor current of BLDC motor with the compensation capacitor and switch at G=600W/m^2. Current is reduced from apeak value of 25 A to a peak value of 17 A at 600W/m^2.

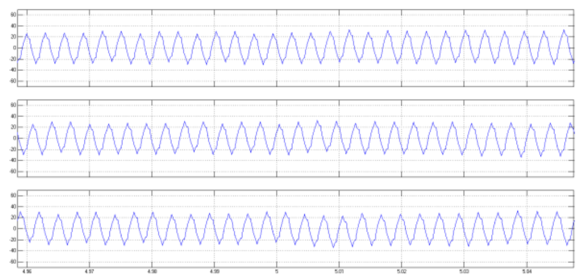


Fig.9. Motor current with compensation capacitor for G= 600 W/m^2

IX. CONCLUSION

The paper provided a torque ripple compensation for a BLDC motor with compensation capacitor. BLDC motor is fed from a solar PV array using buck-boost converter to analyse the new technique. An MPPT technique is used to maintain a constant dc link voltage for a particular irradiance level. Performance of motor with compensation technique was analysed for irradiance level of 1000 W/m^2 and 600 W/m^2. By using this compensation technique, torque ripple was reduced in both cases. The motor is able to operate in the rated speed and torque with the use of the compensation capacitor of low value. The method can be used for water pumping applications. Also, the method can be analysed with SEPIC, Cuk converter or zeta converter.

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