Mitigation of Power Quality Problems in a Wind Driven Isolated Generator by using Static Series Compensator

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Abstract— This paper deals with the performance of a system consisting of a three-phase self excited induction generator (also known as Isolated generator) with static compensator (STATCOM) for feeding the static resistive-capacitive load and investigated in a wind energy conversion system to mitigate the power quality problems such as poor voltage, voltage and current harmonics due to sudden change in load. The cost effective STATCOM providing stable operation, was designed by connecting additional shunt capacitance with the load. A three-phase, insulated gate bipolar transistor (IGBT) based current-control voltage source converter (CC-VSC) known as STATCOM, is used for harmonic elimination caused by sudden changes in load or due to faults. The STATCOM control algorithm was realized by controlling the source current using two control loops with proportional integral (PI) controller, one for SEIG controlling (the SEIG terminal voltage) and the other for maintaining the DC bus voltage to generate the reference current. Here the proposed electrical system is modeled and simulated in MATLAB using Simulink tool box and studied. On the basis of this model, different characteristics of SEIG with STATCOM are analyzed which shows its suitability in SEIG in generating stations like wind energy system.

Keywords— Wind energy system, SEIG (Self Excited Induction Generator), Static Compensator (STATCOM), Voltage Regulation, Voltage source Converter (VSC)

I. INTRODUCTION

The renewable energy resources such as micro, mini hydro and wind are being harnessed to generate electrical energy; however the usage of induction generator for this purpose is getting considerable attention [1-3]. The presence of wind power generation is likely to influence the operation of the existing power system networks, especially the power system stability. The SEIG as reported by Bassett and Potter in 1935 [1] is a squirrel cage induction machine with suitable capacitor bank at stator terminal. In the other manner, an externally driven squirrel cage induction machine with its stator terminals connected to a reactive power source (capacitor bank) is popularly known as SEIG [4].

When an SEIG is driven by prime mover such as biomass, biogas, and biodiesel engine or wind turbine, the frequency of the generated voltage is almost constant from no load to full load. The fast response, improved switching features and the low cost of the power converters have attracted the researchers to explore their applications for SEIG. But poor voltage regulation has been the major drawback of an SEIG in its applications. Hence the terminal voltage of an SEIG needs to be regulated during load perturbations. Several methods for voltage regulation have been reported for SEIG-based autonomous power generation systems. The methods reported in [5-8] have employed the passive element for the voltage regulation. L. Shridhar and B. Singh used the short shunt compensation method for a three-phase SEIG. With the development of fast acting self-commutating switches and PWM techniques, voltage source converter based static reactive compensators STATCOM [9-14] have been evolved. The performance of SEIG-STATCOM system has been discussed for linear loads. There is also available comparative study on operating performance of static series compensated three-phase self excited induction generator with SVC and STATCOM [15].

Contrary to static compensators (STATCOM) has been used effectively in power system for mitigation of resonance, reactive power control, voltage regulation etc [16-22]. The schematic of three-phase STATCOM comprise six pulse Insulated gate bipolar transistor (IGBT) based pulse width modulated with a suitable sized capacitor at DC link. It modulates the effective impedance of the line by injecting a controllable AC voltages in quadrature with the line current and emulates an inductor (or capacitor) when the injected voltage is quadrature leading (or lagging) to the line current.

In this paper, the studies have been carried out on SEIG-SATCOM system for R-C load. For controlling the voltage a static compensator (STATCOM) is used as a reactive power compensator along with harmonic elimination. With the employed control technique the STATCOM is found to capable of generating/absorbing controllable reactive power and maintaining constant voltage during change in load and to damp out the oscillations and to make system stable.

II. SYSTEM CONFIGURATION & CONTROL STRATEGY

A. SEIG-STATCOM System

The block diagram of SEIG-STATCOM system along with the control scheme for generating reference current signals and subsequent gating signals for generating IGBT's are depicted.

The figure 1 shows the system configuration of self excited induction generator, consisting three leg IGBT based voltage source converter and consumer load. The six gating signals for IGBTs of STATCOM are obtained by comparing sensed and

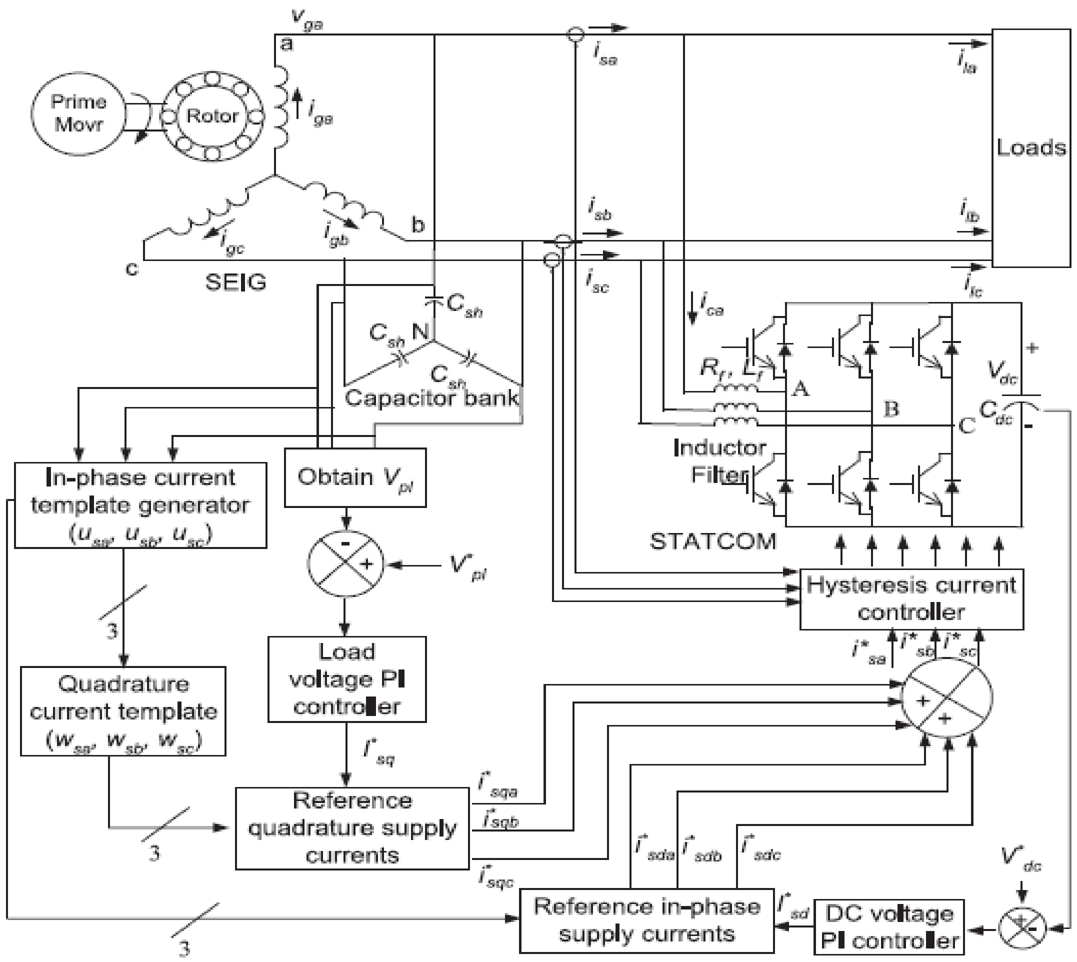

Fig. 1 Representation of SEIG-STATCOM system with control technique

reference supply currents through carrier-less hysteresis current controller. The delta connected three-phase capacitor bank is used for the generator excitation and value of an excitation capacitor is selected to generate the rated voltage at no load. The isolated asynchronous generator or SEIG generates constant power and when consumer load changes; the STATCOM is used to regulate the voltage due to load changes.

STATCOM consists of IGBT based current controlled 3-leg VSC, DC bus capacitor and AC inductors. The output of the VSC is connected through the AC filtering inductors to SEIG terminals. The DC bus Capacitor is used to filter voltage ripples and provides self supporting Dc bus. Fig. 2 shows the control scheme for STATCOM. The proposed control scheme is based on indirect current control and deploys two control loops for generating reference supply currents.

B. Control strategy

The fig. 2 shows the control strategy of the proposed voltage controller for SEIG. The control scheme of STATCOM to regulate the terminal voltage of SEIG which is based on the generation of source currents has two main components, in-phase and quadrature, with AC voltage. The in-phase unit vectors $(u_a \; u_b \text{ and } u_c)$ are three-phase sinusoidal functions, computed by dividing the AC voltages $(v_a \; v_b \text{ and } v_c)$ by their amplitude V_t. Another set of Quadrature unit vectors ($w_a \; w_b$ and w_c) are sinusoidal functions obtained from in-phase vectors (u_a, u_b and u_c). To regulate the AC terminals voltage (V_t), it is sensed and compared with the reference voltage. The voltage error is processed in the Proportional Integral (PI) controller. The output of the PI controller (I^*_{smq}) for the AC voltage drop control loop determines the amplitude of the reactive current to be generated by the STATCOM.

Multiplication of Quadrature unit vectors ($w_a \; w_b$ and w_c) with the output of the PI based Ac voltage controller (I^*_{smq}) yields the q-component of the ref. source currents (i^*_{saq}, i^*_{sbq} and i^*_{scq}). To provide a self supporting DC bus for STATCOM, its DC bus voltage is sensed and then compared with the DC reference voltage.

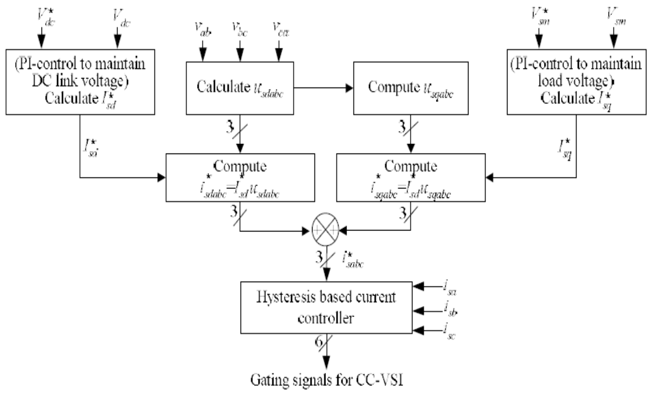

Fig. 2 Control Scheme for STATCOM

The error voltage is processed in another PI controller. The output of the PI controller (I^*_{smd}) determines the amplitude of the active current. Multiplication of in-phase unit vectors (u_a, u_b *and* u_c) with the output of the PI controller (I^*_{smd}) yields in phase quadrature with (i^*_{sad}, i^*_{sbd} *and* i^*_{scd}). The instantaneous summation of quadrature and In-phase component gives the reference source currents (i^*_{sa}, i^*_{sb} *and* i^*_{sc}), both are compared with the sensed line current (i_{sa}, i_{sb} *and* i_{sc}). These current error signals are amplified and then compared with the triangular carrier wave.

If the amplified current error signal is equal to or greater than the triangular carrier wave, the lower circuit of the inverter phase is turned ON and the upper device turned OFF. If the amplified current less than or equal to the triangular carrier wave the lower device of the inverter phase is turned OFF and the upper device turned ON. A non-linear load draws non-sinusoidal currents which causes harmonics to be injected into the generating system. Under unbalanced load conditions, SEIG currents may be unbalanced which may cause the machine to be derated. STATCOM is able to filter out the harmonics and balance the unbalanced load resulting in balanced and sinusoidal currents and voltages in the generator.

III. SYSTEM MODELLING

The system consist SEIG, STATCOM with associated control technique and load. The dynamic model of system components are briefed herewith.

A. Filter

Te inductive filter is used to remove the high frequency components from the output voltage of VSC. The size of the inductive filter is governed by the allowable ripples in the compensation currents. The inductance value depends on the switching frequency f_s and peak ripple current i_{rpp} with associate ripple band K_{rp} and is expressed as,

$$L = \frac{\left(\frac{\sqrt{3}}{2}\right) V_{bat}}{6 a f_s K_{rp} i_{rpp}} \tag{1}$$

B. SEIG modeling

This model is developed in q-d reference frame considering the effect of both main and cross flux saturation and is expressed as

$$p[i] = [L]^{-1}\left([v] - [r][i] - [G][i]\right) \tag{2}$$

$$p\omega_r = \frac{P}{2J}\left(T_p - T_{em}\right) \tag{3}$$

Where $[v]$, $[i]$, $[r]$, $[L]$, $[G]$ and T_{em} are defined in Appendix.

The SEIG voltages (v_{ga}, v_{gb} and v_{gc}) from shunt capacitance bank are expressed as

$$p\left[v_{ga}\ v_{gb}\ v_{gc}\right]^T = \frac{1}{C_{hs}}\left[\left(i_{ga} - i_{sa}\right)\left(i_{gb} - i_{sb}\right)\left(i_{gc} - i_{sc}\right)\right]^T \tag{4}$$

C. Gate signal generation

The IGBT gate signals are derived by relating equation of the PI controller, reference supply current an hysteresis current controller.

Three phase voltages at SEIG terminals (v_{ga}, v_{gb} *and* v_{gc}) are considered sinusoidal and hence there amplitude is computed as

$$V_t = \sqrt{\left\{(2/\ 3)\left(v_a^2 + v_b^2 + v_c^2\right)\right\}} \tag{5}$$

The unit vectors in phase with $\left(v_a\ v_b \text{ and } v_c\right)$ are derived as:

$$u_a = v_a/V_t\ ;\ u_b = v_b/V_t\ ;\ u_c = v_c/V_t \tag{6}$$

The unit vectors in quadrature with $\left(v_a\ v_b \text{ and } v_c\right)$ may be derived using a quadrature transformation of the in-phase unit vectors $\left(u_a\ u_b \text{ and } u_c\right)$ as

$$w_a = -u_a/\sqrt{3} + u_c/\sqrt{3} \tag{7}$$

$$w_b = \sqrt{3}\,u_a/2 + (u_b\ - u_c)/2\sqrt{3} \tag{8}$$

$$w_b = -\sqrt{3}\,u_a/2 + (u_b\ - u_c)/2\sqrt{3} \tag{9}$$

1) Quadrature component of reference source currents:

The AC voltage error at the nth sampling instant is

$$V_{er\,(n)} = V_{tref\,(n)} - V_{t\,(n)} \tag{10}$$

Where, $V_{tref\,(n)}$ is the amplitude of the reference AC terminal voltage.

$V_{t\,(n)}$ is amplitude of the sensed three-phase AC voltage t the SEIG terminals at the n[th] instant.

The output of the PI controller $I^*_{smq\,(n)}$ for maintaining constant AC terminal voltage at the n[th] sampling instant is expressed as:

$$I^*_{smq\,(n)} = I^*_{smq\,(n-1)} + K_{pa}\left\{V_{er\,(n)} - V_{er\,(n-1)}\right\} + K_{ia}V_{er\,(n)} \tag{11}$$

Where K_{pa} and K_{ia} are the proportional and integral gain constants of the proportional integral (PI) controller. $V_{er\,(n)}$ and $V_{er\,(n-1)}$ are the voltage error at n[th] and (n-1)[th] instant and

$I^*_{smq(n-1)}$ is the amplitude of the quadrature component of the reference source current at the (n-1)th instant. The quadrature components of the reference source currents are computed as:

$$i^*_{saq} = I^*_{smq} w_a ; i^*_{sbq} = I^*_{smq} w_b ; i^*_{scq} = I^*_{smq} w_c \quad (12)$$

2) *In-phase component of Reference source currents:*

The error in DC voltage of the STATCOM $V_{dcer(n)} = V_{dcerf(n)} - V_{dc(n)}$

Where $V_{dcer(n)}$ the reference DC voltage and $V_{dc(n)}$ is the sensed DC link voltage of the STATCOM. The output of the PI controller for maintaining the DC bus voltage of the STATCOM at the nth sampling instant is expressed as:

$$I^*_{smd(n)} = I^*_{smd(n-1)} + K_{pd}\{V_{dcer(n)} - V_{dcer(n-1)}\} + K_{id} V_{dcer(n)} \quad (13)$$

$I^*_{smd(n)}$ is considered to be amplitude of the active source current. K_{pd} and K_{id} are the proportional and integral gain constants of the DC bus proportional integral (PI) controller.

The in-phase components of the reference source currents are computed as:

$$i^*_{sad(n)} = I^*_{smd} u_a ; i^*_{sbd(n)} = I^*_{smd} u_b ; i^*_{scd(n)} = I^*_{smd} u_c \quad (14)$$

3) *Reference source currents:*

The Reference currents are given as

$$i^*_{sa} = i^*_{saq} + ^*_{sad}$$
$$i^*_{sb} = i^*_{sbq} + ^*_{sbd}$$
$$i^*_{sc} = i^*_{scq} + ^*_{scd}$$

4) *PWM current controller:*

The total reference currents are compute with the sensed source currents the ON/OFF switching patterns of the gate signals to the IGBTs are generated from the PWM current controller. The current errors are computed as:

$$i^*_{saerr} = i^*_{sa} - i_{sa}$$
$$i^*_{sberr} = i^*_{sb} - i_{sb}$$
$$i^*_{scerr} = i^*_{sc} - i_{sc}$$

The error signals are amplified and then compared with the triangular carrier wave. If the amplified phase 'a' current error signal is greater than triangular wave signal switch S4 (lower device) is ON and switch S1 (upper device) is OFF. If the amplitude current error signal corresponding to i^*_{saerr} is less than the triangular wave the signal switch S1 is ON and switch S4 is OFF. Similar logic applies to other two phases of VSC of STATCOM.

D. *Load Model*

The study is carried out for series connected resistive capacitive load. The modeling equation for load is:

$$p[v_{cla} \; v_{clb} \; v_{clc}]^T = \frac{1}{R_f C_f}[(v_{ga} - v_{ca} - vcla)(v_{gb} - v_{cb} - vcba)(v_{gc} - v_{cc} - vclc)]^T$$

IV. MATLAB BASED MODELLING

The MATLAB model of the SEIG-STATCOM system consists of the asynchronous machine i.e. induction generator with capacitor bank and this circuit is realize in MATLAB version 13. The modeling of SEIG is carried out using squirrel cage 25hp, 415V, 50Hz asynchronous machine and 75kVar delta connected excitation capacitor bank. The STATCOM is realized with a 3-leg voltage source converter and a DC link capacitor. The SEIG is coupled with STATCOM through an L-filter. The complete simulation model of the SEIG-STATCOM system with load circuit is shown in fig 3. The output wave forms are shown in fig 4.

V. RESULT AND DISCUSSION

The performance of SEIG-STATCOM system with static R-C load is shown in fig. 4 and fig. 5. The SEIG is loaded from 6 to 7 seconds, which results into increase in load currents and decrease in speed ω_r. Due to increase in load, additional reactive power loading on STATCOM and the V_{dc}

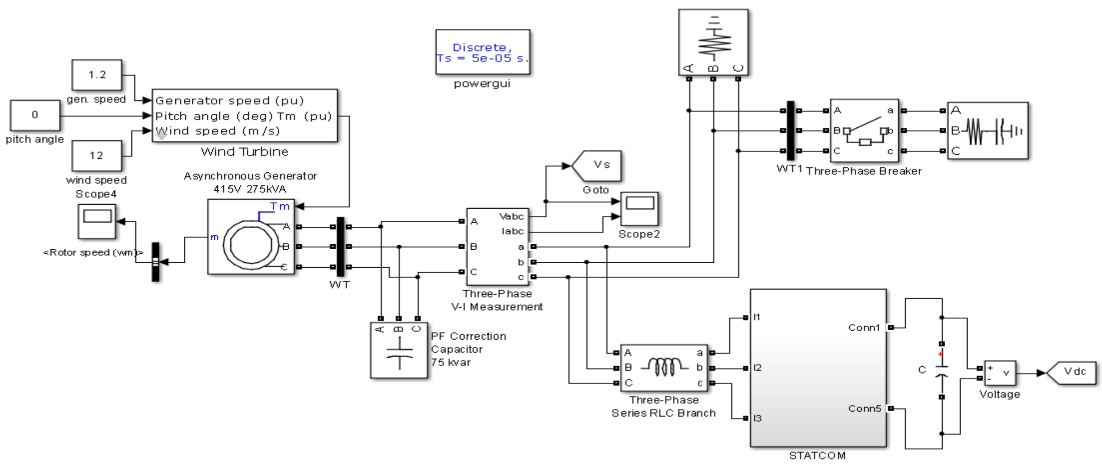

Fig. 3 Simulink model of SEIG-STATCOM system

decreases. This increased loading results into corresponding increase in generator load. But V_{dc} decreases and the later return to its reference value under the PI controller action and maintained voltage constant.

VI. CONCLUSION

The design, modeling and simulation of SEIG with STATCOM have been carried out for static load. For STATCOM the operation in capacitive load is already explained. The proposed STATCOM, which is employing simple and easy to implement PI controller assisted technique to calculate the reference supply current, is found to be elegant. The STATCOM improves the voltage regulation by the injection of compensation currents and is able to regulate the terminal voltage of the generator and suppresses the harmonic currents injected by load.

The developed SEIG-STATCOM combination promises a potential application for isolated power generation using renewable energy sources in remote areas with improved power quality.

Table-1 THD of SEIG-STATCOM system with R-C load

	STATCOM in SEIG System	
	V_g	I_g
THD%	0.20	1.99

A. *Simulaton result of SEIG with increased load*

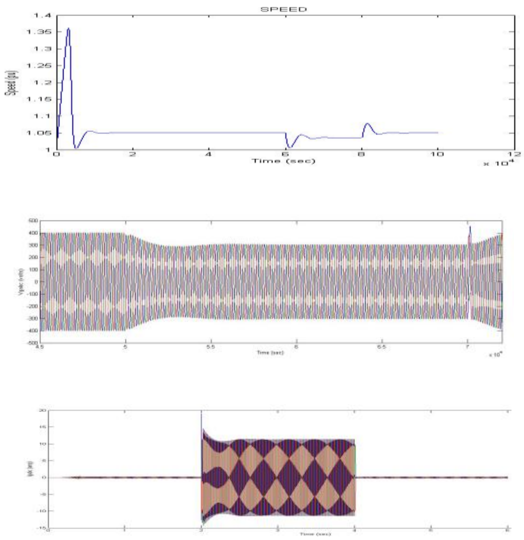

Fig. 4 SEIG output rotor speed, V's & I's without STATCOM

B. *Simulation Result of SEIG with increased load and STATCOM.*

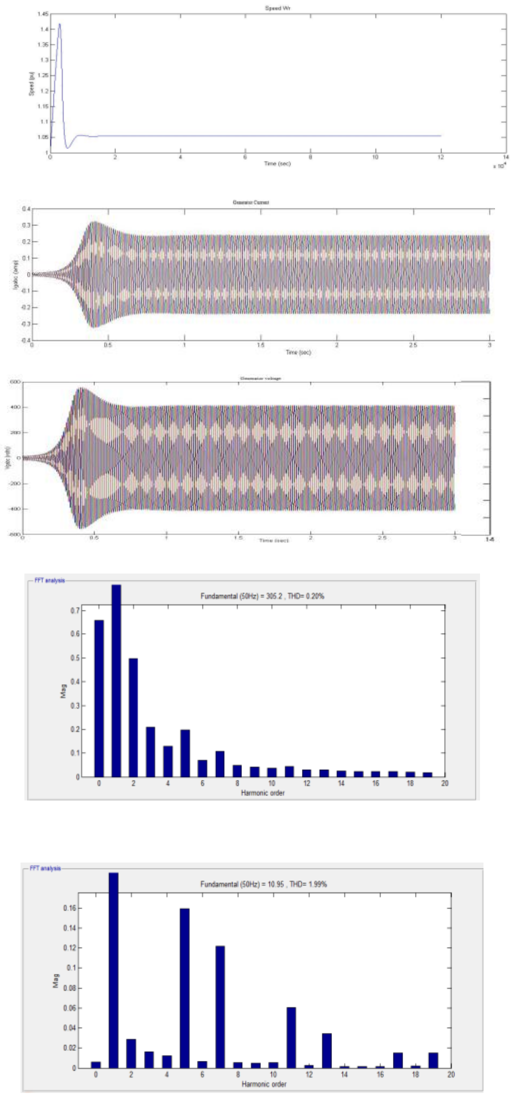

Fig. 5 SEIG output rotor speed, V's, I's & FFT window with STATCOM

APPENDIX

a) Generator parameters:
18 kW, 415V, Y-connected, 50 Hz, 4-pole, J = 0.0854 kg-m^2 cage induction machine.
$R_s = 0.02$ pu, $R_r = 0.025$ pu, $X_{ls}=X_{lr}= 0.048$ pu, $L_m= 0.1589$ pu

b) Load parameters:
Active power = 4500W
Reactive power = 4000W

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