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REVIEW

Stand-alone self-excited induction generator driven by a wind turbine

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SEIG;
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Abstract This publication aims to develop a wind generator (WG) for rural electrification. The WG is equipped by a 1.5 kW self excited induction generator (SEIG) coupled to wind turbine, a bank of capacitors and a variable inductor. The controlled voltage source is performed by using a controller, which adjusts voltage by varying the amount of injected reactive power. An experimental work was done to design size and implement the WG, to alleviate the problem of voltage regulation and to minimize the starting up time of SEIG and fixing the convenient margin of voltage. Many tests are done to define SEIG parameters and to select the convenient bank of capacitors or a variable inductor. A controller is used to meet the requirement of the SEIG frequency regulation.

Contents

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1. Introduction

Design principles of WG need the selection and sizing of its components. SEIG appears to be the right candidate to generate an electric power for remote area applications [1–8]. It is robust and it can operate in a self-excited mode using only the input mechanical power from the rotating wind turbine. It is simple in construction, small in size and weight, reliable, efficient, and with reduced cost of maintenance. Also it has inherent short circuit and overloading protection. Wind turbine speed, reactive power injected, and the load profile affect the terminal voltage and the output frequency [9]. Various schemes such as saturable core reactors, short shunt and long shunt configurations, switched shunt capacitors, static voltage compensator (SVC) [10,11] and voltage or current source converter based static compensator (STATCOM) are done to overcome poor voltage regulation [11]. In this paper two strategies are developed to alleviate the problem of voltage regulation for WG, the first one by adding a bank of capacitors and the second by using an SVC. In the first strategy the bank of capacitors is divided into two parts, a fixed capacitor sized to obtain the desired voltage at unload case, and variable capacitor as shown in Fig. 1 where its maximum is sized to obtain the desired voltage at nominal load case. The second is by using an SVC. It adds a variable inductor to a fixed capacitor size to obtain the desired voltage at nominal load case and variable inductor where its maximum is sized to obtain the desired voltage at unload case.

Accurate modeling of WG components permits to analyze and to control the system. The d-q model is used to predict the transient performance of SEIG under different operating conditions [12,13].

2. Wind generator plant

The configuration of the system is presented in Fig. 1. The system components are a wind turbine, a SEIG, a fixed capacitor bank for starting up with a value of 20 μF, a switched capacitor bank that will be added with a value of 26 μF or a 1.4 H variable inductor and a loop that adjusts the reactive power injected related to the voltage.

2.1. Wind turbine model

The mechanical power of the turbine extracted from the wind is given by formula (1)

$$P_m = \frac{1}{2}\rho S C_p(\lambda,\beta) V_w^3 \tag{1}$$

where ρ: Air density (kg m^{-1}), S: Turbine swept area (m^2), C_p: Performance coefficient of the turbine, λ: Tip speed ratio of the rotor blade, β: Blade pitch angle (deg). V_w: Wind speed. The mechanical speed of the turbine Ω_t (rds^{-1}) is given by Eq. (2).

$$\Omega_t = \frac{\lambda * V_w}{R_t} \tag{2}$$

Introducing the torque coefficient, $C_m = \frac{C_p}{\lambda}$ the expression of the mechanical shaft is defined as (3)

$$P_m = \frac{1}{2}\rho\pi R^3 C_p(\lambda,\beta) V_w^3 \tag{3}$$

A generic equation can be used to model $C_p(\lambda,\beta)$. This equation, based on the modeling turbine characteristics, is represented as (4) [14]:

$$C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{1+\beta^3} \tag{5}$$

C_p represent the aerodynamic performance of wind turbine represented in Fig. 2.

2.2. Gear box model

The gearbox is a mechanical device able to transfer torque loads from a primary mover to a rotary output, related to the angular velocity and torque. It connects the low-speed shaft and the generator. The ratio is dictated by the requirement of the SEIG expressed by (6)

$$r = \frac{\Omega_t}{\Omega_m} = \frac{C_m}{C_t} \tag{6}$$

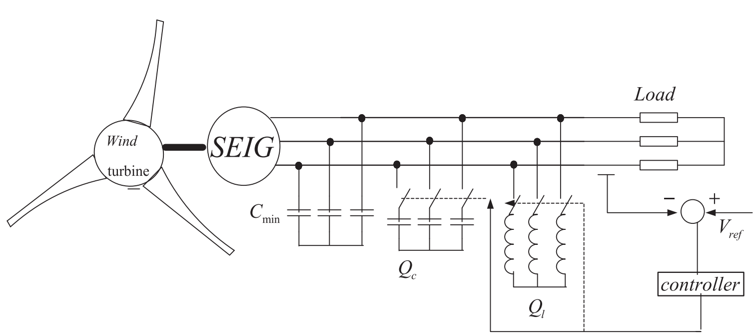

Figure 1 The proposed system.

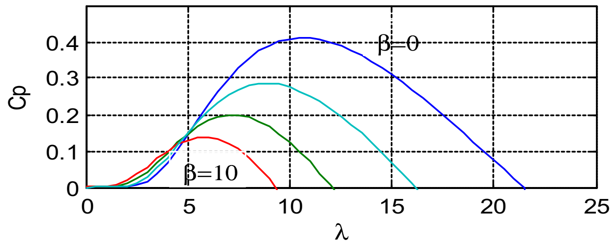

Figure 2 Variation of the performance coefficient Cp.

2.3. Self-excited induction generator model

The per-phase equivalent circuit of SEIG shown in Fig. 3, R_s and ℓ_s represents stator resistance and leakage inductance, R_r and ℓ_r respectively denote the rotor resistance and leakage inductance and s denote the slip factor.

The DC, the no-load and the blocked-rotor tests on a SEIG are realized to identify the equivalent circuit [15]. The SEIG parameters values shown in Fig. 3 are $R_s = 5.51\ \Omega$, $R_r = 2.24\ \Omega$, $\ell_s = \ell_r = 20.35$ mH and $L_{mn} = 0.24$ H.

The magnetizing inductance $L_{mn} = 0.24$ H is a nonlinear function of the magnetizing current [16,17]. By using matlab simulink polyfit function we can approximate L_m by (7)

$$L_m = 1.58^{-11}V_s^4 + 0.51^{-8}V_s^3 - 0.52^{-5}V_s^2 + 1.08^{-3}V_s + 0.24 \tag{7}$$

3. Voltage compensation

A fuzzy logic controller is used to alleviate the problem of voltage regulation for WG, by acting the switching unit and injecting the needed reactive power, in varying the capacitance value. There are two inputs of fuzzy control. Input parameters error $\varepsilon = V_{ref} - V_{dc}$ and its derivative $\frac{d\varepsilon}{dt} = \frac{V_{ref} - V_{dc}}{dt}$ are used to generate the necessary duty cycle to inject the convenient reactive power as shown in Fig. 4.

Trapezoidal and triangular membership functions are presented in Fig. 4 and denoted by BN(Big Negative) N (Negative), Z (Zero) P (Positive) and BP (Big Positive) used

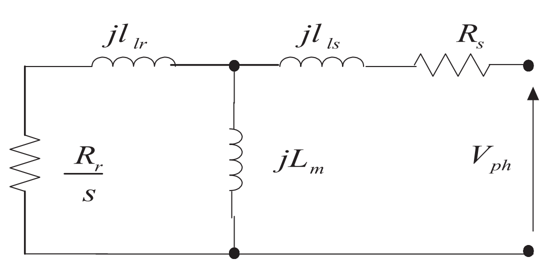

Figure 3 The per-phase equivalent circuit of SEIG.

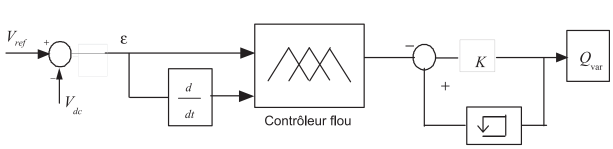

Figure 4 Reactive power injection.

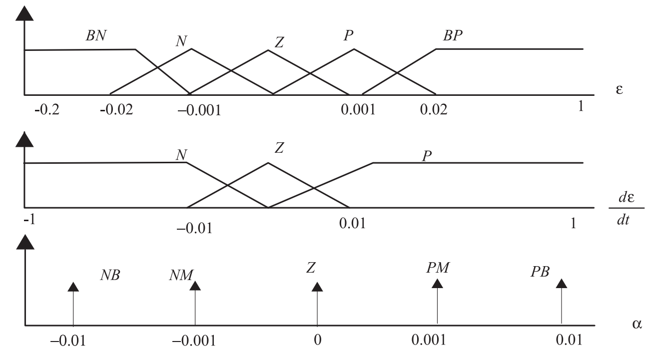

Figure 5 Inputs and outputs membership functions

for both the error and P (Positive) N (Negative), Z (Zero) for its derivative. For the output signals, five triangular membership functions denoted by NB (Negative Big), NM (Negative Middle), Z (Zero), PM (Positive Middle), and PB (Positive Big) are used. The elements of this rule base table are related to ε and $d\varepsilon$ as represented in Fig. 5.

Big errors need big voltage step; however, small errors need fine control, which requires fine input/output variables. The rule table is obtained as shown in Table 3, with error and change in error as inputs.

4. Simulation results

The simulation in this work has been developed under Matlab/Simulink environment. A Wind turbine is used as a prime mover. The command of the Wind turbine is based on the speed equal to 1500 rpm required by the SEIG to provide a 50 Hz frequency generator. This value is computed as a reference SEIG frequency term. The command of the SEIG system is based on the AC voltage required by the load equal to 200 V. This value Vref is computed as a reference AC-bus voltage. The proposed root- mean -square voltage profile is described by the scenario given in Fig. 6.

The SEIG rms voltage converges toward its target with a delay time of 2 s SEIG starting-up voltage. The provided voltage tracks the reference value. Fig. 7 shows the voltage waveform of the SEIG stator phase including the transient self-excitation process. The frequency is equal to 50 Hz and the required voltage is being tracked.

Fig. 8 shows the variation of the capacitance value needed to stabilize the voltage at the required margin.

In the second part the proposed load profile is described by the scenario given in Fig. 9. 40 Ω is computed as a nominal value and decreased by 20% in two steps.

The SEIG voltage converges toward its target with a delay time. The analysis results demonstrate that the controller guarantees robust stability under load variations as presented in Fig. 10.

5. Test environment setup

The execution environment is represented in Fig. 11. It is formed by a separately excited DC 1.5 kw motor as a prime mover, a 1.5 kw SEIG, a 80 μF bank of capacitor, or a 1.4 H inductor. It permits to identify the component parameters

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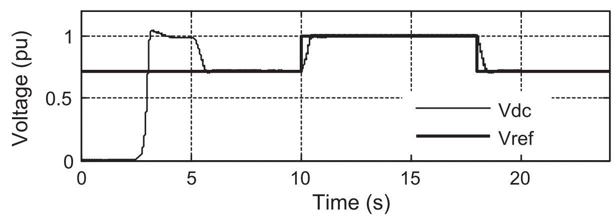

Figure 6 Stator SEIG rms voltage.

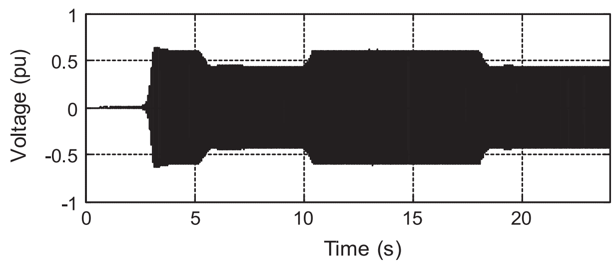

Figure 7 Stator SEIG voltage.

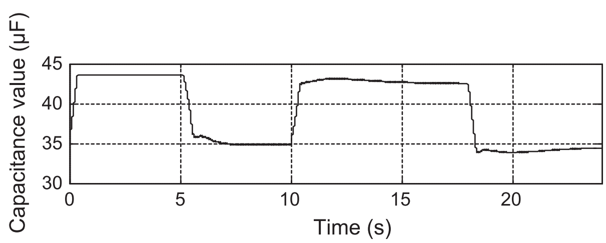

Figure 8 Total capacitance value (µF) .

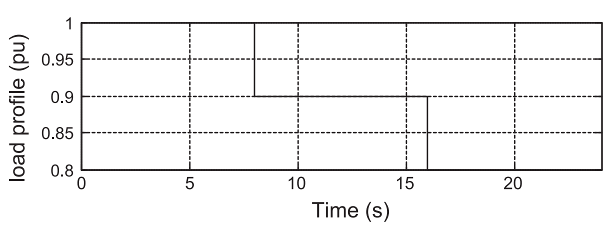

Figure 9 Load profile (pu).

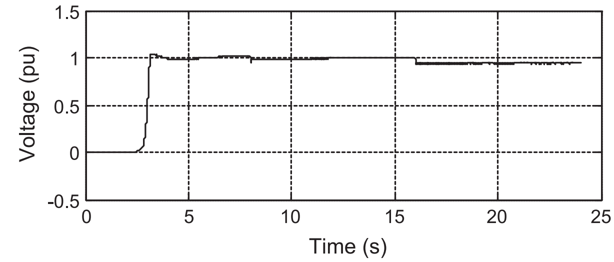

Figure 10 SEIG RMS voltage.

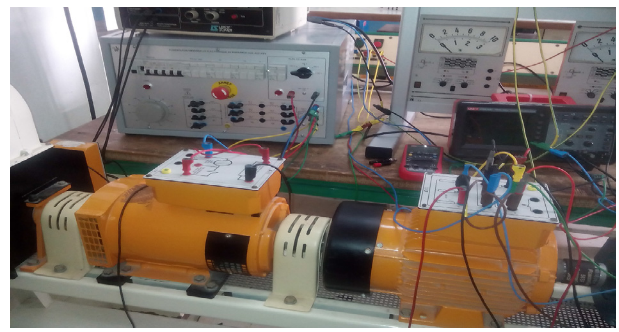

Figure 11 The platform of execution.

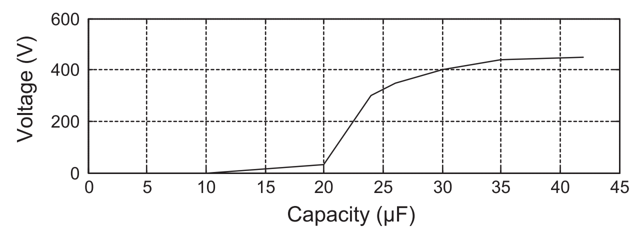

Figure 12 SEIG per line stator voltage (C) at no load and rated speed.

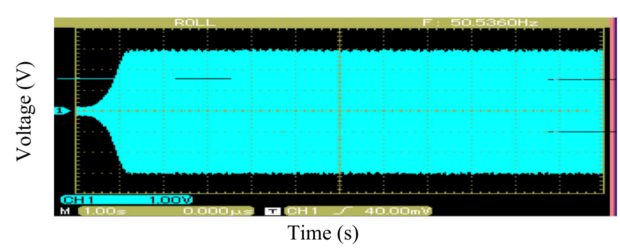

Figure 13 Stator SEIG voltage.

and to experiment the WG operation. The operator sets the voltage frequency and magnitude.

In order to validate the simulation results we have realized a practical test in the same conditions. The choice of the excitation capacity is essential for maintaining the needed voltage. The required reactive power is delivered by the bank of capacitor for SEIG self-excitation [16]. The minimum terminal capacitor required for induction generator at a rated speed and a rated load is equal to 20 µF as it is shown in Fig. 12. The no-load SEIG is driven at a rated speed. Both per line voltage Vs and the starting-up time are affected by the value of capacitors. When the excitation capacitance is less than 20 µf, the WG will fail to build up the voltage and when it is more than 46 µF the generator will be operated at a high voltage level.

To minimize the starting up time, a large value of capacitance is required at the starting up. Fig. 13 represents the experimental voltage waveform of a stator phase during the starting up period with a voltage scale factor 1/100 for the adapter, a voltage scale 1 V/div and a time scale 1 s/div. The prime mover speed is 1500 rpm.

The power produced depends on capacitance value and the voltage decreases when the active power produced increases. The measures carried out show that the SEIG generated voltage depends on three variables speed, field of excitation (bank of capacitors), and load profile. Those relations are nonlinear. At a constant speed and a constant field of excitation the generated SEIG voltage varies when the load varies.

5.1. Voltage control with a bank of capacitors

The bank of capacitors is a device that exchanges capacitive current. Fixed capacitors should be sized to cancel the var load during unload case. Switched capacitors are then sized to maintain the desired voltage. It is formed by six switches to connect or disconnect a part of a bank of capacitor with a step of 5% as shown in Fig. 14.

The reactive power injected is adjusted by acting a switched 44 µF bank of capacitor with a step of 2.2 µF. The reactive power range is given by Eq. (8)

$$U^2\beta_c \leqslant Q_{svc} \leqslant U^2\beta_c + U^2\beta_{c1} \tag{8}$$

The reactive power injected is given by Eq. (9)

$$Q_{svc} = U^2\beta_c + U^2\beta_{c1} * (0.05 * S_1 + 0.1 * S_2 + 0.15 * S_3 + 0.2 * S_4 + 0.25 * S_5 + 0.25 * S_6) \tag{9}$$

where U voltage at bank of capacitors, β_c capacitive susceptance, $\beta_{c\min}$ minimum capacitive susceptance, Q reactive power injected and S_i the control signals. Shunt capacitors are inexpensive, they provide the reactive power compensation, and they maintain the voltage stability with a margin of 3%. The needed value of the bank of capacitor at a frequency of 50 Hz and a nominal per line voltage 346 V is represented in Fig. 15. The curve is approximated by using polyfit function.

5.2. Voltage control with a variable inductor

The variable inductor is a device that exchanges inductive current in order to maintain voltage magnitude constant. The expression of the reactive power injected by the bank of inductors Q_l is adjusted by firing delay angle according to Eq. (10):

$$Q_l = U^2 B_l(\alpha) \tag{10}$$

The reactive power injected is given by Eq. (11)

$$Q_T = U^2 B_c - Q_L = U^2 B_c - U^2 B_l(\alpha) \tag{11}$$

where U voltage at bank of inductors connection points, β_c capacitive susceptance, $B_l(\alpha)$ inductive susceptance, Q reactive power injected and α the duty cycle. The needed value of the bank of inductor at a rated frequency and a nominal per line voltage 346 V is represented in Fig. 16.

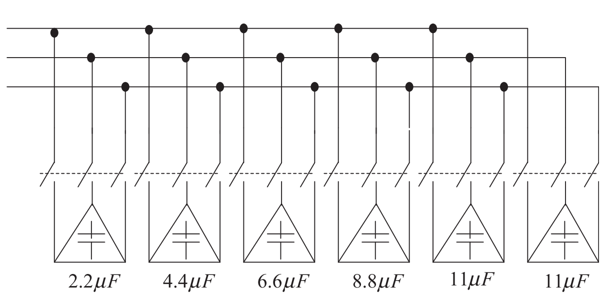

Figure 14 The hybrid system voltage control.

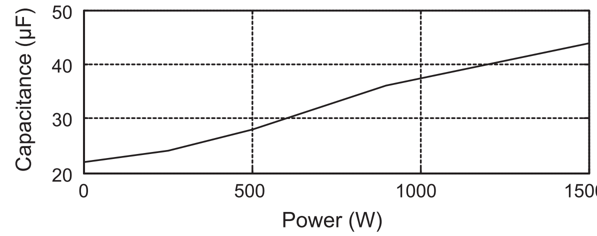

Figure 15 Variation of C under nominal speed.

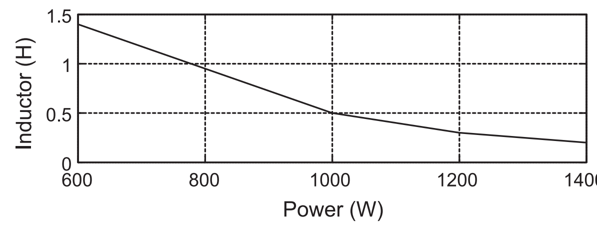

Figure 16 Variation of L under nominal speed.

Table 1 SEIG parameters.

Rated power	1.5 Kw
Rated voltage v_s	230 V
Rated current I_N	3.4 A
Rated speed Ω_N	157 rad/s
Pole pairs P	4
Rotor resistance R_r	2.24 Ω
Stator resistance R_s	5.51 Ω
Stator inductance L_s	20.35 mH
Rotor inductance L_r	20.35 mH

Table 2 DC Motor parameters.

DC supply voltage v_{DC}	220 V
Rated armature current I_{an}	9 A
Rated field supply	220 V/0.6 A
Rated speed Ω_N	157 rad/s
Armature resistance R_a	1.4 Ω
Armature inductance L_a	27 mH

Table 3 The rule table.

		The error ε		
		N	Z	P
dε	N	NB	PM	PB
	Z	NB	Z	PS
	P	Z	NS	Z

6. Conclusion

This work leads to the development of overall characteristics for a wind generator. Three tests were done to identify the circuit parameters, the steady-state and dynamic characteristics

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of SEIG. From the experimental work it is observed that the prime mover speed, capacitance value and the load profile influence both the dynamic and steady-state behaviors. Voltage regulation in SEIG needs an adjustment of the reactive power injected and a speed control. The developed system satisfies voltage and frequency criteria. The first strategy is less expensive and less cumbersome than the second strategy.

Appendix A

See Tables 1 and 2.

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