IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 20, 2020, accepted October 15, 2020, date of publication October 27, 2020, date of current version November 11, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3034291

A Comprehensive Overview of Single–Phase Self-Excited Induction Generators

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ABSTRACT The use of induction generators for electricity production in small power isolated systems represents the topic for a wide research area. As in such topologies single-phase consumers are predominant, besides three-phase induction generators with adequate balancing circuits, single-phase induction generators qualify as a reliable alternative. In the last 38 years, a significant number of research papers have tackled the problems related to the autonomous operation of single-phase induction generators (SPIGs) such as determining excitation capacitors values and their optimal arrangement, ensuring stable operation in terms of voltage and frequency balancing under varying loads and finally enhancing the quality of the energy delivered to the isolated single-phase consumers. While in case of simple topologies the operation of SPIGs is mainly investigated for fundamental electric parameters dependence with loading, excitation capacitance and speed, the use of power electronics based converters ensures stable operation over a wide range of varying/non-linear loads. This paper presents a comprehensive overview of the literature dedicated to SPIGs, focusing on several significant aspects such as main topologies, modeling, steady-state analysis and performance investigations.

INDEX TERMS Induction generator, renewable energy, self-excited, single-phase, two-windings.

I. INTRODUCTION

Renewable energy resources utilization for off-grid power generation has gained significant advance in the last two decades, driven by climate changes concerns and enhancement of life quality for remote communities. Hydro and wind based prime movers driving self-excited induction generators are seen as an appropriate solution for isolated consumers supply. The literature dedicated to the autonomous operation of three-phase induction generators is very vast, a well-documented survey being presented in [1]. Nevertheless, due to single-phase domestic consumers predominance, single-phase power can be provided either by a three-phase generator with a suitable balancing topology or by a single-phase one. In case of the first option, the extensive overview from [2] has reported that balanced operation of the three-phase generator is achieved for fixed loads with the use of one, two or three excitation capacitors, while by adding power electronics based converters the supply of varying loads is achieved. Alternatively, a single-phase induction machine operating as self-excited generator can also be used for single-phase power generation, as they provide good voltage regulation [3]. There are many key aspects that govern the autonomous operation of a single-phase induction generator (SPIG). First the calculation of the capacitor(s) values is performed and then their optimal arrangement is chosen. Next stable operation in terms of voltage and frequency balancing must be ensured, followed by quality enhancement of the energy delivered to the isolated single-phase consumers.

The choice of single-phase self-excited induction generators for remote power generation is sustained by two main reasons. First, compared with similar power single-phase synchronous generators, they have the advantages of lower cost, absence of DC excitation, simpler overall construction, lower maintenance and higher power/weight ratio. The second reason is related to the large market availability of single-phase induction motors which, with adequate addition of extra capacitors/simple power converters can be operated successfully in generator mode.

The operation of a single-phase induction machine relies on two windings, main and auxiliary. In motor mode the auxiliary winding is usually used for starting purposes while in steady-state mode only the main winding is employed. In generator mode, either one or both the windings are used. Fig. 1 shows the basic configuration of an autonomous generating unit based on a SPIG, whereas the prime mover is either a Pico hydro turbine or a small wind one.

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmad Elkhateb.

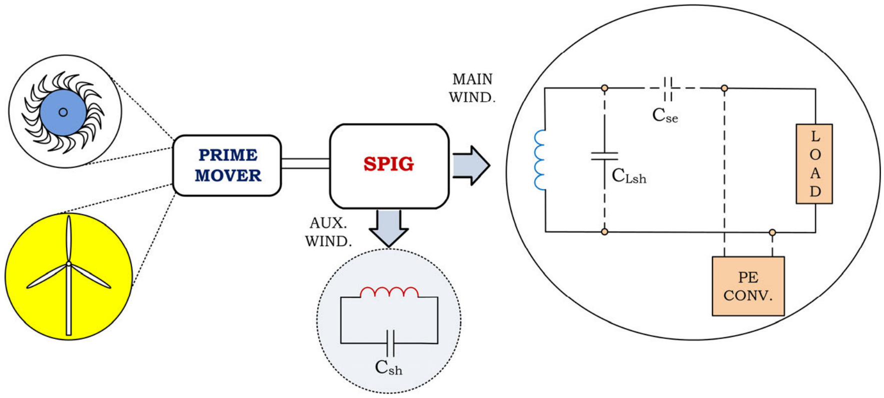

FIGURE 1. Main configuration of an autonomous generating unit powered by a SEIG.

In Fig. 1, the main and auxiliary windings of the stator are highlighted (with dotted line are represented the part/components that can be added, but without mandatory title); if the auxiliary winding is employed it ensures the generator self-excitation through a shunt capacitor. At the main winding one or two capacitors are usually connected, sometimes complementary with power electronic based converters for voltage and frequency control.

The available topologies can be classified based on the number and arrangement of the capacitors required to ensure both the generator self-excitation and stable operation:

i) Single winding generator - the capacitor(s) being connected across the main winding:

- One (shunt) capacitor [4]–[23] (Fig. 2(a)) - power electronics can be used for parameters control [18]–[23];
- Two capacitors in short-shunt connection [24], [25] (Fig. 2(b));

ii) Two-winding generator:

- One capacitor (connected across the auxiliary winding) [26]–[36] (Fig. 2(c));
- Two capacitors: the first being connected across the auxiliary winding and the second one across the main winding in:
  - o Series configuration [37]–[56] (Fig. 2(d));
  - o Shunt configuration plus power electronic based converters [57]–[79] (Fig. 2(e));
- Other topologies:
  - o With one shunt capacitor across the main winding and power electronic converters across the auxiliary winding [80], [89] (Fig. 2(f));
  - o Only with one power electronic converter connected across both windings [90], [91] (Fig. 2(g)).

For SPIGs with shunt capacitor across the main winding, voltage and frequency control is enhanced with the help of power electronics based converters. The most encountered topology is the so-called electronic load controller (ELC), which relies on a diode bridge, DC chopper and a dissipative resistor; it is connected in parallel with the main load, as can be seen in Fig. 2(h). The ELC control structure generates a PWM signal for the DC chopper transistor to keep the voltage and frequency constant [59], [60], [66]. A different ELC structure can be found in [61], consisting of two anti-parallel insulated gate bipolar transistors (IGBTs), each connected through a series diode.

Another topology involves the use of a single-phase inverter bridge, with energy storage elements connected on its DC side [68]–[70], [76] or without storage such in [77]. A more complex structure, named Decoupled Voltage and Frequency Controller (DVFC) [64], [67], integrates both the inverter bridge and the ELC. Reference [65] proposes an alternative to the latter topology, as the ELC is integrated on the inverter DC side, thus reducing the number of semiconductor devices.

Balanced operation can be ensured when the shunt capacitor is interfaced through a triac, whose control enables a $+/-5\%$ voltage regulation [78], [79]. A different approach is investigated in [73], where a DC load is connected to both generator windings through two semi-converters. A battery plus inverter system placed across the auxiliary winding is investigated in [85], [86], the load being connected to the main one. A vector controlled three-leg inverter is used in [90], [91], where to each inverter leg are connected, in order, the auxiliary winding, the windings common point and the main winding. Indirect control is implemented for autonomous operation.

Single-phase induction generators can also be integrated in single-phase microgrids (MG). Such a MG has the load connected across the main winding of a SPIG; an inverter-battery system connected in parallel with the load transfers the power from the other two sources: a permanent magnet synchronous generator (PMSG) - based small wind turbine and a PV panel, both interfaced through power converters with the inverter DC link [71], [72].

In [80], both windings of a SPIG are interfaced through power converters with the MG DC bus. To the DC bus are also connected a PV panel and a PMSG with bridge rectifier and DC/DC converter; the MG AC loads are supplied with the help of a fixed-frequency single-phase inverter. A rather similar configuration can be found in [82]: the

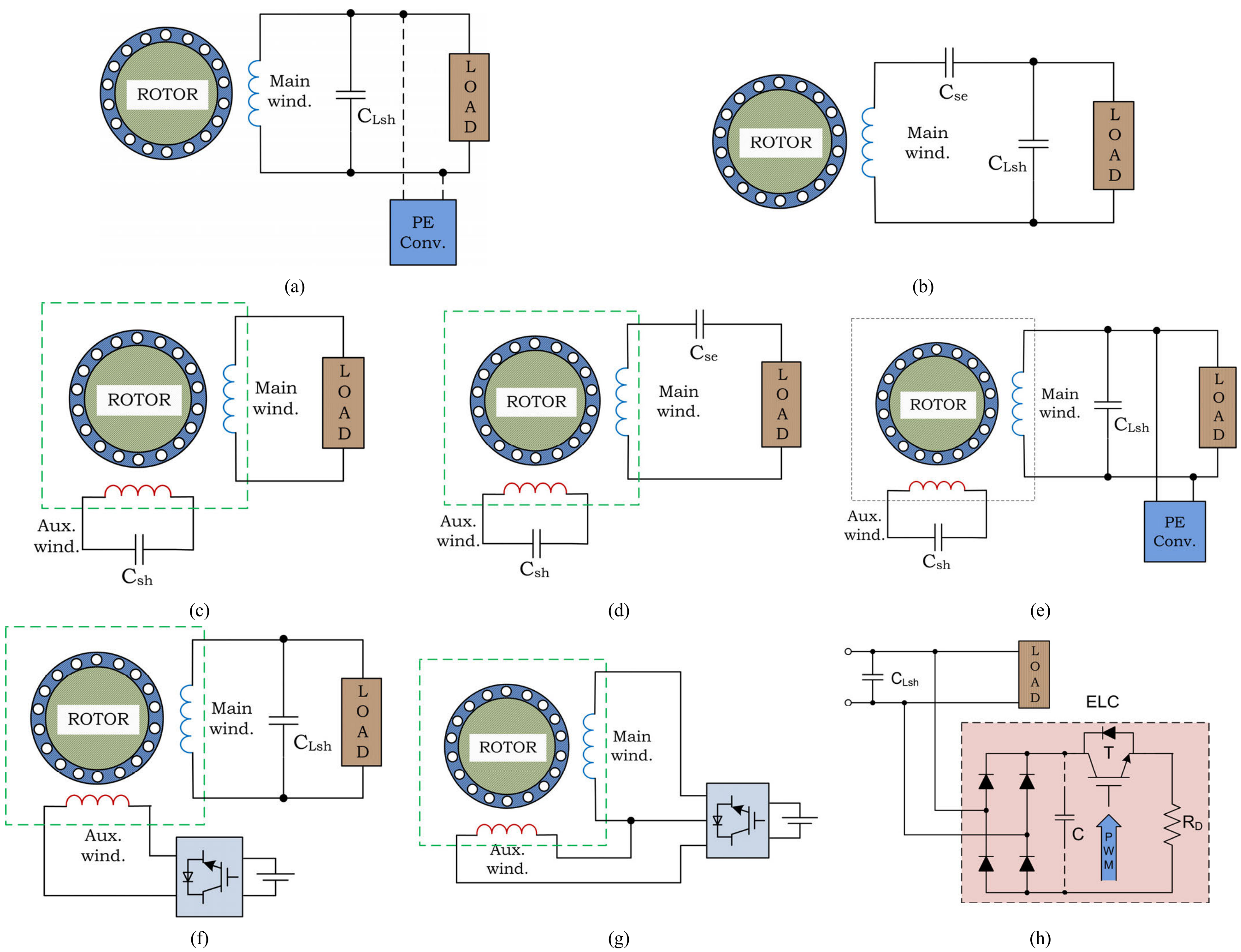

FIGURE 2. **Main topologies for single and two winding SEIGs.**

load is connected across the SPIG main winding while a PV panel plus a battery energy storage system is interfaced through a single-phase inverter with the auxiliary winding.

An alternative to the latter topology involves the load connection to the main winding through an AC/DC/AC conversion scheme [83].

This work presents an overview of single-phase induction generators used for off-grid power generation. The paper is organized as follows: Section II details the modeling aspects and presents the common equivalent circuits, the steady-state and dynamic analysis for parameters determination is presented in Section III while the performance evaluation is addressed in Section IV. Finally, concluding remarks are provided in Section V.

II. MODELING AND EQUIVALENT CIRCUITS

Various models have been developed to quantify the steady-state and transient performance of SPIGs operating in autonomous mode; in the following paragraphs they are grouped into categories. Table 1 shows the main parameters used in both equations and equivalent circuits.

A. IMPEDANCE BASED MODELS

When developing the equivalent circuit for a SPIG, some simplifications are used: for example, in [7], [10], [24] it is assumed that the saturation phenomenon affects only the machine magnetizing reactance X_m, the core losses are neglected and the stator and rotor leakage reactances are considered equal. In many cases the per-unit (pu) rotor speed is used instead of the slip in depicting the equivalent circuit [31].

Simplified models are obtained either by dividing the voltages and impedances by F and assuming that the currents remain unchanged [8], or by expressing the ratio between the generator output voltage and frequency as a third order polynomial of the magnetizing reactance, case in which the equivalent circuit could be reduced to four series impedances [14], [20] in case of a single-winding SPIG. For a two-winding machine a model consisting of five series and parallel impedances was developed in [50].

TABLE 1. Parameters significance 1.

Symbol	Parameter
R_s	Stator resistance
R_r	Rotor resistance
R_M	Main winding resistance
X_{ls}	Stator leakage reactance
X_{lr}	Rotor leakage reactance
X_m	Magnetizing reactance
X_{lM}	Main winding leakage reactance
F	Per unit frequency
ω	Per unit speed
X_C	Excitation capacitor reactance
R_L	Load resistance
X_L	Load reactance
Z_L	Load impedance
Z_{sM}	Stator main winding impedance
I_C	Capacitor current
I_M	Main winding current
I_L	Load current
V_{gb}	Air-gap (backward) voltage
Y_L	Load admittance
Y_C	Capacitor admittance
Y_e	Equivalent admittance
Y_m	Magnetizing admittance
Y_R	Rotor admittance
V_{qs}	q-axis stator voltage
V_{ds}	d-axis stator voltage
λ_{qs}	q-axis stator flux linkage
λ_{ds}	d-axis stator flux linkage
λ'_{qr}	q-axis rotor flux linkage (referred to stator)
λ'_{dr}	d-axis rotor flux linkage (referred to stator)
I_{qs}	q-axis stator current
I_{ds}	d-axis stator current
I'_{qr}	q -axis rotor current (referred to stator)
I'_{dr}	d -axis rotor current (referred to stator)
r_{qs}	q -axis stator resistance
r_{ds}	d -axis stator resistance
r'_{qr}	q -axis rotor resistance (referred to stator)
r'_{dr}	d -axis rotor resistance (referred to stator)
ω_r	Electric angular speed
N_q	Effective number of turns for the q-axis
N_d	Effective number of turns for the d-axis

Reference [12] shows the modeling for a SPIG with single-phase rotor. When a finite element model is developed, only one pole pitch of the generator is taken into account and the residual magnetism of the rotor is depicted as a permanent magnet [16]. In case of a single-winding SPIG, the d-axis voltage equation is eliminated and the equivalent circuit is given for a negative value of the slip [19]. The authors of [32] developed a composite model by separating the equivalent circuits of the main and auxiliary windings.

The equivalent circuit of a single-phase SEIG with a single excitation capacitor and R-L load that can be reduced to four

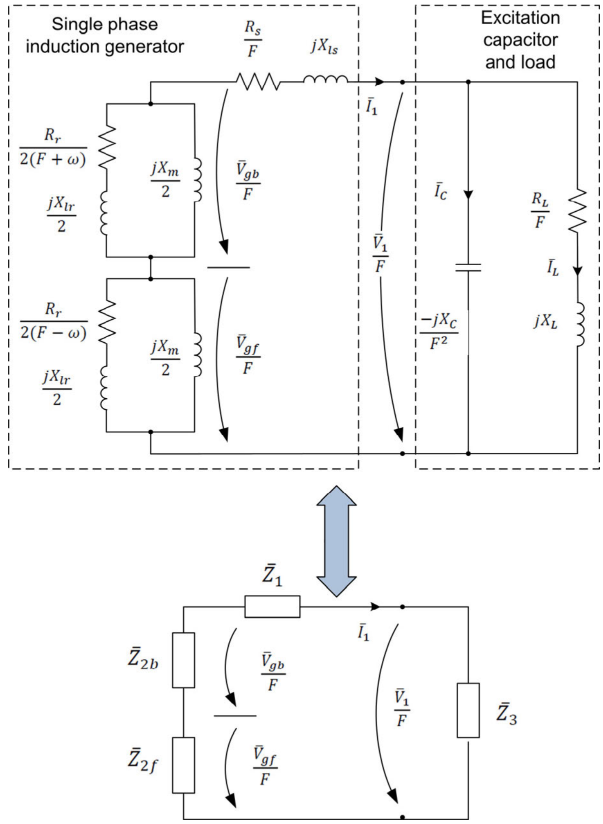

FIGURE 3. Equivalent circuit of a single-phase SEIG with a single excitation capacitor and R-L load.

series impedances [14], using the relations (1-4) is shown in Fig. 3:

$$\bar{Z}_1 = \frac{R_s}{F} + jX_{ls} \tag{1}$$

$$\bar{Z}_{2b} = \left(\frac{1}{\frac{jX_m}{2}} + \frac{1}{\frac{R_r}{2(F+\omega)} + \frac{jX_{lr}}{2}} \right)^{-1} \tag{2}$$

$$\bar{Z}_{2b} = \left(\frac{1}{\frac{jX_m}{2}} + \frac{1}{\frac{R_r}{2(F-\omega)} + \frac{jX_{lr}}{2}} \right)^{-1} \tag{3}$$

$$\bar{Z}_3 = \left(\frac{1}{\frac{-jX_C}{2F^2}} + \frac{1}{\frac{R_L}{F} + jX_L} \right)^{-1} \tag{4}$$

A similar mathematical model was developed for single winding systems by the authors of [38], being governed by eq. (5-8). The corresponding equivalent circuit is given in Fig. 4.

$$\bar{Z}_L = \frac{\frac{-jR_L X_C}{F^3}}{\left(\frac{R_L}{F} - \frac{jX_C}{F^2}\right)} \tag{5}$$

$$\bar{I}_M = \frac{\frac{V_1}{F}}{(\bar{Z}_{sM} + \bar{Z}_L)} \tag{6}$$

$$\bar{I}_C = \bar{I}_M - \bar{I}_L \tag{7}$$

$$\bar{I}_{rf} = \frac{-\frac{\bar{V}_{gb}}{F}}{\left(\frac{R_r}{2(F-\omega)} + \frac{jX_{lr}}{2}\right)} \tag{8}$$

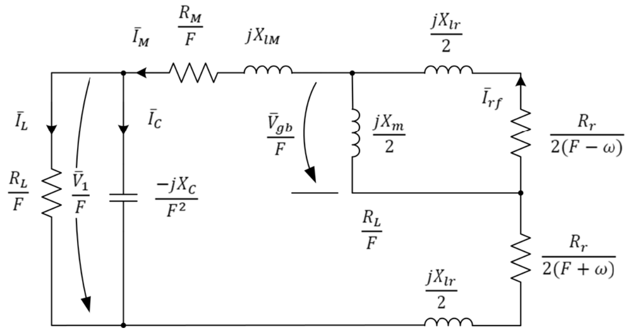

FIGURE 4. Equivalent circuit of a single-phase SEIG considering only the main winding.

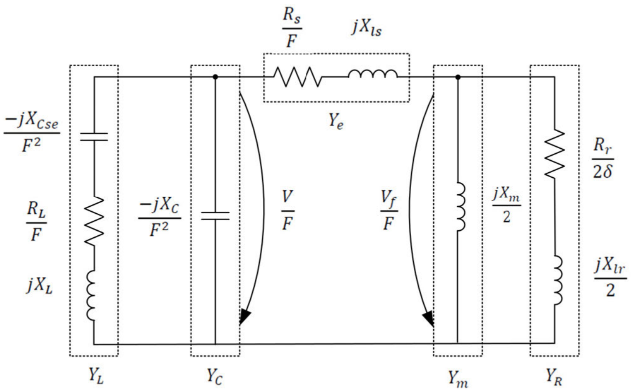

FIGURE 5. The approximate equivalent circuit of the short-shunt SPIG.

B. ADMITTANCE BASED MODELS

An admittance equivalent model is developed in [13], starting with the assumption that the value of F can be determined independent of X_m; a nine-degree polynomial relation resulted. A similar approach is presented in [25], where for the negative-sequence rotor circuit X_m is neglected. The approximate equivalent circuit is depicted in Fig. 5. For a more complex circuit topology, including a static VAR compensator (SVC), a seven-degree polynomial relation was obtained in [21] and even a twelve-degree one in [22]. By using the nodal admittance method, the authors of [33] have developed an equivalent circuit represented thorough seven specific admittances.

C. D-Q REFERENCE MODELS

Various articles [19], [30], [43], [46], [48], [58], [84], [90] rely on generator models developed in the stationary d-q reference frame. A harmonic balance technique, which implies the representation of the state variables with the help of sinusoidal functions that have time-varying magnitudes, is used in [30] to yield the equivalent circuit of a SPIG considering the core losses. For two-windings SPIG with shunt and series excitation capacitors the d-q model is given in stationary reference frame [43], [48], through eq. (9-12). The resulting equivalent circuit is represented in Fig. 6.

$$V_{ds} = r_{ds}I_{ds} + L_{lds}pI_{ds} + p\lambda_{md} \tag{9}$$

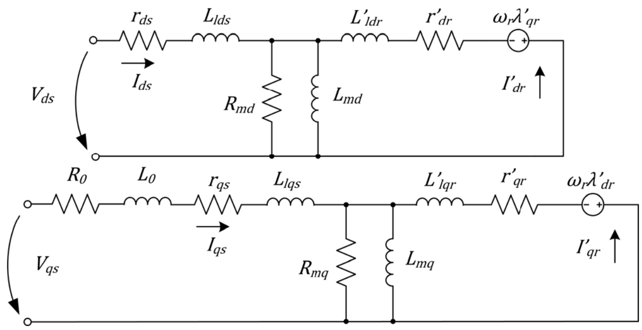

FIGURE 6. Equivalent d-q circuit of a single-phase SEIG with series connected load.

TABLE 2. Analysis overview.

Analysis type	Approach based on	Reference
Steady-state	Loop impedance method	[7, 10, 15, 17, 24, 28, 35, 52, 53, 54]
	Nodal admittance method	[11, 21, 25, 33, 53]
Dynamic	Flux linkages	[29, 48, 51, 87]

TABLE 3. Flow charts.

Result	Reference
Generator performance at constant terminal voltage	[5, 10, 11]
Optimum terminal voltage for maximum power output	[5]
Firing angle of TSC for voltage regulation of generator	[22]
Determination of F and Xm	[33, 35, 53]
Parameters of the equivalent circuit	[37, 41, 42]

$$V_{qs} = (r_{qs}+R_L)I_{qs} + (L_{lqs}+L_L)pI_{qs} + p\lambda_{mq} \tag{10}$$

$$V'_{dr} = r'_{dr}I'_{dr} + p\lambda'_{dr} + \frac{N_d}{N_q}\omega_r\lambda'_{qr} \tag{11}$$

$$V'_{qr} = r'_{qr}I'_{qr} + p\lambda'_{dr} - \frac{N_q}{N_d}\omega_r\lambda'_{qr} \tag{12}$$

III. STEADY-STATE AND DYNAMIC ANALYSIS; PARAMETERS DETERMINATION

The main feature of an autonomous SPIG is the terminal voltage and frequency dependence on prime mover speed, excitation capacitance and load impedance. Also, the machine saturation phenomenon should be taken into account, resulting in a rather complicated analysis for best parameters matching. A synthetic overview for steady-state/dynamic analysis is provided in Table 2 . Flowcharts are often used to help compute/predict the generator performance, a synthetic situation being given in Table 3 .

A. STEADY-STATE AND DYNAMIC ANALYSIS

To evaluate the steady-state performance of a self-excited SPIG, the majority of approaches rely on determining three main parameters: the magnetizing reactance X_m, the air-gap voltage V_g and the per unit frequency F. In [15], five equations, belonging to: stator current, terminal voltage, load and capacitor current, load active and reactive powers, reactive power of the excitation capacitor/ magnetizing reactance are presented. Synchronous speed test is usually used to determine the variation of V_g with X_m, as show in [28]; before that, finding X_m implied solving a second order equation in terms of F.

Within the computational process, the nodal admittance for approximating the frequency-domain equivalent circuit is used in [21]; a 7^{th} order polynomial equation in function of the per-unit slip frequency is being solved with the help of Newton-Raphson method. The series impedance approach is used in [22], involving the deriving of a 12^{th} degree polynomial equation.

The sequential unconstrained minimization technique (SUMT) along with Rosenbrock's method of rotating coordinates was employed in [36] to minimize the objective function of X_m and F. A software tool, namely the *fsolve* routine of Matlab was used by the authors of [37] to assess the SPIG performance characteristics, as it did not imply the detailed derivation of the nonlinear equations describing the model. A similar situation is encountered in [41], where in addition a detailed flowchart for performance characteristics prediction is provided. Another Matlab tool, the *fmincon* function is used for the minimization of the total impedance relations, as being presented in [52], [54].

The authors of [53] applied the genetic algorithm method to both nodal admittance and loop impedance models in order to compute the values of X_m and F.

A set of nonlinear differential equations are presented in [29] to describe the dynamic behavior of the generator; the nonlinear dependence between magnetizing impedance and magnetizing flux was approximated by a 2^{nd} order polynomial relation. In [87], to predict the dynamic behavior of the SPIG with inverter and battery system connected across the auxiliary winding, the small signal stability analysis was used.

B. PARAMETERS DETERMINATION

In some situations, when practical determinations are performed and they involve a real system such an isolated generating unit based on a pico hydro turbine [9], the focus is on designing the generator, as for low power ratings around few kW on the market only single-phase induction motors (SPIM) are available. Thus, a 1HP, 4 poles capacitor run SPIM is redesigned as a 6 pole generator, requiring the calculation of internal parameters such as: outer and inner turn coil numbers, circular mil of new coil, flux per pole, air-gap and tooth density.

Reference [41] studies the influence of various design parameters on the generator performance. Thus, the effect of internal quantities such as steel sheet type, turns ratio and core length on parameters such as slot fullness factor, auxiliary winding excitation capacitance, main winding series capacitance, no/full load voltage, main and auxiliary winding currents is given in table form.

The authors of [34] consider that the output power of the generator is influenced by two parameters: the phase belt width of the main winding α and maximum output power k. In this regard, numerical analysis is performed for various values of α and k, showing results for the capacitive component of the forward rotating field and resistive load current. In case of a 2.2kW SPIG, the Finite element method is used to highlight the magnetic parameters such as flux linkage, current/flux density and the magnetomotive force (MMF) drop along the contour [76].

A significant aspect for the SPIG operation is the appropriate selection of the excitation capacitor(s); a detailed computation for both the auxiliary winding excitation capacitor C_p and main winding series capacitor C_s is provided in [49]. The value of C_p is determined in close relation with forward MMF, while C_s is computed for full load and is dependent on C_p. Another computational procedure for capacitance determination uses the resonance condition for a series LC circuit, where the L value is part of the synchronous impedance. The latter is obtained by injecting an AC current into the main winding while the rotor is rotating at synchronous speed [62].

IV. PERFORMANCE INVESTIGATION

This chapter analyses the experiments and simulations performed to assess the performance of the autonomous SPIG. To be noticed that in terms of nominal power, the overwhelming majority of the experimental setups rely on a 0.75kW generator, only in few cases a specially built machine that can deliver 5kW is used [26], [65], [68].

Depending on the number of capacitors used and their values, many authors have focused on determining, though simulations and/or experimental tests the following characteristics (Table 4 shows the specific parameters that will be addressed throughout this section):

- Variation of terminal voltage with capacitance/speed at no-load;
- Terminal voltage/Main winding current vs. output power;
- Variation of V_g/F with X_m from synchronous speed test;
- Variation of capacitance/reactive power with output power to keep the terminal voltage constant at rated speed.

In addition, for two-winding machines, supplementary characteristics such as the variation of auxiliary winding voltage and current with different excitation capacitors/load power factor values are provided. A synthetic overview of the main dependency characteristics is given in Table 5 , showing those curves that are provided in at least two references. Nevertheless, other performance characteristics, present in the literature, are concentrated in Table 6 . To be pointed out that some papers provide part of the obtained results under table form [30], [34], [35]. Other papers study more particular situations, as being detailed in the following paragraphs.

Both single and double-winding SPIGs behavior is compared under resonance phenomenon, when they supply

TABLE 4. Parameters significance 2.

Symbol	Parameter
V_g	Air-gap voltage
V_T	Terminal voltage
V_0	No-load voltage
V_L	Load voltage
V_M	Main winding voltage
V_A	Auxiliary winding voltage
V_C	Capacitor voltage
ΔV	Terminal voltage variation
f	Frequency
I_S	Stator current (for single-winding generators)
L_S	Stator inductance (for single-winding generators)
I_M	Main winding current
I_{mag}	Magnetizing current
I_A	Auxiliary winding current
P_L	Load active power
Q_{exc}	Reactive excitation power
C_{exc}	Excitation capacitance
L_m	Magnetizing inductance
L_{md}, L_{mq}	Magnetizing inductances of d and q axis
λ_m	Air-gap flux
T	Torque
n	Rotor speed
s	Slip

TABLE 5. Parameters dependency 1.

Characteristic	References
$V_g/F=f(X_m)$	[4, 5, 10, 11, 13, 14, 21, 29, 31, 37, 41, 42, 53, 83]
$V_T=f(P_L)$	[4, 6, 7, 8, 11, 14, 15, 17, 18, 25, 28, 35, 36, 44, 75]
$V_0=f(C_{ex})$	[4, 6, 13, 15, 18, 22, 23, 24, 25, 28, 31, 36, 37, 42, 43, 52, 53, 54]
$V_0=f(n)$	[4, 9, 11, 13, 19, 28, 42, 51, 53, 81, 82]
$V_T=f(I_L)$	[13, 16, 22]
$V_T=f(I_M)$	[4, 37, 39, 41]
$V_L=f(P_L)$	[8, 20, 24, 25, 29, 37, 38, 39, 40, 41, 42, 50-55, 58, 78, 84]
$V_L=f(I_L)$	[26, 31, 58]
$V_L=f(n)$	[18, 26, 46, 78]
$V_M=f(P_L)$	[7, 24, 29, 36-38, 40, 41, 57, 59, 84]
$V_A=f(P_L)$	[24, 28, 29, 33, 36, 37, 40-42, 51, 53, 55, 57]
$\Delta V=f(C_{exc})$	[8, 36, 42, 43]
$f= f(P_L)$	[5-7, 10, 18, 28, 33, 36, 37, 43, 61]
$f= f(I_L)$	[13, 26]
$f=f(n)$	[10, 18, 26]
$I_S= f(P_L)$	[5-8, 11, 15]
$I_S= f(n)$	[9, 11]
$I_M= f(P_L)$	[4, 7, 24, 29, 33, 36, 37, 40-43, 51, 53, 57]
$I_A= f(P_L)$	[24, 28, 29, 33, 36-38, 41, 42, 51, 53, 57]
$I_L= f(P_L)$	[7, 8, 10, 15, 17, 20, 24, 28, 29, 38, 39, 41, 42, 52, 54, 57, 59, 75]
$I_L= f(n)$	[22, 26]
$I_C= f(P_L)$	[10, 15]
$P_L = f(C)$	[8, 25]
$P_L = f(V_T)$	[5, 26]
$P_L = f(n)$	[9, 26, 74]
$P_L = f(Z_L)$	[25, 48, 84]
$Q_{exc}= f(P_L)$	[5, 33]
$Q_{exc}= f(n)$	[11, 26]
$C_{exc}= f(I_L)$	[25, 26]
$C_{exc}= f(P_L)$	[5, 6, 10, 18, 36, 53, 53, 78]
L_{md}, $L_{mq}= f(\lambda_m)$	[46, 47, 58]
$\eta = f(P_L)$	[32, 44]
$T = f(n)$	[30, 32, 49]
$s = f(P_L)$	[23, 48]

consumers that have low power factor values [24]. Experimental findings showed that the single-winding SPIGs reached the resonance point earlier than double-winding ones and also had a larger voltage drop.

A consistent harmonic analysis is performed in [26], for both output voltage and load current in case of varying load conditions, for a SPIG with shunt capacitor across the auxiliary winding.

The experimental determinations on two generators, rated 0.75/5kW showed that voltage total harmonic distortion (THD) decreased almost linearly with voltage decrease, while the currents THD increased with resistive load and also with the prime mover speed reduction.

The short-circuit phenomenon is investigated in [43] for a SPIG with a series capacitor across the main winding. When short-circuit occurs at load terminals the generator sustains the fault, becoming overexcited due to the series capacitor. In case short-circuit is located on the auxiliary winding, the current goes to zero after 4 cycles, triggering the generator de-excitation. Similar results are reported in [55].

A comparison between shunt, short shunt and long shunt topologies in case of a single-winding SPIG was conducted in [7], [8]. Both studies showed that the short shunt connection displays the best behavior, while the long shunt experiences a significant terminal voltage drop. A similar approach was used for two-windings SPIGs having a fixed capacitor across the auxiliary winding and series capacitor / shunt capacitor / series and shunt capacitor (in both long and short shunt) in the main winding [37]. The obtained results showed that series or short shunt configurations ensure the best voltage regulation. In a rather similar investigation [58], eigenvalue analysis showed that both short and long shunt topologies exhibit a good overload capability.

The experimental determinations from [32] yielded that the generator real power output and power factor are not influenced by the rotor spinning direction. Nevertheless, the efficiency was 5-6% higher when it was driven in the reverse direction; also the auxiliary winding voltage was higher in case of forward rotation.

A comparison between a two-winding single-phase induction generator and a three-phase one with a balancing topology, when supplying single-phase loads was accomplished in [40]. Experiments conducted on two machines built on

TABLE 6. Parameters dependency 2.

Parameter variation	In function of	Reference
V_g	I_{mag}	[39]
V_0	I_C	[15]
V_C	P_L	[38]
V_M	n	[74]
	I_M	[84]
V_A	R_L	[58]
	I_A	[84]
V_L	s	[84]
I_S	I_L	[13]
I_R	I	[12]
f	C_{exc}	[22]
	V_g	[26]
C_{exc}	n	[10]
	I_L	[13]
	L_m	[23]
	R_L	[47]
X_m	C_{exc}	[25]
	Z_L	
	V_g	[42]
L_m	V_T	[18]
	Magnetic flux	[29]
R_s	ω_e	[12]
L_S	I_{mag}	
Core loss resistances of d and q axes	λ_m	[46]
λ_m	R_L	[48]
	P_L	[47]
Complex admittance	n	[32]
Capacitive susceptance	P_L	[33]
L_{md}, L_{mq}	V_T	[30]
Core loss resistances of d and q axes		
L_{md}, L_{mq}		
Q_{exc}	V_T	[26]
	I_L	
Active power losses	P_L	[32]
n	P_L	[47]
	C_{exc}	[49]
s	n	[26]
	R_L	[47]
Mechanical power	n	[30]
Efficiency		
I_M		
n	R_L	[46]
V_L		
V_C from d and q axes		
I_{qs} I_{ds}	n	[46]
V_{qs}, V_{ds}		
Peak voltage	P_L	[47]
Terminal voltage THD		[44]
Break thermal efficiency	P_L	[68]

the same frame size showed similar results in terms of voltage regulation, maximum power output and reactive power requirements; only in case of harmonics distortion the three-phase machine had better behavior.

Starting from the minimum air-gap flux linkage necessary to initiate the self-excitation process, the authors of [47] developed bifurcation diagrams regarding the performance characteristics. Eigenvalue analysis along the air-gap vs. load resistance characteristic determined the point above which the self-excitation is possible.

When power electronics based converters are used for parameters control, mainly parameters variation (i.e. V_T and f) with the load is investigated; harmonic analysis is widely used to assess the amount of distortion introduced by the semiconductor devices operation. More stressing situations like nonlinear loads presence is also investigated, as the inverters can also have filtering functionalities implemented within their control structures [65], [67].

For a SPIG with inverter plus battery energy storage system (BESS) a control algorithm that uses a neural network with dynamic learning rate to track the rate of variation of the load current is implemented [69], [70]. To maximize the generated power, the SPIG is controlled to operate in an optimum point corresponding to a reduced saturation level.

Another control algorithm, named adaptive sliding mode control, was developed by the authors of [71], [72] to ensure, besides voltage and frequency regulation, the SPIG-based MG power quality. It involved two control loops for active and reactive power balancing in case of both sudden load variations and primary resources power modification.

To coordinate the control of both BESS and ELC for optimum loads supply, an adaptive vectorial filter is used in [74]. This particular filter outputs the load fundamental component in vector form in function of a frequency adaption coefficient

Another type of control algorithm, namely the normalized adaline (NABC), developed by the authors of [77], is successfully applied when the SPIG supplies intermittent and fluctuating loads, as it relies on a dimensionless adaptation constant, unlike least mean square (LMS) based-algorithms. It ensures the harmonics detection and compensation, as well as proper voltage regulation.

When complex MG structures are investigated, the focus shifts from investigating the SPIG characteristics/behavior towards ensuring the MG control for autonomous operation with the help of power converters [71], [72].

V. CONCLUSION

The literature overview regarding the operation of self-excited single-phase induction generators has yielded several significant aspects:

- Both single and double winding configurations are investigated in the literature, with more papers focusing on the latter configuration;

- For the single-winding SPIG the excitation is ensured by a single capacitor in shunt connection across the main winding;
    - o power electronics based converters in parallel with the main load are added to enhance the operation in case of variable/nonlinear loads;
- In case of double-winding SPIGs the number of capacitors varies from one to three, with one being connected across the auxiliary winding;
    - o the topology employing a shunt capacitor across the main winding has also power converters for voltage and frequency stabilization;
    - o not all configurations rely on capacitors for ensuring the self-excitation, but use power converters connected across the auxiliary winding;
- In terms of modeling, impedance based-models are widely used – nevertheless d-q reference and admittance based ones are also developed;
- To evaluate the steady-state performance of a self-excited SPIG, many approaches rely on determining three main parameters: the magnetizing reactance (X_m), the air-gap voltage (V_g) and the per unit frequency (F);
- The majority of early papers have focused on determining the SPIG performance characteristics dependable on the number, arrangement and value of the capacitor(s) used for excitation/balanced operation in relation with load and/or prime-mover speed variation;
- As power converters (in the form of electronic load controllers and voltage source inverters) and sometimes energy storage systems were included in more recent studies, complex topologies resulted, being able to successfully mitigate also nonlinear and fluctuating loads as well as the intermittent behavior of prime movers such as small wind turbines;
- Single-phase induction generators are also integrated in single-phase microgrids, operating in parallel with permanent-magnets synchronous generators and/or PV panels.

The main conclusion in case of SPIGs supplying remote consumers is that simpler topologies allowed stable operation in a rather narrow range in terms of load power/type, while the introduction of power electronics based converters (and in some cases of energy storage units) enabled the successful supply of various load types (mainly nonlinear ones). In future, the major challenge will be to adequately balance the complexity of the control structures in relation to performance improvements.

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