Variable Speed Constant Capacitance Operation of Self-Excited Induction Generator

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Abstract – **This paper presents theoretical and experimental results of self-excited induction generator under varying rotor speed operation research. Three-phase squirrel-cage 1.5 kW induction machine, excited with symmetrical capacitor bank and loaded with symmetrical three-phase resistive load, was the subject of investigation. Experimentally obtained results have been compared with calculated performance curves and very good agreement between them has been achieved.**
Keywords – **Induction generator, Self-excitation, Variable speed.**

I. Introduction

Although the basics of self-excited induction generator (further: SEIG) theory have been established almost one century ago [1], SEIG still occupies attention of researches from all over the world. For a long period of time, it has been neglected as a device suitable for electric power generation, due to great difficulties related to voltage and frequency regulation.

Growing demands in electric power generated from renewable energy resources aroused researchers' interest in SEIG during last several decades. Three-phase squirrel-cage induction machine operated as a SEIG has many advantages compared to conventional electric generators. The most important are: low starting investments and maintenance costs, simplicity, robustness and extremely good behaviour in the case of sudden short circuit. Intensive research that is actual nowadays [2]-[6], combined with development of power electronics should overcome weakness of voltage and frequency regulation in the future. The great work is still to be done in order to expand commercial use of SEIGs [7].

One of SEIG's possible applications is stand-alone wind power generation on the sites with considerable wind potential [4], [5], [8]. In specific applications, it is even unnecessary to achieve full voltage and frequency regulation. For example, resistive consumers (boilers, heaters, etc.) are not significantly affected by actual voltage and frequency value. Such appliances could be supplied from unregulated SEIG driven by small wind turbine, whenever there is enough wind power on one side and need for energy on the other.

The motivation for work presented in this paper has been to identify how does variation of rotor speed affect voltage, frequency, stator current, generated power and shaft torque of the SEIG. Theoretical and experimental research was done assuming that SEIG was loaded with three-phase symmetrical resistive load and excited with symmetrical capacitor bank connected to the stator.

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II. Formulation of the Problem

When an induction machine operates as a SEIG, there is no external power grid that defines voltage and frequency on the stator terminals. Thus, both of them are unknown variables whose values change independently, being affected by rotor speed, capacitance of excitation capacitors and loading conditions. Saturation level of the magnetic circuit is also variable, which means that magnetizing inductance can not be considered as constant. In such circumstances, standard equivalent circuit of an induction machine is not suitable for analysis, and specific modifications have to be made. Several different variants of SEIG's equivalent circuit can be found in literature [9]-[12], but common point for all of them is that they neglect power losses in the magnetic core of the machine. Since SEIG always operates in the saturated region of the magnetizing curve, it is clear that such simplification can diminish accuracy of prediction. On the other hand, simplifications of this kind were necessary, due to great mathematical difficulties that follow attempts to solve high-degree nonlinear equations obtained from equivalent circuit.

Recently, Haque [13] proposed a new method for solving of these equations, based on MATLAB Optimization Toolbox routine named *fsolve*. In distinction from standard iterative methods that demand long-lasting and fatiguing mathematical transformations, this approach is very simple and fast. It also allows use of exact equivalent circuit that takes core losses into account. Such equivalent circuit is shown on Fig. 1.

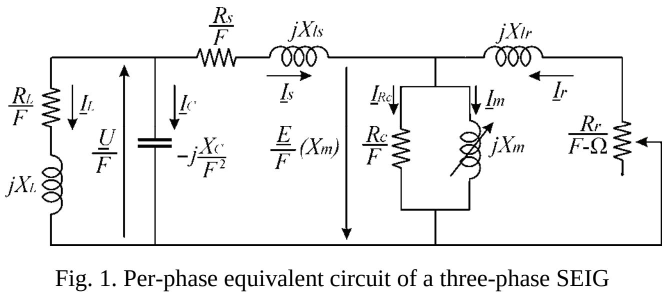

Fig. 1. Per-phase equivalent circuit of a three-phase SEIG

Symbols used in Fig. 1 have following meaning:

- R_L, X_L - load resistance and reactance;
- R_s, X_{ls} - stator resistance and leakage reactance;
- R_r, X_{lr} - rotor resistance and leakage reactance;
- R_c, X_m - magnetizing resistance and reactance;
- X_C - capacitor reactance;

U - stator voltage;

$\frac{E}{F}$ - normalized air-gap voltage;

F - per-unit value of stator frequency;

Ω - per-unit value of rotor speed.

Parameters and variables describing the rotor part of the equivalent circuit are referred to stator. All reactances in equivalent circuit are valid for rated frequency. Per-unit stator frequency F and per-unit rotor speed Ω are expressed in terms of rated frequency of the machine and rated synchronous speed, respectively. Magnetizing reactance at rated frequency is considered as variable, what is of essential importance in order to take variation of saturation level into account. Finally, normalized air-gap voltage is represented as function dependant on actual value of X_m. Identification of that function can be performed by processing results obtained from ideal no-load test at rated frequency and several different voltages.

Parameters of the equivalent circuit that are available for external control are load impedance at rated frequency $\underline{Z}_L = R_L + jX_L$ and capacitor reactance at rated frequency X_C. Rotor speed Ω is also defined externally, by the appropriate prime mover (e.g. wind turbine). When operates in steady state, SEIG can be treated as stable oscillator with stator current of constant effective value. Total impedance seen by stator current $\underline{I}_s$ can be described as

$$\underline{Z}_{tot} = \underline{Z}_s + \underline{Z}_1 + \underline{Z}_2 =$$

$$= \frac{R_s}{F} + jX_{ls} + \left(\frac{R_L}{F} + jX_L\right) \| \frac{-jX_C}{F^2} +$$

$$+ \frac{R_c}{F} \| jX_m \| \left(\frac{R_r}{F-\Omega} + jX_{lr}\right), \qquad (1)$$

and have to be equal with zero, otherwise self-excitation will not exist. After necessary mathematical transformations, total impedance can be separated into real and imaginary part, which leads to basic equations of a SEIG:

$$\mathrm{Re}\{\underline{Z}_{tot}\} = 0 \qquad (2)$$

$$\mathrm{Im}\{\underline{Z}_{tot}\} = 0 \,. \qquad (3)$$

If all parameters of equivalent circuit are known, system defined by Eqs. (2) and (3) can be solved for desired rotor speed Ω. Calculated roots of the system, F and X_m, have to be real values and have to fulfill criterion

$$(F > 0) \wedge (0 < X_m < X_{muns}) \,, \qquad (4)$$

where X_{muns} is magnetizing reactance of unsaturated machine at rated frequency. Otherwise, self-excitation is not possible for the selected combination of values $(\underline{Z}_L, X_C, \Omega)$.

When F and X_m are known, it is easy to solve equivalent circuit and to calculate all other quantities that are of interest. If Ω is being varied in small steps, starting with minimum value that allows self-excitation for assumed $\underline{Z}_L$ and X_C, simultaneous calculations of stator voltage U, stator current I_s, load power P_L and torque on the shaft T_{sh} lead to identification of desired performance curves. The upper limit of rotor speed, at which calculation should be ended is usually determined by mechanical limitations, or by the fact that stator voltage or stator current significantly exceeds rated value. It is important to notice that modified equivalent circuit shown on Fig. 1 can be successfully used for calculations of currents and voltages, but power and torque have to be calculated regarding the original circuit in which resistive elements are not divided by F.

III. Experimental Results

In order to validate explained theoretical approach, series of experiments was performed in laboratory, using a real three-phase squirrel cage, Y-connected induction machine as SEIG. Machine's rated values for motor mode of operation are: $1.5\,kW$, $380\,V$, $50\,Hz$, $3.2\,A$, 2860 rpm. This machine was externally driven by separately excited DC motor, what allowed arbitrary variation of rotor speed. On the stator side, machine was loaded by symmetrical, three-phase, Y-connected resistive load of constant value R_L. Symmetrical three-phase capacitor bank of constant per-phase capacitance C was connected in parallel with load and stator, in order to enable self-excitation. Varying rotor speed from the lowest value that allows existence of self-excitation to the upper limit that has been set to 120 % of rated synchronous speed, a large number of experimental points were recorded. Finally, recorded values were compared with calculated performance curves. Parameters of the machine that was used in experiments are given in Table I.

TABLE I
MACHINE PARAMETERS

R_s	4.05 Ω
R_r	2.75 Ω
X_{ls}	4.34 Ω
X_{lr}	2.77 Ω
X_{muns}	226 Ω
R_c	1200 Ω

From the results of ideal no-load test performed at rated frequency and with different voltages applied to the stator of the machine, pairs of values $(E/F, X_m)$ that define the shape of the $E/F = f(X_m)$ curve have been identified. Inside the acceptable range of X_m values, which is defined by Eq. (4), experimentally obtained pairs of values $(E/F, X_m)$ can be approximated by third-degree polynomial defined as:

$$\frac{E}{F} = A_0 + A_1 X_m + A_2 X_m^2 + A_3 X_m^3 \qquad (5)$$

Experimentally obtained points can be seen on Fig. 2.

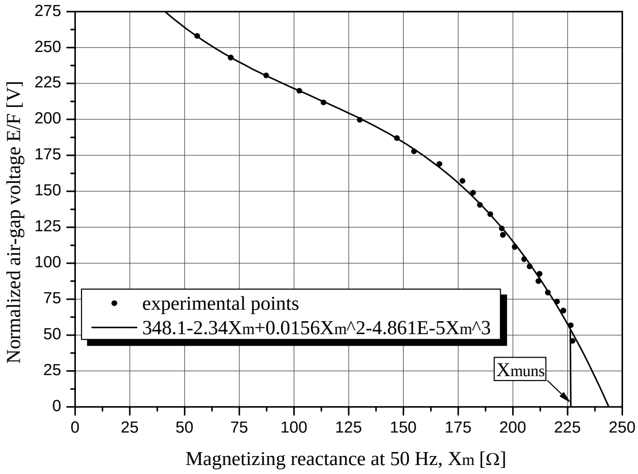

Fig. 2. Normalized air-gap voltage versus X_m

Experiments were performed for two different values of load resistance $R_{L1} = 517\,\Omega$ and $R_{L2} = 104\,\Omega$. Two different values of excitation capacitance per phase, $C_1 = 20\,\mu F$ and $C_2 = 30\,\mu F$, were also used. Experimentally obtained results are shown in Figs. 3-6, along with calculated curves. Since shaft torque has not been measured, Fig. 7 shows only calculated curves.

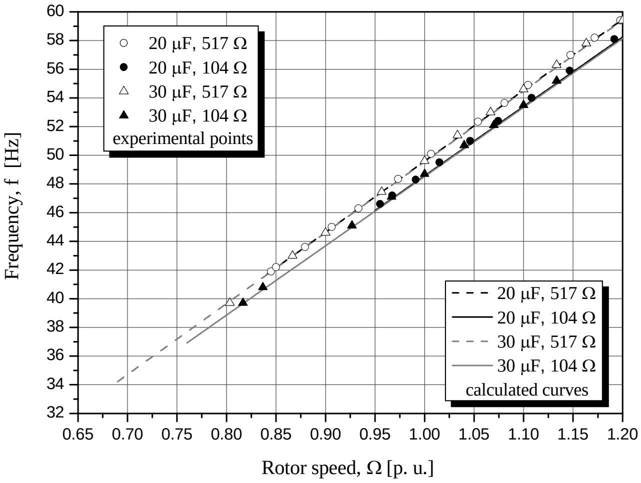

Fig. 3. Frequency f versus Ω, for $R_L = \text{const.}$, $C = \text{const.}$

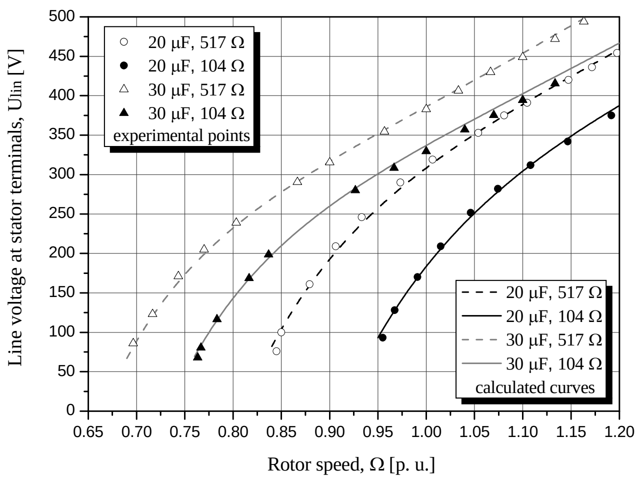

Fig. 4. Line voltage U_l versus Ω, for $R_L = \text{const.}$, $C = \text{const.}$

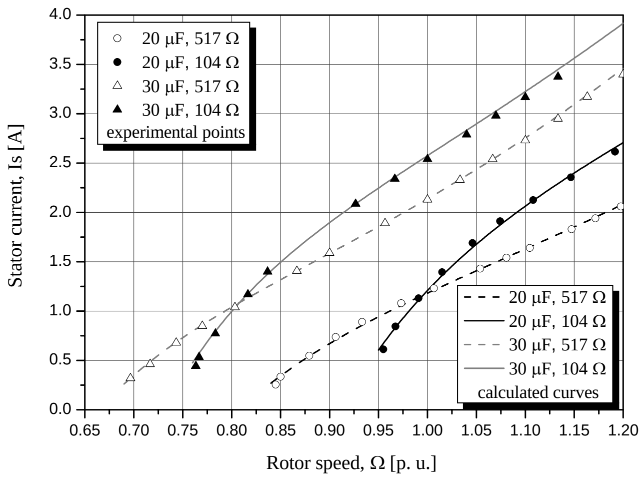

Fig. 5. Stator current I_s versus Ω, for $R_L = \text{const.}$, $C = \text{const.}$

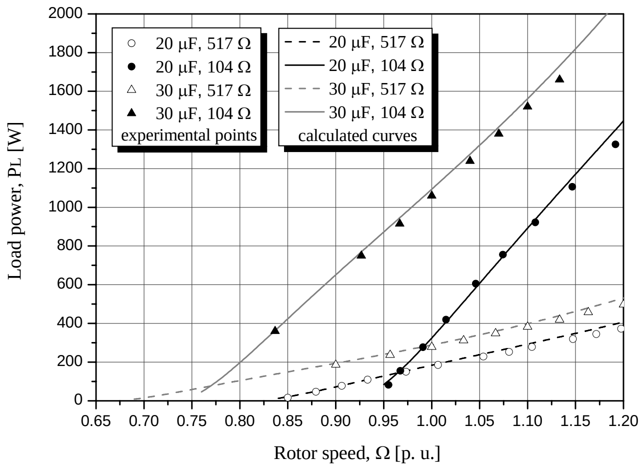

Fig. 6. Load power P_L versus Ω, for $R_L = \text{const.}$, $C = \text{const.}$

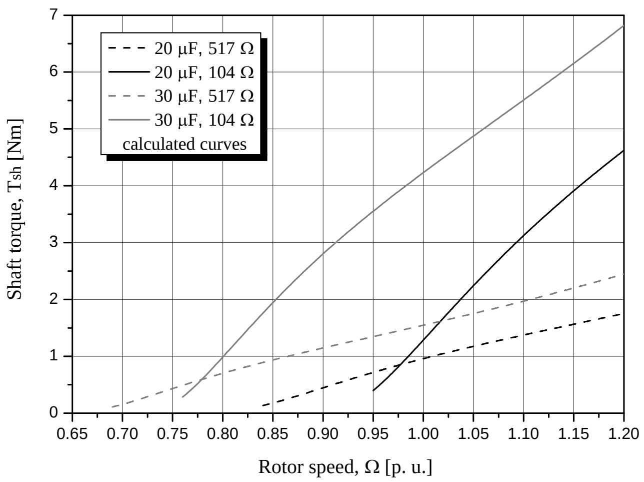

Fig. 7. Shaft torque T_{sh} versus Ω, for $R_L = \text{const.}$, $C = \text{const.}$

IV. Discussion

Very good agreement between experimentally measured values and calculated performance curves has been achieved. This fact confirms validity of exploited calculation method and enables more serious research in future, when model will be expanded by inclusion of equations that describe a real turbine. Slight disagreement between calculated and measured values can be noticed at higher rotor speeds, which could be explained by the fact that all parameters of the equivalent circuit except magnetizing reactance have been considered as constant. In reality, that is not true because stator and rotor resistances depend on actual temperature of windings. Magnetizing resistance R_c is also depends on actual frequency and saturation level. Further, leakage reactances may be treated as functions of stator current [10]. Finally, tolerance of excitation capacitors that were used in experimental work is 5%. As a consequence, capacitor bank was not perfectly symmetrical.

Inside the normal operating region, where rotor speed is close to rated synchronous speed and excitation capacitance is reasonably small, dependence of SEIG's frequency upon rotor speed is almost perfectly linear. It is obvious from the Fig. 3 that value of excitation capacitance has no important influence to the frequency. As for the value of rotor resistance, situation is slightly different. It is obvious that lower value of R_L causes notable drop of stator frequency for the same rotor speed. This can be explained by the fact that at lower values of load resistance more power is transferred from rotor to stator, which causes greater difference between angular velocity of rotor and rotating magnetic field.

Generally spoken, higher values of load resistance and excitation capacitance allow sustain of self-excitation at lower speeds. After self-excitation has been established at minimum speed for selected combination of R_L and C, voltage, current, load power and shaft torque constantly grow as speed reaches higher values.

If both load resistance and excitation capacitance are high, voltage at the stator terminals can easily exceed rated value (Fig. 4). On the other hand, if high value of capacitance is combined with low load resistance, stator voltage will remain inside acceptable boundaries, but stator current exceeds rated value (Fig. 5). It is obvious that exact definition of practically acceptable operating area of a SEIG is the problem that can not be easily solved. Thus, it deserves serious consideration in future research.

Fig. 6 shows that for constant values of R_L and C, generated power is almost proportional to the rotor speed. The angle between Ω-axis and function $P_L = f(\Omega)$ is greater when applied capacitors have larger capacitance. Similar rule can also be observed on Fig. 7, which shows calculated performance curves $T_{sh} = f(\Omega)$. In distinction from $P_L = f(\Omega)$ curves, torque on the shaft of the machine becomes slightly saturated at higher speeds.

V. CONCLUSIONS

Specific operating mode of SEIG, characterized by constant load resistance and constant excitation capacitance, but variable rotor speed, has been considered in this paper. Such operation is very interesting from the aspect of exploitation in small, stand-alone wind power generation units. Identification of performance curves that show how does variation of rotor speed affect voltage, frequency, stator current, generated power and shaft torque of the SEIG was successful. Proposed mathematical approach was verified through experimental investigation. Comparison of calculated performance curves to measured data shows that good agreement between them has been achieved.

In future research, accuracy of prediction can be taken to a higher level by considering of several nonlinearities that are neglected at this moment. Also, mathematical model will be expanded by including of equations that describe actual wind turbine. That will be of essential importance in study of practical applications in real environment.

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