VOLTAGE AND CURRENT OUTPUT PERFORMANCES OF A LOW-POWER, LOW-SPEED INDUCTION GENERATOR

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ABSTRACT

This paper addresses the voltage and current output performance of a low-power low-speed induction generator obtained as a modification result of single-phase capacitor motor. This application is prospective for microhydro power generation in rural regions, considering various prohibitive conditions in acquiring brand-new generators. Importing from far away or even from foreign countries sometimes is also difficult to do because of the low purchasing power of the local people, in addition to the lack of human resources with appropriate know-how to establish local machinery industry. Generating voltage up to its nominal value is not always easy to achieve even though rotation speed has reached or even exceeded its synchronous speed. Moreover, it also has to be excited using pre-charged capacitor. During start-up, any load should be disconnected in order not to discharge the capacitor. Once approaching its nominal output voltage value, load can be connected gradually. Increasing the rotation speed above its synchronous value will increase the resulted generator frequency, even though it is not linearly proportional to the rotation speed increase. The loading experiment is demonstrated using resistive load in the form of incandescent light bulbs. It is shown that the resulted generator voltage is of sinusoidal form, but certain distortion is found on the current waveform as a result of energy oscillation between the excitation capacitor and the generator winding inductance.

Keywords: capacitor motor, induction generator, low-power low-speed generator.

INTRODUCTION

The development of local renewable energy sources, such as photovoltaic, wind, micro-/pico-hydro, biogas, etc., is considered as alternatives for supplying energy to rural/remote areas [1-2]. The use of induction generators, due to many benefits obtained in terms of cost, simplicity, ruggedness, and ease of manufacture, has long been considered appropriate for renewable power generation in remote areas [3]. However, sometimes it is difficult to acquire some generators for specific needs in remote areas. It is because of either low local purchasing power or distance/transportation difficulty. Consequently, it would be advantageous if the generator could be made locally. However, the machinery industry is normally not available nearby. A solution can be taken by modifying some used motors to be converted into generators, as induction motors are easy to find considering that they are ones of the largest users of electric power [4]. Normal single-phase induction motors have been known unsuitable for single-phase self-excited induction generator (SEIG) [5-9], so that a specially designed machine is needed. In [10] the modification of capacitor motor intended to be used as low-power low-speed generator is discussed. In this paper, the loading performance of generator resulted from such modification is presented.

Induction generator can generate voltage (in volts) and real power (in watts) only when being supplied with sufficient reactive power [3]. An example of configuration of self-excited induction generator (SEIG) is shown in Figure-1 [6]. It uses an excitation capacitor C_{ex}, being inserted in the auxiliary winding.

The output voltage V_M increases as a function of excitation capacitance C_{ex} and rotation speed n, $V_M = f(n, C_{ex})$. If inductive load is to be supplied, additional capacitor needs to be added. As shown in Figure-1, the additional capacitor can be connected in series with the main winding and the load. The energy conversion process involves 2 (two) independent variables, i.e. rotation speed (n) and capacitor capacitance (C_{ex} and C_{se}), and 3 (three) dependent variables, i.e. output voltage (V_L), frequency (f), and power (P).

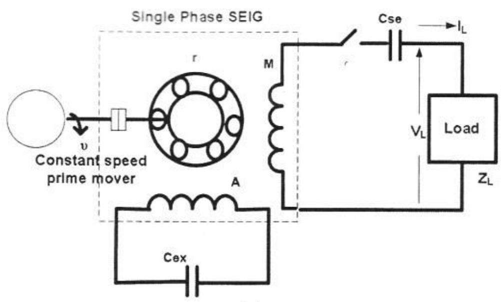

Figure-1. Self-excited single-phase induction generator with excitation capacitor inserted in the auxiliary-windings [6].

The problem often arising during the operation of a low-power self-excited induction generator is its instability because of the load increase. A small increase of load above its capacity (±102 %) could cause the output

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voltage to collapse, in addition to its low efficiency [10]. For the same construction and operating speed of generators, the resulted power capacity depends only on the machine dimension. Lower power with the same rotation speed will require smaller dimension, i.e. smaller diameter and length of the iron core, whereas the change in rotation speed while maintaining the output power will also require the change in dimension. If it is desired to get a low-speed generator while maintaining the output power, the required dimension will be higher.

SEIG UNDER NO-LOAD CONDITION

An excitation capacitor C_{ex} needs to be connected to the auxiliary-winding in order to generate voltage under no-load condition. Figure-2 shows the test results of no-load terminal voltage V_M as a function of capacitor capacitance C_{ex} at various operating speeds as obtained in [6].

As indicated, the voltage V_M increases when the capacitance of the excitation capacitor C_{ex} and the rotation speed n increase. In this case, there are two independent variables C_{ex} and n, and one dependent variable V_M, i.e. $V_M = f(n, C_{ex})$. The required C_{ex} value depends on the allowable maximum terminal voltage of the machine. In [6], capacitance of 30μF could be used to generate 240V at a rotation speed of 3100 rpm on a single-phase induction generator of 2-pole, 750W, 230V, 50Hz.

It is also known that the no-load generated voltage was sensitive to the speed change. As can be seen in Figure-2, using excitation capacitor of 30μF, the change in the generated voltage from 200V up to 260V was resulted from rotation speed of 2900 rpm up to 3200 rpm.

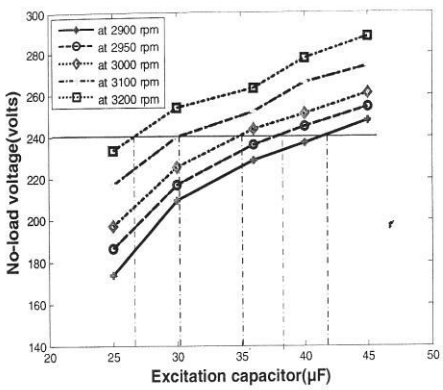

Figure-2. No-load terminal voltage as a function of excitation capacitance at various operating speed (test-data) [6].

The Figure also shows that at certain rotation speed the voltage increase could be attained by increasing the capacitance of excitation capacitor. The relationship between the no-load generated voltage and the needed excitation capacitance was shown to be relatively proportional. To obtain the generated voltage of 240 V, the excitation capacitance range of 28-42 μF could be used with speed-change range of 2900-3200 rpm.

SEIG UNDER LOADED CONDITION

The characteristics of loaded induction generator are normally represented with its relationship between the change in terminal voltage V_L (in volts) and the load power P_L (in watts) at constant rotation speed and excitation capacitance. The disadvantage of self-excited induction generators, both of single- and three-phase types, is their voltage regulations, as it is difficult to control their voltage [10,11]. As can be seen from Figure-1, an additional series capacitor is needed on the load side.

The experiments in [6] to obtain the generator characteristics under load were done at rotation speed of 3100 rpm and with excitation capacitance of C_{ex}=30μF. The obtained characteristic under loaded conditions without and with series capacitor of C_{se}=90μF were compared, as shown in Figure-3.

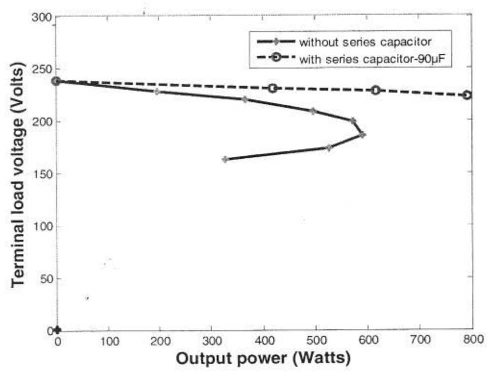

Figure-3. Relationship between terminal load voltage V_L and output power P_L with and without series capacitor [6].

It indicates that the addition of series capacitor on the load side makes the reduction of terminal load voltage relatively linear with the increase of the load. It also indicates the higher increase in voltage reduction when there was no series capacitor added. This reduction was much higher (from 200 volt to 160 volt) when it was approaching its nominal load condition (600 watt or 80% of its capacity), because of the lack of magnetic flux during the load increase. The terminal load voltage even dropped far below its nominal value.

The analyses of voltage, current, and frequency can be done using the equivalent circuit shown in Figure-4. It is the equivalent circuit for operation at fundamental frequency [12]. V_1 represents the generator terminal voltage (in volts), V_m the magnetizing voltage (in volts), I_m the magnetizing current (in amps), X_m the magnetizing reactance (Ω), R_1 the stator resistance (Ω), X_1 the stator reactance (Ω), R_2 the rotor resistance (Ω), X_2 the rotor reactance (Ω), whereas s is the slip.

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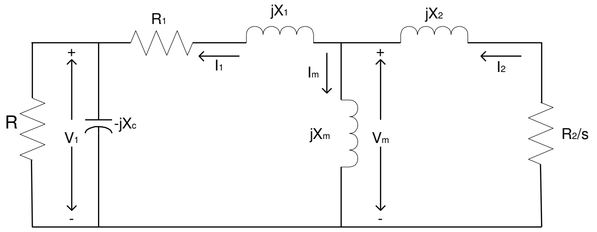

Figure-4. Equivalent circuit at fundamental frequency of a single-phase induction generator under loaded condition in stand-alone operation [12].

The equivalent circuit of induction generator at no load condition is shown in Figure-5.

Under no-load condition, the magnetizing voltage can be found as:

$$|V_m| = X_m I_m = \left[\left(\frac{V_1^{\,2}}{I_m^{\,2}} - r_1^{\,2} \right)^{1/2} - X_1 \right] I_m \quad (1)$$

Under the same no-load condition, the capacitor current can be calculated as:

$$I_C = V_1 \omega C = \frac{V_1}{X_C} \quad (2)$$

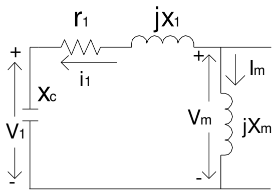

Figure-5. Per-phase equivalent circuit of an induction generator in stand-alone operation [12].

The stator reactance X_1 is much less than the magnetizing reactance X_m, when the negative slip value approaches zero. As a result, the capacitor current can be assumed of the same value as magnetizing current at synchronous speed [12],

$$I_C X_C = I_m X_C \quad (3)$$

which furthermore gives:

$$I_m = \frac{V_m}{X_m} \approx \frac{V_1}{X_m} \quad (4)$$

During steady-state condition, the line $I_m X_C$ must cut across the magnetizing curve, being represented using V_m as a function of I_m, as shown in Figure-6.

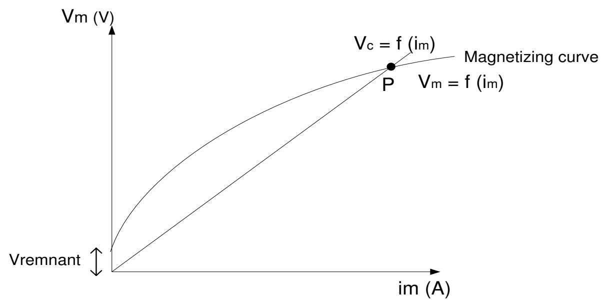

Figure-6. Determination of the operating point of an induction generator under no-load condition [13].

Using Equation (4), V_m is proportional to V_1, so that using the operating point P, the following equation is obtained.

$$V_1 = I_m X_C \quad (5)$$

Considering that,

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} \quad (6)$$

at steady-state condition,

$$I_m = 2\pi f C V_1 \quad (7)$$

and the operating frequency becomes.

$$f = \frac{I_m}{2\pi C V_1} \quad (8)$$

The operating frequency is normally pre-determined, so that using Equation (8) the required capacitor to supply reactive power to the stand-alone induction generator can be found [13].

In order to enable self-excitation, a capacitor is required by the generator to provide the needed reactive power, which is obtained from the product of complex power with certain coefficient factor [14] using Equation (9)-(11).

$$Q = \frac{P}{\cos\varphi} \frac{I_0}{I_f} \frac{1}{K} \quad \text{VAR} \quad (9)$$

$$Q = I_c^2 X_c \quad (10)$$

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$$= \frac{V_c^2}{X_c^2} X_c = \frac{V_c^2}{X_c} \quad (11)$$

Considering Equation (6), then $Q = 2\pi f C V^2$, so that the required capacitor value becomes

$$C = \frac{Q}{2\pi f V^2} \quad (12)$$

with P represents the generator output power (in watts), Q reactive power (in VARs), cosφ power factor, I_0 no-load current (in amps), I_f nominal current (in amps), K constant (K=1.15), and C capacitor capacitance (in farad).

VOLTAGE AND CURRENT WAVEFORMS

The physical configuration and construction of generator, which include the stator core, poles plane and winding phases, determine the waveform of generator output voltage. Ideally this waveform is sinusoidal. The actual waveform could contain certain distortion to some extent. Simple construction of generator and inappropriate excitation capacitor value could result in distortion in the voltage waveforms, and consequently harmonics waves.

Harmonics are often defined as certain disturbance occurring in electric power systems being caused by voltage and current waveforms distortion. The waveform, even at the point of generation, contains a small amount of distortion due to no uniformity in the excitation magnetic field and discrete spatial distribution of coils around the generator stator slots. The distorted wave can be considered as a combination of a sinusoidal waveform of fundamental frequency f with a sum of sinusoidal waves of its multiple frequencies. In the early 1800s, French mathematician, Jean Baptiste Fourier formulated it as [15],

$$v(t) = V_0 + V_1 \sin(\omega t) + V_2 \sin(2\omega t) + V_3 \sin(3\omega t) + \cdots + V_n \sin(n\omega t) + V_{(n+1)} \sin((n+1)\omega t) + \cdots (3.13)$$

where V_0 represents the constant or the DC component of the waveform, V_1, V_2, V_3, …, V_n are the peak values of the successive terms of the expression.

The correlation between the generated voltage and current waveforms and the overall generator performances is discussed in this paper.

MACHINE MODIFICATION AND LOADING EXPERIMENT METHODS

The applied research methodology has been based on experimental research. The creation of low-power, low-speed self-excited single-phase induction generator has been carried out by modification of a capacitor motor. The modification has been done by enlarging the stator slots and reconfiguring the windings structure. The original machine capacity of 1500W is to be intended to generate power of 500W. The resulted stator slots of the generator are shown in Figure-7. It can be seen that there are 36 slots. The final windings configuration of the stator is shown in Figure-8. The main-phase contains 12 winding, whereas the auxiliary-phase contains 6 windings. The original poles number of 4 is to be modified into 12 poles.

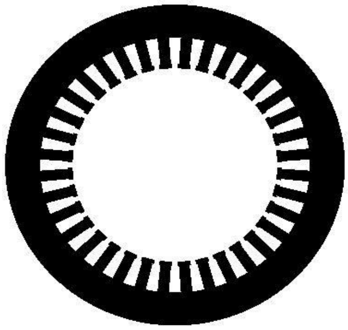

Figure-7. The stator slots of the SEIG under consideration.

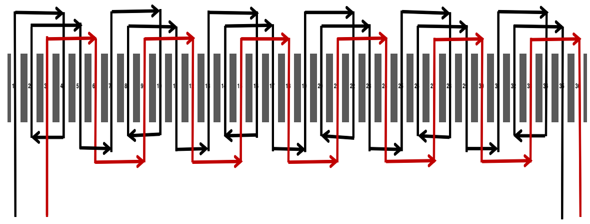

Figure-8. Windings configurations of the SEIG under consideration.

The loading performance of the SEIG has been carried out based on the set-up shown in Figure-9. Different from the experiment done in [9], the results in this paper have been obtained by maintaining constant the output voltage (at 220± 5% volt) and the excitation capacitor, while adjusting the prime mover whenever the change in loading occurs. Each of the main- and auxiliary windings is connected to resistive load. Generator speed and capacitor reactive power are adjusted until the nominal output generator is achieved.

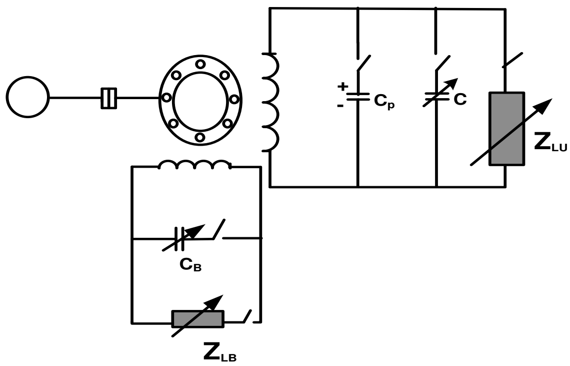

Figure-9. Experiment set-up to test the loading performance of the SEIG.

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RESULTS ND DISCUSSIONS

Starting up low-power, low-speed self-excited single-phase induction generator is not always easy to do. Initial generated voltage cannot always be obtained even though the remnant voltage at synchronous speed condition exceeds its nominal value. Certain value of initial voltage needs to be provided using pre-charged excitation capacitor C_p. Before turning the generator, any loads should be disconnected in order not to discharge the capacitor to load. The specification of machine used in the experiments is shown in Table-1.

Table-1. Data of machine used in the experiments.

Symbol	Quantity	Value	Unit
P	generator output power	500	[watt]
D	stator inner diameter	105	[mm]
L	stator core length	85	[mm]
S	Stator slots number	36	[-]
p	Pole-number	12	[-]
V	Nominal voltage	220	[volt]
$Z_{ek,m}$	Equivalent impedance of the main-winding	14	[Ω]
$R_{ek,m}$	Equivalent resistance of the main-winding	5.20	[Ω]
$X_{ek,m}$	Equivalent reactance of the main-winding	12.99	[Ω]
C_M	Capacitor of the main-winding	64	[μF]
$Z_{ek,A}$	Equivalent impedance of the auxiliary-winding magnetization	22.67	[Ω]
$R_{ek,A}$	Equivalent resistance of the auxiliary-winding	8.78	[Ω]
$X_{ek,A}$	Equivalent reactance of the auxiliary-winding	20.90	[Ω]
C_A	Capacitor of the auxiliary-winding	26.00	[μF]

Results of experiment show that the generator will only generate voltage and power when being turned far above its synchronous speed. Under loading condition, the change in the resulted frequency value is not linear with respect to the change in rotation speed, as commonly found in synchronous generator case. As can be seen in Figure-10, the voltage waveform is relatively sinusoidal, but certain distortion appears on the current waveform because of the oscillation between the excitation capacitor and the winding inductance.

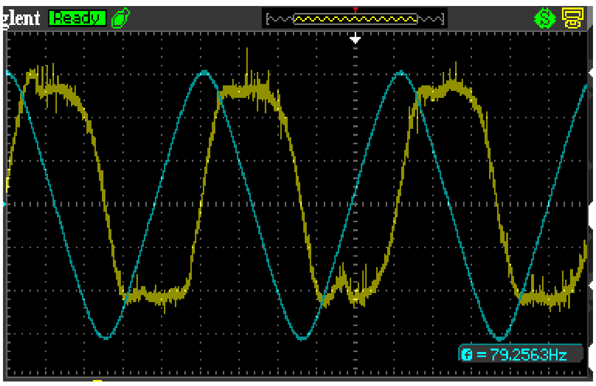

Figure-10. Self-excited induction generator output voltage and current waveforms.

Figure-11 shows the relationship between the power and rotation speed. It indicates that both the input power to prime-mover and the generator output power increase proportionally with the increase in rotation speed. The increase of output power is also proportional to the

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increase in the input power to prime-mover, as can be seen in Figure-12.

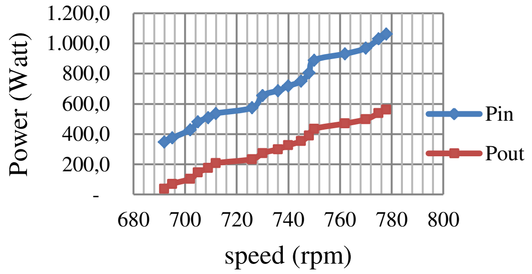

Figure-11. Relationship between generator output power to rotation speed.

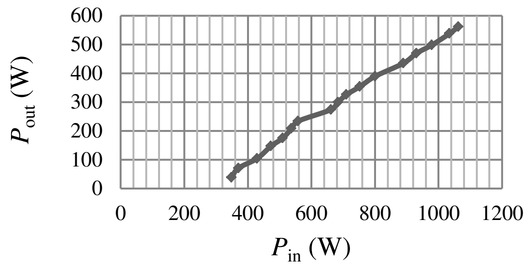

Figure-12. Relationship between input to output power.

Figure-13 shows the relationship between generator efficiency to its output power. The obtained generator efficiency is still low (around 50%), being caused by the copper losses and possibly by the harmonics. At load approaching its nominal value, loss of voltage happens (collapse), possibly being engendered by the excitation saturation so that the need of more reactive power could not be fulfilled.

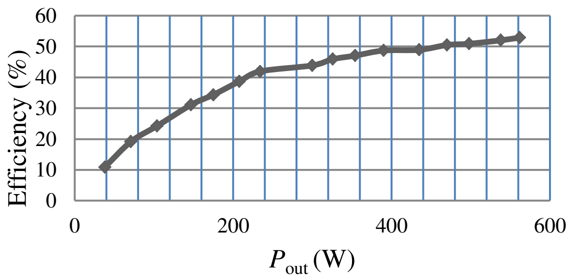

Figure-13. Relationship between generator efficiency to output power.

CONCLUSION AND PERSPECTIVES

This paper presents some results of loading experiments on a low-power low-speed self-excited single-phase induction generator as a modification result of single-phase capacitor motor. Some conclusions to be drawn from the discussions are as follows:

a) The low-power low-speed (500 rpm) self-excited induction generator could only generate power when being rotated far over its synchronous speed (more than 150% of its synchronous speed), because the voltage on the cage conductors could only be generated at sufficiently high speed.

b) For the single-phase generators being considered in this paper, both the main- and auxiliary windings could be used to generate power when each of them was equipped with appropriate capacitor.

c) The resulted generator voltage is of sinusoidal form, but certain distortion is found on the current waveform as a result of energy oscillation between the excitation capacitor and the generator winding inductance.

d) Efficiency of the single-phase low-power low-speed self-excited induction generator considered in this paper is still low because of its high power losses originated from the high resistances in the winding as well as because of harmonics.

The research, some results of which are presented in this paper, will still be continued with machines of more poles (12 or 18), less winding resistances using conductors with larger cross-section, and larger slots in order to lessen winding losses and voltage drop.

Some perspectives on the application of the low-power, low-speed generator with good efficiency would cover the pico- and micro-hydro power generations. The use of some simple mechanical transmission system modification enables the harnessing of renewable and eco-friendly potential energy so far not fully utilized, which is the low-capacity hydro-power. Functioning as motor, the low-power, low-speed application also becomes a prospect in special electric vehicle/transportation.

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