Capacitor Motor as Low-Power, Low-Speed Single-Phase Generator

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***Abstract*—In this paper, some results of experiment on modification of induction motor into generator are described. Not as usually done on three-phase motor, the modification has been done on capacitor motors normally supplied with single-phase source. The resulted induction generator should be able to self-excite and has been intended for low-power, low-speed applications. These applications are prospective for example in rural renewable energy generations and as motors for some special electric vehicles. Machine modification instead of total design-production or new machine acquisition is considered more appropriate for remote rural electrification. Distance and transportation difficulties, unavailability of nearby machine industry, lack of human resources with 'high-tech savvy', besides the low purchasing power of population in remote rural areas are some reasons behind the consideration. Experiment results indicated that voltage generation up to nominal value is not always easy to attain in a capacitor motor, even when functioning beyond its synchronous speed. An additional pre-charged capacitor should be used to initiate voltage generation. During start-up, load and the pre-charged capacitor had to be removed from generator to avoid capacitor discharge. Load could then be added gradually once generator approached its nominal output value. It was also shown that in order to generate power the generator must be rotating over its synchronous speed. The resulted frequency values did not vary linearly to the rotation speed and the obtained efficiency was still low.**

Keywords*— capacitor motor; low-power, low-speed applications; self-excitation; single-phase induction generator

I. Introduction

Rural and remote electrification in many developing countries are normally considered to be not economical when being done by extending the existing grids. Large investments as well as the resulted high losses in transmission and distribution lines become prohibitive because of the distance. Consequently, local renewable energy sources, such as photovoltaic, wind, micro-/pico-hydro, biogas, etc., are being considered as alternatives for supplying energy to rural/remote areas [1-2].

Power generation in rural/remote areas requires the use of locally and readily available resources, and of the applied technology which is simple, rugged, cost-effective, and user friendly. Most of the electrical equipments and loads used by domestic/commercial consumers in remote areas are of the single-phase types, so that the choice of single-phase power generators becomes appropriate and suitable for remote areas with limited condition of local resources availability [3-4].

Induction generators, due to many benefits obtained in terms of cost, simplicity, ruggedness, and ease of manufacture, have long been considered appropriate for micro-hydro power generation in remote areas with related hydropower potential. Many researches have been done on three-phase induction generators [5-12], but not so many dedicated to the single-phase ones. Besides, most of the researches on single-phase induction generators concerned the operating speeds which are not too different from those of their three-phase machine counterparts.

Very often it is found difficult to acquire some generators for specific needs in remote areas, because of either low local purchasing power or distance/transportation. 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 machines to be converted into generators.

Normal single-phase induction motors have been known unsuitable for single-phase self-excited induction generator (SEIG) [8-12], so that a specially designed machine is needed. In this research, a motor has been modified into a low-power, low-speed single-phase generator to be used to supply loads. The motor considered in this study is a capacitor motor, with variation of capacitor capacitance both in the main- and auxiliary windings based on the basic configuration used in [9].

Unlike in many commonly encountered power generations, the designed generator is intended to be used for low speed, low-power rural renewable energy generations and is also prospective for applications in special electric vehicles when functioning as motor.

Induction generator is capable to generate voltage (in volts) and real power (in watts) if it is supplied with sufficient reactive power. A configuration example of self-excited induction generator is shown in Fig. 1. [9]. An excitation capacitor C_{ext} is shown being connected to the auxiliary-winding to enable self-excitation. The selection of an excitation capacitor and a series capacitor is very important for voltage regulation of a single-phase SEIG. Their capacitance values must be chosen so that the desired terminal voltage level at the given speed and range of loads is obtained.

The generated voltage V_M across the main-winding will increase as capacitance and rotation speed increase, V_M=f(n,C_{ex}). When an inductive load is connected, a capacitor needs to be added to the main-winding. One connection method is to insert the capacitor C_{se} in series between the load and the main-winding, as shown in Fig. 1. The energy conversion process will involve two independent variables, i.e. rotation speed n and capacitances of C_{ex} and C_{se}, and three dependent variables, i.e. the output voltage V_L, frequency f, and output power P.

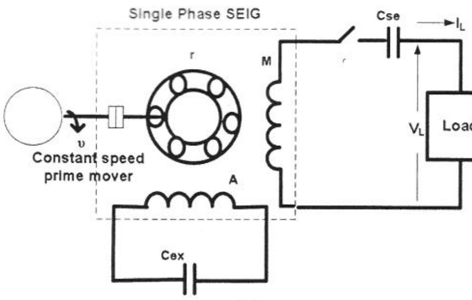

Fig. 1. Self-excited single-phase induction generator with capacitors connected to both the main- and auxiliary-windings [9].

II. Self-Excited Induction Generator (SEIG)

A. 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. Fig. 2 shows the test results of no-load terminal voltage V_M as a function of capacitor capacitance C_{ex} at various speeds as obtained in [9].

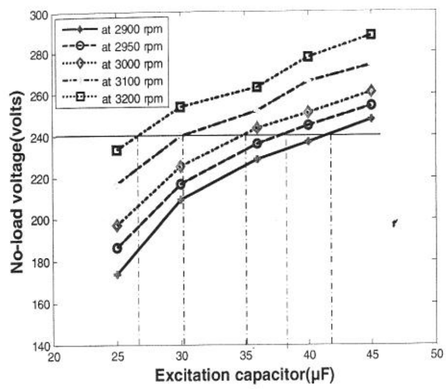

Fig. 2. No-load terminal voltage asa function of excitation capacitor capacitance at various speed (test-data) [9].

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 [9], capacitance of 30μF could be used to generate 240V at a rotation speed of 3100 rpm on a single-phase induction generator with specifications 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 Fig. 2, using excitation capacitor of 30μF, the change in the generated voltage from 200 V up to 260 V was resulted from rotation speed of 2900 rpm up to 3200 rpm. 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.

B. SEIG with Load Condition

The characteristics of loaded induction generator are normally represented with its relationship between the change in terminal voltage V_L (volt) and the load power P_L (watt) 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. As can be seen from Fig 1, an additional series capacitor is needed on the load side.

The experiments in [9] to obtain the generator characteristics under load were done at rotation speed of 3100 rpm and excitation capacitance of C_{ex}=30μF. The obtained characteristic under loaded conditions without and with series capacitor of C_{se}=30μF were compared, as shown in Fig. 3.

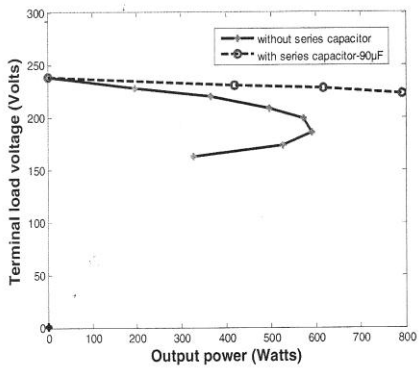

Fig. 3. Relationship between terminal load voltage V_L and output power P_L with and without series capacitor [9].

Fig. 3 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 Fig. 4 [13]. It is the equivalent circuit for operation at fundamental frequency. V_1 represents the generator terminal voltage (volt), V_m the magnetizing voltage (volt), I_m the magnetizing current (ampere), 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.

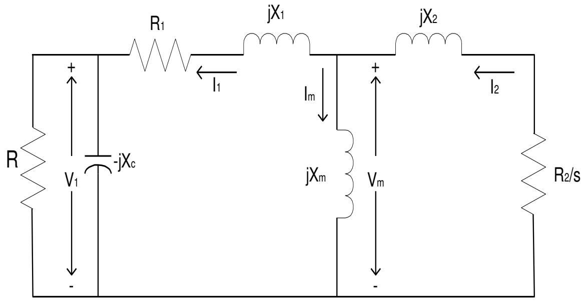

Fig. 4. Equivalent circuit at fundamental frquency of a single-phase induction generator under loaded condition in stand-alone operation [13]

The equivalent circuit of induction generator at no load condition is shown in Fig. 5 [13].

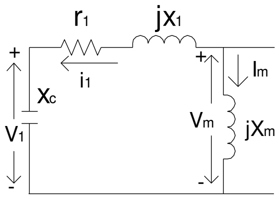

Fig. 5. Per-phase equivalent circuit of an induction generator in stand-alone operation [13]

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:

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

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 [13],

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

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 Fig. 6. Using Eq. (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

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

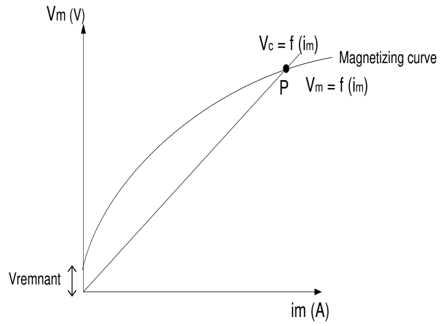

Fig. 6. Determination of the operating point of an induction generator under no-load condition [14]

The operating frequency is normally pre-determined, so that using Eq. (8) the required capacitor to supply reactive power to the stand-alone induction generator can be found [14].

III. Induction Machine Modification Method

Generator has been built using aused machine originally designed to function as motor. It was intended for low-power and low-speed applications. As widely known, low-speed applications in power plants are dominated by three-phase synchronous generators. Low-power applications could become a prospect in rural electrification, low-cost special electric vehicle, etc. The functional changing from motor to generator has been achieved through stator winding modification. The winding modification has been carried out with the purpose of changing the poles number. The pole-number changing is aimed to enable the machine to be used as low-power, low-speed generator. Pole-number has been changed from its original condition 4 to 12.

Capacitor has been used to enable self-excitation. The capacitance of capacitor to be used has been determined based on generator parameters value. Experiments have been done to obtain the generator parameters value.

A series of laboratory experiments needed to be done to test the generator performance and to obtain the generator characteristics. The experiment set-up is shown in Fig. 7. While regulating the generator speed, capacitive power has been obtained from capacitors connected in parallel to a load of the main-winding and also in the auxiliary-winding which is also in parallel to a load.

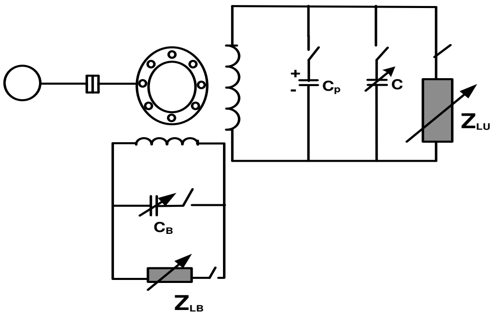

Fig. 7. Experiment set-up to test the generator performance and to obtain the generator characteristics.

In this research, experiments to know the performance of single-phase self-excited induction generator for low-power, low-speed applications have been done by connecting variable loads to both windings, i.e. the main- as well as auxiliary-windings. Generator rotation speed and reactive power from excitation capacitors were regulated until the generated voltage reached its nominal value, while the resistive loads were being connected. Algorithm to perform these regulations is shown in Fig. 8. All measurement data, either of the dependent or independent variables, are presented in a form of graphics. In this way, the relationship between variables could represent better the generator characteristics.

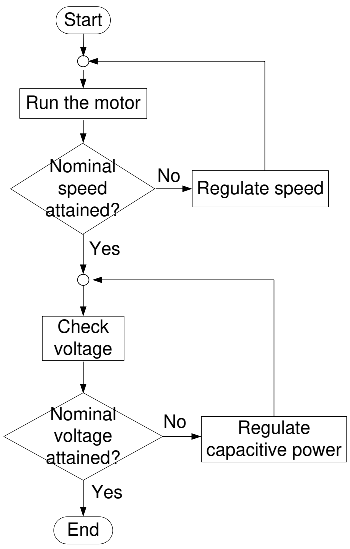

Fig. 8. Algorithm to regulate generator speed and voltage.

IV. Results and Discussion

The specification data of the machine used in the research are indicated in Table I.

During the starting-up of generator under consideration, initial voltage was difficult to obtain even though the remnant voltage at synchronous speed had been 2% exceeding its nominal value. Pre-charging the triggering capacitor C_p was needed. All loads had to be removed before running the generator to avoid the capacitor discharge to the loads.

TABLE I
Data of Machine used in the Experiments

Symbol	Quantity	Value	[Unit]
P	generator output power	500	[watt]
D_s	stator inner diameter	105	[mm]
D_r	rotor outer diameter	105	[mm]
L	stator core length	90	[mm]
S	Stator slots number	36	[-]
p	Pole-number	12	[-]
V_{nom}	Nominal voltage	220	[volt]
$Z_{ek,m}$	Equivalent impedance of the main-winding	14.00	[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	26.00	[Ω]
$R_{ek,A}$	Equivalent resistance of the auxiliary-winding	9.60	[Ω]
$X_{ek,A}$	Equivalent reactance of the auxiliary-winding	24.16	[Ω]
C_A	Capacitor of the auxiliary-winding	26	[μF]

Results of experiment showed that voltage and power could only be generated when the rotation was exceeding its synchronous speed. Under loading condition, the resulted frequency values were increasing almost linearly to the increase of speed, as can be seen from Table II and Fig. 9. It is shown that the frequency of induction generator depends on the type and the loading level.

TABLE II
Generator Frequency
as a Function of Rotation Speed

n (rpm)	f (Hz)
692	74.5
687	74.7
702	75.4
692	75.1
709	76.6
712	76.4
706	76.7
736	77.5
732	77.7
732	77.4
748	77.6
743	79.0
750	79.9
762	79.8
778	80.1
798	81.3
778	81.4

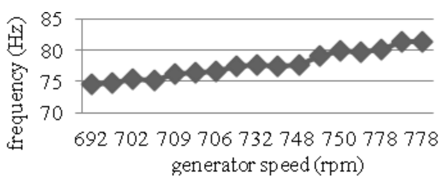

Fig. 9. Result of experiment on the relationship between generated frequency and generator speed.

The output power of the low-speed self-excited single-phase induction generator considered in this study is composed of the power being used to supply the loads connected to the main-winding and the auxiliary-winding. In this study, low-speed means the rotation speed below 1000 rpm. The input power is obtained from the multiplication of rotation speed by the measured torque of the driving motor.

In Table III the relationships between the change in load and the resulted efficiency as well as the terminal voltage of the main and auxiliary windings are shown. As can be seen in Table III and Fig. 10, the obtained efficiency of the generator so far is still low.

TABLE III
EFFICIENCY, MAIN- AND AUXILIARY-WINDING TERMINAL VOLTAGES AS FUNCTIONS OF LOAD POWER

P_L (watt)	η (%)	V_M (volt)	V_A (volt)
38	10.9	222	225
71	19.2	220	224
104	24.2	222	226
147	31.1	220	226
175	34.3	220	230
208	38.7	220	232
234	41.9	220	232
274	41.4	220	235
300	43.9	220	238
326	45.9	220	240
354	47.0	220	240
390	48.7	220	245
435	48.9	220	248
470	50.5	220	250
498	50.9	220	250
538	50.7	220	250
562	52.9	218	225

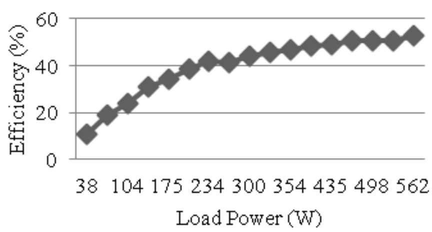

Fig. 10. Results of experiment on the relationship between efficiency and output power.

Terminal voltages of the main- and auxiliary windings as functions of the resistive load changes are also shown in Table III. As indicated in Fig. 11, the main-winding terminal voltage of the generator could be maintained relatively constant around its nominal value until nominal loading level limit by adjusting its mechanical input power while excitation capacitor being kept constant.

Under the same treatment as on the main-winding but with reduced loading level adapted to the auxiliary-winding (50%), higher voltage values have been obtained on the auxiliary-winding terminals. This could be due to the phase-angle of the auxiliary-winding impedance which was not the same as that of the main-winding. The load change could just be balanced with the change in input mechanical power.

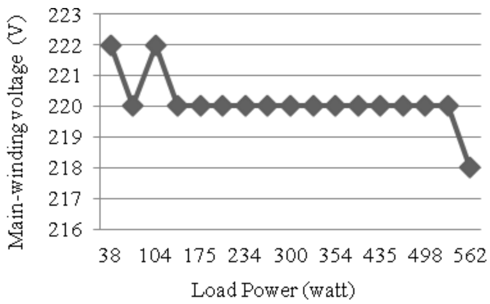

Fig. 11. Result of experiment on the relationship between main-winding terminal voltage and the load power change

Relationships between the main-winding capacitor current and the generated voltage and frequency values are shown in Table IV. It compares the data of experiment and those of theory (5) and (8). As seen in Fig. 7, the generator winding, excitation capacitor, and the load are connected in parallel, so that theoretically all would be under the same voltage conditions.

TABLE IV
COMPARISON OF EXPERIMENT RESULTS TO THEORY ON THE RELATIONSHIP BETWEEN MAIN-WINDING CAPACITOR CURRENT AND THE GENERATED VOLTAGE AND FREQUENCY

I_{CM} (A)	V_{Theory} (Hz)	V_{Exp} (Hz)	f_{Theory} (Hz)	f_{Exp} (Hz)
6.88	229.77	222	77.1	74.5
6.85	228.16	220	77.5	74.7
6.76	223.07	222	75.8	75.4
7.25	240.19	220	82.0	75.1
6.71	218.81	220	75.9	76.3
7.05	229.59	220	79.7	76.4
6.61	214.42	220	74.8	76.7
7.09	227.62	220	80.2	77.5
6.68	213.90	220	75.5	77.7
6.61	212.48	220	74.8	77.4
6.78	217.38	220	76.7	77.6
6.83	215.11	220	77.2	79.0
7.05	219.53	220	79.7	79.9
7.14	222.62	220	80.7	79.8
6.89	214.02	220	77.9	80.1
7.30	223.40	220	82.6	81.3
7.24	221.30	218	82.6	81.4

As indicated in Fig. 12, the generated voltage values resulted from experiments are relatively constant around the nominal voltage. The proportionality changes in voltage to capacitor current values are still valid (5). The value differences could be brought about by the phase difference between the generator and the main-winding capacitor currents.

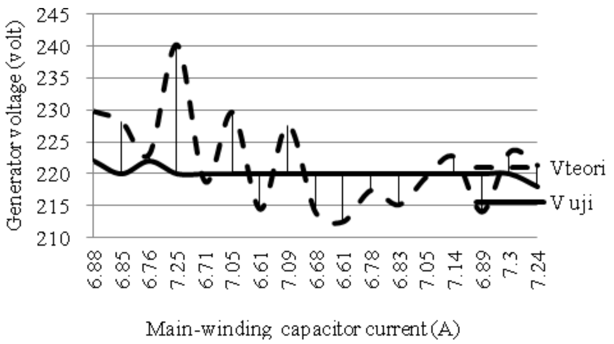

Fig. 12. Comparison of experiment to theory results of the relationship between the main-winding capacitor current to the generator voltage.

In theory (8), under constant capacitor capacitance and voltage value, the generated frequency will be directly proportional to the capacitor current. As indicated in Fig. 13, the rising tendency of frequency because of the increasing capacitor current of the main-winding resulted from experiment is in accordance with theory. The proportionality changes in frequency to capacitor current values are still valid (8). The value differences are still plausible.

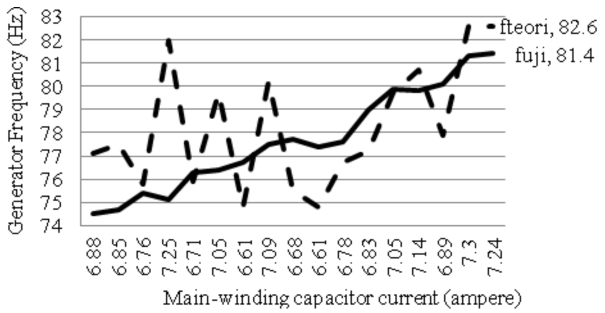

Fig. 13. Comparison of experiment to theory results of the relationship between the main-winding capacitor current to the generator frequency

V. Conclusions and Perspectives

Some conclusions that can be drawn from previous discussions are as follows:

1) The obtained single-phase low-power low-speed (500 rpm) self-excited induction generator could only generate power when being rotated far over its synchronous speed (40% over its synchronous speed), because the voltage on the cage conductors could only be generated at sufficiently high speed.

2) For the single-phase generators modified from capacitor motors 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.

3) Efficiency of the single-phase low-power low-speed self-excited induction generator considered in this paper was still low because of its high power losses originated from the high resistances in the windings.

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 these research results 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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