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# LABORATORY VOLTAGE AND FREQUENCY CONTROL FOR SELF EXCITED INDUCTION GENERATOR USING PROGRAMMABLE LOGIC CONTROLLERS*

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## ABSTRACT:

The self excited induction generators have been receiving attention for last decades as the most suitable power solution for remote areas. These have voltage and frequency regulation problems that stand against their spreading. This paper presents two simple voltage and frequency regulation methods for such stand-alone induction generators. The first and desired method, based on stepped capacitor uses programmable logic controllers (plc) in order to maintain constant values of the terminal voltage at different loads while frequency under different loads is regulated by regulating the prime mover speed by the same plc. The second method was developed by using an external resistance in series with the terminal capacitor while frequency under different loads is regulated by regulating the prim-mover speed .both methods were experimentally verified using a 1.5 kw squirrel cage induction generator supplying resistive loads. A computer simulation model depending on the generator steady state performance was developed. The experimental data show good agreement with computed results.

**KEY WORDS:** Induction generators, Self-excited, Voltage and Frequency regulation, PLC, External resistance.

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## REGULATION DE TENSION ET DE FREQUENCE POUR GENERATRICE ASYNCHRONE AUTO-EXCITEE UTILISANT DES CONTROLEURS LOGIQUES PROGRAMMABLES

## RÉSUMÉ:

La version autonome générateurs d'induction d'avoir l'attention de ces dernières décennies que la solution d'alimentation la plus appropriée pour les zones rares. Mais ils ont un problème de régulation de tension et de fréquence qui se dresse contre leur propagation. Cet article présente deux de tension et de méthodes simples régulation de fréquence pour les générateurs d'induction autonome. La première méthode souhaitée sur la base intensifié condensateur a utilisé des contrôleurs logiques programmables (PLC) afin de maintenir des valeurs constantes pour les deux tensions aux bornes et la fréquence sous différentes charges. La seconde méthode obtenue en utilisant une résistance externe en série avec la borne du condensateur. Les deux méthodes sont expérimentalement vérifiées à l'aide de 1,5 kW à induction à cage d'écureuil générateur alimentant des charges résistives. Un modèle de simulation informatique dépend de la performance de l'État générateur soutenu produit. Les résultats expérimentaux montrent un bon accord avec les résultats calculés.

**MOTS CLES**: générateurs d'induction, auto-excitée, la tension et la fréquence, PLC, une résistance externe.

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# 1. INTRODUCTION

Self excited induction generators (SEIG) have a great importance to non-conventional, clean and renewable energy sources. They have become the most economical and suitable solution for remote and isolated areas because of their simplicity, low cost, low maintenance requirements, absence of separate power source for field excitation and self protection against overloading or short circuit faults [1]. However the reactive power required for the generator and its load can be provided by the terminal capacitor bank. The amount of the capacitance required for excitation varies with load current, power factor and the rotor speed, causing unsatisfactory voltage and frequency regulation problem [2].

Many researches have discussed the voltage regulation problem of (SEIG) presenting some suitable solutions. A very simple method uses series capacitors connected to the generator terminals when a small variation in the terminal voltage takes place [3]. Another method uses switched capacitor in order to change the capacitance with load variation to provide a good voltage regulation by simple and fast control method using (GTO) or (IGBT) switches [4]. In ([5] and [6]) static var compensator is used to have a combination of switching capacitors and controllable reactors in order to provide continuous control of the reactive current.

The poor frequency regulation due to the (SEIG) loading appears as another serious problem standing against using it as the main option for generation systems. Although the methodologies mentioned before attain an improvement in voltage regulation, they have solved the problem only partially as the frequency regulation problem has not been solved yet. Besides that, there still exists a variation in the magnetization characteristic of the generator, which leads to more capacitance requirement.

The induction generator works at rotor speed higher than its synchronous speed that means negative slip (S) where

$$S = \frac{N_S - N_r}{N_S}$$

$N_r$**:** The rotor speed

$N_S$**:** The synchronous speed = $\frac{120F}{P}$

F**:** The generator frequency

Increasing the power required by the load yields a drop in the generator frequency which requires a higher rotor speed to maintain the frequency at constant value that's causing a higher negative slip (S)

The frequency drop is aggravated by variable speed prime movers such as wind and micro-hydro turbines. As a result of the frequency reduction the magnetization characteristic is reduced as well (assuming the air gap flux is constant). The capacitive reactance is affected by the frequency changing as.

$$X_c = \frac{1}{2\pi \times F \times C}$$

As shown in Fig (1) at no-load conditions the generator frequency is $Fs_1$ and the capacitive reactance at this frequency is $X_{C1}$. The working point "A" is the point of intersection of the magnetization curve and the capacitive reactance.

By loading the generator the frequency reduces to $Fs_2$ and the capacitive reactance at this frequency is $X_{C2}$. The working point at this condition will be "B", causing a drop in the generated voltage.
By increasing the load current applied to the generator the frequency is reduced again from $fs_2$ to $Fs_3$ and the capacitive reactance will be $X_{C3}$. The working point will be "C" causing furyher reduction in the generated voltage.

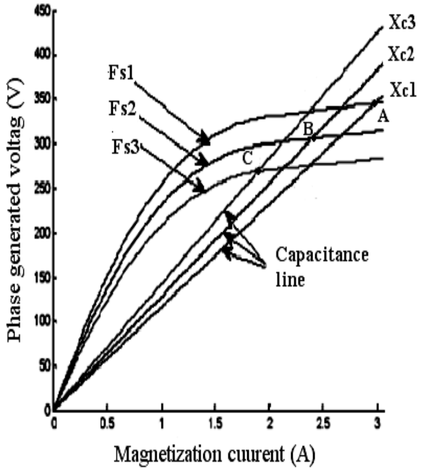



**Fig. (1): Variation of magnetization characteristics**

Some articles have solved this problem using the development of power electronics in order to transfer the terminal voltage of the induction generator from AC to DC voltage using rectifiers and then from DC to AC by using PWM inverters with certain frequency ([7] and [8]).
This paper presents two simple control methods for standalone induction generators. The first method based on stepped capacitor regulation principle using the great development of electronics in order to maintain constant value of the terminal voltage at different loads while frequency under different loads is regulated by regulating the prime over speed by the same PLC. These schemes permit (SEIG) to operate at constant voltage constant frequency conditions. This method uses PLC as a controller fed from voltage and frequency detectors. The second method is even simpler. It uses an external resistance in series with the terminal capacitor in order to regulate the terminal voltage while frequency under different loads is regulated by regulating the prim- over speed. A 1.5 KW three phase squirrel cage induction generator with a DC motor as a prime mover was used to verify these two methods experimentally.

## 2. STEADY STATE MODELING FOR SEIG

The steady state operation of the (SEIG) is analyzed using the equivalent circuit shown in Fig. (2). Nodal impedance technique is used to solve the equivalent circuit [9].

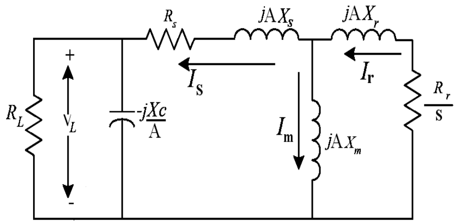



**Fig. (2): Equivalent circuit of self excited induction generator**

$$I_m + I_S - I_R = 0$$

$$Z_{Lc} = \frac{R_L \times -j\frac{X_C}{A}}{R_L - j\frac{X_C}{A}} = R_{LC} + jX_{LC}$$

$$R_{LC} = \frac{X_C^2 R_L}{A^2 R_L^2 + X_C^2}$$

$$X_{LC} = \frac{-A X_C R_L^2}{A^2 R_L^2 + X_C^2}$$

$R_{1L} = R_S + R_{LC}$

$X_{1L} = AX_S + X_{LC}$

$$\frac{E_g}{R_{1L} + jX_{1L}} + \frac{E_g}{jAX_m} - \frac{E_g}{\frac{R_r}{s} + jAX_r} = 0 \quad (1)$$

The generator frequency varies with the load current and the rotor speed, the machine reactance values changes with the frequency so a ratio between the machine frequency and the base frequency must be taken in consideration.

where $A = \frac{F_a}{F_b}$

**Fa:** Generator actual frequency

**Fb:** Base frequency 50 HZ

**RS:** Stator phase resistance

**Rr:** Rotor phase resistance

**XS:** Stator phase reactance

**Xr:** Rotor phase reactance

And equating both the real and imaginary parts of equation (1) to zero, the following two equations are obtained.

$$\frac{\frac{R_r}{s}}{(\frac{R_r}{s})^2 + A^2 X_r^2} + \frac{R_{1L}}{R_{1L}^2 + X_{1L}^2} = 0 \quad (2)$$

$$\frac{S^2 A X_r}{R_r^2 + S^2 A^2 X_r^2} + \frac{1}{AX_m} - \frac{X_{1L}}{R_{1L}^2 + X_{1L}^2} = 0 \quad (3)$$

With some mathematical manipulation a second order equation is obtained from equation (2)

$aS^2 + bS + C = 0$ (4)

Where $a = A^2 X_r^2 R_{1L}$

$b = R_r (R_{1L}^2 + X_{1L}^2)$

$C = R_{1L} R_r^2$

Solving equation (4) two solutions are obtained. The lower solution value is the desired one. Another equation is deduced from equation (3)

$$X_m = \frac{-R_r (R_{1L}^2 + X_{1L}^2)}{S} \quad (5)$$

Now by substitution of S in equation (5) $X_m$ is obtained. With the aid of the magnetizing curve which is obtained experimentally the air gap voltage (Eg) is found and the equivalent circuit is now completely solved to yield the steady state performance of the generator.

$$I_s = \frac{Eg}{\sqrt{R_{1L}^2 + X_{1L}^2}}$$

$$I_R = \frac{Eg}{\sqrt{\frac{R_r^2}{S^2} + X_r^2}}$$

The load voltage:

$$V_L = E_g - I_s \sqrt{R_S^2 + X_S^2}$$

The load current: $I_L = \frac{V_L}{R_L}$

The output power: $P_O = 3 I_L^2 R_L$

$P_{C1} = 3*(I_S)^2 \times Rs$

$P_{C2} = 3*(I_R)^2 \times Rr$

The iron and friction losses can be neglected so the input power can be calculated

$Pin = P_O + P_{C1} + P_{C2}$

The efficiency: $\eta = \frac{P_o}{P_{in}}$

A simulation model based on the Matlab package is developed to obtain the steady state performance of the generator. This program is developed in order

to solve the previous equations and also to find the relationship between the generator parameters change and the generator performance with loading conditions.
The simulation program is mainly for the steady state analysis of the generator and its flow chart is shown in Fig. (3).

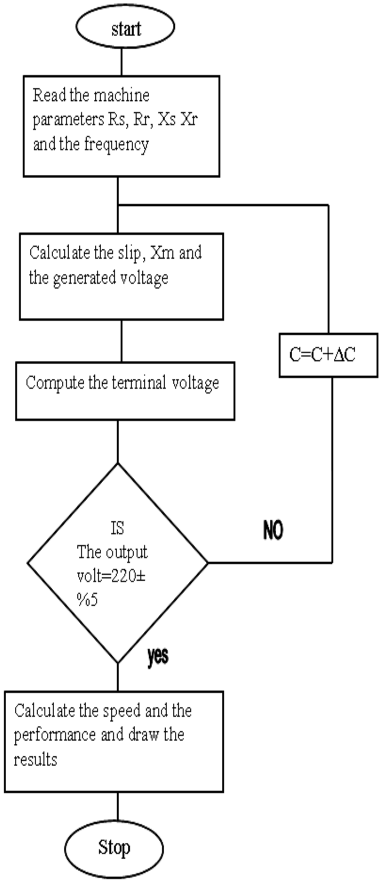



**Fig. (3): Flow chart of the simulation program**

## 3. CONTROL SYSTEMS DESCRIPTION

This part explains both the control systems and describes the used methods and devices for voltage and frequency control.

### 3.1 Voltage and Frequency Control Using PLC

This control system depends on the stepped capacitor principle using PLC to choose the suitable capacitor bank in order to maintain the terminal voltage constant within 5% of the generator rated voltage. As shown in Fig. (4), the system has a fixed capacitor bank C1 connected to the stator terminals in order to provide the self excitation and generate the desired voltage value at no load. The capacitor C1 is connected continuously in order to prevent the voltage failure during the switching time. Three different capacitor banks ($C_2$, $C_3$ and C4) are connected to the stator terminal through three contactors K1, K2 and K3 where ($C_2 < C_3 < C_4$).

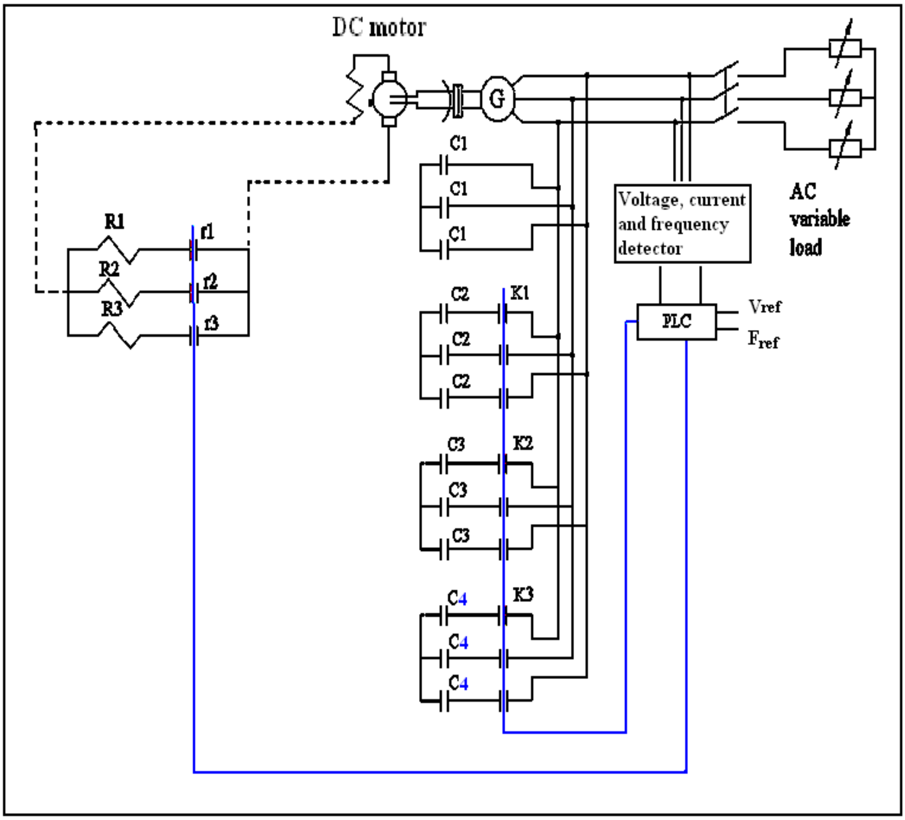



**Fig. (4): Control system diagram**

A voltage detector device senses the terminal voltage changes. Another detector used to observe the generator frequency variation with load. Three resistors R1< R2< R3 are connected by three relays $r_1$, $r_2$ and $r_3$ in series with the field windings of the shunt DC motor which acts as prime mover as shown in Fig. (4)
The main controlling device in this system is the PLC which acts as intelligent controller taking input signal from the detectors. By loading, the terminal voltage of the generator is decreased to minimum value (Vmin). In order to maintain the voltage value within acceptable limit of 5% the capacitor value must be increased with the load current. Small signals feeding the PLC is produced by the voltage and current detectors due to voltage reduction lower than 5% of the rated value. The contactor K1 is now connected by the PLC.
The reactive power is now supplied from (C1+C2) where C2 is the difference between the initial capacitor C1 and the required value to maintain the voltage. The required capacitance value is easily obtained from Fig. (5)

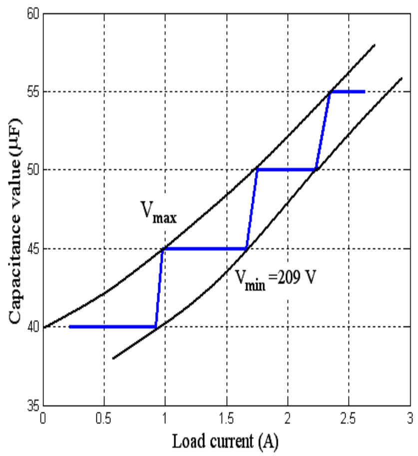



**Fig (5): Variation of capacitor value with load current**

This Fig is obtained by a Matlab simulation model using trial and error method to calculate the suitable capacitor value at different load currents [10]. The model was verified experimentally.

$\mathbf{V_{max}}$: Maximum voltage value can be reached at each capacitor Value

$\mathbf{V_{min}}$: Minimum voltage value can be reached at certain capacitor Value = 209V

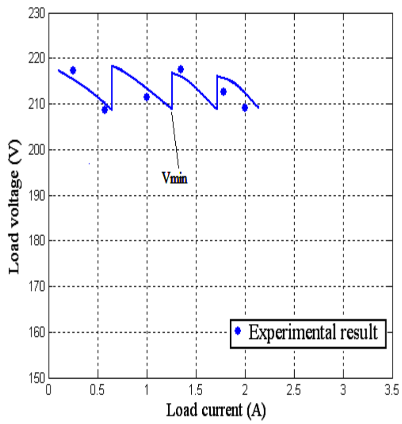



**Fig. (6): Variation of load voltage with the load current**

The terminal voltage is now suddenly increased due to the sudden connection of the new capacitor value (C2). The new capacitance value can maintain the voltage within limits till certain load current as shown in Fig (6).

With increasing of the load current value, the voltage decreased again so a new capacitor value is now required to maintain the voltage. The contactor K2 is now connected by the PLC. The working capacitor value is now (C1+C3). And so on for higher load currents higher capacitance values is required.

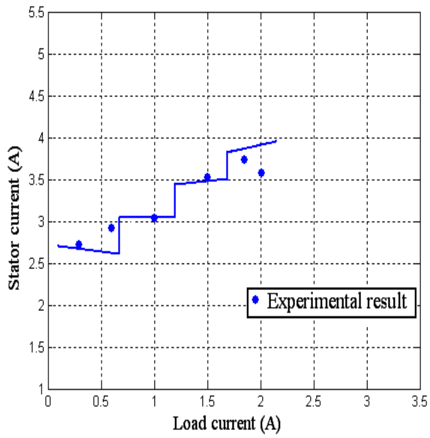



**Fig. (7): Variation of stator current with load current**

The variation of the stator and capacitor currents with load current at each capacitor step is shown in Figs. (7) and (8) respectively. Both currents rise with the capacitor bank due to the voltage.

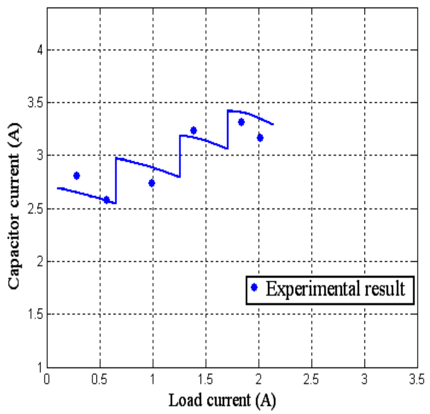



**Fig. (8): Variation of capacitor current with load current**

As a result of loading generator, the frequency is reduced. Changing of the excitation capacitor affects the voltage only therefore the frequency regulation still represents a problem. In order to maintain the generator frequency, the DC motor speed is controlled. A relation between the load current and the desired speed to maintain the frequency is shown in Fig. (9).

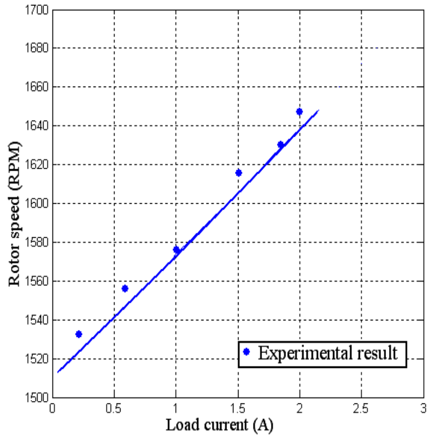



**Fig. (9): Variation of rotor speed with load current.**

This figure is obtained by the Matlab simulation model. The model was verified experimentally.
By connecting an external series resistance Rx in series with the field winding as shown in Fig. (10) the dc motor speed can be controlled.

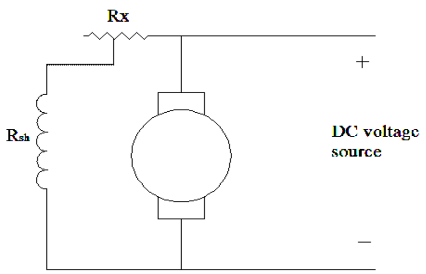



**Fig. (10): The external resistance connected to control the field current of the DC motor**

This method can obtain speed higher than the motor normal speed by controlling the field current where

$$N_{DC}=\frac{V_{DC}-E}{K\phi}$$

$N_{DC}$**:** The DC motor speed
$V_{DC}$**:** The DC voltage source
K: The dc motor constant
$\phi$ **:** The DC motor field which is appropriate to the field current ($I_{sh}$).

$$I_{sh}=\frac{V_{DC}}{R_{sh}+R_X}$$

$Rsh$ : Shunt field resistance.

$Rx$ : External added resistance

Nonlinear relationship between the motor speed and the external field resistance is shown in Fig. (11).

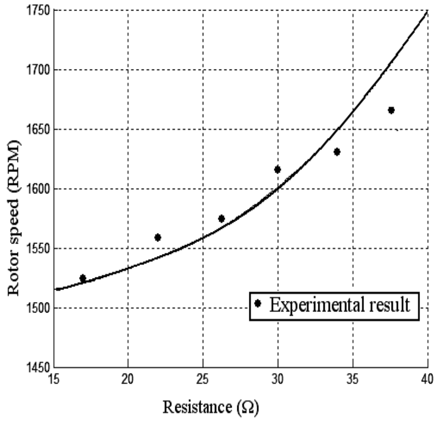



**Fig. (11): Variation of rotor speed with external resistance.**

This figure is obtained experimentally and by Matlab curve fitting the relation between the motor speed and the external field resistance is obtained. The rotor speed increases proportional to the external resistance. R1 is connected for no load condition. By loading the generator its frequency is reduced and a higher external resistance is needed. Relay r2 is now connected by means of PLC and the resistance R2 is on duty. The rotor speed is now increased to maintain the generator frequency. For higher load current the frequency reduced and a higher resistance value is needed. R3 is in duty by turning on the relay r3.

## 3.2. Experimental and Simulation Results

A FATEK (FBs-24EA (P)) PLC with four digitals input channels and eight digitals output channel is the PLC type is used to achieve the control system. And A/D module with two input channels and six output channels is used to detect the load current and send a digital signal to the PLC.

A three phase induction machine was used and its rating was

V =220/380 volt Δ/Y

Output power = 2 hp

I = 3.3 A/ph

And its parameter was obtained experimentally by no-load and blocked rotor testes and it was

The induction generator parameters

$R_s = 4.877\ \Omega$

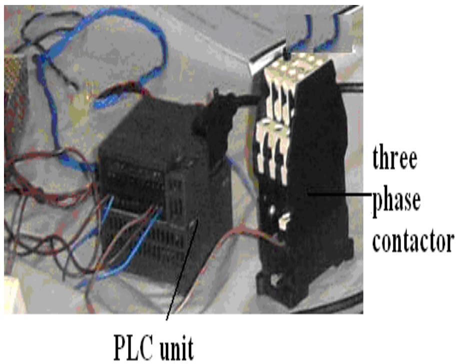
$R_r = 7.623\ \Omega$

$X_s = X_r = 6.329\ \Omega$

$R_m = 702.996\ \Omega$

$X_m = 75.7943\ \Omega$

At first a ladder diagram is achieved by using winproladder package in order to program the PLC. The program purpose is to detect the generator voltage and current and for voltage lower than 209V the PLC chooses the suitable capacitor bank according to the load current by turning on its contactor in order to maintain the load voltage.




Which capacitor bank needed is determined by the load current as shown in Fig. (6).

For volt les than 209V and current between 0.6 and 1.3 A 45μF capacitor bank is needed so the PLC out put will be (on off off) in other words the contactor connected to the first output channel will be turned on while the others is turned off.

For current between 1.3 and 1.8 A C3 bank is needed so the PLC out put will be (off on off) in other words the contactor connected to the second output channel will be turned on. And so on the PLC output is determined by both generator voltage and current.

At first the SEIG operates at no load with capacitor bank of 40 µF to provide a self excitation at the terminal voltage of 218 V. the capacitor value increases by 5 µF each step so C2=5 µF, C3=10 µF and C4=15 µF . The prime mover speed has to be increased to 1510 to maintain the frequency at 50 Hz at no-load. With loading the initial capacitor can maintain the voltage within the limit to a load current of 0.6A, and then the voltage is reduced by 9.3%. The voltage detector observes the voltage for a minimum voltage value of 209 V then the detector sends a signal to the PLC which turn the contactor K2 on after .1 sec . The capacitor value is increased now to be (C1+C2) = 40+5= 45 µF. The new capacitor value can maintain the voltage at a value higher than 209V till a load current reaches 1.3 A. A capacitor of 50 µF is now needed to deliver the voltage more than Vmin so the capacitor C3 is connected by means of the PLC after a time 0.3 sec and the capacitor C2 is now disconnected. The voltage is maintained within a suitable range of 5% till a load current of 1.8 A. For higher current C4 is needed.

The generator rotor current increases significantly with the load current so the generator is loaded by 75% of its rated current so that three capacitor banks are enough to control the voltage during the loading region.

With respect to the generator frequency the frequency detector takes a response for frequency lower than 48 HZ. An external resistance is connected in series to the field windings with a value of 18Ω. This resistance maintains the frequency as it of the no load till a load current 0.72 A, then a higher external resistance is needed as shown in Fig. (12).

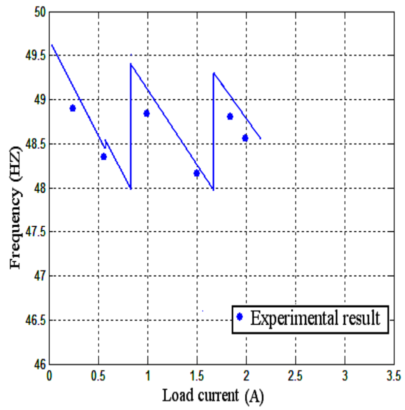



**Fig. (12): Variation of frequency with load current**

For higher load current a higher external resistance is needed in order to increase the rotor speed to maintain the generator frequency.

By the same way the PLC turn on the relay r2 to connect resistance R2 which raises the DC motor speed to 1532 RPM that increase the frequency to be 49.4 HZ. For load current higher than 1.6A a speed of 1560 RPM is necessary to have the same generator frequency. Resistance R2 is now disconnected and resistance R3 is on duty. The generator frequency now reaches 49.3 Hz and the frequency kept higher than 48 Hz.

The Laboratory errors such as human faults and measuring devices accuracy

must take in consideration with the experimental results.
The desired control system maintains both the voltage and the frequency within permitted tolerance of 5% for any load current. For machines with higher rated currents more capacitor steps can be added and more external resistance which connected in series to the field windings of the DC motor can be added as well in order to maintain the generator voltage and frequency.

### 3.3 Voltage and Frequency Control Using an External Resistance

Avery simple control method for suitable loading range could be achieved by connecting a suitable external resistance in series with the terminal capacitor bank.

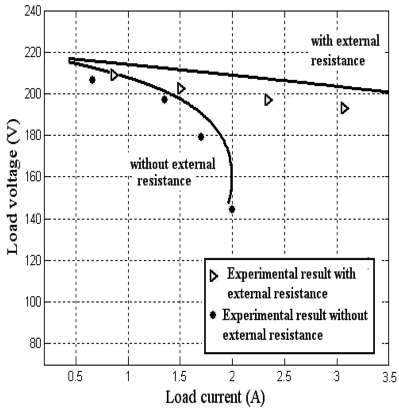



**Fig. (13): Variation of load voltage with the load current**

As shown in Fig. (13) for the same capacitor value of 40 μF the voltage is kept with limit al over the machine rated load current by connecting 1KΩ. Without external resistance the voltage reduces and then collapses with load current of 1.7 A.

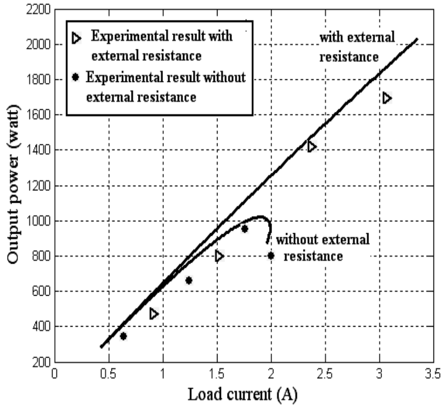



**Fig. (14): Variation of output power with the load current**

The external resistance improves the generator voltage without any reduction in the output power as shown in Fig. (14).
The required speed to maintain the generator frequency with external resistance is lower than the one needed without resistance as shown in Fig. (15). The frequency maintained within limit with speed control as the same way which explained in the part (A) using PLC.

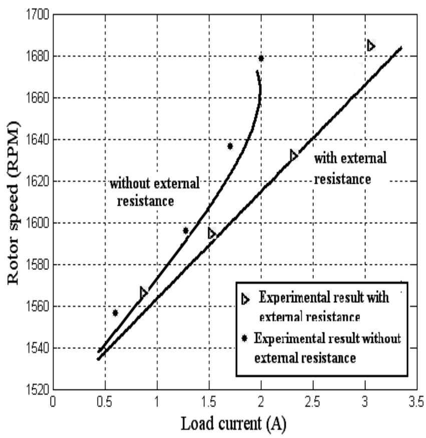



**Fig. (15): Variation of rotor speed with the load current**

This method has been verified experimentally with using 1.5 kW squirrel cage induction generator supplying resistive loads with a DC motor which used as a prime mover.

## 4. CONCOLUSION

The developed voltage and frequency control system achieved good results with permitted tolerance of 5%.
The simulation model using Matlab allows us to adjust parameters like capacitance value and predict the suitable capacitor value and rotor speed to maintain the voltage and frequency constant.
The experimental results and the simulation model results are in good agreement

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