

## **Performance Study Of A Self-Excited Single-Phase Induction Generator With Different Types Of Loads**

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### **Abstract:**

*This paper presents the performance study of self-excited single phase induction generator. This generator consists of a three-phase squirrel-cage induction machine and three capacitors connected in series and parallel with a single-phase load. An experimental set up of single phase induction generator driven by dc motor is presented to show the performance of the generator. The generator is tested with resistive, inductive, dynamic and non-linear loads. The results of voltage, frequency and efficiency of induction generator with respect to the output power with different types of loads are obtained. The results show good voltage regulation, small variation in the frequency and high efficiency of induction generator. The harmonic spectrums of output voltage with different types of load are obtained. These spectrums show no waveform distortions (sinusoidal output voltage).*

**Keywords:** Single-phase induction generator, capacitor self-excitation, all types of single-phase load.

### **دراسة أداء المولد الحثي ذو الإثارة الذاتية والأحادي الطور مع مختلف الأحمال**

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### **الخلاصة:**

في هذا البحث تم دراسة أداء المولد الحثي أحادي الطور ذو الإثارة الذاتية. أن هذا المولد يتكون من ماكينة حثية ثلاثية الطور ذات دوار نوع قفص سنجابي حيث تم ربط ثلاثة متسعات على التوالي والتوازي مع الحمل أحادي الطور. تم بناء نموذج عملي يتكون من المولد الحثي أحادي الطور ومحرك تيار مستمر لغرض تدوير المولد. لقد تم اختبار المولد مع مختلف الأحمال (مقاوميه، حثيه، ديناميكية وكذلك اللاخطية). كانت نتائج التنظيم للفولتية والتردد جيدة وكذلك كفاءة المولد كانت عالية ولكافة أنواع الأحمال. كما أظهرت نتائج الطيف للتوافقيات مع مختلف الأحمال عدم حصول أي تشوه للفولتية الخارجة (فولتية جيبيية).

## 1. Introduction

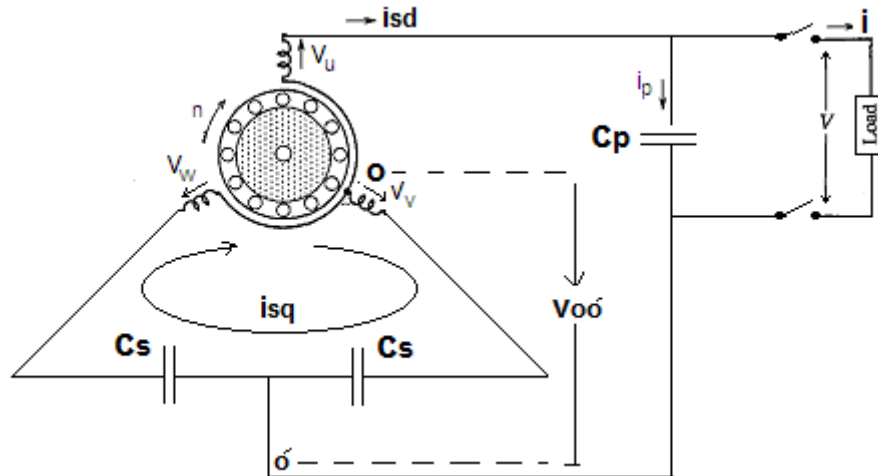
The squirrel cage induction generators are being used for power generator from renewable energy sources, such as, wind, biomass, biogas and mini-hydro plants. Since, in remote and rural areas, the electric loads are usually of single-phase types, the single-phase power supply is preferred over three-phase one in order to make the distribution system simple and cost effective <sup>[1], [2]</sup>. The single-phase ac generators fall into two types: synchronous and induction generators. Traditionally, the single-phase synchronous generator has been shown to be the preferred choice due to clear performance advantage, principally its good voltage characteristics. However, the single-phase induction generator can perform certain benefits over the single-phase synchronous generator such as maintenance-free, simple and inexpensive structure due to its squirrel-cage rotor type, Also the induction generator is self excited (no need to external supply for excitation like synchronous generator) <sup>[3], [4]</sup>. Three capacitors are externally connected in series and parallel with the stator winding of three-phase squirrel cage induction machine, and they will provide a self-regulating feature as well as a self-excitation, thus in the single-phase capacitor self-excited induction generator based on this scheme, a good voltage-regulation will show with respect to resistive, inductive and nonlinear loads without any control <sup>[5],[6],[7]</sup>. If this generator is adopted, a high reliability, high-performance are obtained compared with the single-phase synchronous generator.

In this paper, the system configuration, operation principle of the self-excited single phase induction generator are presented. The performance and basic characteristics with resistive, inductive, dynamic, and nonlinear (Thyristor controlled ac chopper) loads are investigated by means of simple analysis and experiments with a laboratory squirrel cage induction machine driven by dc machine.

## 2. System configuration and operating principle

### 2.1 System configuration

**Figure(1)**, shows a schematic diagram of the generator. The generator consists of a Y-connected squirrel cage three-phase induction machine and three capacitors,  $C_s$ ,  $C_p$ , connected in series and parallel with a single-phase load. Excitation with the three capacitors  $C_s$  and  $C_p$ , the generator will produce an excitation MMF efficiently, and so it can be obtained a stable excitation system even in the induction load. Moreover, since the two capacitors  $C_s$  are connected in series with the load, the generator can obtain the self-regulating feature. Furthermore, employing a Y-connected stator winding, the suppression of harmonic voltage will be easy, and the output voltage can be made sinusoidal.



**Fig.(1) Schematic diagram of the capacitor self-excited single-phase induction generator [5].**

## 2.2 Operation principle and method of voltage build-up

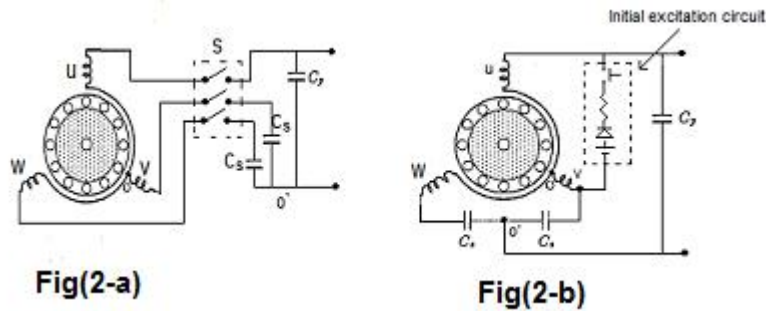
When the rotor of the generator is rotated using dc motor as a prime mover, the output voltage  $V$  will be build up across the load terminals by the self- excitation phenomenon due to the residual magnetism of the rotor and leading current flowing in the three capacitors  $C_s$  and  $C_p$ . The output voltage can be expressed see **Figure.(1)** as [5]:

$$\begin{aligned}
 V &= V_u - V_{o'o} \\
 &= V_u - [V_v + (j / (\omega C_s)) (-\frac{I_{sd}}{2} + I_{sq})] \\
 &= V_{uv} - (j / \omega C_s) (-\frac{I_{sd}}{2} + I_{sq}) \dots\dots\dots(1)
 \end{aligned}$$

Where  $V$ ,  $I_{sd}$  and  $I_{sq}$  are the phasor quantities of  $v$ ,  $i_{sd}$  and  $i_{sq}$  respectively.  $V_u$  and  $V_{o'o}$  are vector representations of  $v_u$  and  $v_{o'o}$  respectively. By assuming that the exciting current  $I_{sq}$  is constant independent of the load, it is seen from equation(1) that the voltage  $V_{o'o}$  which expresses the vector difference of line voltage  $V_{uv}$  and the voltage drop of  $C_s$ , acts so as to increase the output voltage.  $V$  with the increase of load due to the effect of  $C_s$  ( $I_{sq}$  is constant and  $I_{sq}/2$  increases with load). The output voltage  $V$  is loading condition becomes larger theoretically. However, in reality, it decreases due to the influences of the magnetic saturation and demagnetization of the air gap flux under load that are neglected in this study. Therefore, if the values of  $C_s$  and  $C_p$  are properly selected, the variation of the output voltage can be automatically compensated with respect to resistive and inductive loads.

The voltage is built up across the output terminals of the generator by using either the method shown in **Figure (2-A)** Or **Figure (2-B)**. Rotating the rotor by prime mover (DC

motor in this study) to its rated speed then the switch S is turned on as shown in **Figure(2-A)** The voltage is built up due the residual magnetism of the rotor core. Although it is enough with this method, there is a case where the voltage does not generate due to a small value of residual magnetism. In such case, it is desirable to use a method shown in **Figure (2-B)** by which, supplying dc current to the stator winding with a battery for short time, the voltage can be easily built up.



**Fig .(2) Circuit diagram showing the methods of voltage build-up .**

### 3. Experimental Results

In this section, the experimental setup is presented in order to obtain the performance of the induction generator by illustrating the basic characteristics in the resistive, inductive, dynamic and nonlinear load conditions.

#### 3.1 Experimental setup

The schematic diagram of the system is shown in **Figure(3)**. The system consists of a 4-pole, 5.5 kW, 50 Hz, 380V, Y- connection squirrel cage three-phase induction machine driven by dc motor. The speed is adjusted by varying the field current or armature voltage of dc motor. The characteristics described below show the results when the power rating of the tested machine for a single-phase load is estimated as a 3.17 kW( $=5.5/\sqrt{3}$ ). The maximum output power taken from induction generator is limited to 1.5 kW due to the limitation of the power rating of drive machine ( dc motor). In this test, the values of  $C_s$  and  $C_p$  so as to minimize the voltage regulation were also taken as 100 $\mu$ f by experiment. Further, the rotating speed was maintained constantly as 1500rpm.

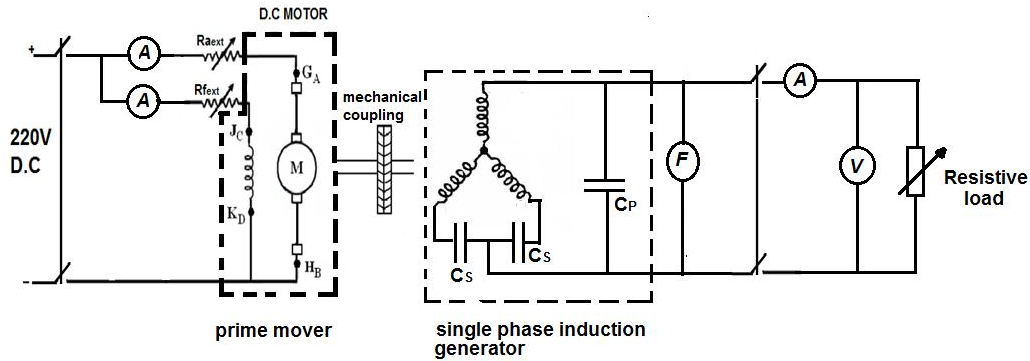


Fig .(3) Schematic diagram of the experimental setup with resistive load.

### 3.2 Results and discussion

The performance of the induction generator is experimentally studied for all types of load, and the results are shown as follows:

#### 3.2.1 Results for resistive load

**Figure (4)** shows the output voltage, efficiency ( $\eta$ ), load current ( $I$ ) and frequency ( $f$ ) with output power. The series capacitors ( $C_s$ ) and parallel capacitor ( $C_p$ ) are chosen as  $100\mu\text{f}$  and  $80\mu\text{f}$  respectively. The speed is maintained constant as 1500 rpm. From figure 4, it is confirmed that the voltage regulation of the generator is very small due to the effect of two series capacitors  $C_s$ . The frequency is approximately constant with very small variation around the 50-Hz value (about 0.37Hz at 1.37 kW). As shown in the figure, the maximum value of efficiency  $\eta$  of tested machine is equal to 86.6%.

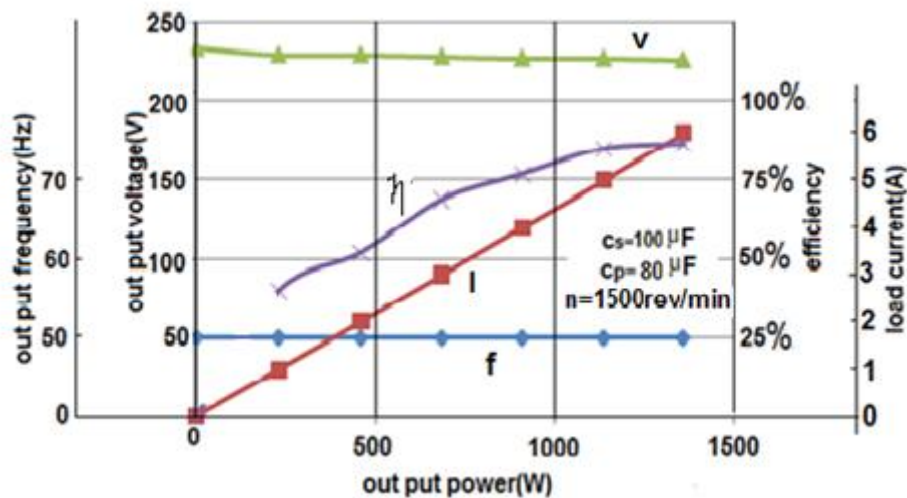


Fig .(4) Load characteristics for resistive load with  $C_s = 100\mu\text{F}$  and  $C_p = 80\mu\text{F}$ .

**Figure (5)** shows the output voltage, efficiency, load current and frequency with output power for  $C_s=C_p=100\mu\text{F}$  and the speed is maintained constant at 1500rpm. In this case the maximum efficiency of the tested machine is equal to 92%. The variation of the frequency was small about 0.4 Hz at 1.35kW.

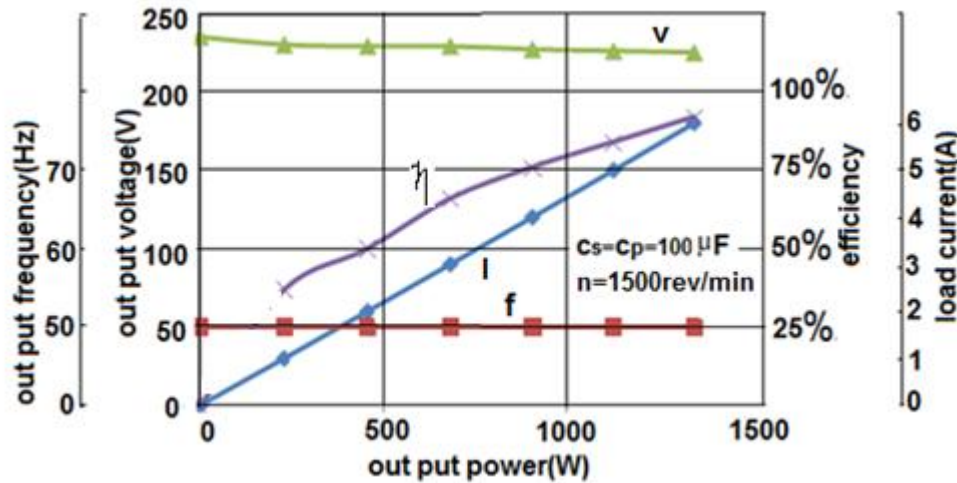


Fig .(5) Load characteristics for resistive load with  $C_s=C_p=100\mu\text{F}$  .

**Figure (6)** shows waveform and harmonics spectrum of the output voltage at 1.35 kW. In the used induction generator, since the stator winding is Y- connected three-phase the output voltage (load voltage) waveform is sinusoidal, which has no waveform distortions due to odd harmonics of multiple of 3.

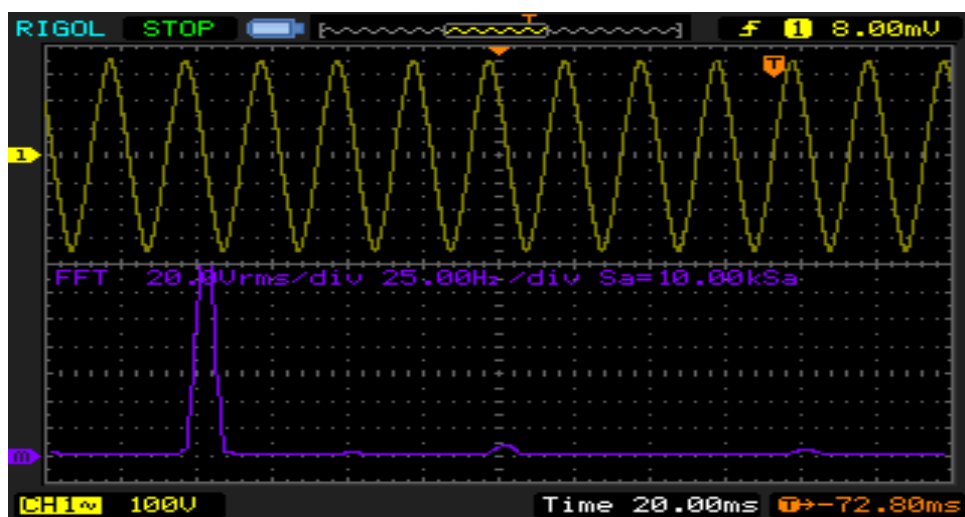
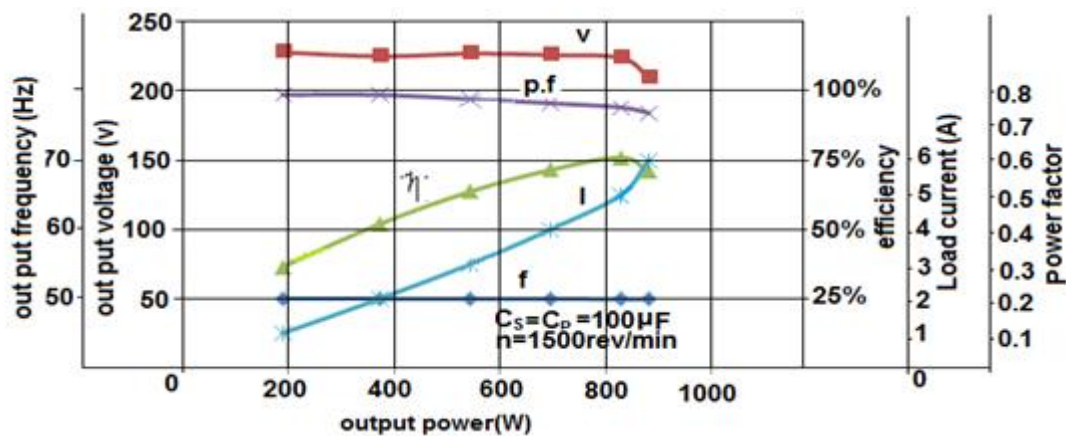


Fig .(6) Waveform and harmonics spectrum of output voltage at output power of 1.35Kw .

### 3.2.2 Results for inductive load

**Figure (7)** shows the output voltage, frequency, efficiency, load current and power factor with output power for  $C_s = C_p = 100\mu\text{F}$ . For output power less than 800W, the regulation of output voltage is small ( $\pm 5\text{V}$  around operating voltage of 220V), the regulation becomes larger at power higher than 800W. The variation of output frequency is very small around operating frequency (0.4-Hz at 0.88kW). The maximum efficiency of the tested machine is equal to 76% at 0.828kW.



**Fig .(7) Load characteristics for inductive load with  $C_s=C_p=100\mu\text{F}$**

Output voltage, frequency, efficiency and load current with output power are shown in **Figure (8)** for  $C_s=C_p=100\mu\text{F}$  and constant power factor of 0.8 value. The regulation of the output voltage is better compared with **Figure (7)**. The variation of the output frequency is small (0.5Hz) and the maximum efficiency is equal to 68.8% at 0.927kW. Comparing figure7 and figure8, we can notice that voltage regulation is better (small) for power factor equals or larger than 0.8 and bad voltage regulation is obtained at power factor smaller than 0.7. The reactive power that is required for induction generator to excite it and reactive power for inductive load depend on the values of capacitors. For higher load, the need to reactive power becomes more, this cause a drop in the output voltage and more current drawn from the motor which causes also a drop in the efficiency. Therefore for the same values of capacitors, the output power for good voltage regulation and efficiency are higher for resistive load .If one needs to increase the load (output power) for inductive load ,the values of capacitors must be increased to obtain small voltage regulation.



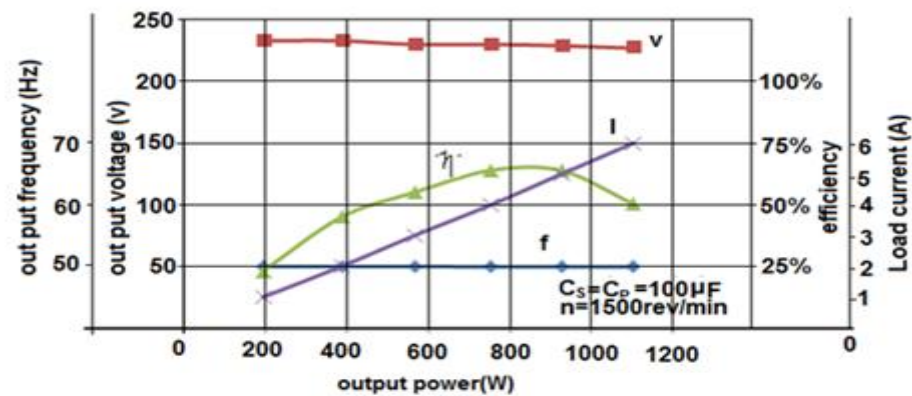


Fig .(8) Load characteristics for inductive load with  $C_s=C_p=100\mu F$  and constant power factor of 0.8

Figure (9) shows waveform and harmonic spectrum of the output voltage at 0.927kW output power and 0.8 power factor, no odd harmonic are noticed and the waveform of output voltage is sinusoidal.

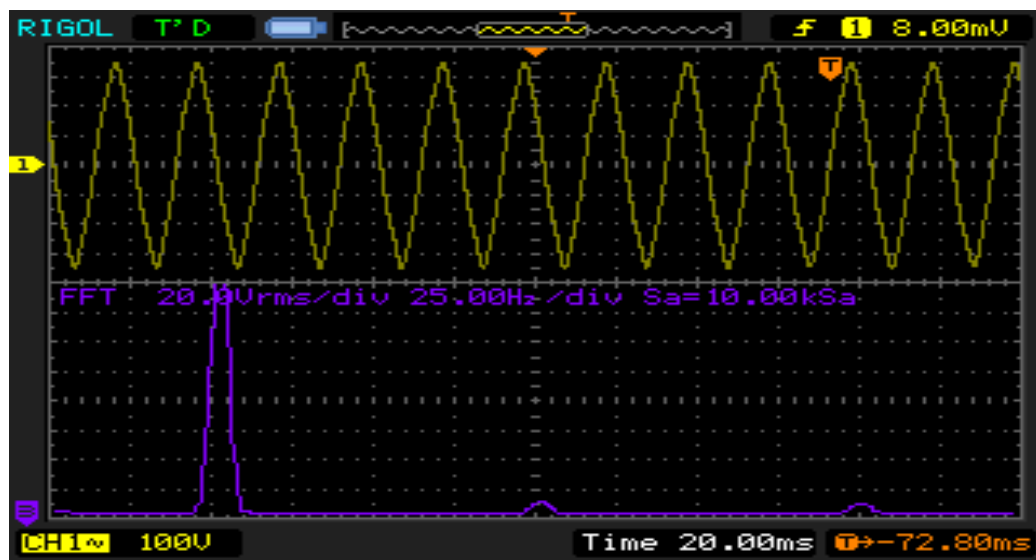
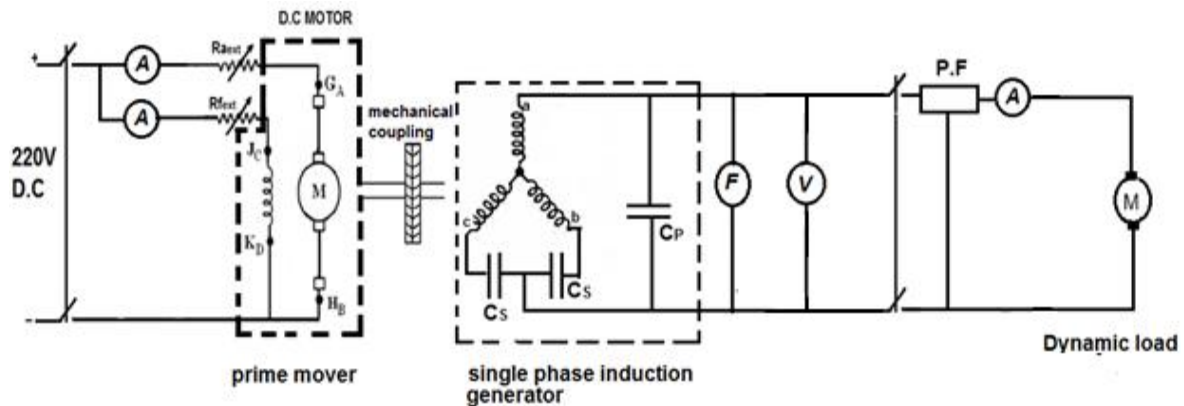


Fig .(9) Waveform and harmonics spectrum of output voltage for output power of 0.927Kw.



### 3.2.3 Results for dynamic load (load is single phase induction motor)

The schematic diagram of the single-phase induction generator feeding dynamic load is shown in **Figure (10)**.



**Fig .(10) Schematic diagram of single feeding single phase induction generator phase induction motor.**

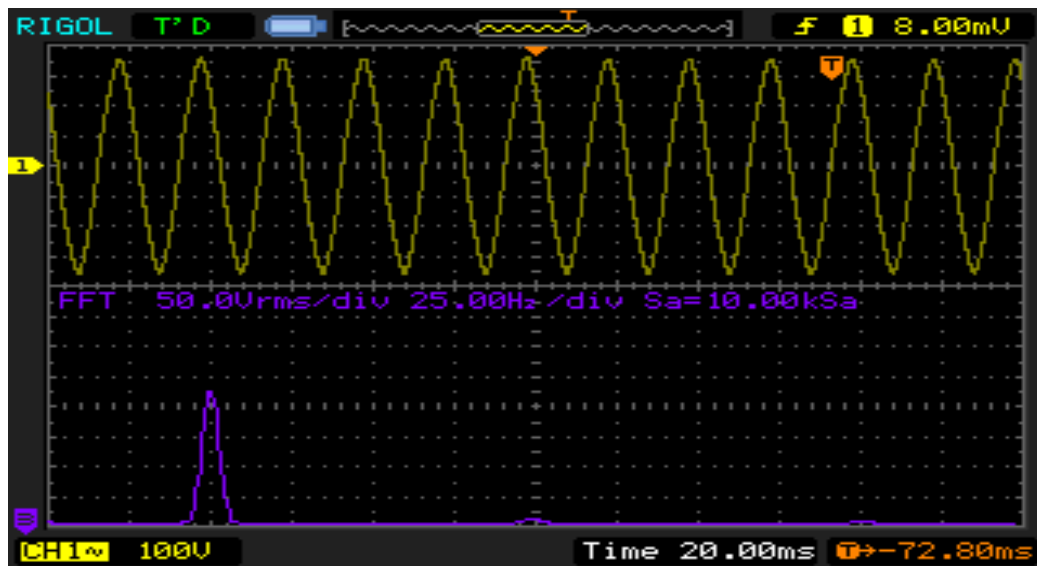
The generator consists of a three-phase star- connected induction machine with three capacitor,  $C_p$  and two  $C_s$  and a single-phase induction motor as a load. Two capacitors ( $C_s$ ) are connected in series with the two phases of the stator winding and one ( $C_p$ ) is connected in parallel with the motor load.

Two type of single phase induction motor are used : permanent capacitor motor and capacitor start motor. The specifications of permanent capacitor motor are (220V, 0.37kW(0.5hp), 2.5A, 2900rpm and  $C=10\mu\text{F}/450\text{V}$ ).The results for permanent capacitor single phase induction motor are shown in **Table (1)**

**Table (1) Results for permanent capacitor single phase induction motor as a load**

Generator voltage(V)	$I_L$ (A)	$f$ (Hz)	Pf	$I_a$ (A)	$I_b$ (A)	$I_c$ (A)
235	1.0	49.8	0.8	3.25	5.2	3.6

**Figure(11)** shows waveform and harmonics spectrum of the output voltage of generator for permanent capacitor single phase induction motor as a load. Clearly one can see that the voltage is sinusoidal with no waveform distortion at starting and steady state.



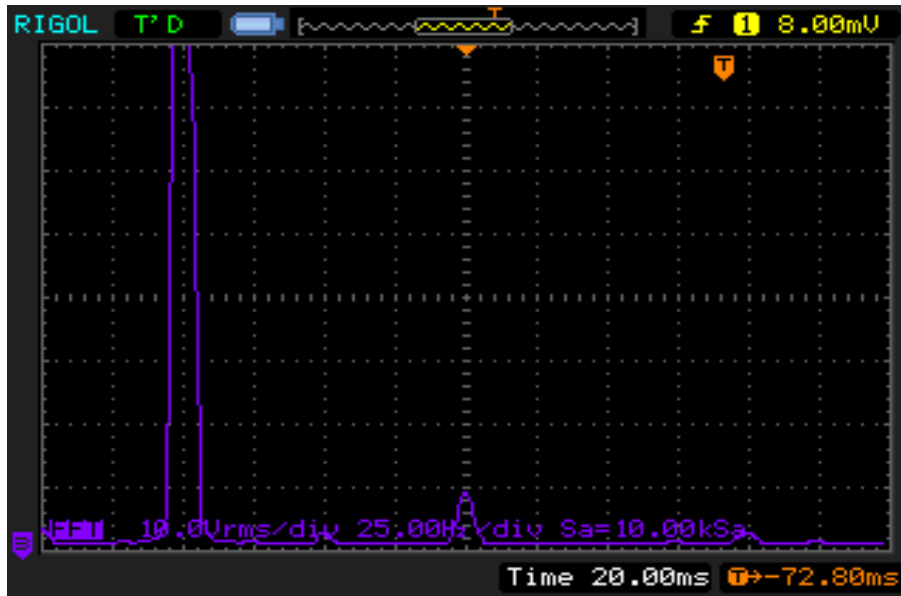
**Fig .(11) Waveform and harmonics spectrum of output voltage of single phase generator feeding permanent capacitor single phase induction motor**

The specifications for capacitor- start single phase induction motor that is used as a load are: 220 V, 50Hz, 1400rpm, 1.6A, 0.25hp, starting capacitor =  $9\mu\text{F}/450\text{V}$  .The results for this type of load are shown in **Table (2)**.

**Table (2 )Results for capacitor-start motor as a load**

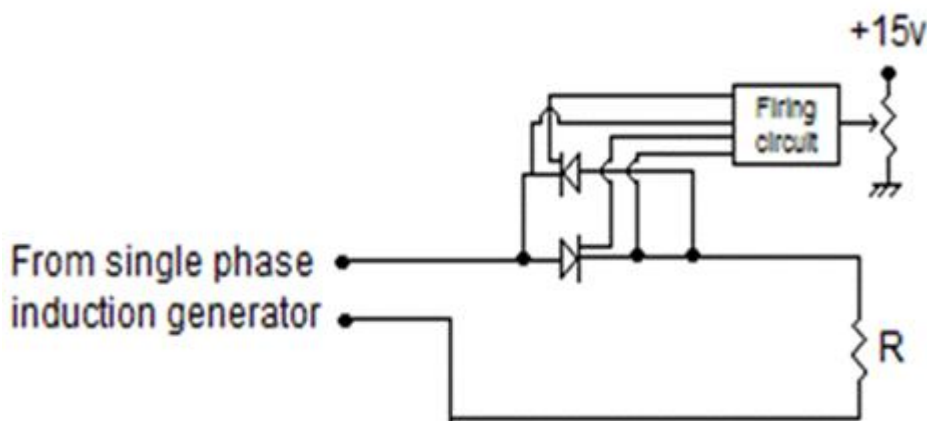
Generator voltage(V)	$I_L$ (A)	f(Hz)	Pf	$I_a$ (A)	$I_b$ (A)	$I_c$ (A)
235	1.6	50	0.95	3.47	4.75	5.87

**Figure(12)** shows waveform and harmonics spectrum of the output voltage of generator for capacitor start single phase induction motor as a load. The waveform of the voltage is sinusoidal with no harmonics at starting and running.



**Fig .(12) Harmonics spectrum of output voltage for single phase induction generator feeding capacitor-start single phase induction motor.**  
**3-2-4 Results for non-linear load using thyristor AC chopper**

**Figure (13)** shows the schematic diagram of non-linear load fed from single phase induction generator. An ac chopper is used and single phase firing circuit is presented to fire thyristors of ac chopper with different firing angles through control voltage. The output of ac chopper is applied to resistive load. **Table (3)** shows the results for different firing angles and  $R=200\Omega$



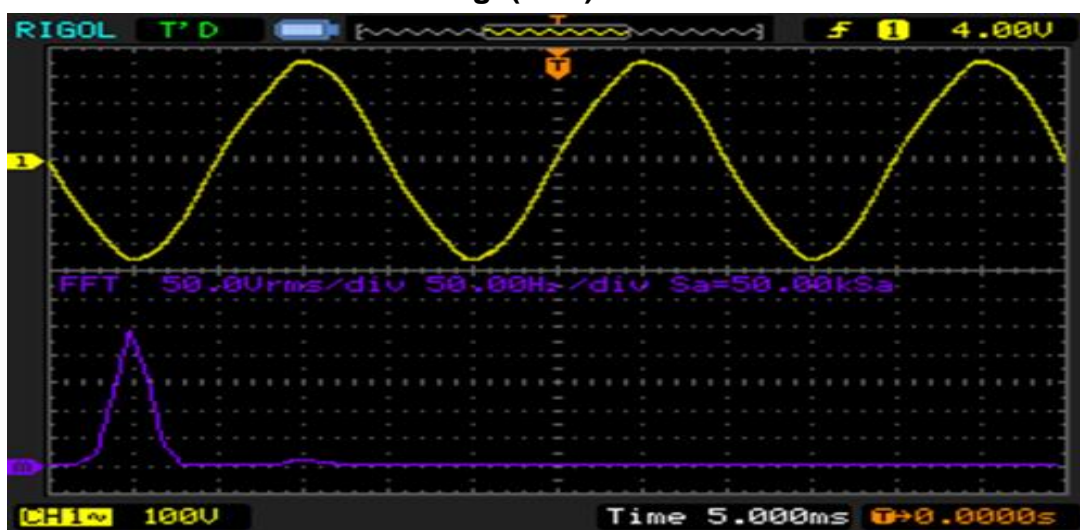
**Fig .(13) Schematic diagram of nonlinear load (thyristorac chopper in series with resistive load)fed from single phase induction generator.**

**Table (3) Results for different firing angles and  $R=200\Omega$** 

Firing angle $\alpha$ in degrees	Generator voltage(V)	Load current(A)	Pf	f(Hz)	Load voltage(V)
18	240	1.0	0.98	49.9	238
90	241	0.6	0.65	49.9	145

From above table we can notice that the power factor and load voltage are reduced with increasing firing angle.

**Figure (14)** shows the waveforms and the harmonics spectrum of the load voltage and generator voltage for firing angle of  $18^\circ$  value. Fig. 15 and fig. 16 are similar to fig. 14 but with  $90^\circ$  and  $144^\circ$  firing angles respectively. The generator voltage is not affected (remains sinusoidal) by varying the firing angle but the load voltage is chopped and its RMS value is reduced depending on the firing angle.

**Fig .(14-a)****Fig .(14-b)**

**Fig .(14) Waveform and harmonics spectrum of a-load voltage , b-generator voltage .Firing angle= $18^\circ$**

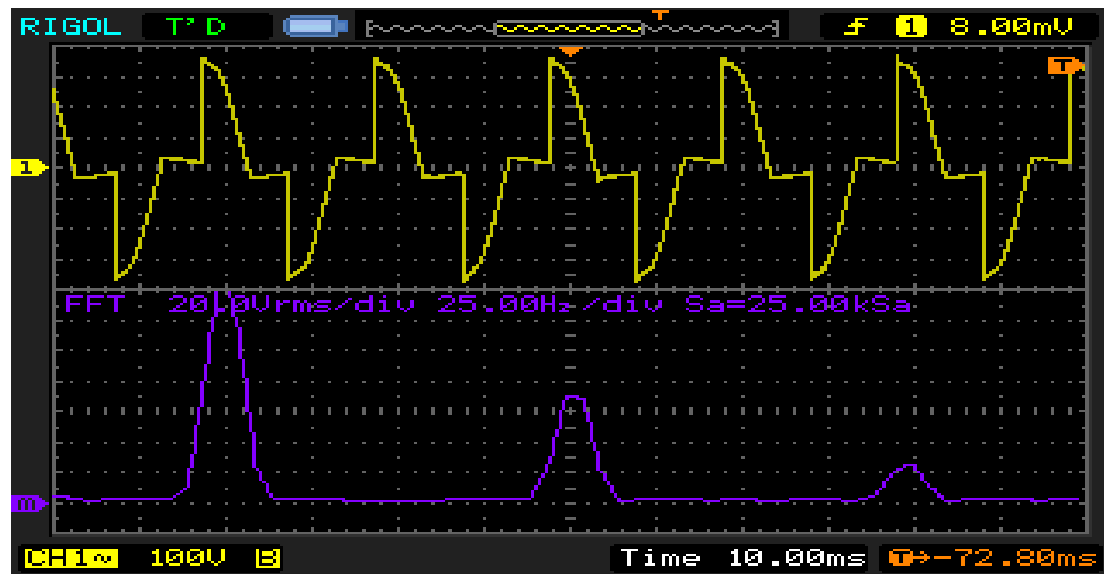


Fig .(15-a)

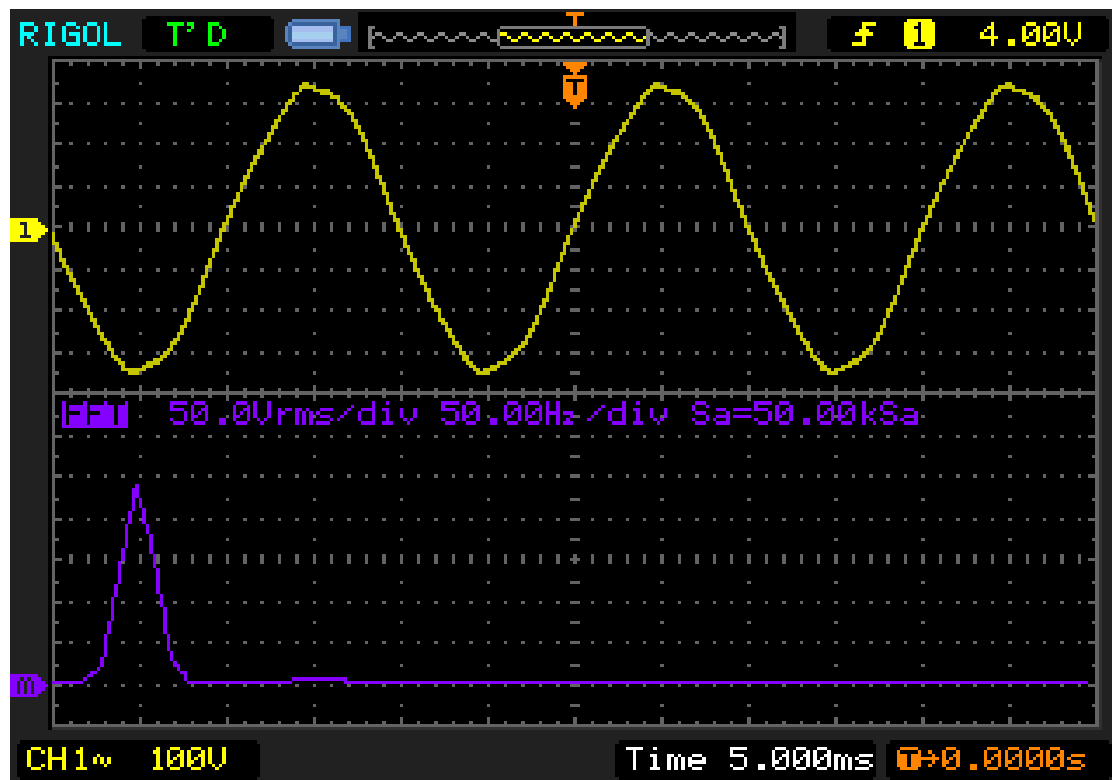


Fig .(15-b)

Fig .(15) Waveform and harmonics spectrum of a-load voltage ,b-generator voltage .Firing angle= $90^{\circ}$ .

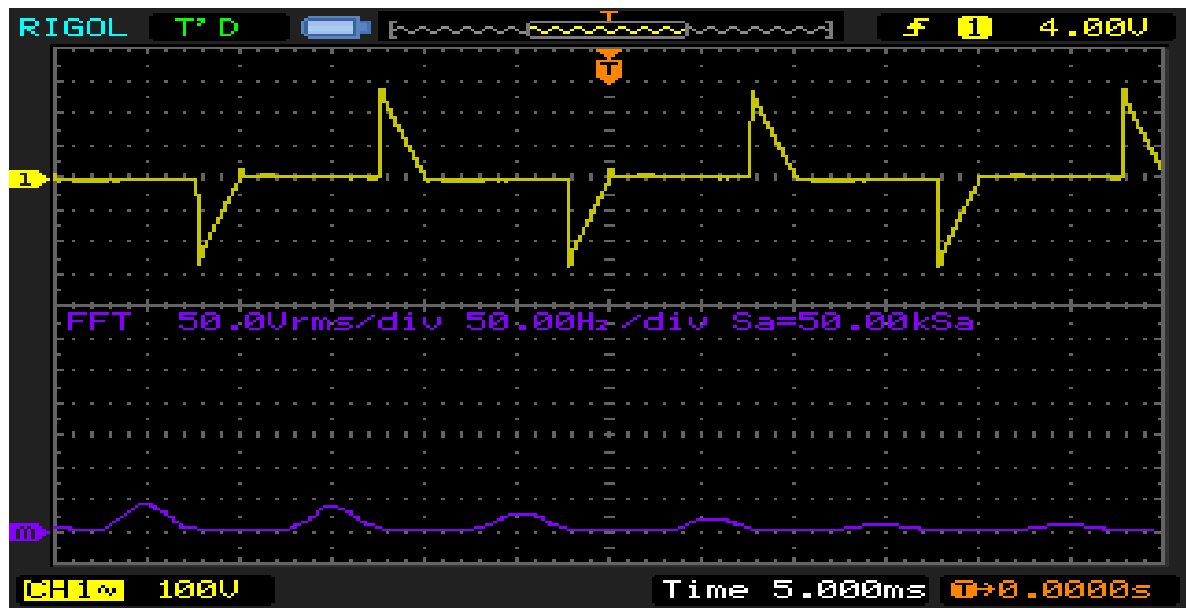


Fig .(16-a)

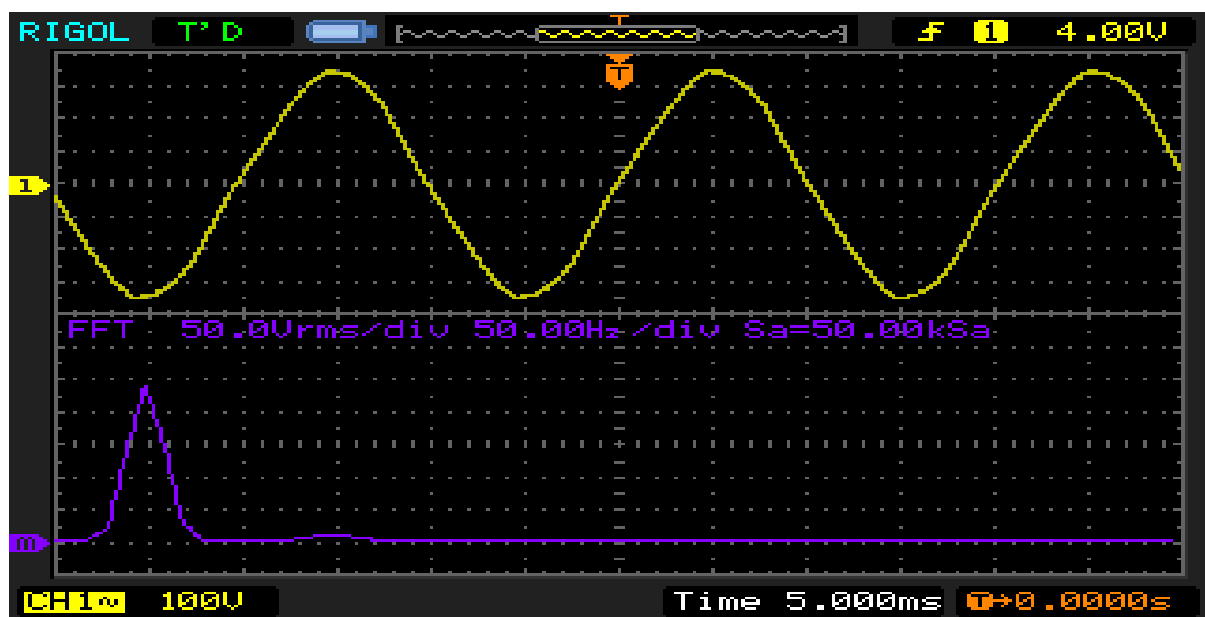


Fig .(16-b)

Fig .(16) Waveform and harmonics spectrum of a-load voltage, b-generator voltage. Firing angle= 144°.

## 4. Conclusions

In this paper, we tested a single-phase induction generator with self-regulating feature that consists of the three-phase induction machine and the three capacitors. Different types of load are used such as resistive, inductive, dynamic (single-phase induction motor) and nonlinear (thyristor AC chopper) loads.

The operating principle and basic characteristics are clarified by experiments. The generator has the following advantages:

- (1) Exciting with the three capacitors, it can be obtained a stable excitation even in the inductive, dynamic and non-linear loads.
- (2) Its voltage regulation is very small due to the effect of three capacitors with all types of load.
- (3) Since the Y-connected stator winding is employed, the waveform of the output voltage can be made sinusoidal.
- (4) With operation of constant speed, the regulation of frequency is very small and is not affected by the output power for all types of load.
- (5) The obtained results show that the self-excited single-phase induction generator has good performance with different types of loads (low voltage regulation and small frequency variation with constant speed). A good application for this generator is a portable engine generator with a few hundred watts to about 5-kilowatts. Rectifier-inverter cascade is required for wind energy application to obtain 220V, 50 Hz output voltage across the load due to variation of wind speed( the frequency of generator voltage is varied with speed).

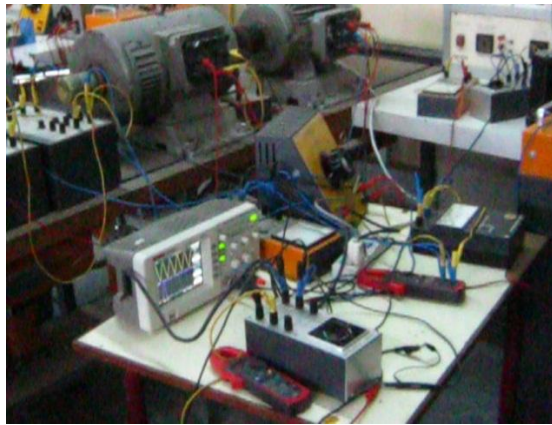
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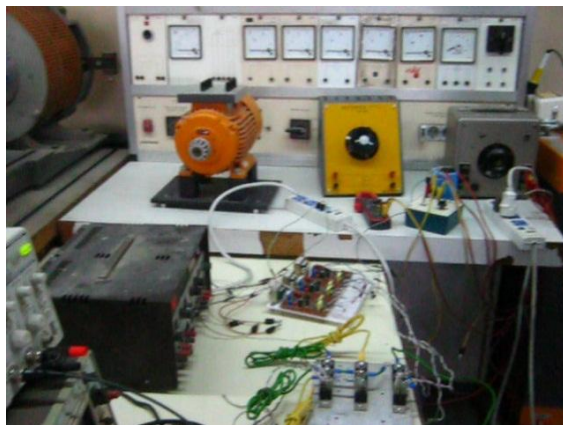
## Appendix :Setup Photos



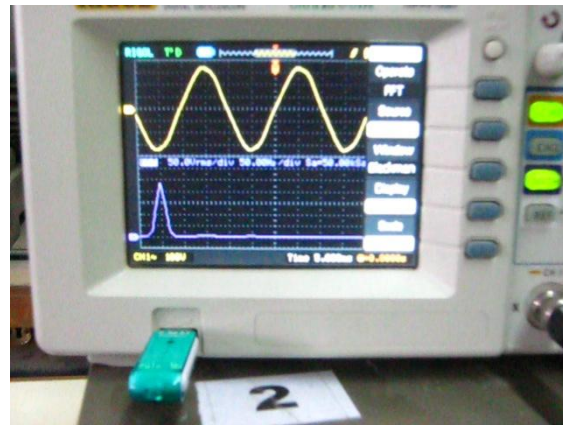
(a)



(b)



(c)



(d)

**Fig .(A-1System setup) : (a) DC motor , induction generator and measurement instruments. (b)Series and parallel capacitors. (c) AC chopper circuit and firing circuit. (d) Oscilloscope showing the waveform and spectrum of generator voltage.**