"Study and Measure the Active and Reactive Power Developed By a Three Phase Induction Generator with Capacitive Load"

Surajit Mondal, Oisik Mishra, Sanchari Chakraborty, Tirtharaj Sen

***Abstract*— An induction generator or asynchronous generator is a type of AC electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotor faster than the synchronous speed, giving negative slip. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls. An induction generator must be excited with a leading voltage; this is usually done by connection to an electrical grid, or sometimes they are self excited by using phase correcting capacitors.**

In this project we use different combinations of capacitors to study and analyze the active and reactive power flow of an induction generator.

***Index Terms*— Induction Generator, Active power, Reactive Power, Capacitive load bank.**

I. INTRODUCTION

An induction generator or asynchronous generator is a type of AC electrical generator that uses the principles of induction motors to produce active power. A prime mover drives the rotor above the synchronous speed. The presence of residual magnetism produces a stator flux. A relative motion between the rotor and the stator flux is achieved. The stator flux follows the rotor in the operation of an induction generator .However the stator flux still manages to induce current in the rotor conductors which give rise to the rotor flux. The opposing rotor flux now cuts the stator coils, an active current is produced in stator coils, and the motor now operates as a generator. However a source of excitation current for magnetizing flux (reactive power) for stator is still required, to induce rotor current. A capacitor bank is used to supply the reactive power to the motor when used in stand-alone mode.

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The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor. Terminal voltage will increase with capacitance, but is limited by iron saturation.

II. INDUCTION GENERATOR OPERATION

Generator Operation

- In generator operation
  - – The rotor spins above synchronous speed
  - – It develops a counter-torque that opposes the over speed
    - same effect as a brake
  - – The rotor returned the power as electrical energy instead of dissipating it as heat
    - referred to as asynchronous generation
    - kinetic energy is converted into electrical energy
  - – The motor delivers active power to the electrical system
  - – The electrical system must provide reactive power to create the stator's rotating magnetic field

Active power delivered to the line is directly proportional to the slip – higher engine speed produces greater electrical output

– Rated output power is reached at very small slips, $|s| < 3\%$

Reactive power sources

-Capacitor across the motor terminals will supply the VARs.

- The motor supplies the3-phase electrical load without an external 3-phase source
- The frequency generated is slightly less than corresponding to the speed of rotation
- The terminal voltage increases with capacitance, but limit by iron saturation
- Insufficient capacitance causes the voltage not to build up

-Capacitors must at least supply the KVAr normally absorbed when the machine operates as a motor.

Complete Torque Speed Characteristics

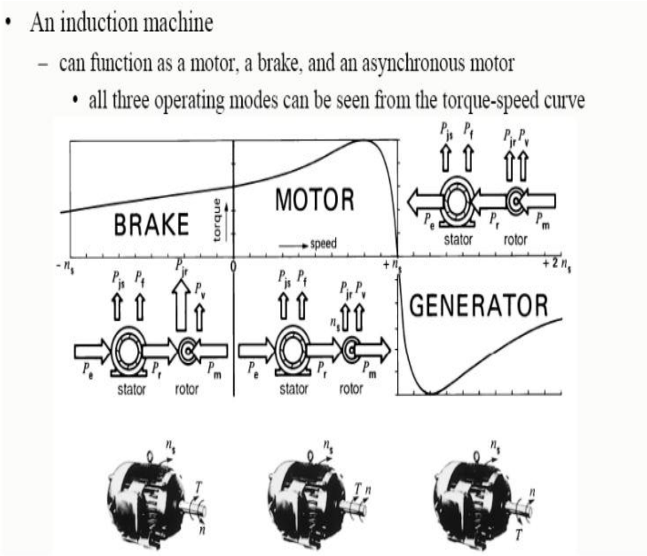


Fig 1 : braking, Motoring and Generating Characteristics of an Induction Motor

Braking Mode (s>1)
For this mode slip is greater than unity. A slip(s) more than one can be obtained by driving the rotor, with a prime mover opposite to the direction of the rotating field. But such an use in practice is rare. A practical utility of slip more than one is obtained by bringing the rotor to a quick stop by braking option called plugging. For obtaining s>1 or for obtaining plugging any two stator leads are interchanged. With this the phase sequence is reversed and therefore the direction of rotating magnetic field becomes suddenly opposite to that of the rotor rotation. The electromagnetic torque now acting opposite to rotor rotation produces the braking action. Thus the motor can be quickly brought to rest by plugging, but the stator must be disconnected from the supply before the rotor can start in the other direction.

Motoring Mode (0<s<=1)
Under normal operation, rotor revolves in the direction of the rotating field produced by stator currents. As such the slip varies from 1 at standstill to zero at synchronous speed i.e. 1<=s>=0.

Generating Mode (s<0)
For this operating mode slip is negative i.e. s<0. An induction motor will operate in this region only when its stator terminals are connected to constant frequency-voltage source and its rotor is driven above synchronous speed by a prime mover. The connection of stator terminals to voltage source is essential in order to establish the rotating air gap field at synchronous speed. In case stator is disconnected from voltage source and rotor is driven above synchronous speed by the prime mover no generating action would take place.

Induction Machines, the most widely used motor in industry, have been traditionally used in open-loop control applications, for reasons of cost, size, reliability, ruggedness, simplicity, efficiency, less maintenance, ease of manufacture and its ability to operate in dirty or explosive conditions. However, because the induction machine requires more complex control methods, the dc machine has predominated in high performance applications. With developments in Micro-processors/DSPs, power electronics and control theory, the induction machine can now be used in high performance variable-speed applications.

The induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control. But both of these schemes result in very low efficiencies at lower speeds. The most efficient scheme for speed control of induction motor is by varying supply frequency. This not only results in scheme with wide speed range but also improves the starting performance.

Applications

- With energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.
- Because of their simplicity and small size per kilowatt of output power, induction generators are also favored very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer's total power needs. In such operation, the power system can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction.

III. Comparison of Synchronous and Induction Generators

There are two types of generators available: Synchronous and Induction types.

Synchronous generators have the DC field excitation supplied from batteries, DC generators or a rectified AC source. When DC generators are used they may be driven from the AC generator shaft directly or by means of a belt drive or they may be separately driven, independent from the AC generator. In any of the above applications, DC is applied to the field through brushes riding on slip rings attached to the rotor.

Brushless generators use a small AC generator driven directly from the shaft. The AC output is rectified and the DC is applied directly to the main generator field. The exciter generator configuration is reversed from the normal generator in that the armature is rotated with the main generator shaft and the field is fixed. In this way, the AC output can be fed to a rectifier assembly which also rotates and the resulting DC connected directly to the main generator field without brushes or slip rings.

Synchronous generators are rated in accordance with NEMA Standards on a continuous duty basis. The rating is expressed in KVA available at the terminals at 0.80 power factor. The corresponding KW should also be stated. For example, a 400

KW generator would be rated 500 KV A at 0.80 power factor.

An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

When a squirrel cage induction motor is energized from a power system and is mechanically driven above its synchronous speed it will deliver power to the system. Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. For example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc.

Since the induction generator is actually an induction motor being driven by a prime mover, it has several advantages.

1. It is less expensive and more readily available than a synchronous generator.

2. It does not require a DC field excitation voltage.

3. It automatically synchronizes with the power system, so its controls are simpler and less expensive. The principal disadvantages of an induction generator are listed.

1. It is not suitable for separate, isolated operation

2. It consumes rather than supplies magnetizing KVAR

3. It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)

4. In general it has a lower efficiency.

IV. Mathematical Verification of Generator Operation

All parameters are per phase values

Let

V_1= applied voltage to stator of the induction motor
I_1= stator current
I_2= rotor current
I_m= magnetizing current
R_1=stator resistance
R_2=rotor resistance
X_1=stator reactance
X_2=rotor reactance
X_m=magnetizing reactance
s= slip
Pg= air gap power (direction of flow from stator to rotor)
Ns= synchronous speed
Nr= rotor speed

s= (Ns-Nr)/Ns & Pg= $I_2^2R_2/s$
To operate as an induction generator the rotor of an induction motor is run above the synchronous speed i.e. Nr>Ns
s= - (Ns-Nr)/Ns
Hence slip is negative
So, Pg= $-I_2^2R_2/s$ (-ve)
Therefore the air gap power Pg is negative i.e. power flows from rotor to the stator i.e. the motor behaves as a generator.

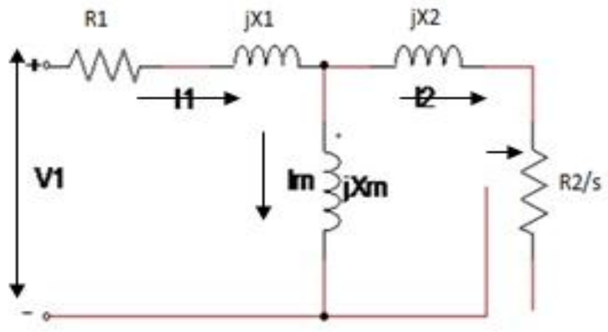


Fig: 2 Equivalent Circuit of Induction Motor showing parameter values

V. Voltage Build Up in an Induction Generator

The build-up of voltage of the d-c shunt generator is known to depend upon residual magnetism in the field poles of the machine and upon the resistance of the field circuit, the final build-up voltage being determined by the field circuit resistance. It has been discovered that the induction generator with static capacitance connected in shunt across its terminals will build up its voltage in a manner similar to the build-up of the d-c shunt generator. Residual magnetism in the iron of the magnetic circuit sets up a small alternating voltage in the stator; this voltage applied to the capacitance causes a lagging magnetizing current to flow in the stator windings. If the capacitance is of the proper value, the current that can flow will be large enough to increase the flux existing in the air gap. An increase in the air gap flux gives rise to higher voltage larger exciting current drawn by the capacitance, more air gap flux and so on until the terminal voltage reaches its final build up value. This value is determined by the saturation curve of the machine and by capacitive reactance of the connected capacitance. Operating as a shunt generator, a short circuit will cause the generator to lose its voltage and the residual magnetism is destroyed preventing the machine from again building up. Any method which gives temporary excitation to the iron will restore the residual magnetism.

A capacitor bank is connected across the stator terminals of a 3 phase induction machine. When the rotor of the induction machine is run at required speed, residual magnetism present in the rotor iron generates a small terminal voltage ‘oa’ across stator terminals .This voltage produces a capacitor current 'ob'. This current 'ob' creates a flux which aids the residual flux, thus producing more flux and therefore more generated voltage 'b c' across stator terminals. This voltage 'bc' sends a current 'od' in the capacitor bank which eventually generates voltage 'de' .This cumulative process of voltage build up continues till the saturation curve of induction generator intersects the capacitor load line at point 'f', thus giving a no load generated e.m.f. of 'gf' for magnetizing current Im_1. The voltage build up process is similar to shunt generator. If the residual flux is absent in the rotor iron then the induction generator will not build up. This problem can however be overcome by running the machine as a poly phase induction motor for some time to create residual magnetism.

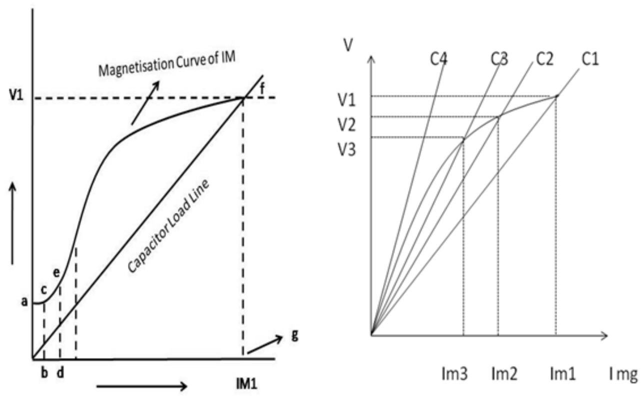


Fig 3 : Volatgebuild up process in 3 phase induction generator.

The voltage build up depends on the value of the capacitor. Higher the value if capacitance, greater is the voltage build up. In case capacitor load line does not intersect the magnetization curve of induction machine there would be no voltage build up. Hence voltage build up for capacitor C4 does not occur.

EFFECT OF CAPACITOR BANK CONNECTED ACROSS STATOR TERMINALS OF A 3 PHASE INDUCTION GENERATOR

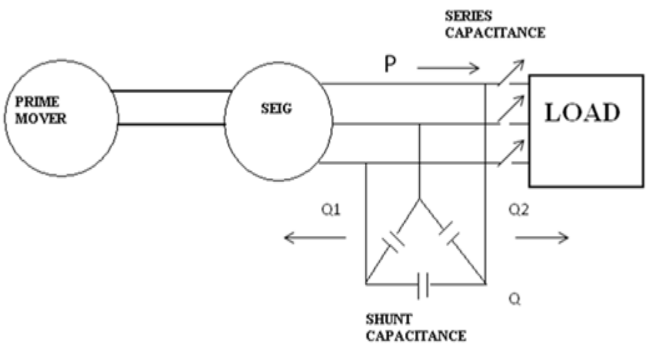


Fig 3: A Capacitor bank connected across the stator terminals of a 3 phase induction generator

Capacitive reactive power = reactive power needed by 3 phase induction generator (Q1) + reactive power needed by the load (Q2)

VI. EXPERIMENT

AIM – Study and measure the active and reactive power developed by a 3 phase induction generator with capacitive load

APPARATUS- A dc shunt motor mechanically coupled to a Squirrel Cage Induction motor, 3 phase rectifier, Ammeter, Multi-meter, Wattmeter, Capacitive load bank, Tachometer and connecting wires.

SPECIFICATIONS

DC motor (Prime Mover)
Output-3.5 K.W
Voltage-220V
Current-17Amps
Speed-1440 rpm
Wound-Shunt
Insulation- Class B
Maker- ELECTRO ENTERPRISE

Induction motor
K.W/H.P- 5.5/7.5
Phase-3
Pole-4
Volt- 415+10%
Current-11Amps
Speed-1440 rpm
Ambient Temperature-45^{o}C
Delta connected
%Duty-51
Maker-Compton Greaves

3 phase rectifier

AC	DC
Phase-3	Volts- 0-220 V
Volts- 440 V	Amperes- 0-30 A
Amperes-10 A	
Cycles-50	

Rating- CMR
DEVP&DESGND (Electrical Engineering Service Supply Syndicate)

Capacitive load bank
6uF / 440 V + 10% AC
Cycles- 50

Measuring Instruments

SL No	Name of Instrument	Quantity/Type	Range	Maker
1.	Ammeter	1/M.I	0-1-2A	MECO V
2.	Multi-meter	1	0-600V & 0-1KHz	CIE
3.	Wattmeter	2/Electrodynamometer	C.C 0-1-2 A P.C 0-150V-300V-600V	Automatic Electrical Limited
4.	Tachometer	1	0-9999 rpm	LUTRON
5.	Rheostat	1	500 Ohms/ 2A	EESSS(I)
6.	MCB	1/EA	415 V/ 10,000 A	HAVELL'S

VII. PROCEDURE

In this experimental procedure we successfully generated electrical power from an *induction motor* by operating it as an *induction generator*. In order to run an induction motor above the *synchronous speed* to make it operate as an induction generator we have taken a dc machine (as a motor) with a shunt field connection. The connection is made using a *rheostat* for field flux control to obtain a variable speed operation. 3phase supply is obtained from the main's which is rectified using a 3 phase *rectifier*. Two of the leads are used as the supply to the dc machine. The speed of the dc machine is controlled and a speed above the synchronous speed of the 3 phase induction motor is achieved. Thus the 3 phase induction motor is operated as an induction generator. Then in order to measure the active and reactive power flow, a capacitive load bank is connected using a MCB and the *two wattmeter method* of power measurement is used.

CIRCUIT DIAGRAM

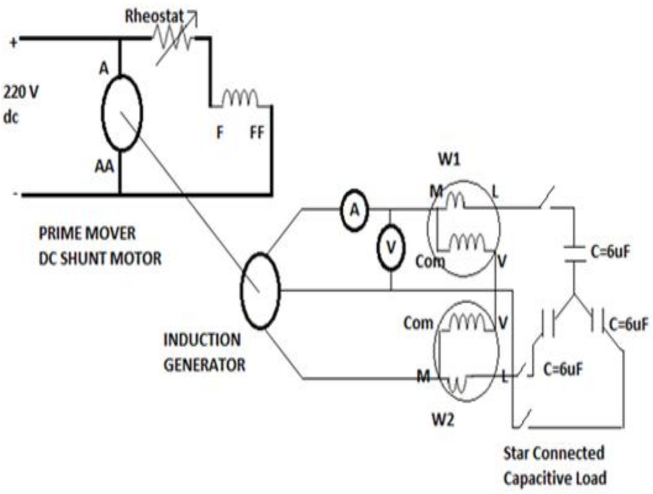


Fig 3: Circuit Diagram for the experiment

CALCULATIONS USED

W1= Wattmeter 1 reading
W2= Wattmeter 2 reading
Per phase active power delivered to the load P= (W1+W2)/3
Now, P=VI Cos θ V= Multi-meter reading, I= Ammeter reading, Cos θ= P/ (V*I)
Sin θ= (1- (Cos θ) ^2) ^1/2
Reactive Power Q= VI Sin θ

OBSERVATION

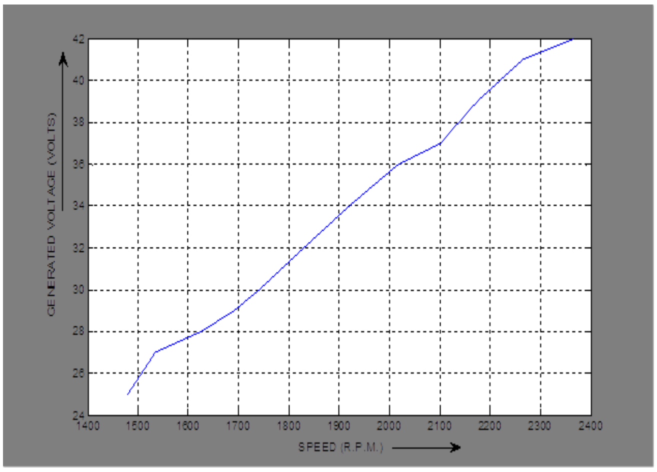
The induction motor under observation is a 4 pole machine hence its synchronous speed is given as Ns= 120*f/p f= operating frequency, p= No of poles. So Ns= 120*50/4= 1500 rpm.

No Load condition

SL No	SPEED OF INDUCTION MACHINE (rpm)	GENERATED VOLTAGE BY INDUCTION GENERATOR (Volts)
1	1480	25
2	1535	27
3	1628	28
4	1692	29
5	1740	30
6	1830	32
7	1920	34

8	2016	36
9	2100	37
10	2175	39
11	2265	41
12	2364	42

VARIATION OF GENERATED VOLTAGE BY THE INDUCTION GENERATOR AND THE SPEED OF THE INDUCTION GENERATOR



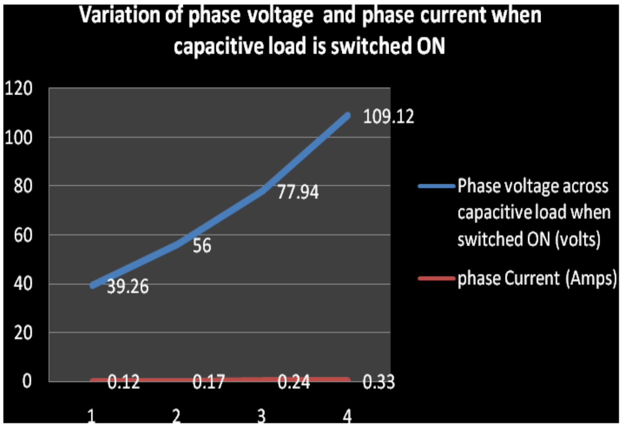
Previously due to presence of residual magnetism in the stator core of the induction generator even though the speed of the controlled prime mover is slightly less than the synchronous speed we obtain a certain amount of voltage as the stator flux is linked with the rotor conducting bars of the squirrel cage rotor of the induction generator. With a considerable amount of increase in the speed of the induction machine by the prime mover above the synchronous speed of the induction machine under consideration the generated voltage also increases.
On Load (When Capacitive Load bank is switched ON)
When 6uf/440 Volts Capacitor (Connected in star) is used as Load

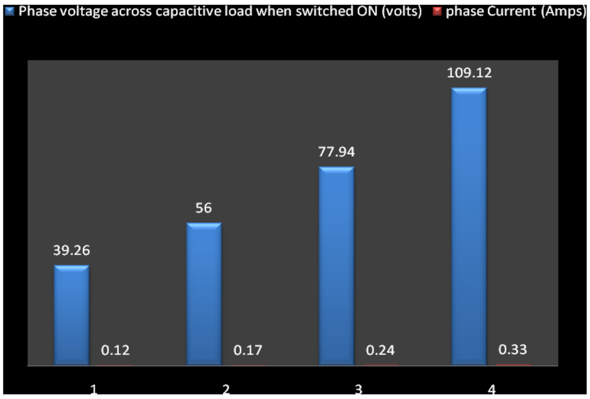
SL No	Speed (rpm)	Line to Line voltage impressed across the capacitive load initially when switched OFF (volts)
1	1798	31
2	1920	34
3	2016	36
4	2364	42
6	1830	32
7	1920	34
8	2016	36
9	2100	37
10	2175	39
11	2265	41
12	2364	42

Under load when a 6uF/440 volts capacitive load bank is connected across the load terminals of the induction generator a different speed the capacitive load bank supplies the induction generator with lagging reactive VA in order to sustain the magnetic field of the rotor. We notice the increase in voltage from no load to load conditions when the capacitive load bank is switched ON. With an increase in the speed under load the load voltage, load current and the operating frequency of the machine also increases.

Variation of load voltage and load current of the induction generator connected to a capacitive load bank.

Phase voltage across capacitive load when switched ON (volts)	phase Current (Amps)
39.26	0.12
56	0.17
77.94	0.24
109.12	0.33



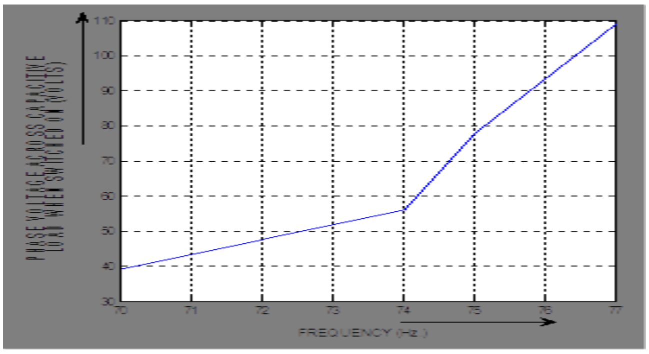


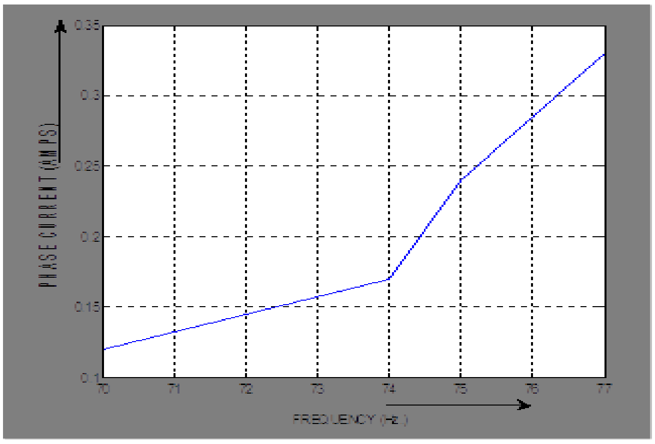
VIII. Calculation of Active and Reactive Power

SL No	Speed rpm	Per phase power (W1+W2)/3 watts	Per phase voltage with capacitive load connected(volts)	Load current (Amps)	Frequency	Power factor Cos θ	Sin θ	Total Active Power Delivered by the IG (=per phase power*3) (Watts)	Total Reactive power absorbed by the IG (=per phase power*3) (Watts)
1	1798	1	39.26	0.12	70	0.21	0.98	3	13.85
2	1920	3.33	56	0.17	74	0.35	0.94	10	26.85
3	2016	9	77.94	0.24	75	0.48	0.88	27	49.4
4	2364	20.33	109.12	0.33	77	0.56	0.83	61	89.66

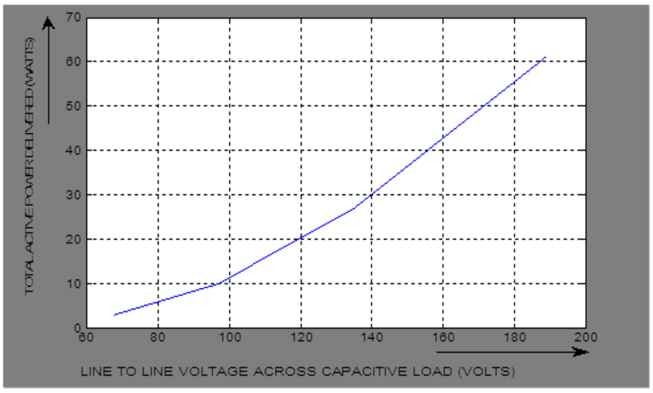
It can be witnessed that with an increase in speed there is an increase in frequency, power factor, active power delivered by the machine and the reactive power absorbed by the machine.

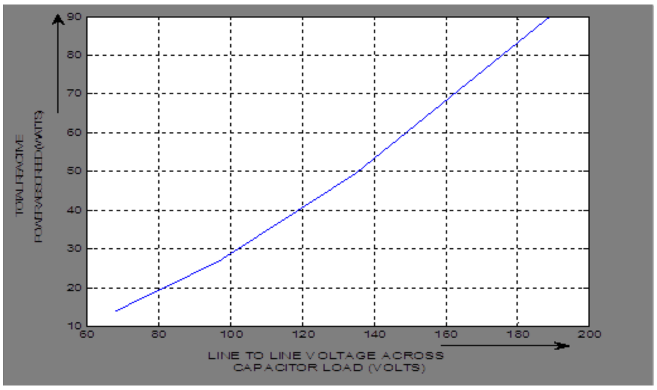
Variation in operating frequency of the induction generator with load voltage and load current





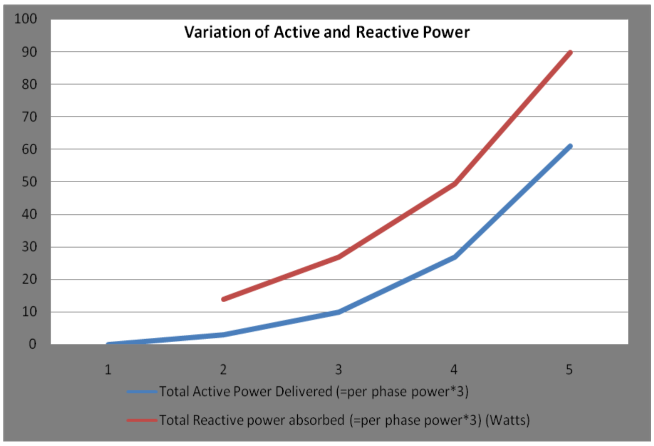
Active Power (Watts) Vs. Line To Line Voltage (Volts) Across Capacitor Load Plot





Reactive Power (Watts) Vs. Line To Line Voltage (Volts) Across Capacitor Load Plot:

The amount of reactive power consumed by the induction generator is more compared to the amount of active power delivered by the machine. In this case the capacitive load bank supplies the reactive power to the induction generator to sustain the magnetic flux of the rotor.



IX. CONCLUSION

This experiment successfully helped to acknowledge the operating principle of an induction generator. The induction generator was operated under both no load and on load conditions which helped us to derive the changes in various operating parameters like frequency, power factor etc. We measured the amount of active and reactive power delivered and consumed by the induction generator when operating under stand alone condition. Such a study is very essential regarding the future implication of induction generator in various fields.

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