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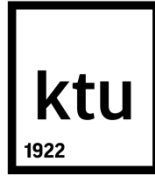Siva Krishna, Rangisetti

INVESTIGATION OF AIR COMPRESSORS CONTROL SYSTEM

Final project for Master degree

Supervisor
Assoc. Prof. Dr. Brazauskas Kestutis

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Control Technology (code 621H66001)

Supervisor
(signature) Assoc. Prof. Dr. Brazauskas Kestutis
(date)

Reviewer
(signature)
(date)

Project made by
(signature) Siva Krishna, Rangisetti
(date)

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" INVESTIGATION OF AIR COMPRESSORS CONTROL SYSTEM"

DECLARATION OF ACADEMIC HONESTY

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Summary:

In the investigation of air compressor control system, it chooses the "HV turbo single stage air compressor". We are considering in this the parallel air compressors which are coupled with the three-phase squirrel cage induction motor for the power supply. By considering the measurement values we identified the two types of algorithms, performance characteristics of Volumetric flow and power are designed in "Matlab Simulink" and also how the input power, output power, volumetric flow rate, Energy and Efficiency are calculated at different load positions. And the parallel air compressors are maintained under constant pressure. In this two Simulink models are created with the results and schematics diagram is included mainly in this report.

Chapter 1-2 deal with, about the air compressor and types. In this we use the HV turbo compressors are explained in detail. Chapter 3 deals with the components of compressor.

Chapters 4-5 are the schematic representation and algorithm's has been identified, Simulink model has designed by using the measured values and performance characteristics.

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Letter's Notation:

L: The average valve positions are said to be load and it is in %

F: Total volumetric flow rate in m3/h (cubic meter per hour).

A: The atmospheric air was taken from outside.

F1: The first compressor of volumetric flow rate in m3/h (cubic meter per hour).

F2: The second compressor of volumetric flow rate in m3/h (cubic meter per hour).

F3: The third compressor of volumetric flow rate in m3/h (cubic meter per hour).

F4: The fourth compressor of volumetric flow rate in m3/h (cubic meter per hour).

V1: The first valve position of collector in %.

V2: The second valve position of collector in %.

V3: The third valve position of collector in %.

V4: The fourth valve position of collector in %.

T: The temperature is in K (Kelvin).

P1: The first compressor consumed power is in Kw (kilo- watts).

P2: The second compressor consumed power is in Kw (kilo- watts).

P3: The third compressor consumed power is in Kw (kilo- watts).

P4: The fourth compressor consumed power is in Kw (kilo- watts).

OP1: The First compressor output power is in Kw (kilo- watts).

OP2: The second compressor output power is in Kw (kilo- watts).

OP3: The Third compressor output power is in Kw (kilo- watts).

OP4: The Fourth compressor output power is in Kw (kilo- watts).

V: Voltage of Three-phase squirrel-cage-motor in V (Volt).

I1: Current of first compressor in A (ampere).

I2: Current of second compressor in A (ampere).

I3: Current of third compressor in A (ampere).

I4: Current of fourth compressor in A (ampere).

K: Compressor was indicated by this letter for user identification.

P: Summation of all powers in Kw (kilo- watts).

p: pressure of collector tank is in 680mbar (millibar).

M: Three-phase squirrel-cage-motor.

η_m = motor efficiency

P_{out} = shaft power out (Watt, W)

P_{in} = electric power in to the motor (Watt, W)

1. INTRODUCTION:

An **air compressor** is a device that converts power (usually from an electric motor, a diesel engine or a gasoline engine) into kinetic energy by compressing and pressurizing air, which, on command, can be released in quick bursts. There are numerous methods of air compression, divided into either positive-displacement or negative-displacement types.

An air compressor takes the air in a room and forces it into a container under pressure. The more air forced into the container the greater the air pressure that builds up inside. The compressed air can be discharged from the container at a controlled rate. The compressed air is used to power a variety of tools and machinery. For example, compressed air is used to power pneumatic wrenches and lifts in automobile service stations. Compressed air is also used for heavy machinery and paint spray booths in industrial plants.

There are several types of air compressors. The different types include the reciprocating, centrifugal, rotary and solar compressors. The only real difference between these compressors is the way in which they compress the air. The most commonly used air compressor is the reciprocating air compressor. Air compressors are sometimes called air pumps. The air compressors can be powered by electric motors, internal combustion engines or steam turbines.

The most common power source is an electric motor. A typical industrial air compressor is in some locations there may be a buildup of flammable gases. For example, there may be a buildup of flammable gases in service stations and workshops. Flammable gases are usually heavier than air and fall to the floor before spreading outward. The flammable gases are easily ignited by sparks and high temperatures. They may be ignited by the heat generated by the air compressor. If the flammable gases are ignited inside the compressor it will cause an explosion.

2. Air Compressor Types and Components

There are three basic types of air compressors:
   a) Reciprocating (Recip),
   b) Rotary Screw (Screw),
   c) Rotary Centrifugal (Centrifugal),
   d) Turbo compressor.

a) Reciprocating Units:

Reciprocating air compressors are positive displacement compressors. This means they are taking in successive volumes of air which is confined within a closed space and elevating this air to a higher pressure. The reciprocating air compressor accomplishes this by using a piston within a cylinder as the compressing and displacing element.

The intake gas enters the suction manifold, then flows into the compression cylinder where it gets compressed by a piston driven in a reciprocating motion via a crankshaft, and is then discharged. Applications include oil refineries, gas pipelines, plants, natural plants and refrigeration plants. One specialty application is the blowing of plastic bottles made of polyethylene terephthalate (PET).

Fig 2.a. The reciprocating air compressor with one collector.

The reciprocating air compressor is considered single acting when the compressing is accomplished using only one side of the piston. A compressor using both sides of the piston is considered double acting.

The reciprocating air compressor uses a number of automatic spring loaded valves in each cylinder that open only when the proper differential pressure exists across the valve.

Inlet valves open when the pressure in the cylinder is slightly below the intake pressure. Discharge valves open when the pressure in the cylinder is slightly above the discharge pressure.

A compressor is considered to be single stage when the entire compression is accomplished with a single cylinder or a group of cylinders in parallel. Many applications involve conditions beyond the practical capability of a single compression stage. Too great a compression ration

(absolute discharge pressure/absolute intake pressure) may cause excessive discharge temperature or other design problems.

For practical purposes most plant air reciprocating air compressors over 100 horsepower are built as multi-stage units in which two or more steps of compression are grouped in series. The air is normally cooled between the stages to reduce the temperature and volume entering the following stage.

One or more pistons are moved inside a cylinder to increase the gas pressure. This is similar to a combustion engine without the ignition of fuel. Just like a car, the pistons generate much heat so the reciprocating compressor is typically cooled by air or water. Multi-stage reciprocating compressors pass the compressed gas from one cylinder to another, increasing the pressure in each stage. Most industrial compressors are multi-stage, ranging from one to 500 or more horsepower.

In the ionic liquid piston compressor many seals and bearings were removed in the design as the ionic liquid does not mix with the gas. Service is about 10 times longer than a regular diaphragm compressor with reduced maintenance during use, energy costs are reduced by as much as 20%. The heat exchangers that are used in a normal piston compressor are removed as the heat is removed in the cylinder itself where it is generated. Almost 100% of the energy going into the process is being used with little energy wasted as reject heat.

In a reciprocating compressor, a volume of gas is drawn into a cylinder; it is trapped and compressed by piston, then discharged into the discharge line. The cylinder valves control the flow of gas through the cylinder; these valves act as check valves.

Reciprocating air compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations, may be packaged, and provide a wide range of pressure and capacity selections.

b) **Rotary Screw Compressors**:

Rotary air compressors are positive displacement compressors. The most common rotary air compressor is the single stage helical or spiral lobe oil flooded screw air compressor. These compressors consist of two rotors within a casing where the rotors compress the air internally. There are no valves. These units are basically oil cooled (with air cooled or water cooled oil coolers) where the oil seals the internal clearances.

Construction:

A typical oil flooded twin screw compressor consists of male and female rotors mounted on bearings to fix their position in a rotor housing which holds the rotors in closely toleranced intersecting cylindrical bores. The rotors basic shape is a screw thread, with varying numbers of lobes on the male and female rotors. The driving device is generally connected to the male rotor with the male driving the female through an oil film.

In refrigeration, four or five lobed male rotors generally drive six or seven lobe female rotors to give a female rotor speed that is somewhat less than the male speed. Some designs connect the drive to the female rotor in order to produce higher rotor speeds thus increasing displacement. However, this increases loading on the rotors in the area of torque transfer and can reduce rotor life.
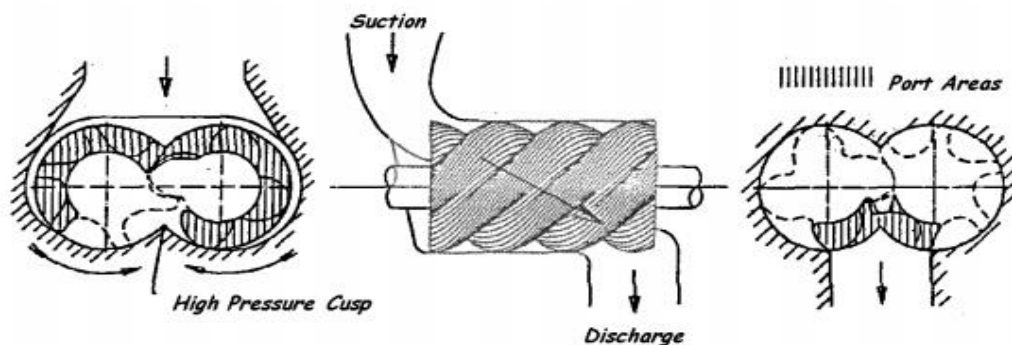

Fig 2.b.1: The compressor vanes of how it sucks and discharge of air diagram.

Fundamentals of operation:

A screw compressor is best described as a positive displacement volume reduction device. Its action is analogous to a reciprocating compressor more than any of the other common compressor types. It is helpful to refer to the equivalent recip. process to visualize how compression progresses in a screw. Gas is compressed by pure rotary motion of the two intermeshing helical rotors. Gas travels around the outside of the rotors, starting at the top and traveling to the bottom while it is transferred axially from the suction end to the discharge end of the rotor area.

Suction process:

Suction gas is drawn into the compressor to fill the void where the male rotor rotates out of the female flute on the suction end of the compressor. Suction charge fills the entire volume of each

screw thread as the enmeshing thread proceeds down the length of the rotor. This is analogous to the suction stroke in a reciprocating compressor as the piston is drawn down the cylinder.
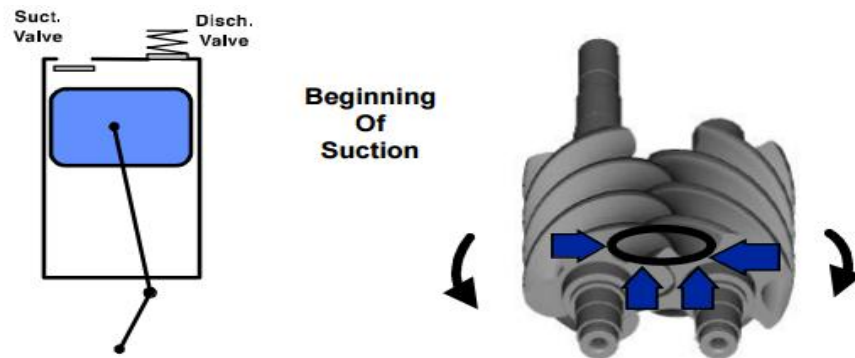

Fig 2.b.2: Compressor beginning of suction.

The suction charge becomes trapped in two helically shaped cylinders formed by the screw threads and the housing as the threads rotate out of the open suction port. The volume trapped in both screw threads over their entire length is defined as the volume at suction, (Vs). In the recip. analogy the piston reaches the bottom of the stroke and the suction valve closes, trapping the suction volume, (Vs).
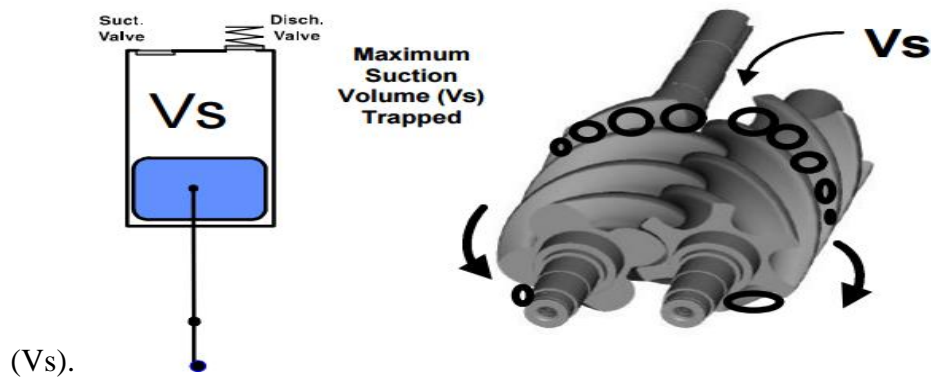

Fig 2.b.3: Compressor maximum suction volume trapped by vanes.

The displacement per revolution of the recip. is defined in terms of suction volume, by the bore times the stroke times the number of cylinders. The total displacement of the screw compressor is the volume at suction per thread times the number of lobes on the driving rotor.

Compression:

The male rotor lobe will begin to enter the trapped female flute on the bottom of the compressor at the suction end, forming the back edge of the trapped gas pocket. The two separate gas cylinders in

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each rotor are joined to form a "V" shaped wedge of gas with the point of the "V" at the intersection of the threads on the suction end.

Further rotation begins to reduce the trapped volume in the "V" and compress the trapped gas. The intersection point of the male lobe in the female flute is like the piston in the recip. that is starting up the cylinder and compressing the gas ahead of it.
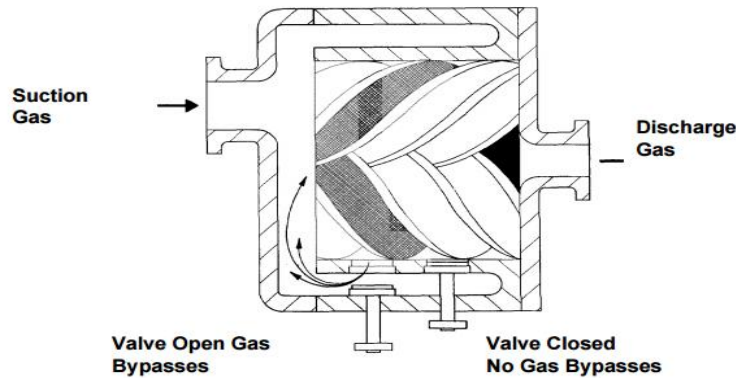

Fig 2.b.4: Rotary Screw Compressors

The gas compression process of a rotary screw is a continuous sweeping motion, so there is very little pulsation or surging of flow, as occurs with piston compressors.

Two helical rotors force gas into a chamber that decreases in size, thereby increasing the pressure of the gas. The screws in the rotary screw compressor can be lubricated with oil or non-lubricated. Oil-free compressors are used for gas that must remain clean and uncontaminated. Rotary screw compressors are typically sized from 30-200 horsepower.

Rotary compressors consist of a rotor with a number of blades inserted in radial slots in the rotor. The rotor is mounted offset in a larger housing that is either circular or a more complex shape. As the rotor turns, blades slide in and out of the slots keeping contact with the outer wall of the housing. Thus, a series of decreasing volumes is created by the rotating blades.

Since the cooling takes place right inside the compressor, the working parts never experience extreme operating temperatures. The rotary compressor, therefore, is a continuous duty, air cooled or water cooled compressor package.

Because of the simple design and few wearing parts, rotary screw air compressors are easy to maintain, operate and provide great installation flexibility. Rotary air compressors can be installed on any surface that will support the static weight.

Small rotary compressors are available in 4-37 kW (5-50 hp) sizes with fixed or variable speed options. Ingersoll Rand small rotary compressors provide whisper quiet and efficient operation that yields up to 35% energy savings. Utilizing design simplicity and Ingersoll Rand's legendary reliability, you can maximize your productivity with a small rotary compressor

The two stage oil flooded rotary screw air compressor uses pairs of rotors in a combined air end assembly. Compression is shared between the first and second stages flowing in series. This increases the overall compression efficiency up to fifteen percent of the total full load kilowatt consumption.

The two stage rotary air compressor combines the simplicity and flexibility of a rotary screw compressor with the energy efficiency of a two stage double acting reciprocating air compressor. Two stage rotary screw air compressors are available air cooled and water cooled and fully packages.
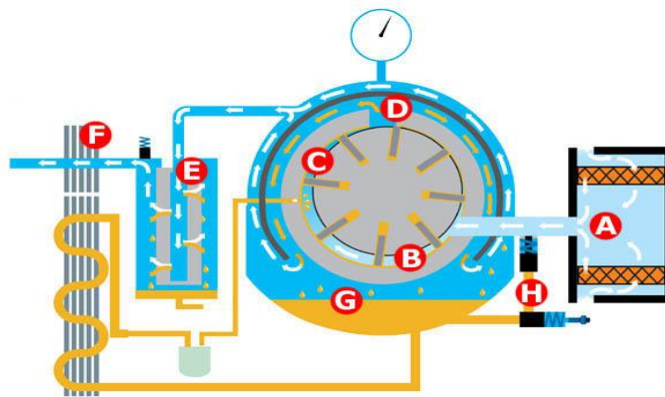

Fig 2.b.5: Working of Rotating vane compressors

The oil free rotary screw air compressor utilizes specially designed air ends to compress air without oil in the compression chamber yielding true oil free air. Oil free rotary screw air compressors are available air cooled and water cooled and provide the same flexibility as oil flooded rotaries when oil free air is required.

Rotary screw air compressors are available air cooled and water cooled, oil flooded and oil free, single stage and two stage. There is a wide range of availability in configuration and in pressure and capacity.

c) Centrifugal Compressor:

The centrifugal air compressor is a dynamic compressor which depends on transfer of energy from a rotating impeller to the air. The rotor accomplishes this by changing the momentum and pressure of the air. This momentum is converted to useful pressure by slowing the air down in a stationary diffuser.
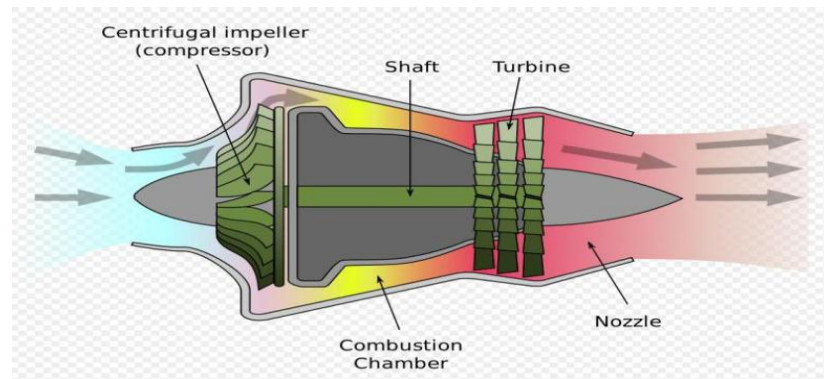

Fig 2.c: The working of centrifugal air compressor

Centrifugal compressors speed up and compress gas via a rotor with blades. Centrifugal force is used to force the air or gas to an outer chamber under higher pressure. Centrifugal compressors are designed to operate above 75-80% speed. Surging can occur below these speeds. This makes the centrifugal compressor ideal for continuous high duty operation.

Rotary screw compressors are widely used today in industrial refrigeration for compression of ammonia and other refrigerating gases.

Simple in concept, the screw geometry is sufficiently difficult to visualize that many people using screws today have only a vague idea how they actually work. An understanding of the basics of their operation will help in applying them correctly, avoiding nuisance problems in operation, and achieving the best overall system designs.

The centrifugal air compressor is an oil free compressor by design. The oil lubricated running gear is separated from the air by shaft seals and atmospheric vents.

The centrifugal is a continuous duty compressor, with few moving parts, that is particularly suited to high volume applications, especially where oil free air is required. Centrifugal air compressors are water cooled and may be packaged; typically the package includes the after-cooler and all controls.

d) **Turbo compressor:**

Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers. In the centrifugal-type dynamic compressors, the shape of the impeller blades determines the relationship between air flow and the pressure (or head) generate.

Driver:
In general the units are equipped with a standard, 2-poled or 4-poled, foot mounted horizontal electric motor, but drivers such as turbines or gas engines can be supplied.

**Local Control panel:**
(optional)
The HV-TURBO local control panel is specially designed for monitoring and controlling HV-TURBO compressors in automatic operation.

Gearbox:
The gearbox is integrated with the compressor, and designed to meet compressor power and speed demands.

Compressor:
The compressor is a single stage, high performance, centrifugal compressor, developed to meet demands for high efficiency, wide regulating range, and stable operation.
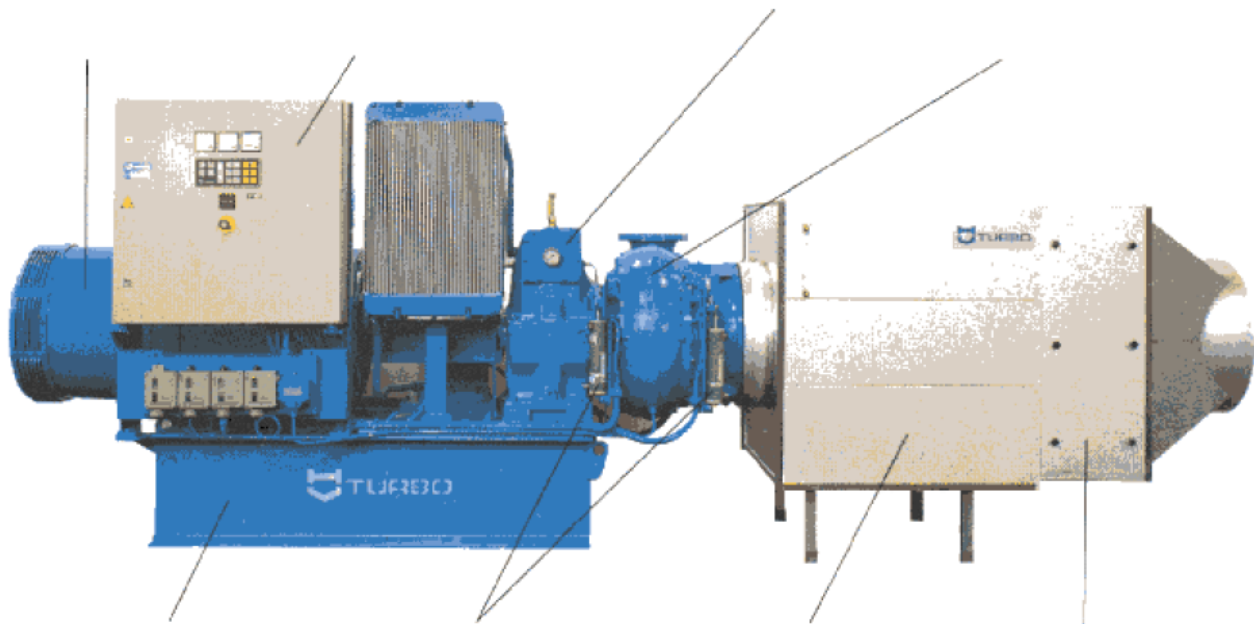
Baseplate:
The integrally geared compressor and the driver are mounted an a common rigid base plate, in which the lube oil system is integrated as well.

Linear actuators:
Linear actuators, electric or pneumatic, control the compressor head and flow capability.

Inlet silencer:
The inlet silencer reduces the suction noise and can be delivered for suction from inlet duct or from the compressor room.

Inlet filter (optional):
Inlet filter mounted on inlet silencer equipped with replaceable filter elements.

Fig 2.d.1: The construction part of turbo compressor.

HV-TURBO designs and manufactures the complete turbo compressor installation, i.e.:

· Compressor package comprising integrated compressor/gearbox, coupling, electric motor, and lube oil system all mounted on a common base plate with silent blocks.

Main Features

· Variable flow with a turn down to 45% at a constant speed.

· Low operation costs due to extremely high efficiency over the whole regulating range.

· Low noise level without pressure pulsations means that discharge silencer can be omitted.

· Compact design and low weight means low housing and installation costs.

· Guaranteed oil free air delivery

· Long lifetime with minimum maintenance.

Turbocharger is a device added to the internal combustion engine that leverages the exhaust gas to inject air into the cylinder (combustion chamber). A turbocharger includes a pair of radial rotors connected in one axis, which rotate as one side and the other as a turbine compressor.

This impeller is a centrifugal compressor , responsible for capturing the atmospheric air and compress it at the entrance of the intake or intake manifold of the engine via hoses or pipes high pressure.
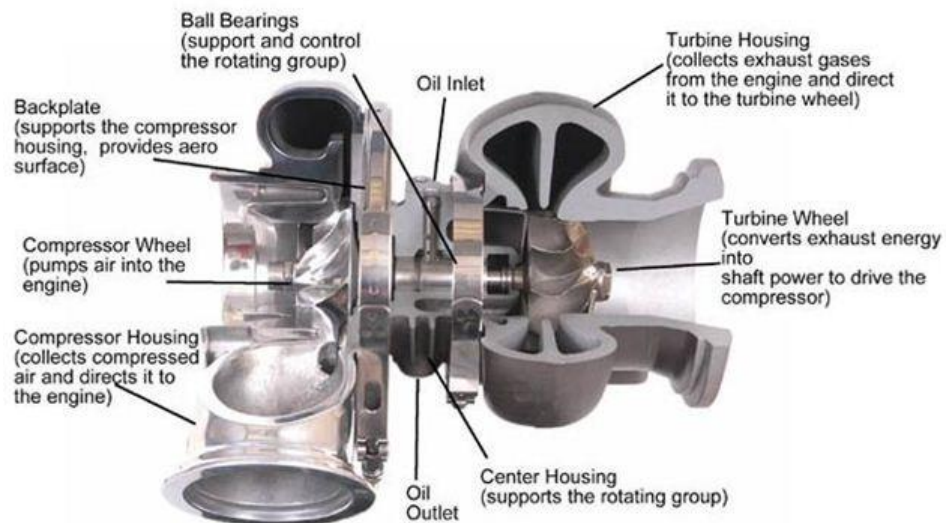

Fig 2.d.2: Mechanical part of Turbo compressor

With increasing density of the air due to the compression , one can add more fuel to this mixture which is forwarded to the combustion chamber of the engine, so that more work is produced per cycle. For example, if a turbocharger was working with a pressure of about 1 kg / cm ², assuming the engine was 2 atmospheres, or double air occupying in the same physical space without changing the dimensions of the cylinder.

Safety System

HV-TURBO compressors are normally provided with the following safety guards)

. Pressure control monitoring too low oil pressure

. Thermostat monitoring too high oil temperature

. Thermostat monitoring too high inlet temperature(which occurs in case of air re-circulation (high frequency surge).

. Surge detector monitoring low frequency surge.

The electric main motor is protected against over-heating by thermal sensors. All connections are carried to a terminal strip in the HV-TURBO Local Control panel type LC, which is normally mounted on the base plate as the compressor.

If the HV- TURBO Local Control panel is mounted separately or if the Local Control panel is supplied by others a terminal box mounted at the compressor base plate will be supplied.

Local Control Panel (LC)

The HV-TURBO Local Control panels type LC are specially designed for monitoring and controlling of the HV-TURBO compressors and are provided with a PLC system which automatically will shut down the compressor in case of :

. Low oil pressure

. High oil temperature

. High inlet temperature (re-circulation)

. Surge

. High temperature of electric motor

Further the Local Control panel is provided with contactors for auxiliary equipment such as:

. The actuator for the blow off valve

. The electric motor for the lube oil pump

. The electric motor for the air/oil cooler fan (if any)

. The servomotor for the variable diffuser (if any).

. The servomotor for the variable prerotation system (if any)

Fig 2.6: Local control panel for operating the HV turbo air compressor

Start Sequence (automatic)

. Start the electric driven lube oil pump

. Bring the variable diffuser in min. position

. Open the blow-off valve

. Check at all safety guards

. Start signal to Motor Control Centre

After the compressor has reached its full R PM, the blow-off valve will be closed in steps, building up the pressure in the discharge pipe.

Stop sequence (automatic)

. Bring the variable diffuser in min. position

. Open the blow-off valve

. Drop of start signal to Motor Control Centre

When the main electric motor is stopped the electric lube oil pump will continue lubrication for 5 minutes.

The front of the Local Control Panel is provided with:

. Finger-touch pads with symbols and light emitting diodes for indication of functions, in Solid, dirt-resistant diaphragm technique

. Hour meter

. Ammeter

. Emergency Stop

. Meter for variable diffuser position

. Meter for variable prerotation position

Operation of Turbo compressor:

The regulating system operates as follows:

The first compressor will be started up in minimum. When the air demand increases the compressor will be regulated up until it reaches its maximum (100%).

If there is still a demand for an increased air capacity the next compressor will be started automatically, but locked in its minimum position (45%). The first compressor will automatically be regulated back to 55% capacity (as 45% + 55% = 100%).

If there is still a demand for an increased air capacity the first compressor will regulate up from 55% to 100%. When the first compressor reaches the maximum the second time, it will be locked in its maximum position and the second compressor will start to regulate from 45 to 100%. When the second compressor reaches maximum the third compressor will automatically be started and so on. If the air demand is decreasing the regulating system works vice versa.

The important feature by this controlling system is that all compressors can as a standard be regulated from 45% - 100%, but only one compressor at a time.

Each of the installed compressors is in one of the following modes:

. Operating and regulating from 45% to 100%,

. Operating and locked in the minimum position,

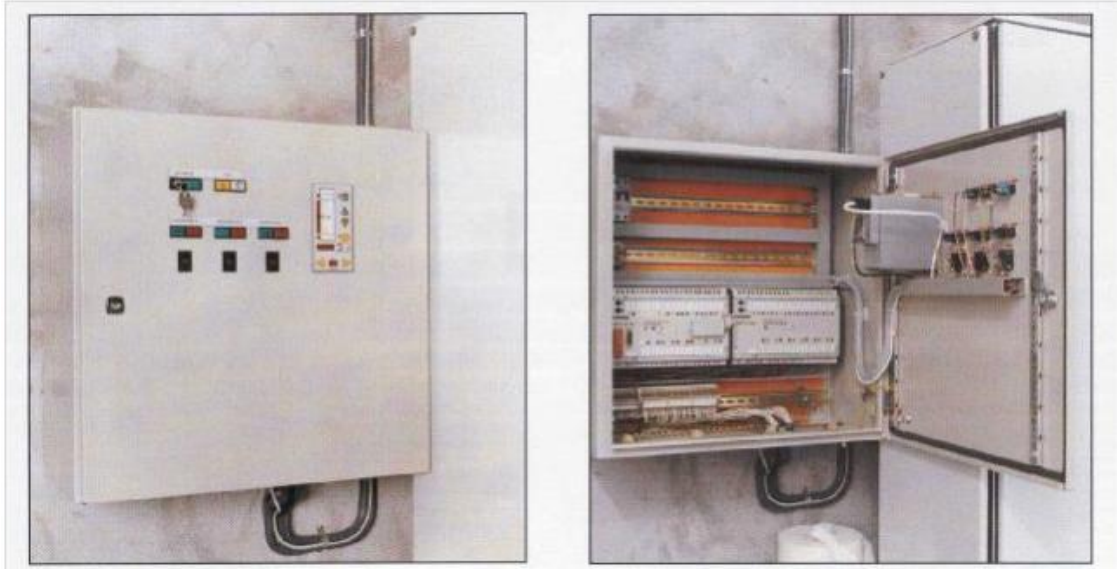. Operating and locked in the maximum position,

. Not operating.

Fig 2.7: The Master Control Panel type (MCP) switch for operation of parallel air compressors.

This system has proved to be reliable, causing no instability problems ("hunting").

The HV-TURBO Master Control Panel type MCP is show in above figure. It is designed for monitoring and control of automatic operation of two to six HV-TURBO compressors working in parallel. The MCP is equipped with a micro-processor and is delivered in a steel panel assembly or as a unit for mounting into an existing control panel. The MCP is connected to each Local Control panel (LC) by means of a shielded cable. On the front of the Master Control Panel are mounted:

. Coding switches for changing of priority.

. Lamp indication for wrong priority.

. Lamp indication for blower in operation/blower common alarm.

. Lamp indication for automatic operation.

. Process controller (PC).

The above mentioned control systems are HVTURBO standards.

3. Components of Air Compressor:

3.1 Receiver Tanks

The air receivers:

. Provide storage capacity to prevent rapid compressor cycling.

. Reduce wear and tear on compression module, inlet control system, and motor.

. Eliminate pulsing air flow.

. Avoid overloading purification system with surges in air demand.

. Damp out the dew point and temperature spikes that follow regeneration.

3.2 Air Dryers:

3.2.1 Refrigerated air dryers:

Refrigerated air dryers remove moisture from the compressed air through a mechanical refrigeration system to cool the compressed air and condense water and lubricant vapor. Most refrigerated dryers Cool the compressed air to a temperature of approximately 35EF, resulting in a pressure dew point range of 33EF - 39EF. Keep in mind that this range is also the lowest achievable with a refrigerated design since the condensate begins to freeze at 32EF.

3.2.2 Desiccant dryers:

It is utilize chemicals beads, called desiccant, to absorb water vapor from compressed air. Silica gel, activated alumina and molecular sieve are the most common desiccants used. (Silica gel or activated aluminas are the preferred desiccants for compressed air dryers.) The desiccant provides an average -40EF pressure dew point performance. Molecular sieve is usually only used in combination with silica gel or activated alumina on -100EF pressure dew point applications.

3.2.3 Deliquescent air dryers:

Deliquescent air dryers utilize an absorptive type chemical, called a desiccant, to provide a 20EF to 25EF dew point suppression below the temperature of the compressed air entering the dryer. The moisture in the compressed air reacts with the absorptive material to produce a liquid effluent which is then drained from the dryer. Keep in mind that this effluent is typically corrosive and must be disposed of in accordance with local regulations.

3.3 TYPES OF DRIVES:

Most compressors are driven with electric motors, internal combustion engines, or engine power takeoffs. Three types of drives are commonly used with these power sources.

3.3.1 V-Belt Drives:

It is most commonly used with electric motors and internal combustion engines. V-Belt drives provide great flexibility in matching compressor load to power source load and speed at minimum cost. Belts must be properly shielded for safety.

3.3.2 Direct Drives:

Provide compactness and minimum drive maintenance. Compressors can be flange mounted or direct-coupled to the power source. Couplings must be properly shielded for safety. Lower horsepower compressors also are built as integral assemblies with electric motors.

3.3.3 Engine Drives:

Gasoline or diesel engine, or power takeoff drives, are used primarily for portability reasons. A gearbox, V-Belt, or direct drive is used to transmit power from the source to the compressor.

3.4 Filters:

Coalescing filters are the most common form of compressed air purification. These filters remove liquid water and lubricants from compressed air and are installed downstream in a refrigerated air dryer system or upstream in a desiccant dryer system.

Filters are rated according to liquid particle retention size (micron) and efficiency, such as 0.50 micron and 99.99% .O.P. efficient, or 0.01 micron and 99.9999% D.O.P efficient.

Coalescing filters can only remove previously condensed liquids; they do not remove water or lubricant vapors from the compressed air. Any condensation produced from subsequent compressed air cooling will have to be eliminated. When seeking to remove water and lubricant vapors from compressed air, specify an air dryer.

Piping Distribution System

The piping distribution system no only controls how the air gets from the compressor room to the tools, it is a major factor in the energy consumed by the compressor.

3.5 Application Overview Compressor

A compressor is a mechanical device that takes in a medium and compresses it to a smaller volume. Compressors can either increase or decrease a given mass to a lower or higher pressure. A mechanical or electrical drive is typically connected to a pump that is used to compress the medium.

3.6 Compressors have many everyday uses, such as:

Air conditioners, (car, home),

Air pumps,

Home and industrial refrigeration,

High pressure car washes,

Hydraulic compressors for industrial machines,

Air compressors for industrial manufacturing,

Compressors are used by many industries that depend on the power of compressed gas or fluid to power manufacturing processes of all kinds.,

3.7 Application Challenges:

Varied compressor I/O that must interface with the AC drive to control compressor functions.

- Reduce energy consumption
- Constant pressure regulation

Some positive displacement compressors are constant torque. For those use A1000 or V1000

4. Scheme of Parallel HV Turbo Air Compressors:

Here, we are having the five parallel compressors which were coupled with the three-phase squirrel cage induction motor but only one collector and this model is considered under HV Turbo compressor.

The air was taken from the atmosphere and it was compressed by HV Turbo compressor which consists of a rotor vanes and the compressed air was passes to the collector through the pipe. When the discharge valve opens, the compressed air is released into some equipment without disturbing the pressure the compressors automatically adjusts with respect to the required flow.
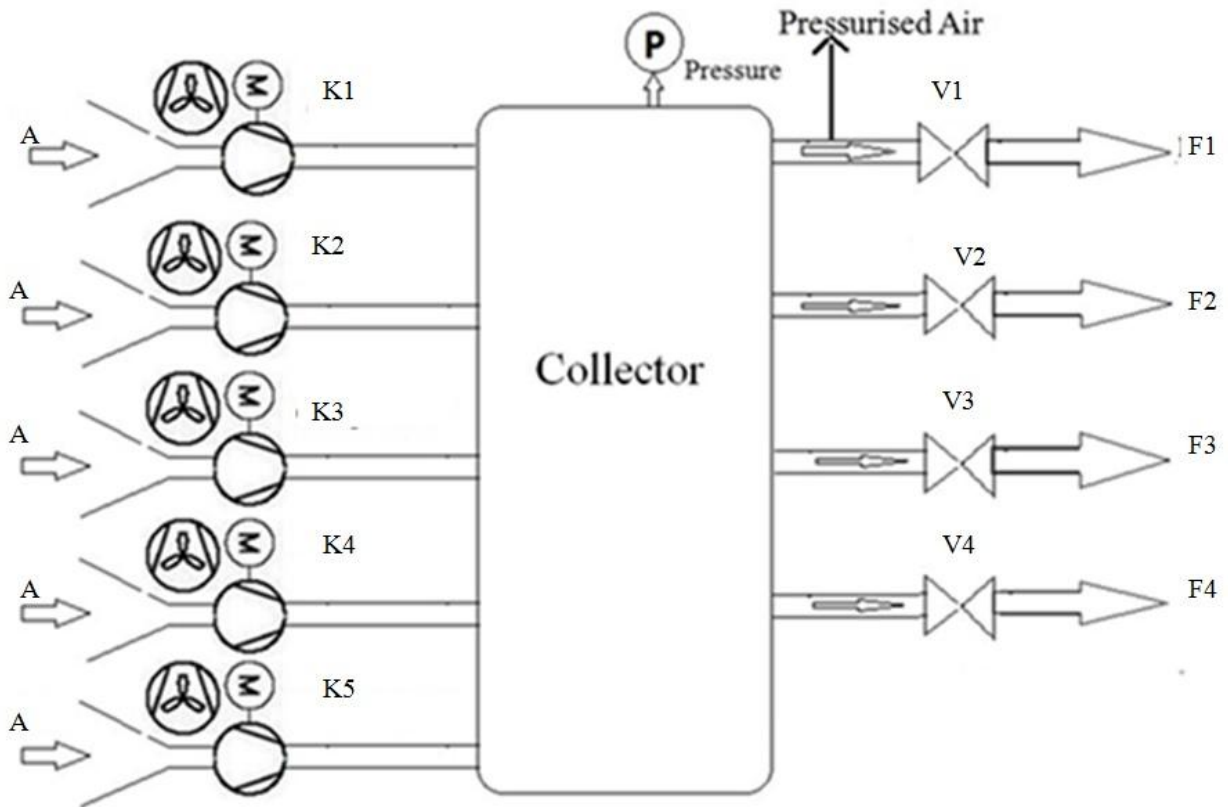
Fig4.1: The Technical scheme of parallel air compressors

Here, the air flow is depends on the load conditions. In this we are using four compressors and one is optional. If any of the four compressors gets damaged, we use the optional compressor.

We have observed the data from the measurement of four valve positions with respect to the energy,

V1: The minimum and maximum discharge valve position is 30-50%,

V3: The minimum and maximum discharge valve position is 50-70%,

V2: The minimum and maximum discharge valve position is 70-80%,

V4: The minimum and maximum discharge valve position is 80-95%.

From the above discharge valve positions the air flow was identified as high in the valve 1 and valve3.

4.1 Calculating the Load of parallel air compressor:

The averages of all valve positions of collector are to be considered as a load, and it was calculated by the following formula:

$$L= (V1+ V2+ V3+ V4)/4 \quad ---- (1)$$

4.2 Calculating the Power of induction motor:

Three-phase squirrel-cage-motor:

Squirrel cage three phase induction motor: The rotor of the squirrel cage three phase inductions motor is cylindrical in shape and have slots on its periphery. The slots are not made parallel to each other but are bit skewed (skewing is not shown in the figure of squirrel cadge rotor beside) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of motor more smooth and quieter.
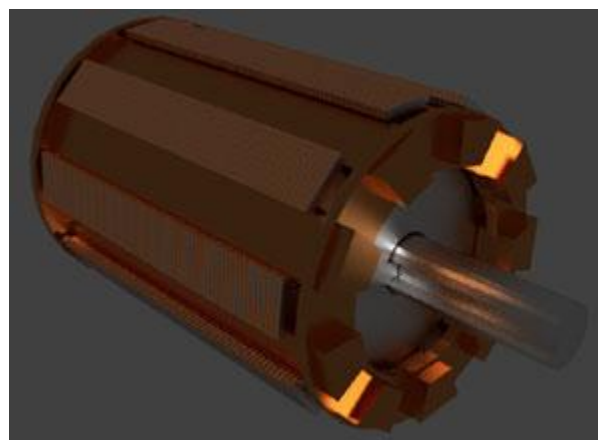
Fig 4.2: The Three-phase squirrel-cage-motor with the rotor shaft

The squirrel cage rotor consists of aluminum, brass or copper bars (copper bras rotor is shown in the figure beside). This aluminum, brass or copper bars are called rotor conductors and are placed

in the slots on the periphery of the rotor. The rotor conductors are permanently shorted by the copper or aluminum rings called the end rings. In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor". The squirrel cage rotor winding is made symmetrical.

As the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are permanently shorted. The absence of slip ring and brushes make the construction of Squirrel cage three phase induction motor very simple and robust and hence widely used three phase induction motor.

These motors have the advantage of adapting any number of pole pairs. The below diagram shows squirrel cage induction rotor having aluminum bars short circuit by aluminum end rings.

Advantages of squirrel cage induction rotor-
      a) Its construction is very simple and rugged.
      b) As there are no brushes and slip ring, these motors requires less maintenance.
Applications:
Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc.
Electrical data of induction motor:

The Three-phase Squirrel cage induction motor is having the rated voltage of 400V for the delta connection and 690V for the star connection at the frequency of 50Hz. Sometimes we use the frequency of 60Hz at that that time for delta connection load we need to consider the voltage of 460V.

The rated motor power voltage for 50Hz is 200KWand for 60Hz it was 224KW, the rated speed of the motor for 50Hz, 60Hz is 2982 per minute, 3582 per minute respectively. For this motor the rated torque was 641NM and 597NM, the rated motor current is 325A, 320A for the two different frequencies are 50Hz, 60HZ.

The Three-phase squirrel cage starting rated motor current is 6.7A, break-down rated motor torque is 2.9NM and starting rated motor torque is 2.3NM

For this compressor, we can use either 400V (which is in delta connection) or 690V (which is in Star connection). But for the eliminating of grounding effect we need neutral point which is in the star connection. So, we are using the star connection voltage which was 690V.

In the five parallel compressors there was only four compressors are working for that we have the different valve positions (in %) operating with respect to the load conditions and also we have the current (in Amp) values.

We are using the three-phase squirrel cage motor and here we have to calculate the power.

$$P = P1+P2+P3+P4. \qquad\qquad ---- (2)$$

$$P1=v*I1, P2=v*I2, P3=v*I3, P4=v*I4, \qquad ---- (3)$$

$$P1=690*I1, P2=690*I2, P3=690*I3, P4=690*I4. \qquad ---- (4)$$

$$P=690*(I1+I2+I3+I4), \qquad\qquad ---- (5)$$

$$P=690*(\textstyle\sum I) \qquad\qquad ---- (6)$$

Where,

P= the sum of each compressor Power in kilo-watts (KW),

$\sum I$= the sum of each compressor current in Amp (A).

For the all compressors we have the different currents, from that we can identify the power.

4.3 Calculating the volumetric Flow rate at the collector end:

The flow was depends on the power, here we should divide power with constant value of 0.0217 to reach the volumetric flow rate to get similar performance characteristics.

$$F =F1+F2+F3+F4. \qquad\qquad ---- (7)$$

$$F1= P1/0.0217, F2= P2/0.0217, F3= P3/0.0217, F4=P4/0.0217,$$

$$F= (P1+P2+P3+P4)/0.0217, \qquad ---- (8)$$

$$F= (\textstyle\sum P)/0.0217. \qquad\qquad ---- (9)$$

Where,

F= Volumetric Flow rate in cubic meter per hour (m3/h)

P= the sum of each compressor Power in Kilo-watts (KW)

4.4 Priority of parallel air Compressors:

Before that, here we need to find the priority of compressors. So, for that consider the MATLAB SCRIPT for the volumetric flow rate with respect to the time as following:

Here, the first compressor is not working for all the time. But the second compressor, fourth compressors are continuously working and consuming the power of 220KW each.

The third and the fifth compressors are working and consuming the power of 110KW each.

4.5 Air compressors Load (in %):
The load of parallel compressors was observed with respect to time, for the purpose of which valve was working exactly to know:
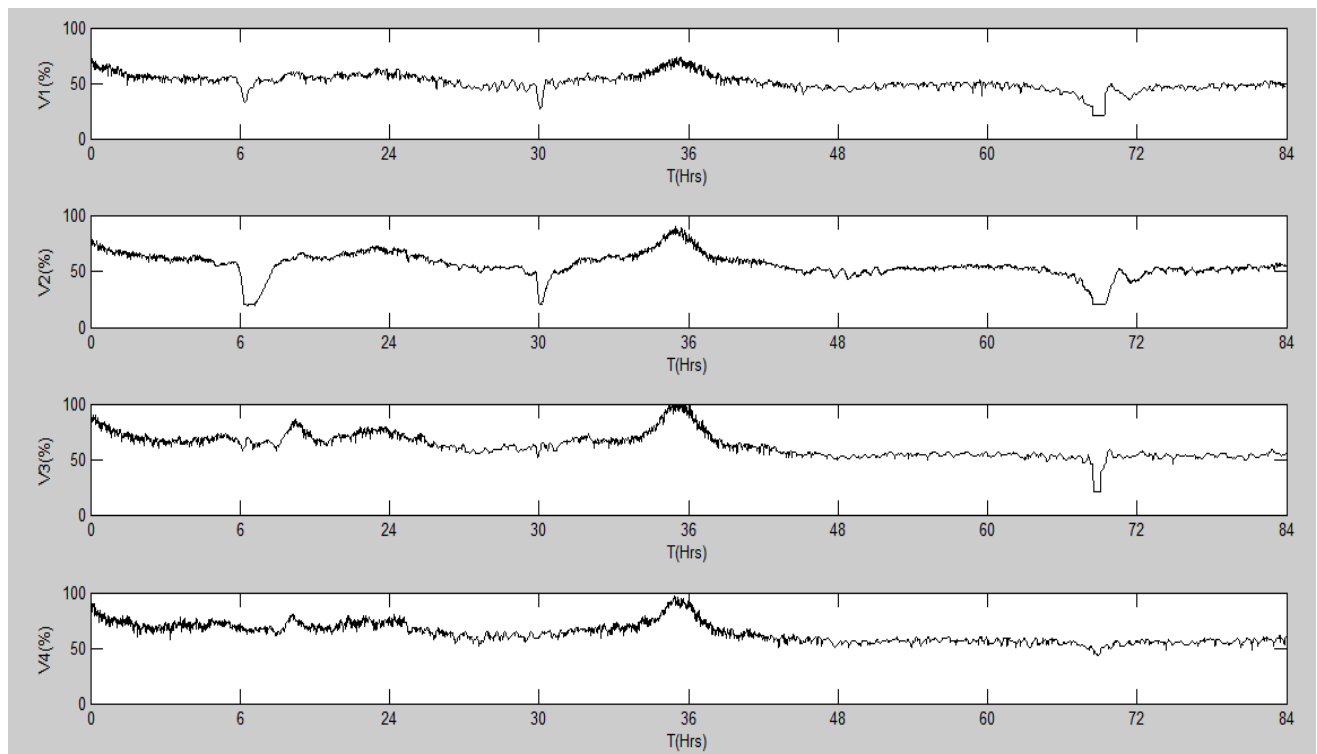
Fig 4.5(a): The characteristic represents the air compressor load (%) with respect to the time (hrs).
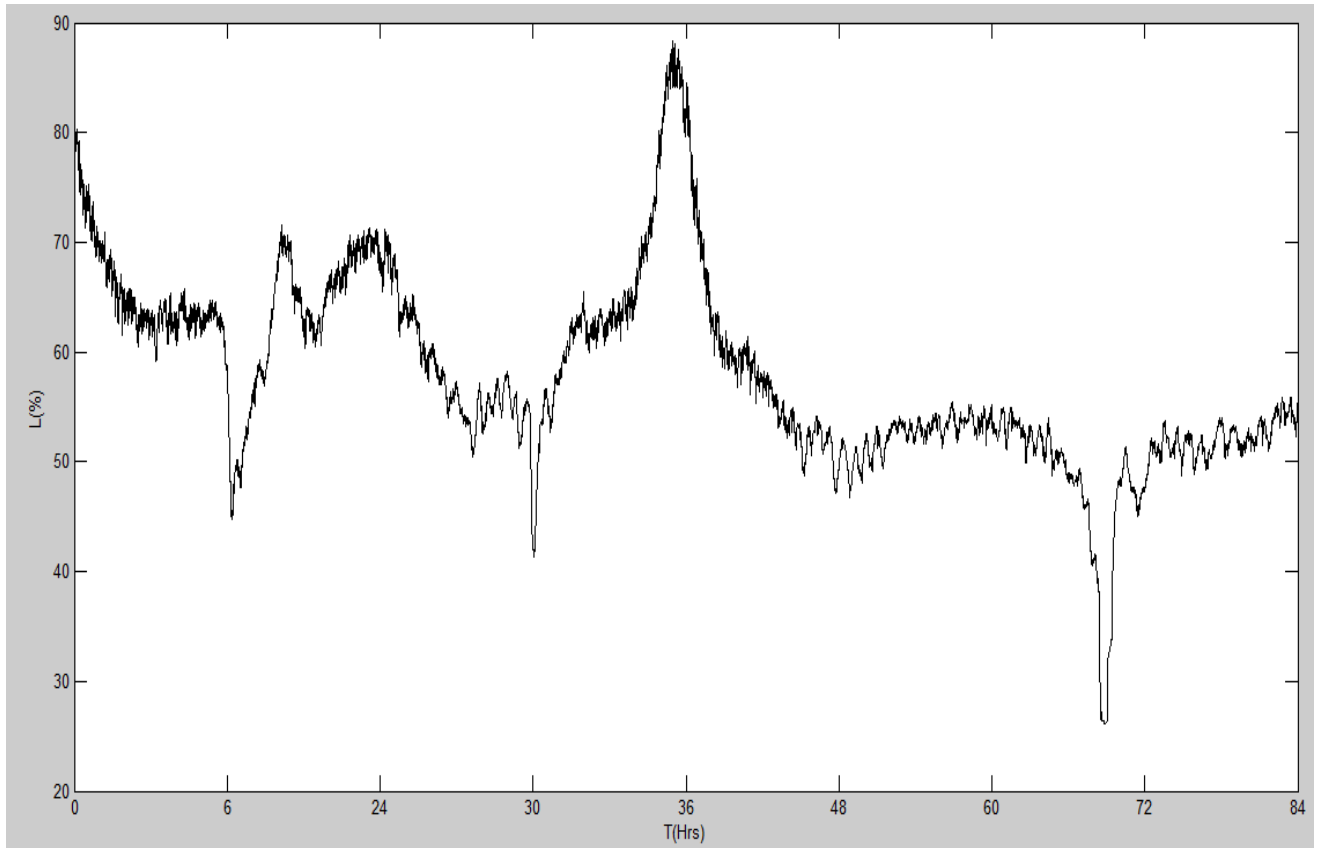
Fig 4.5(b): The characteristic represents the overall load of HV turbo air compressor in time

4.6 Identifying the working of volumetric Flow rate (in m3/h):

The volumetric flow rate of measured data values was calculated with respect to the time in order to know the priority of compressors.
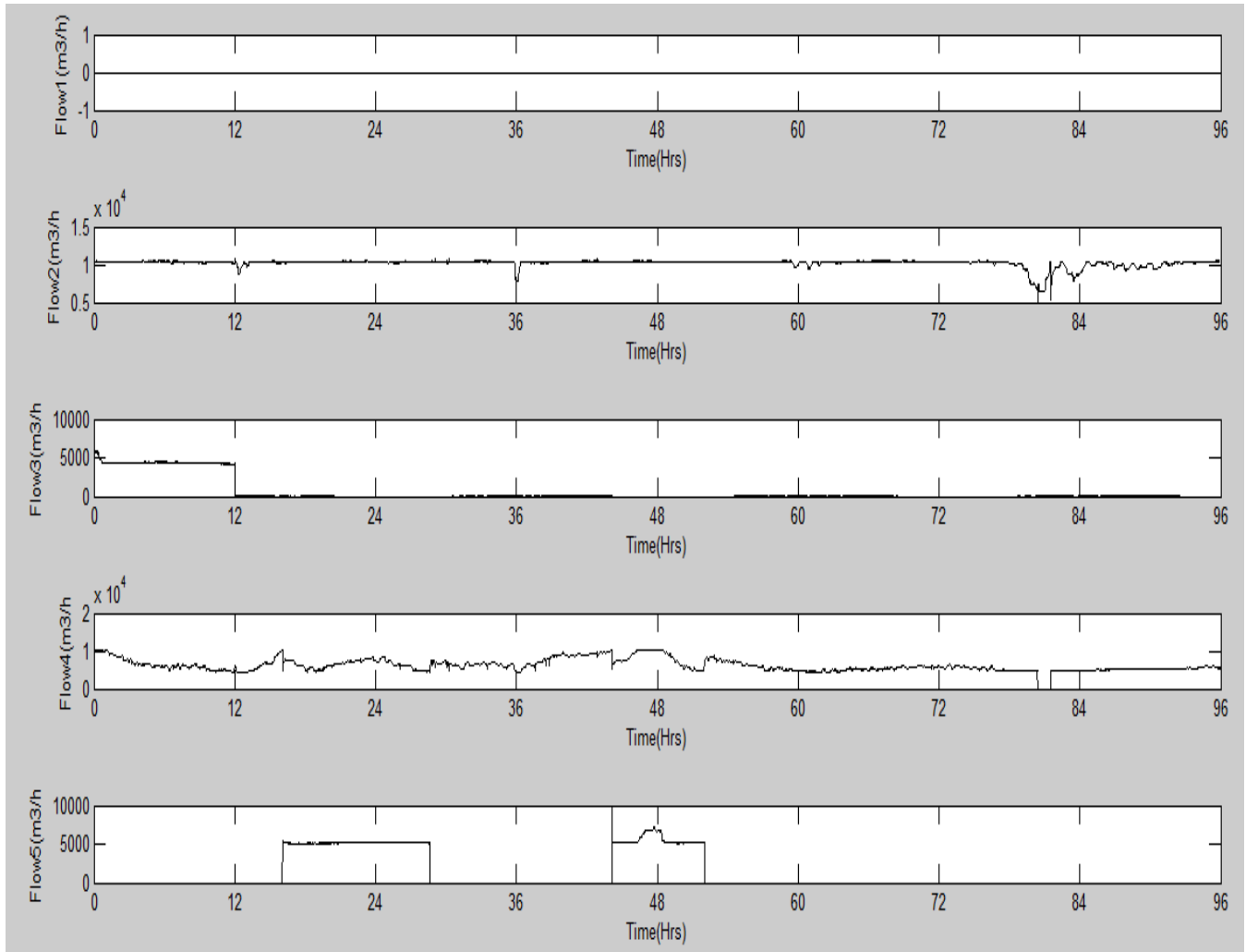
Fig 4.6: The characteristic represents how the volumetric flow rate (m3/h) varies with respect to the time (hrs)

Day1:

The second compressor, fourth compressor is continuously working, consuming the power of 220Kw each. Third compressor is working for half day ,consuming power of 110Kw, fifth compressor is working last 8hours of first day, consumes power of 110Kw. First compressor is not at all working, and here we have the priority of each compressor are:

Note: Compressor-K

K2- 1 (Flow is 10,000m3/h, power is 220Kw, load is 65%)

K4- 2 (Flow is (10,000-8,000) m3/h, power is (220-180) Kw, load is 85%)

K3- 3 (Flow is 5,000m3/h, power is 110Kw, load is 75%)

K5- 4 (Flow is 5,000m3/h, power is 110Kw, load is 85%)

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K1- 5 (Flow is 0m3/h, power is 0Kw, load is 0%)

Day2:

The second compressor, fourth compressor is continuously working, consuming the power of 220Kw and 200-220Kw. Fifth compressor is working for first 6hours and last 6hours in a day2, consuming power of 110-140 Kw, Third and First compressor is not at all working, and here we have the priority of each compressor are:

Note: Compressor-K

K2- 1 (Flow is 10,000m3/h, power is 220Kw, load is (65-75) %)

K4- 2 (Flow is (8,500-10,000) m3/h, power is (220-200) Kw, load is (75-95) %)

K5- 3 (Flow is (5,000-7000) m3/h, power is 110-160Kw, load is (75-85) %)

K3- 4 (Flow is 0m3/h, power is 0Kw, load is (80-95) %)

K1- 5 (Flow is 0m3/h, power is 0Kw, load is 0 %)

Day3:

The second compressor, fourth compressor is continuously working, consuming the power of 220Kw and 200-180Kw. Fifth compressor is working for first 5hours in a day3, consuming power of 110 Kw, Third and first compressors is not at all working, and here we have the priority of each compressor are:

Note: Compressor-K

K2- 1 (Flow is 10,000m3/h, power is 220Kw, load is (50-75) %)

K4- 2 (Flow is (5,000-10,000) m3/h, power is (110-220) Kw, load is (90-60) %)

K5- 3 (Flow is (5,000-7000) m3/h, power is (110-160) Kw, load is (60-80) %)

K3- 4 (Flow is 0m3/h, power is 0Kw, load is (65-90) %)

K1- 5 (Flow is 0m3/h, power is 0Kw, load is 0 %)

Day4:

The second compressor, fourth compressor is continuously working, consuming the power of 220Kw and 180-140Kw. Fifth, third and first compressors are not at all working, and here we have the priority of each compressor are:

Note: Compressor-K

K2- 1 (Flow is 10,000m3/h, power is 220Kw, load is 50 %)

K4- 2 (Flow is (7,000) m3/h, power is (150) Kw, load is 60 %)

K5- 3 (Flow is 0 m3/h, power is 0Kw, load is 60 %)

K3- 4 (Flow is 25m3/h, power is 0.5Kw, load is 65 %)

K1- 5 (Flow is 0m3/h, power is 0Kw, load is 0 %)

For the Graphs we can consider, the priority of compressors of last 3 working days is:

K2=1,

K4=2,

K5=3,

K3=4,

K1=5,

Note: Compressor-K

4.7. Pneumatic structure of Air compressor:

We need to design the model, by considering the theoretical values, excel data values, compressors performance characteristics.
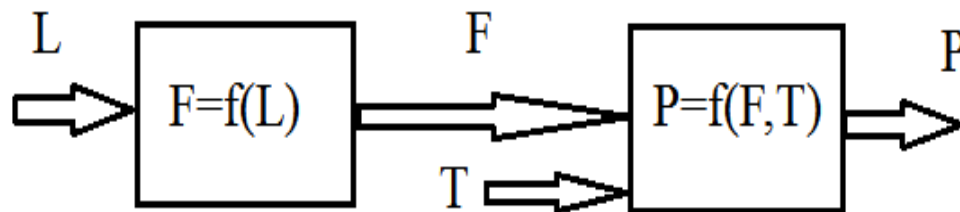
Fig 4.7: Structure of Air compressor.

Where,

L= Load i.e. average of total four compressors Valve positions (%),

F= Volumetric Flow rate in cubic meter per hour (m3/h),

P= Power in Kilo-watts (KW),

T=Temperature in Kelvin (K),

F: f (L) = The relationship between Flow (m3/h) and Load (%),

P: f (F, T) = The relationship between Power (KW), flow (m3/h) and Temperature (K)

For finding the load vs. volumetric flow rate relation, first consider from the excel data values of load and flow rate to write the MATLAB SCRIPT after getting the relation of those values just enter in the look-up table. Similarly we need to calculate the relation between Flow, temperature and power relationship should be given to the look-up table.

4.8. Relationship of Load Vs Flow:

From the measured values of data we need to consider the load (in %) and total volumetric flow rate (in m3/h).

The characteristic was similar to linear, and we obtained this characteristic in between the L and F.
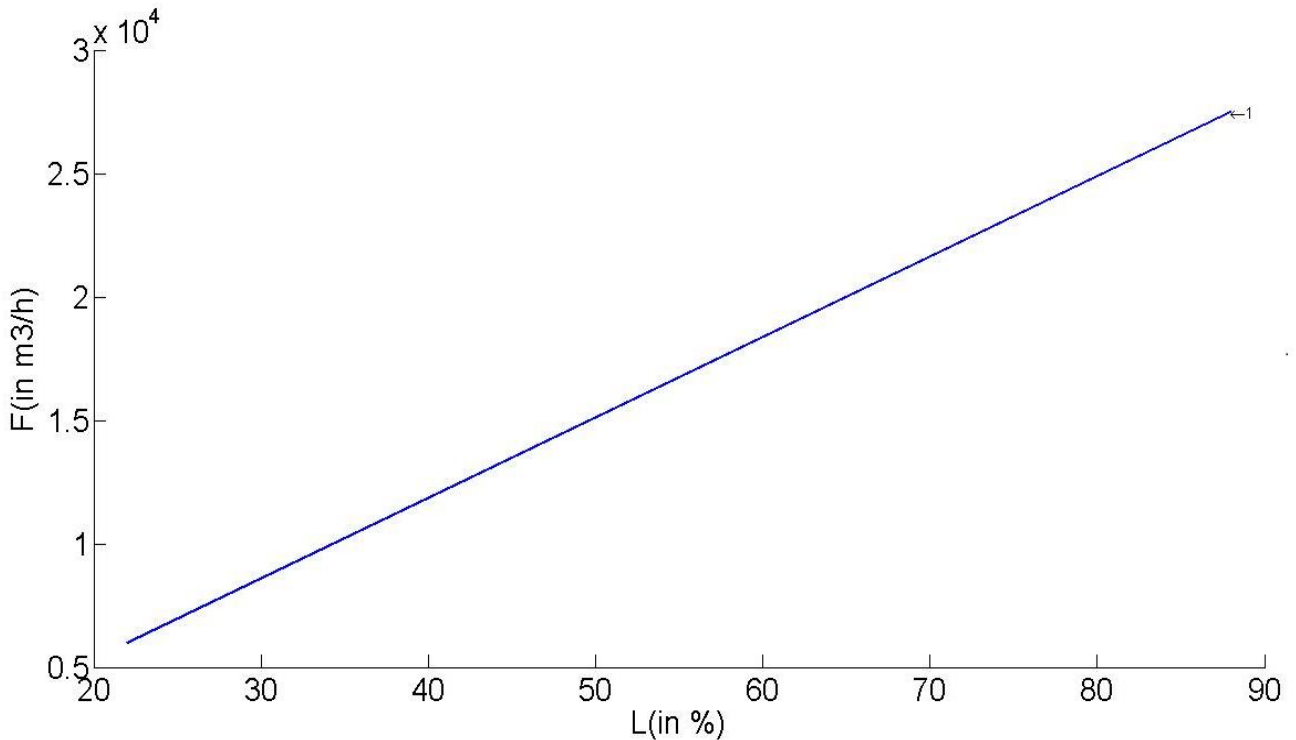
Fig 4.8: characteristic represents the L (Load in %) Vs F (Flow in m3/h) of parallel air compressors

By observing the graph, we need to give this relation in the SIMULINK model by using the 1-D lookup table.

4.9. Relationship between Total volumetric flow rate to the Individual Flow rate:

4.9.1. First algorithm:

In this algorithm, the regulating of volumetric flow rate is operate at a time of only one air compressor, After reaching the maximum position the next compressor will start to regulate from minimum position to maximum position.
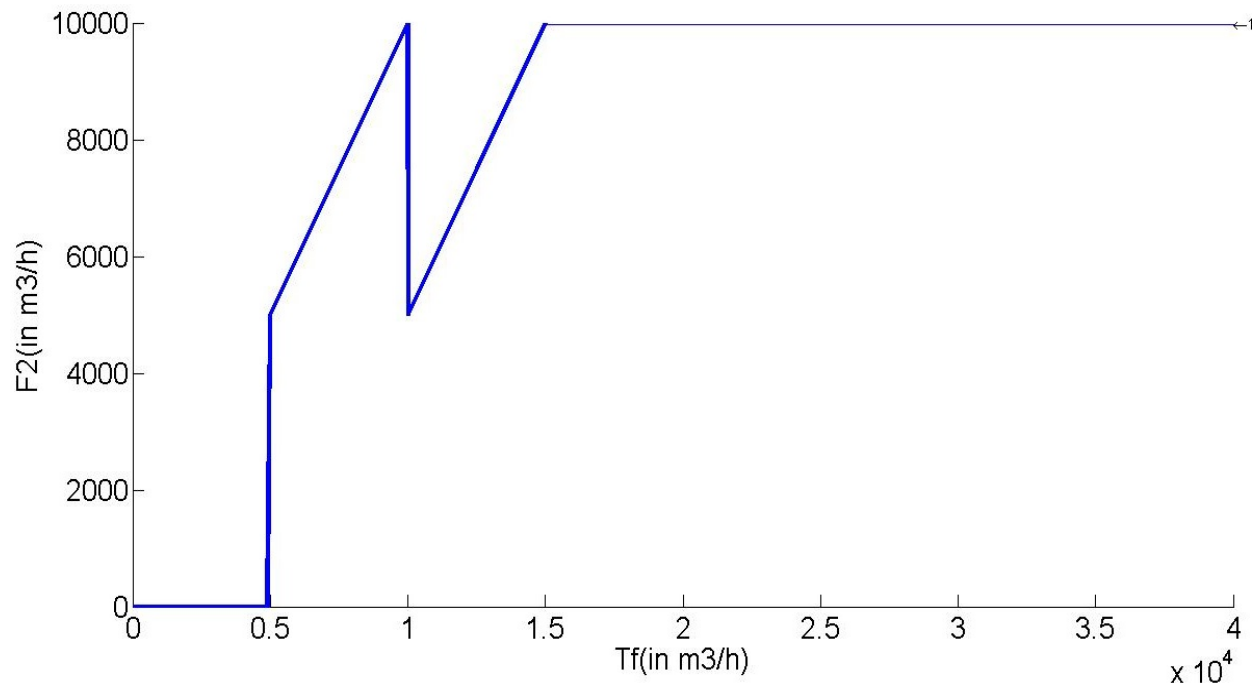
Fig 4.9.1(a): The characteristic of the parallel air compressors volumetric flow2 Vs Total flow
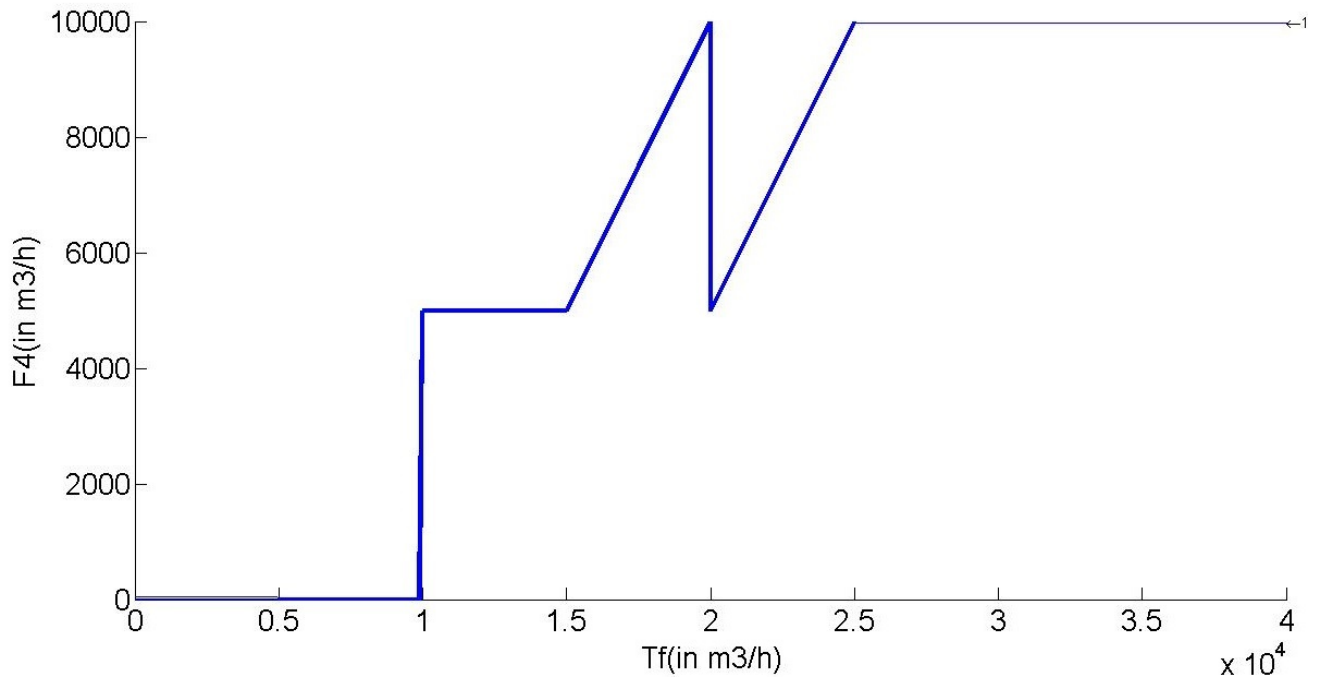
Fig 4.9.1(b): The characteristic of the parallel air compressors volumetric flow4 Vs Total flow
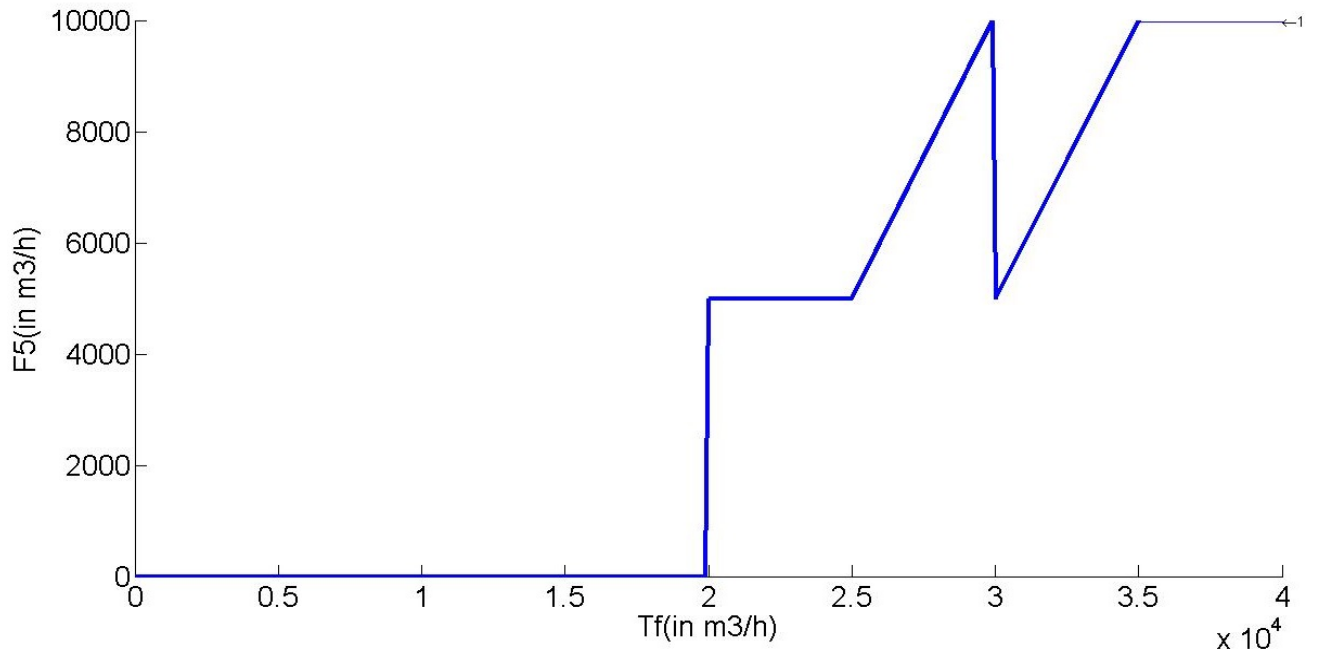
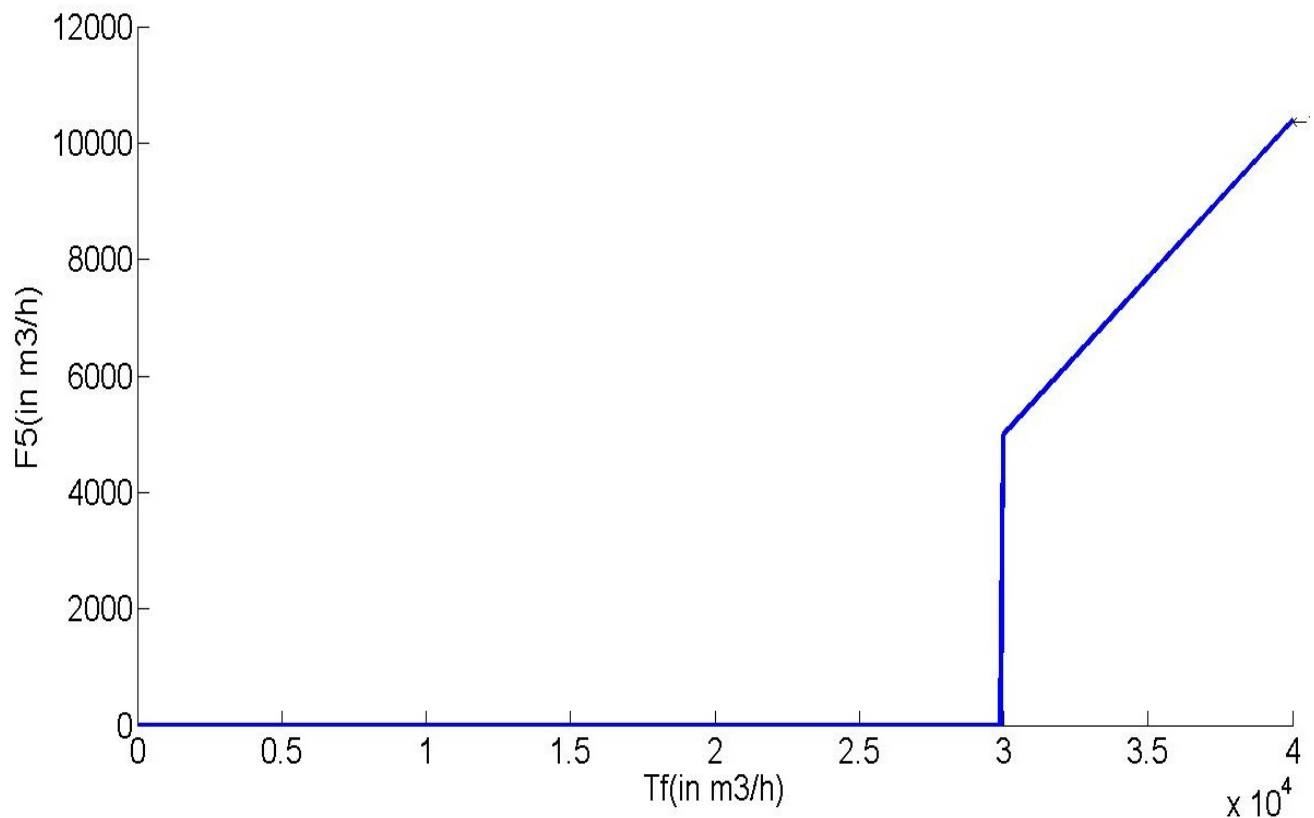Fig 4.9.1 (c): The characteristic of the parallel air compressors volumetric flow5 Vs Total flow
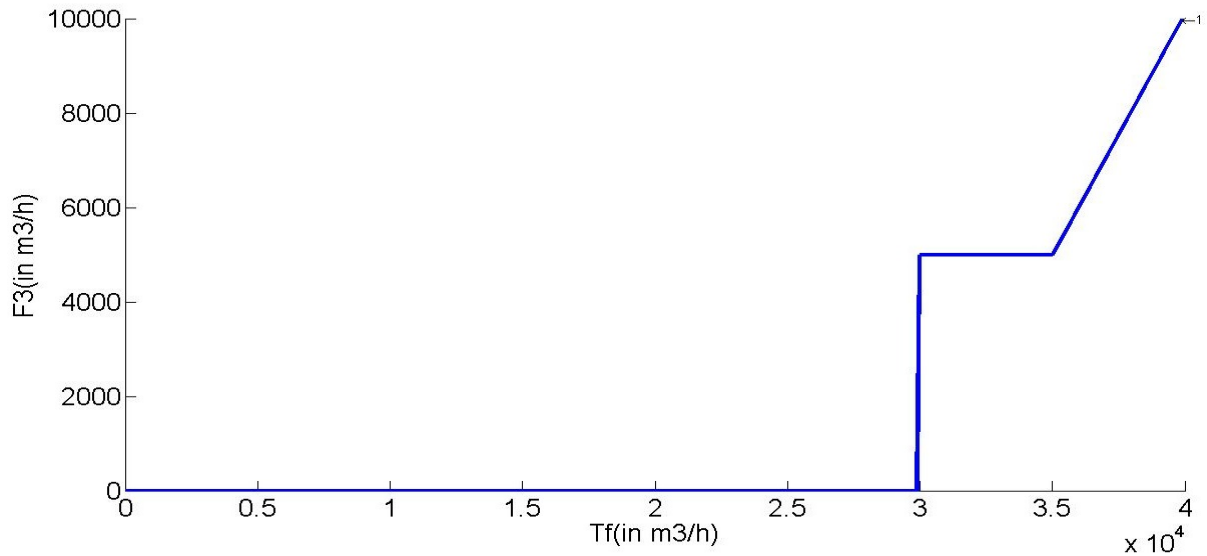
Fig 4.9.1(d): The characteristic of the parallel air compressors volumetric flow3 Vs Total flow

By observing these graphs, we can know that if we need 40,000 m3/h of volumetric flow rate the four compressors should work at maximum flow. So, the minimum volumetric flow rate of each compressor was 5,000m3/h and the maximum flow of each compressor was 10,000m3/h.

4.9.2. Second algorithm:

In this algorithm, the regulating of volumetric flow rate is operating both air compressors at a time.
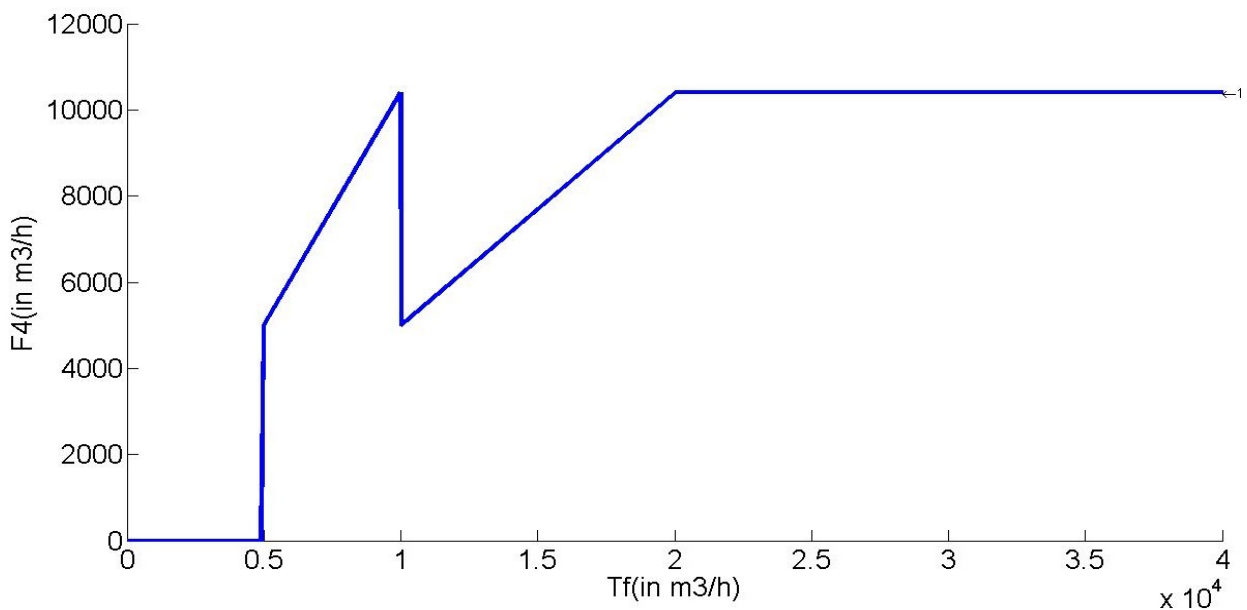
Fig 4.9.2 (a): The characteristic of the parallel air compressors volumetric flow4 Vs Total flow
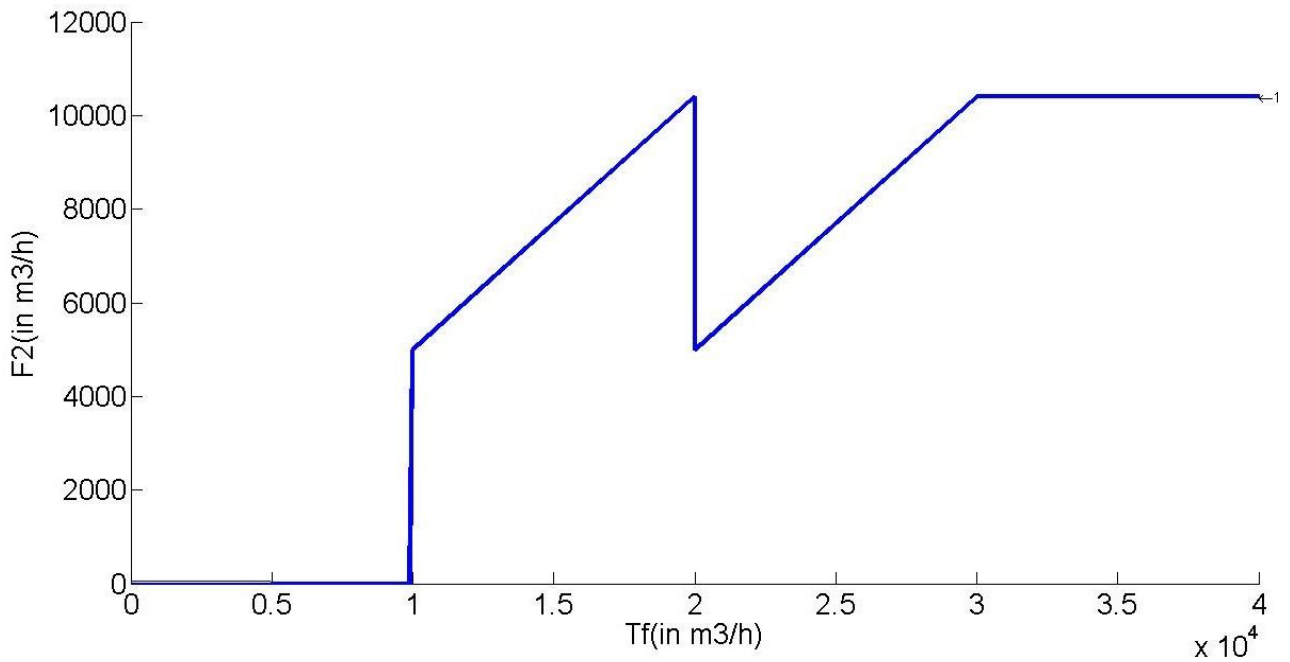
Fig 4.9.2 (b): The characteristic of the parallel air compressors volumetric flow2 Vs Total flow
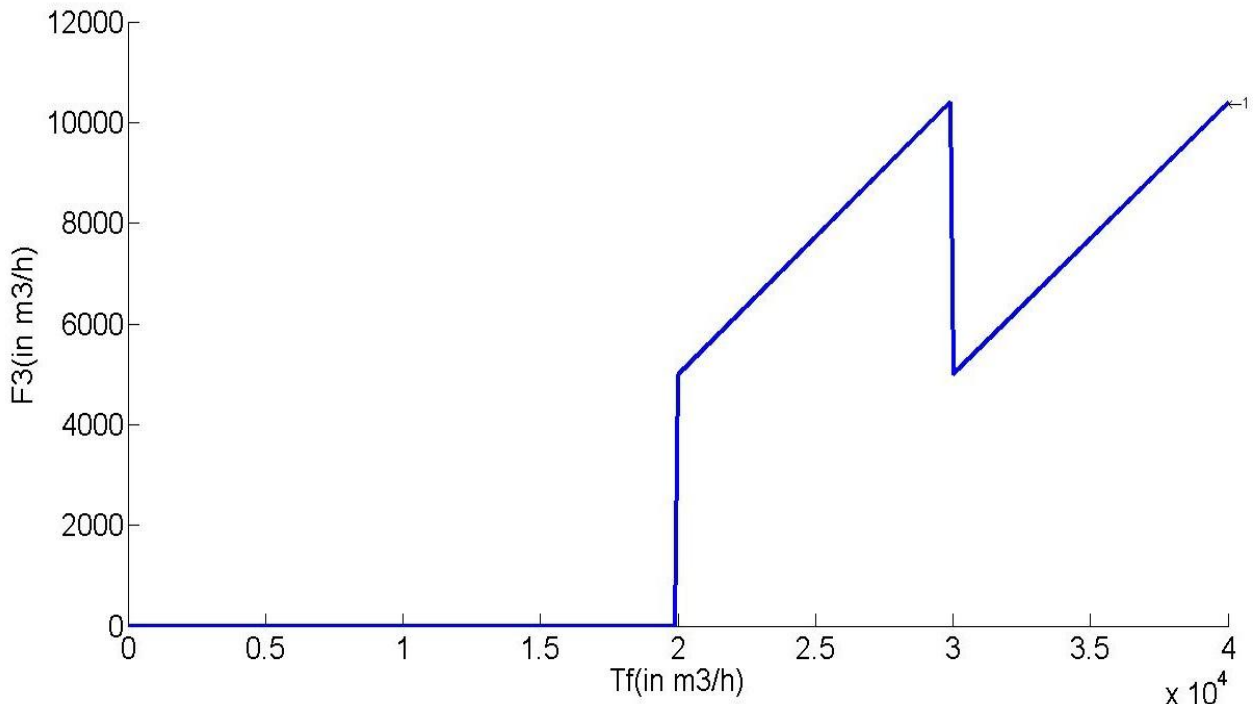
Fig 4.9.2 (c): The characteristic of the parallel air compressors volumetric flow3 Vs Total flow

Fig 4.9.2 (d): The characteristic of the parallel air compressors volumetric flow5 Vs Total flow

4.10. The relationship between individual flow Vs power:

From the measurement data values we can write in the MATLAB script, to get the relationship in between the individual volumetric flow (m3/h) to the power (Kw).

Now, we need to give these characteristics in 2-d look up table with different temperatures.

Inputs for the look-up table:

1) From the individual volumetric flow rate to the one input of 2-d look up table,
2) The temperature we use for the air compressors are 306K, 273K, and 249K.
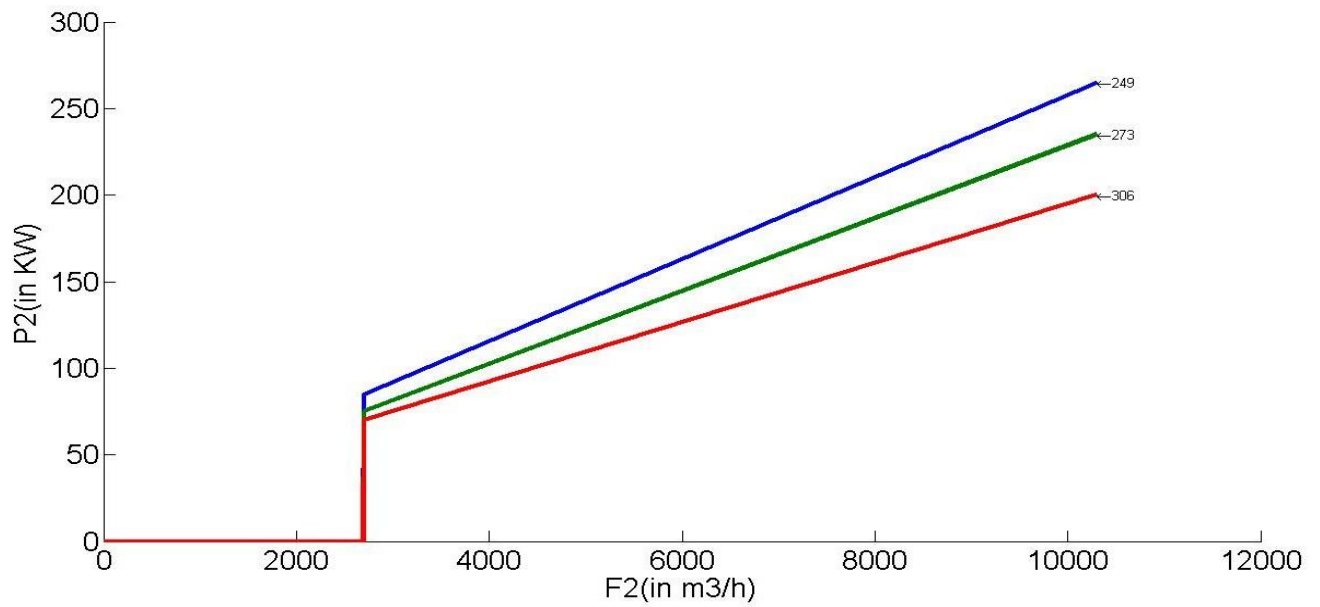
Fig 4.10(a): The second compressor characteristics of volumetric flow rate2 (in m3/h) Vs power2 (in Kw) at different temperatures.
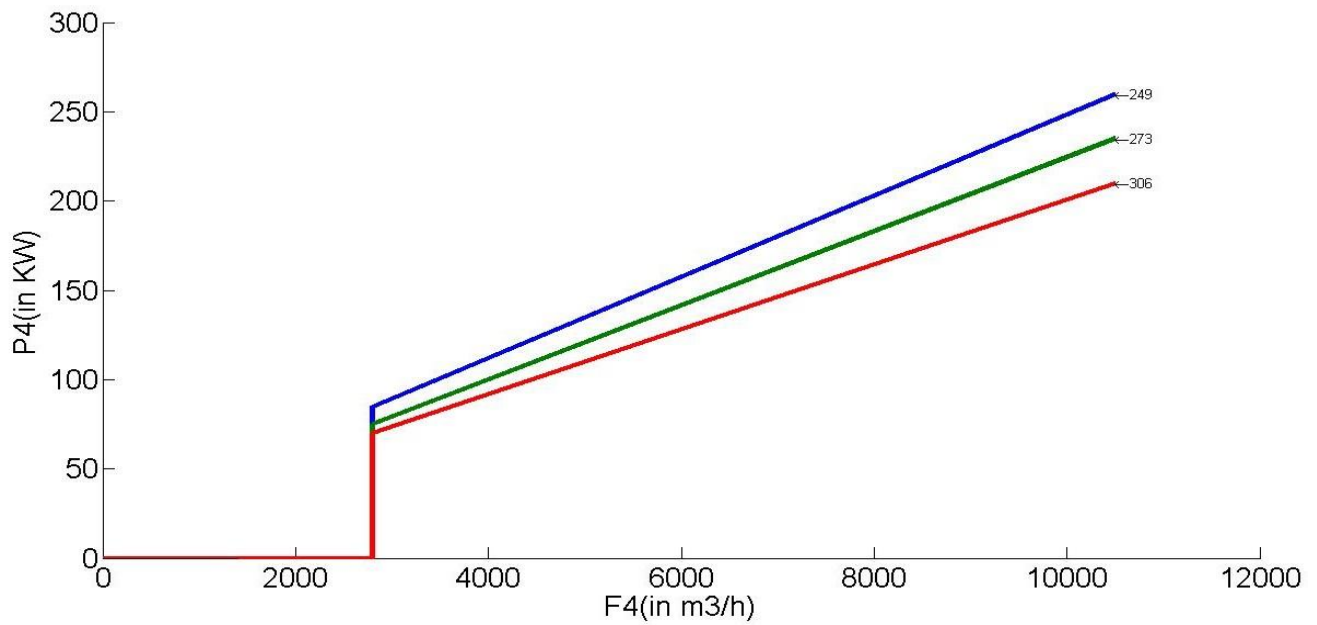
Fig 4.10(b): The fourth compressor characteristics of volumetric flow rate4 (in m3/h) Vs power4(in Kw) at different temperatures.
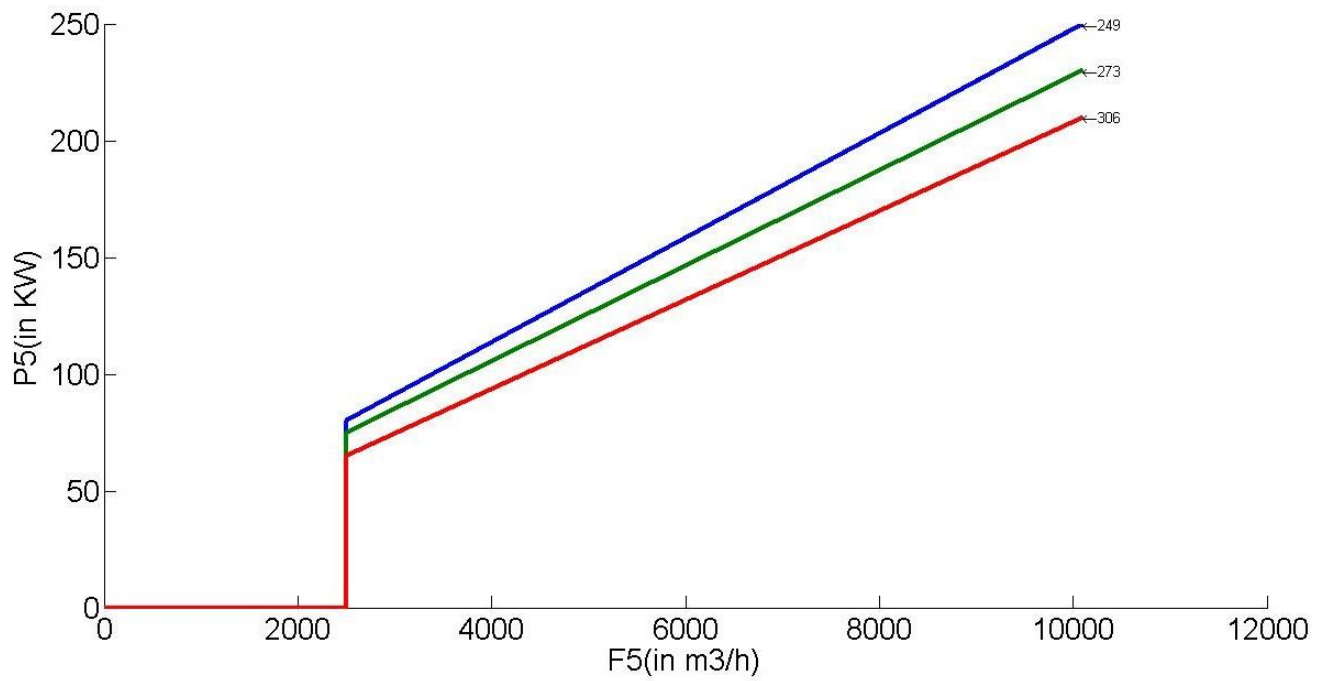
Fig 4.10(c): The fifth compressor characteristics of volumetric flow rate5 (in m3/h) Vs power5 (in Kw) at different temperatures.
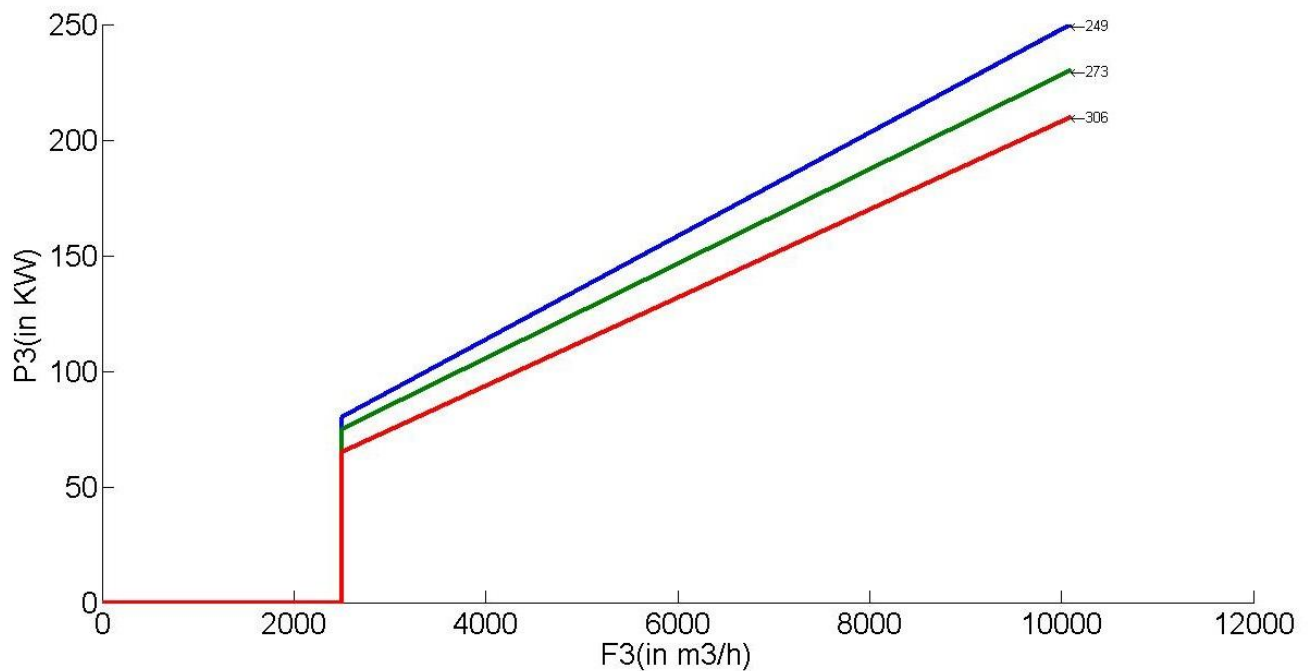

Fig 4.10(d): The third compressor characteristics of volumetric flow rate3 (in m3/h) Vs power3 (in Kw) at different temperatures.

4.11. Calculating the Output power, efficiency and Energy of the HV Turbo air compressor:

The output power was calculated by using the input power and the efficiency of motor.

Output Power= (Input Power)* (Efficiency).

$$P_{out} = P_{in} * \eta_{m.} \qquad\qquad \text{---- (10)}$$

Electrical motor efficiency is the ratio between the shaft output power - and the electrical input power.

The relation of output power to the efficiency is as shown below:
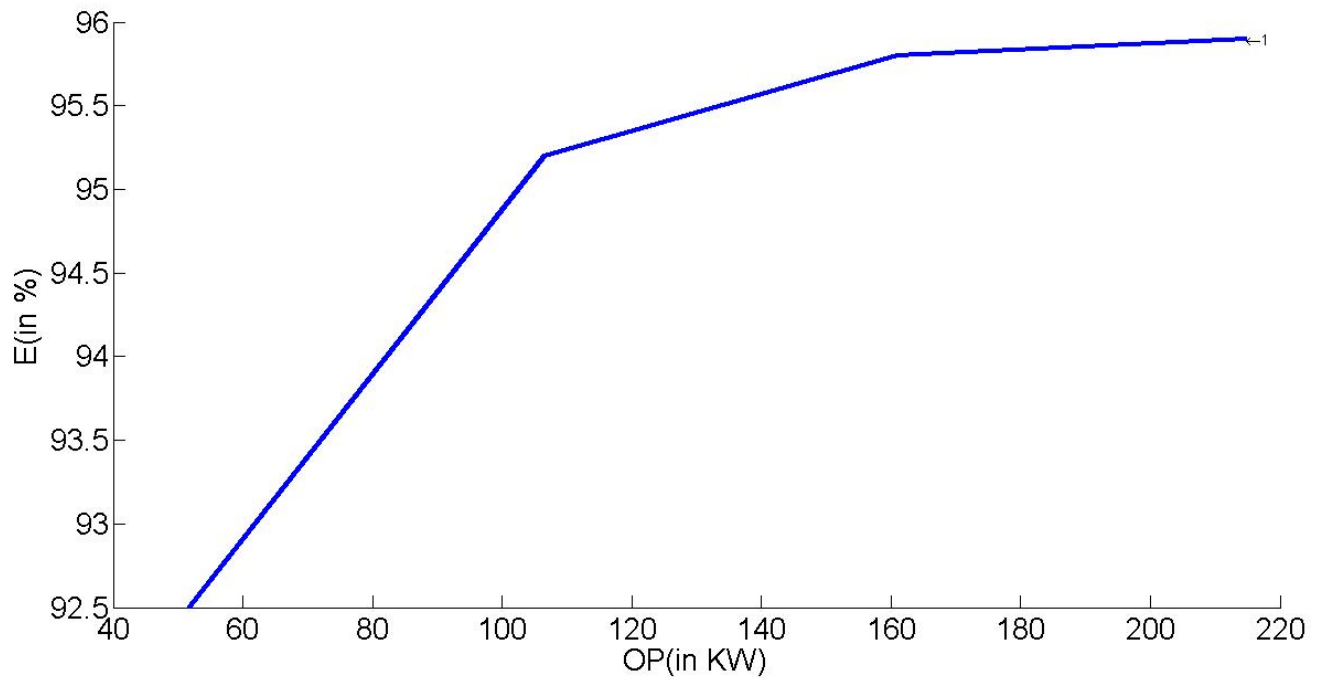
Fig 4.11: The output power and efficiency curve.

Electrical Motor Efficiency when Shaft Output is measured in Watt

If power output is measured in Watt (W), efficiency can be expressed as:

$$\eta_m = P_{out} / P_{in} \qquad\qquad \text{---- (11)}$$

Where, η_m = motor efficiency

P_{out} = shaft power out (Watt, W)

$$P_{in} = \text{electric power in to the motor (Watt, W).}$$

5. Building a Simulink Model by using the different algorithms and volumetric flow rate to power characteristics:

5.1. For the first measurement data values the Simulink model is:

The model represents the here, we are giving the load values with respect to that we need to calculate the how much the power is consuming and from that we need to calculate the energy.

The formula of energy for 3 days (i.e., 72hours) is:

$$E= \int P.\,dt \qquad\qquad \text{---- (12)}$$

In this algorithm, the first compressor will be started up in minimum. When the air demand increases the compressor will be regulated up until it reaches its maximum (100%).

If there is still a demand for an increased air capacity the next compressor will be started automatically, but locked in its minimum position (50%). The first compressor will automatically be regulated back to 50% capacity (as 50% + 50% = 100%).If there is still a demand for an increased air capacity the first compressor will regulate up from 50% to 100%. When the first compressor reaches the maximum the second time, it will be locked in its maximum position and the second compressor will start to regulate from 50 to 100%.

When the second compressor reaches maximum the third compressor will automatically be started and so on. If the air demand is decreasing the regulating system works vice versa. The important feature by this controlling system is that all compressors can as a standard be regulated from 50% - 100%, but only one compressor at a time.

The data is for the 3days which is 72hours of data we are considering in the first measuring values file.

Here, the fig 5.1 is builded in the Simulink is as shown below; and load values are loaded from the matlab script to that one-dimensional look up table is connected to the load values, in this block will have the one characteristic which was considered by the measurement values in between load(in %) and total volumetric flow rate(in m3/h) and performs the operation, gives the respected values.
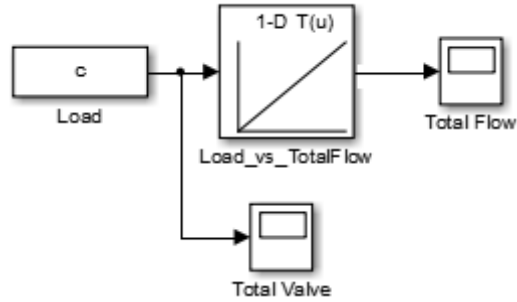
Fig 5.1: Load values (in %) with respect to the flow (m3/h)

In the model after getting the output from total volumetric flow (m3/h), we need to split according to the priority of compressors, and here the each compressor minimum position is 5000(m3/h) and maximum is 10000(m3/h). The building algorithm main reason was to split the total flow into the individual flow, keeping in mind that all the compressors are identical and in this algorithm only one compressor will regulate at a time. So, when the first compressor is getting flow of maximum position, still it needs the air flow then the second compressor gets to be on at a minimum position and first will falls to minimum position, the second compressor is kept constant up to the first compressor should regulate to the maximum position and then second will start to regulate the compressor. This is how the first algorithm is considered.
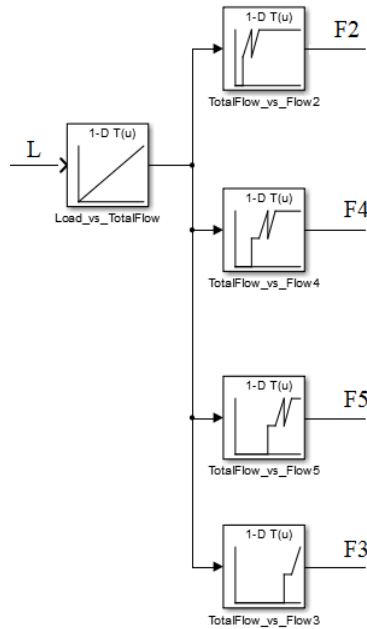
Fig 5.2: The algorithm of parallel air compressor.

From the individual volumetric flow rate (in m3/h) and temperature it goes to the two-dimensional functional block which consists of the relation between the flow and power considered by the performance characteristics.
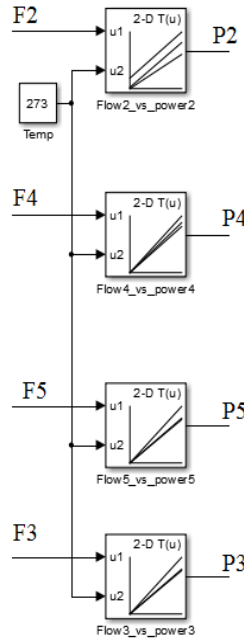

Fig 5.3: The Individual flow (in m3/h) to the power (in KW)

The power was consuming depends up on the volumetric flow rate and there are the loads like 100%, 75%, 50% and 25%. So, lying on the maximum power of compressors it operates and the fig 5.4 shown below:
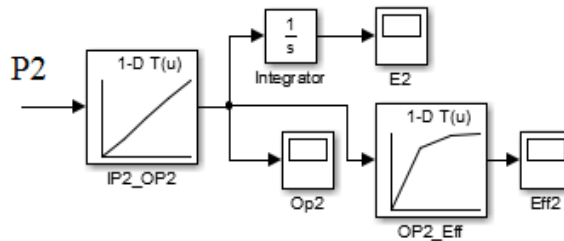

Fig 5.4: Output power (in KW) to energy (in KWH) and efficiency (in %).

Energy is calculated using the power values and time, for that both values the integral should be applies, and then we get the energy values.

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As we know that, we had done all these investigations for the purpose of building the parallel air compressors in SIMULINK MODEL and the following as:
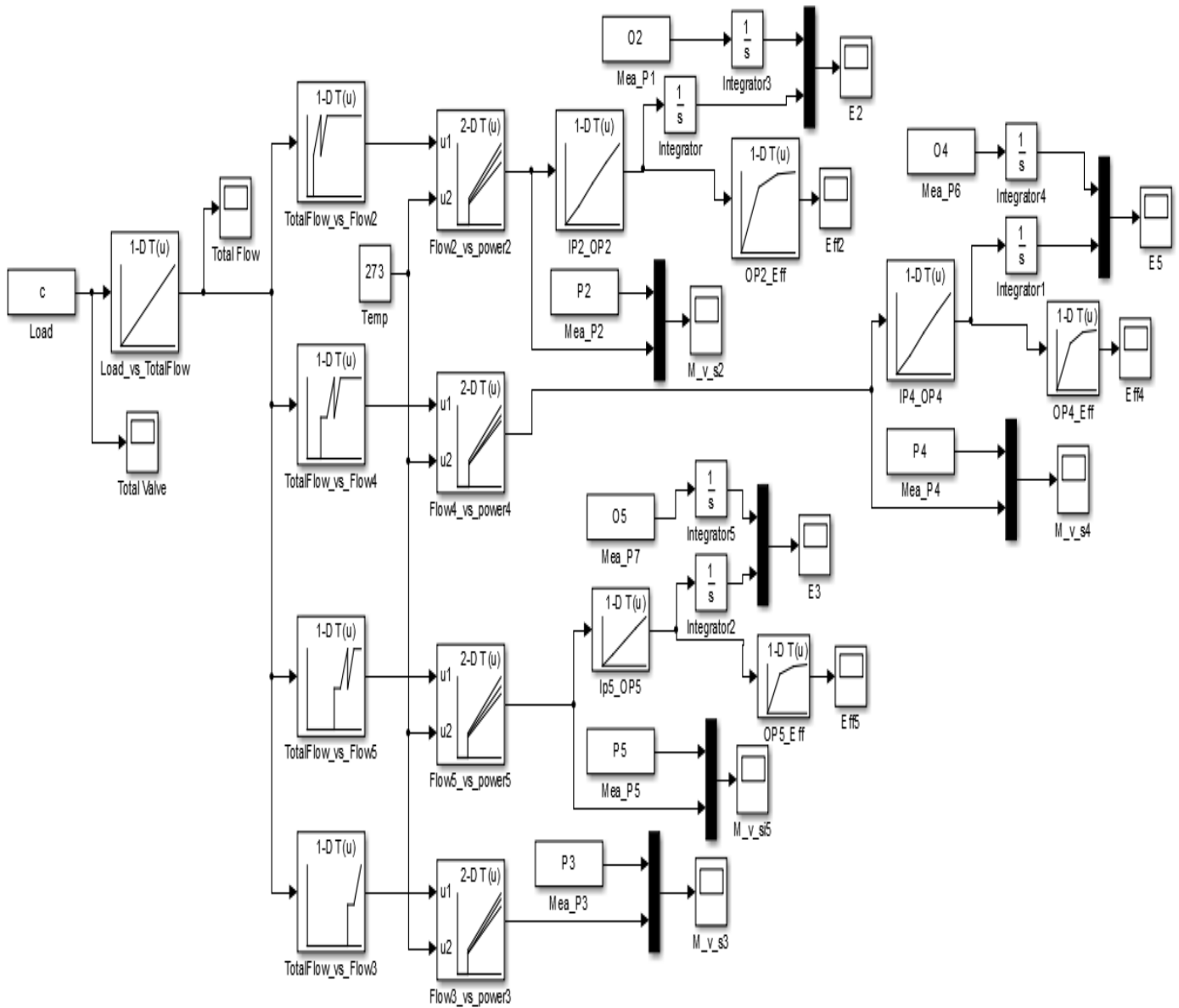

Fig 5.5: Parallel air compressors are builded in SIMULINK MODEL with the help of Flow (in m3/h) and power (in Kw) characteristics.

Result:

The power and energy values are identified by using the above Simulink model with the help of load from the measurement values and temperature at 273K:
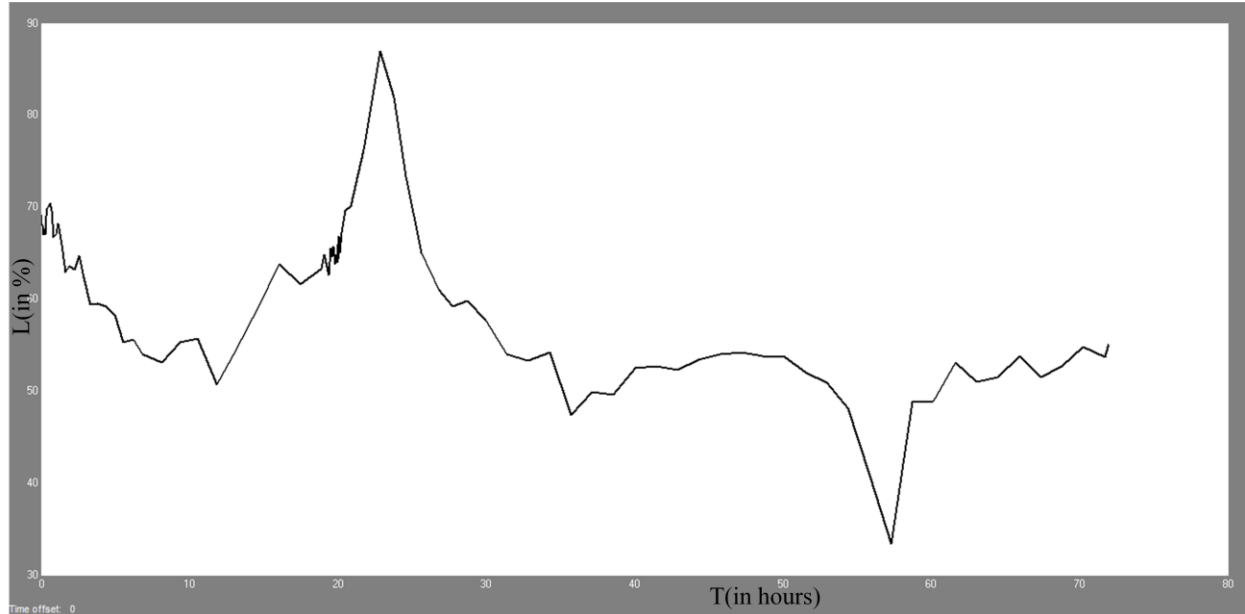

Fig 5.5 (a): The characteristic represents, the compressor Load (in %) with time (in hours) for measurement values.
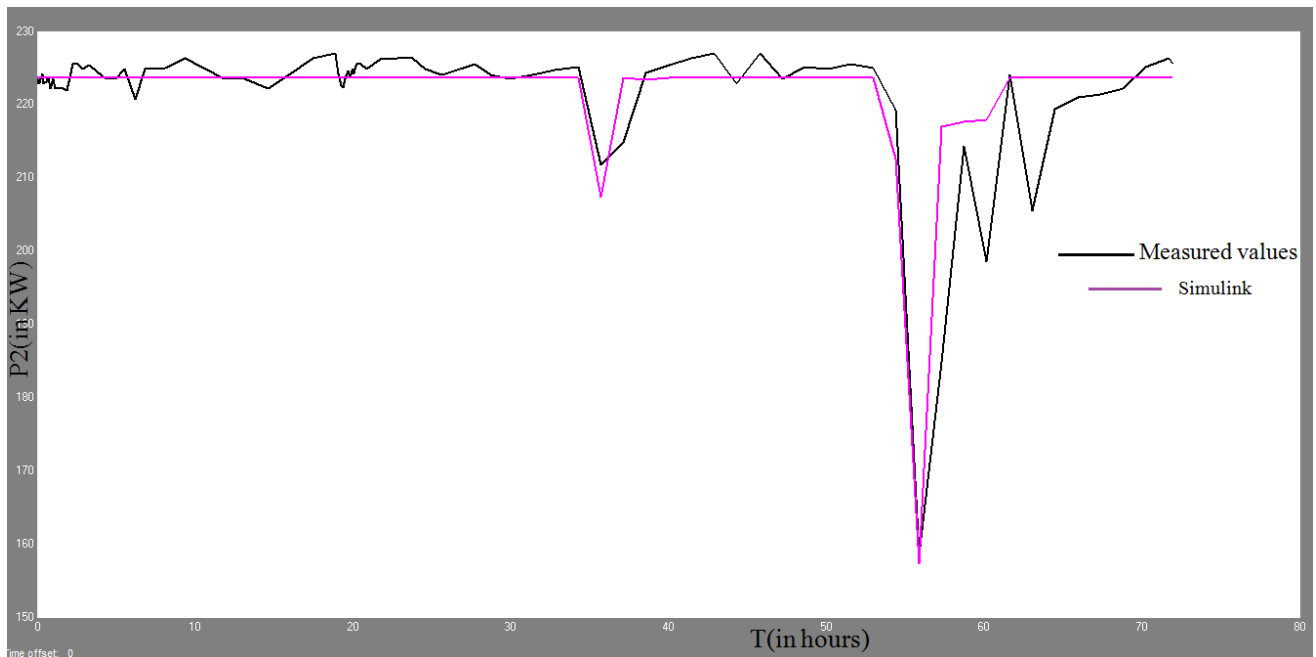

Fig 5.5 (b): The output result of the second compressor consuming power2 (in Kw) for Simulink and measurement values.
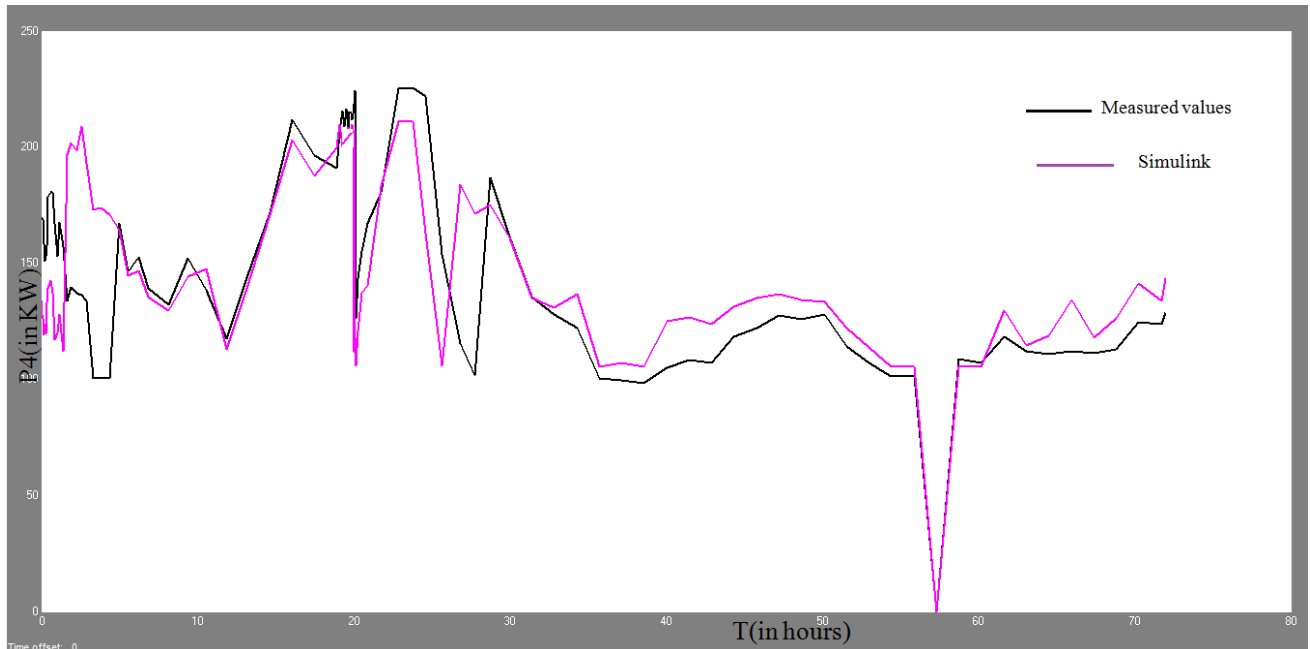
Fig 5.5(c): The output result of the fourth compressor consuming power4 (in Kw) for Simulink and measurement values.
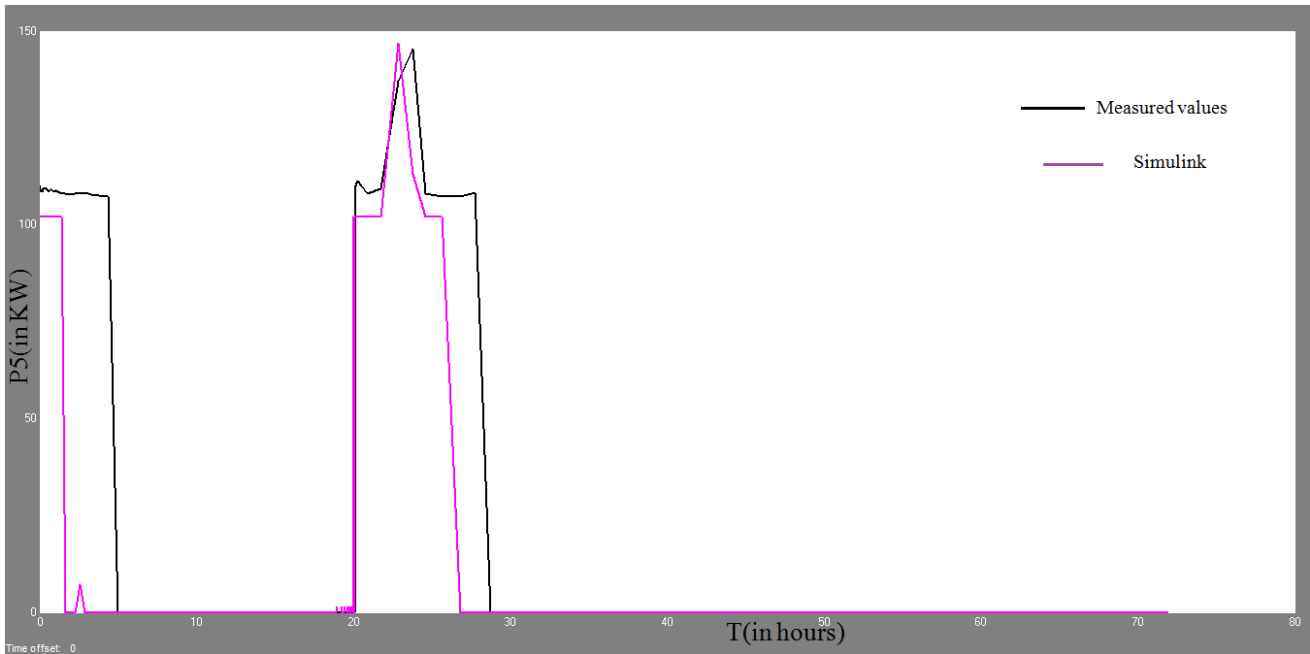

Fig 5.5 (d): The output result of the fifth compressor consuming power5 (in Kw) for Simulink and measurement values.

Energy values of Simulink:

The energy was consumed by the second compressor is:

For Simulink model values: 15232KWH

The energy was consumed by the fourth compressor is:

For Simulink model values: 9602KWH

The energy was consumed by the fifth compressor is:

For Simulink model values: 764KWH.

The total energy consumed by the all parallel compressors by using the first algorithm is:

$E_{First\ algorithm}$: 25598KWH.

5.2. Simulink Model For the another measurement values for 24hours:

5.2.1. 1st algorithm:

In this algorithm, the first compressor will be started up in minimum. When the air demand increases the compressor will be regulated up until it reaches its maximum (100%).

If there is still a demand for an increased air capacity the next compressor will be started automatically, but locked in its minimum position (50%). The first compressor will automatically be regulated back to 50% capacity (as 50% + 50% = 100%).

If there is still a demand for an increased air capacity the first compressor will regulate up from 50% to 100%. When the first compressor reaches the maximum the second time, it will be locked in its maximum position and the second compressor will start to regulate from 50 to 100%.

When the second compressor reaches maximum the third compressor will automatically be started and so on. If the air demand is decreasing the regulating system works vice versa.

The important feature by this controlling system is that all compressors can as a standard be regulated from 50% - 100%, but only one compressor at a time.
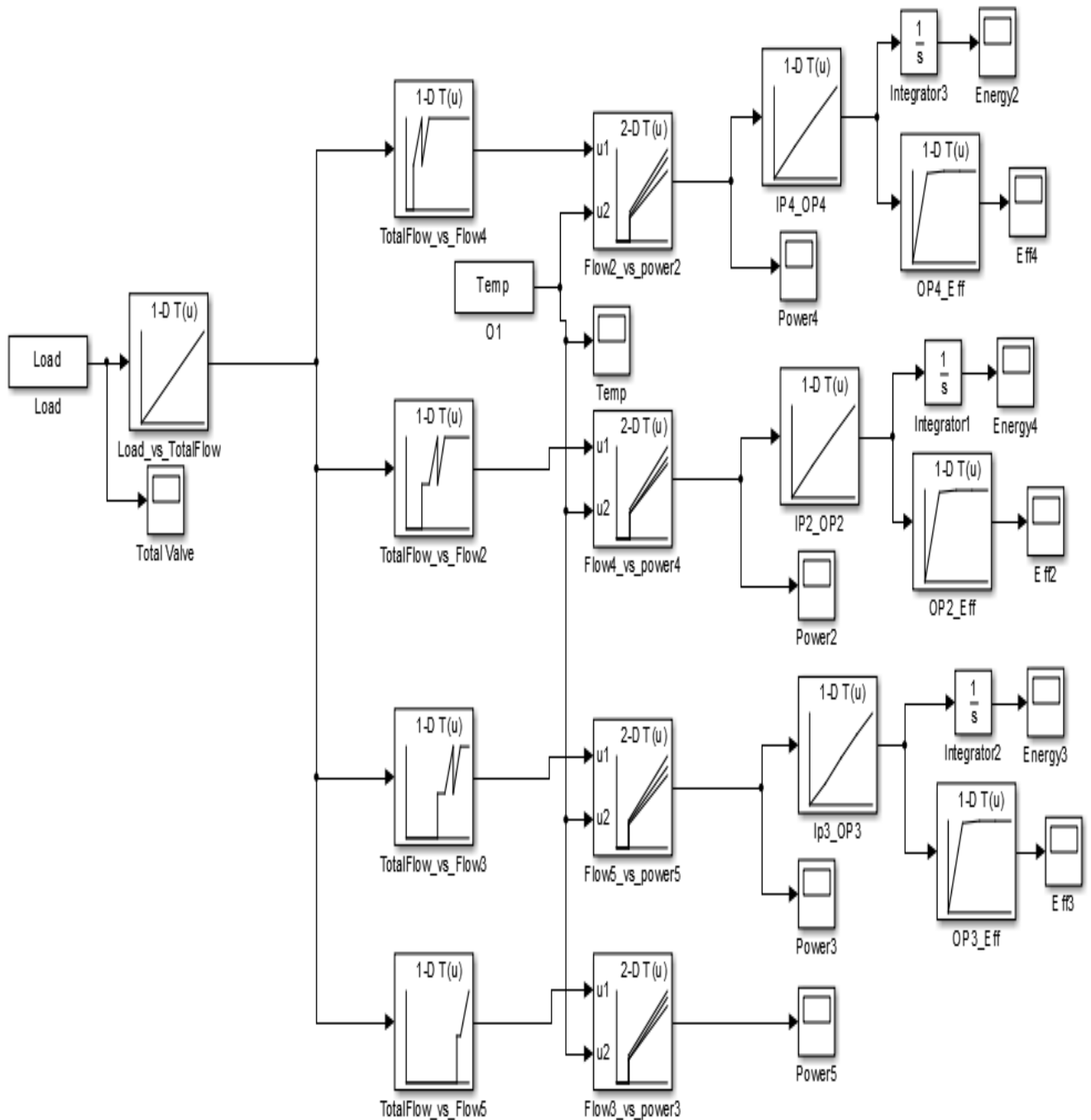
Fig 5.2.1: Parallel air compressors are builded in SIMULINK MODEL with the help of Flow (in m3/h) and power (in Kw) characteristics.

Result:

The power and energy values are identified by using the above Simulink model with the help of load from the measurement values and temperature:
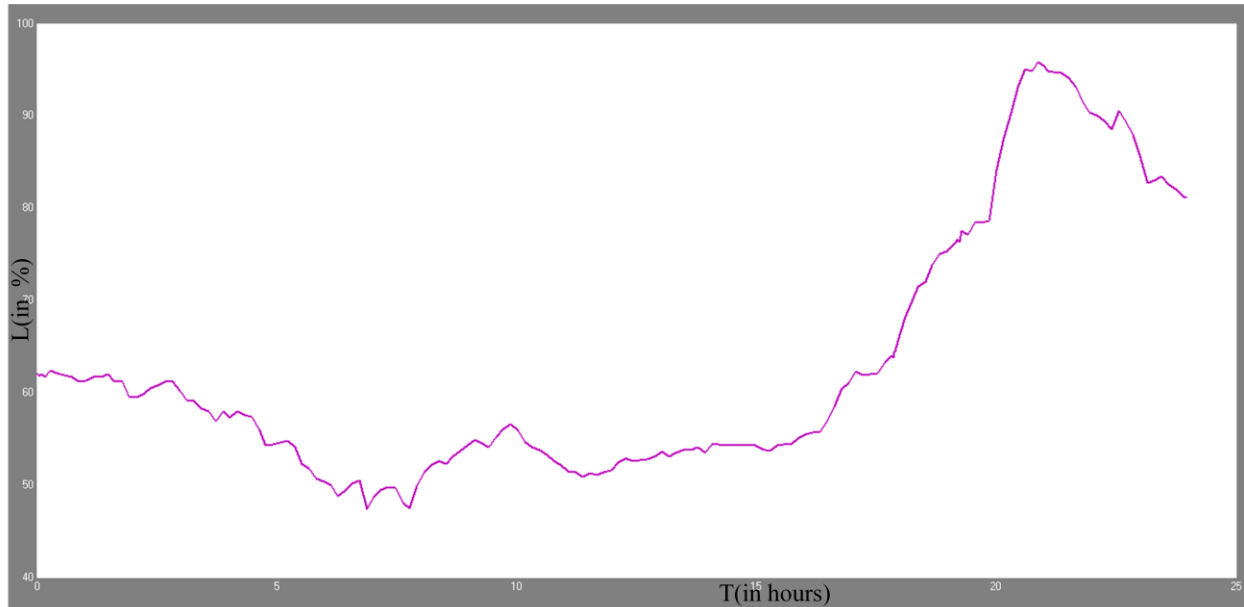

Fig 5.2.1 (a): The measurement values for compressor Load (in %) with time (in hours)
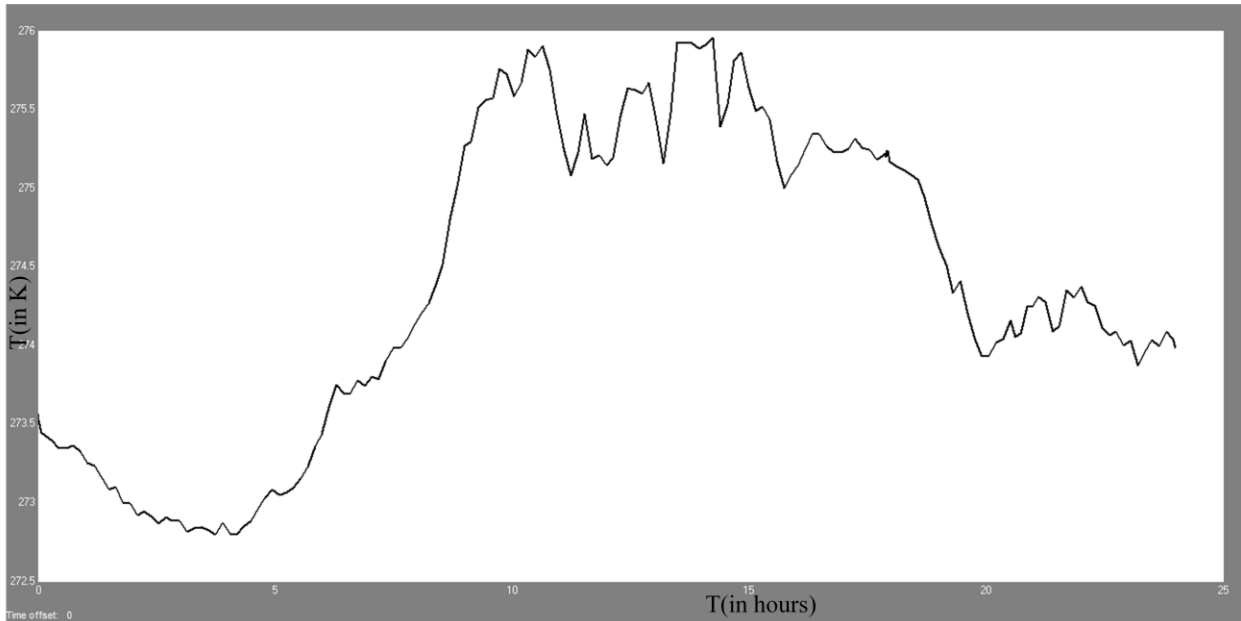

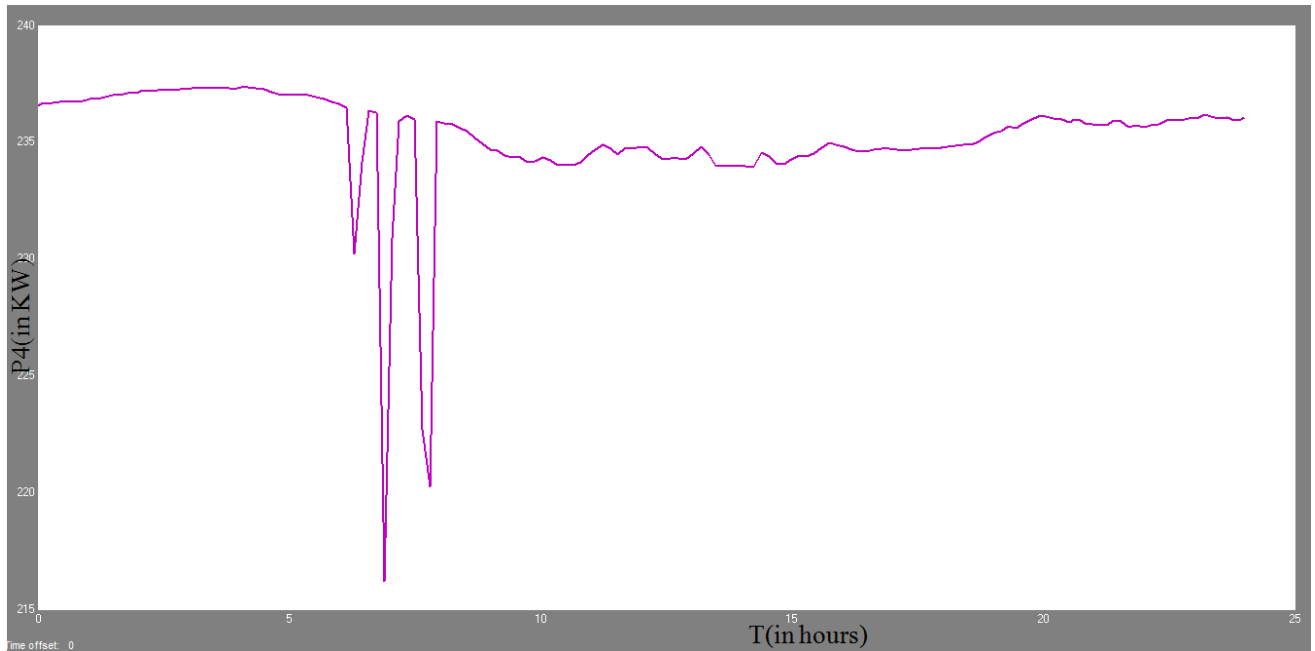Fig 5.2.1 (b): The Temperature (in K) varying with time (in hours)

Fig 5.2.1 (c): The output result of the fourth compressor consuming power4 (in Kw) for Simulink and measurement values.
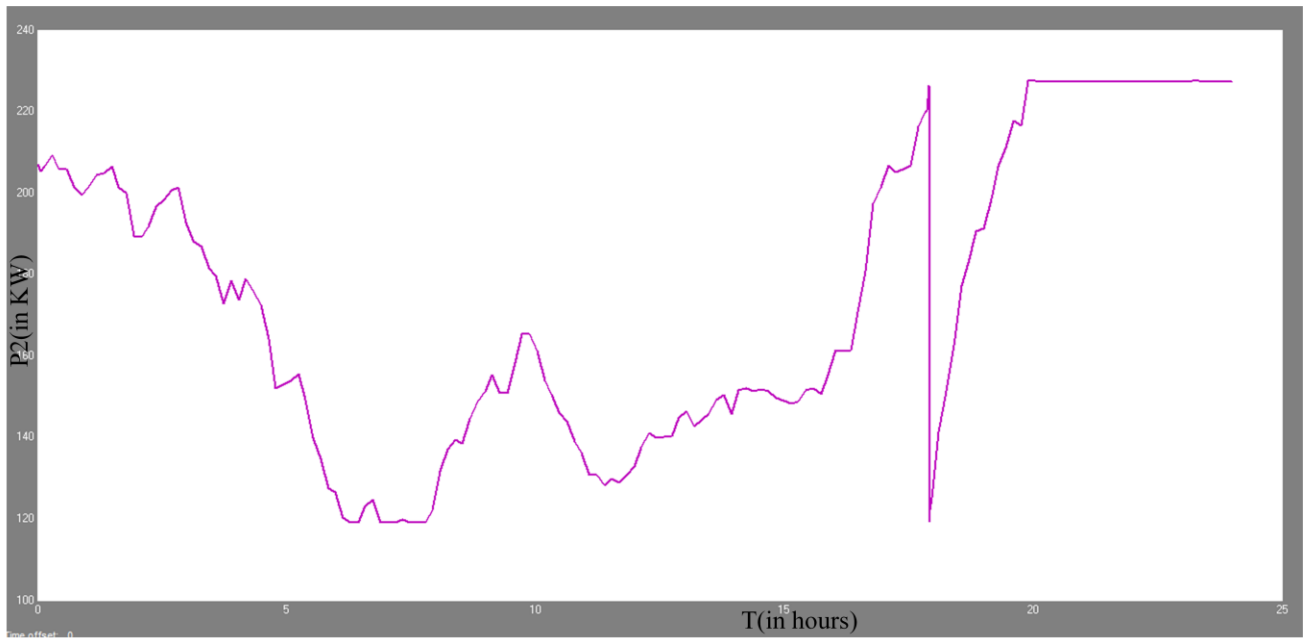

Fig 5.2.1 (d): The output result of the second compressor consuming power2 (in Kw) for Simulink and measurement values.
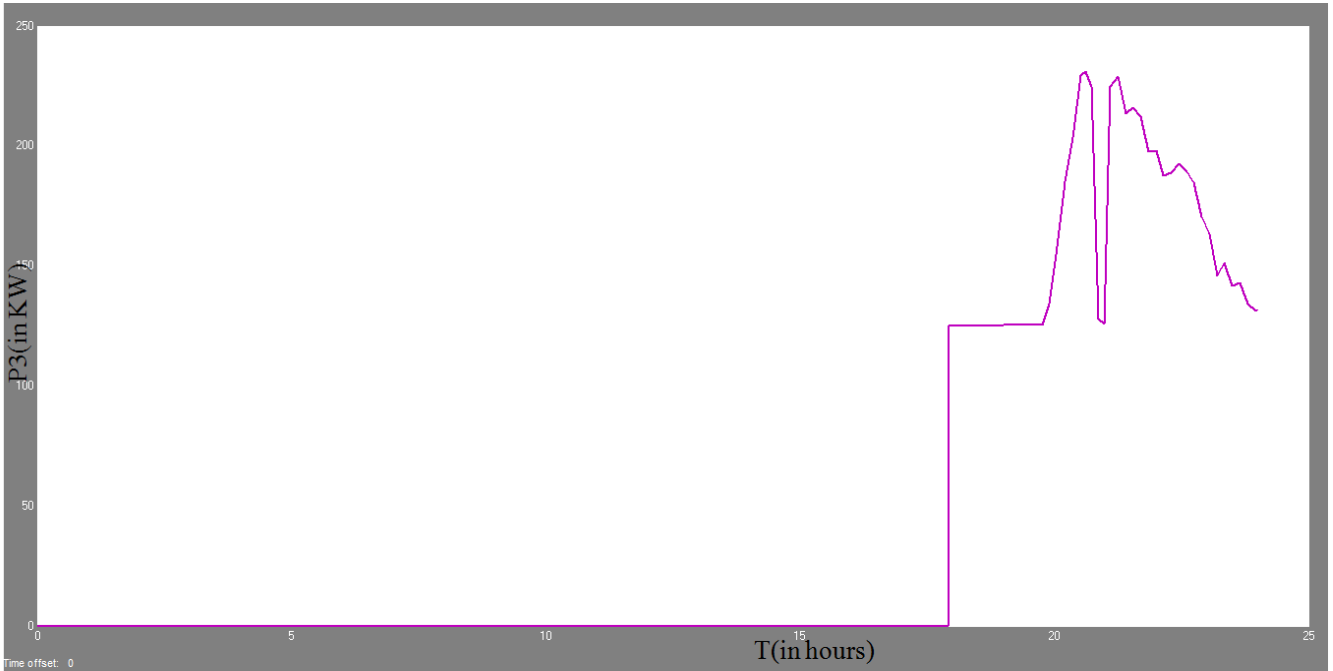
Fig 5.2.1 (e): The output result of the third compressor consuming power3 (in Kw) for Simulink and measurement values.

Energy values of Simulink:

The energy was consumed by the fourth compressor is:

For Simulink model values: 5107KWH.

The energy was consumed by the second compressor is:

For Simulink model values: 3807KWH.

The energy was consumed by the third compressor is:

For Simulink model values: 755KWH.

The total energy consumed by the all parallel compressors by using the first algorithm is:

$E_{First\ algorithm}$: 9669KWH

5.2.2. Second algorithm:

In this algorithm, the first compressor will be started up in minimum. When the air demand increases the compressor will be regulated up until it reaches its maximum (100%).

If there is still a demand for an increased air capacity the next compressor will be started automatically, but locked in its minimum position (50%). The first compressor will be regulated back to 50% capacity (as 50% + 50% = 100%).If there is still a demand for an increased air capacity the first and second compressor will regulate up from 50% to 100%. Here the first and second compressor reaches the maximum the position and the compressor will start to regulate from 50 to 100% at a time. If the air demand is decreasing the regulating system works vice versa.
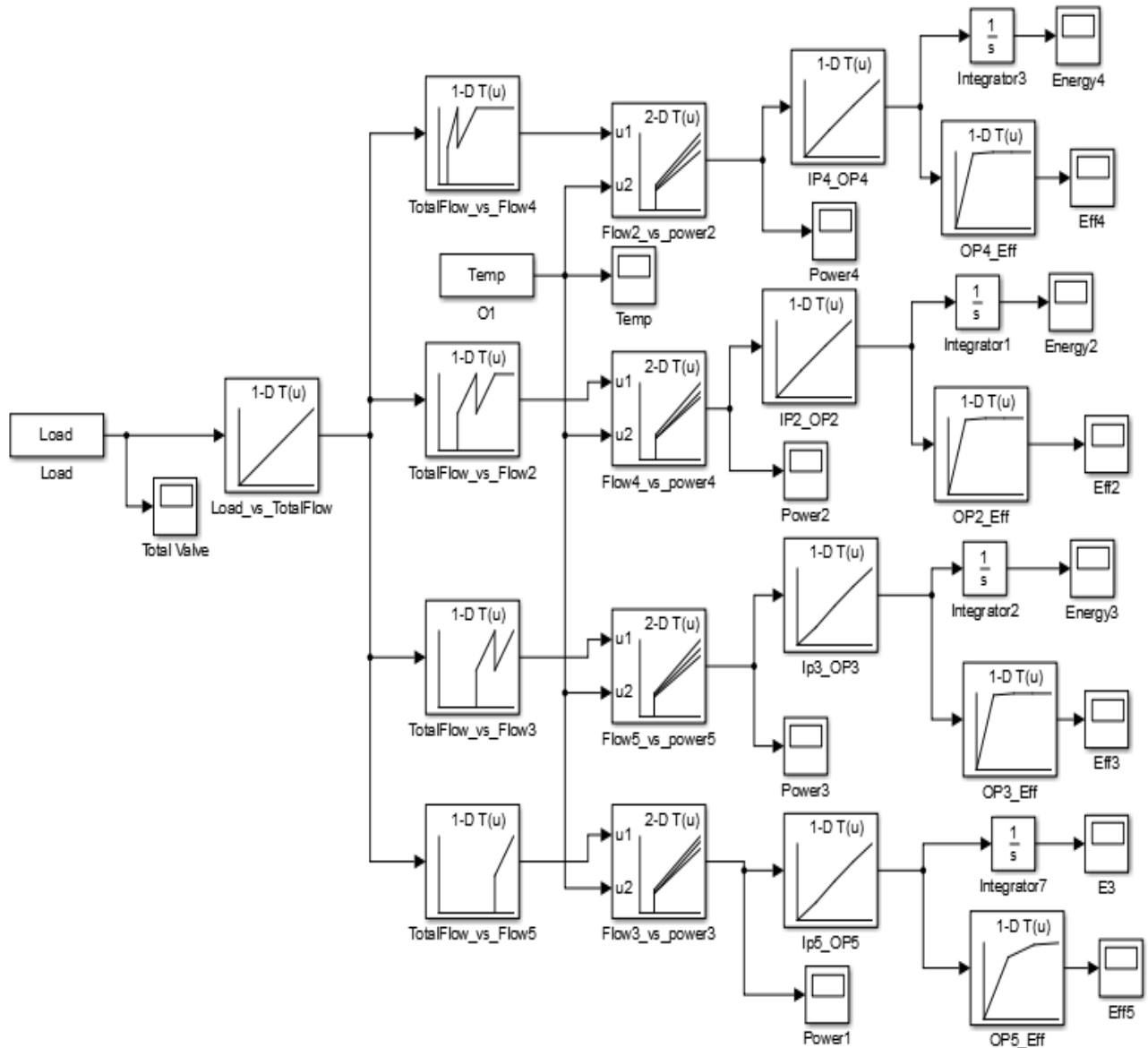

Fig 5.2.2: Parallel air compressors are builded in SIMULINK MODEL with the second algorithm of Flow (in m3/h) and power (in Kw) characteristics.

Results:

The power and energy values are identified by using the above Simulink model with the help of load from the measurement values and temperature:
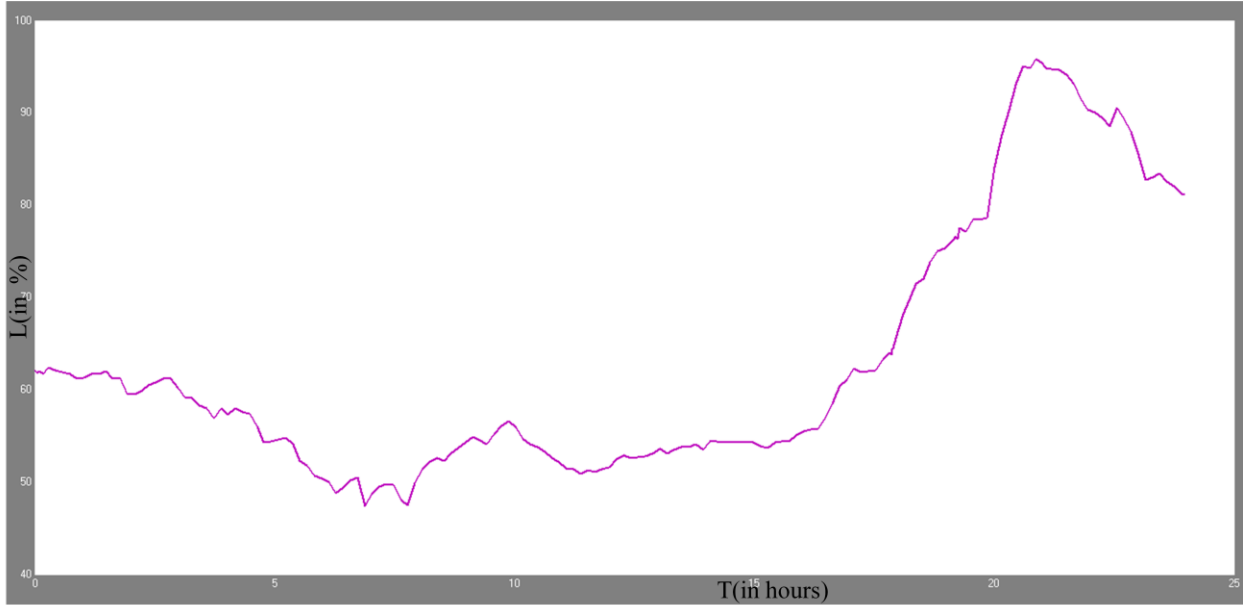

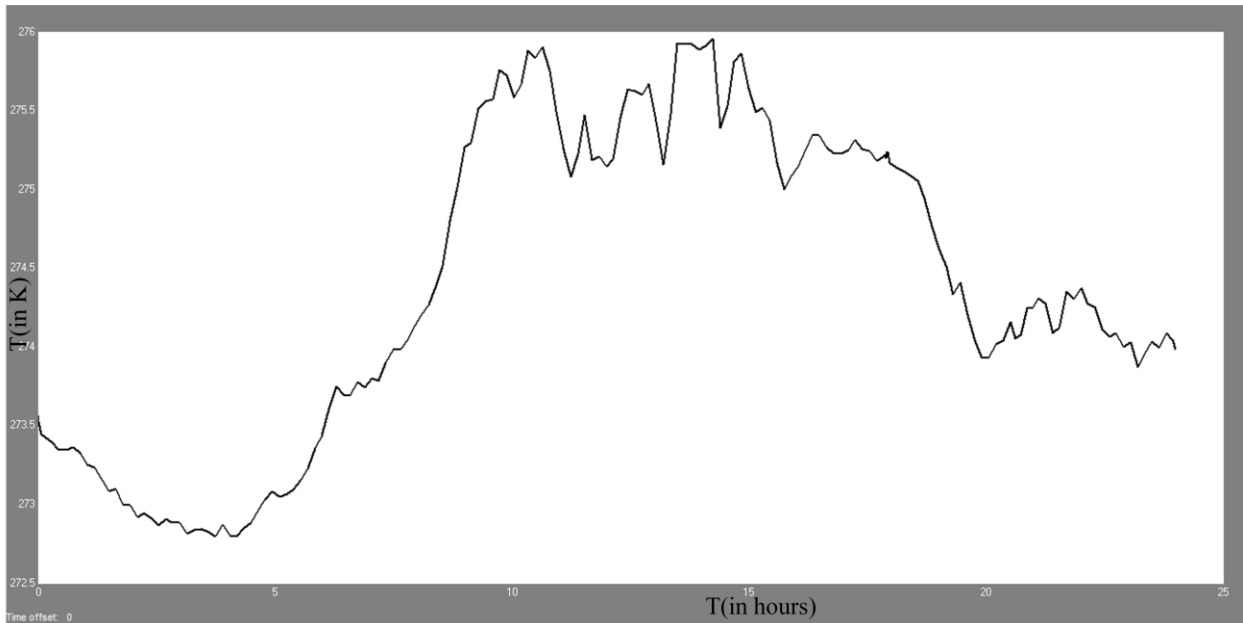Fig 5.2.2 (a): The measurement values for compressor Load (in %) with time (in hours)

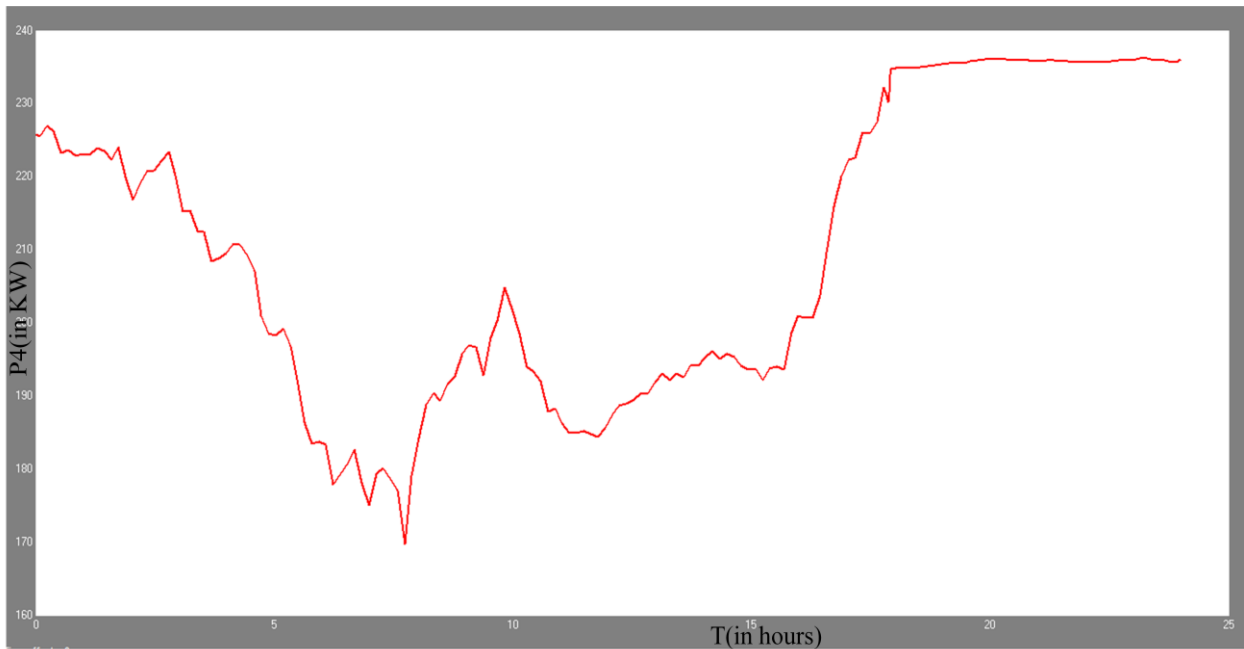Fig 5.2.2 (b): The Temperature (in K) varying with time (in hours)

Fig 5.2.2 (c): The output result of the fourth compressor consuming power4 (in Kw) for Simulink and measurement values.
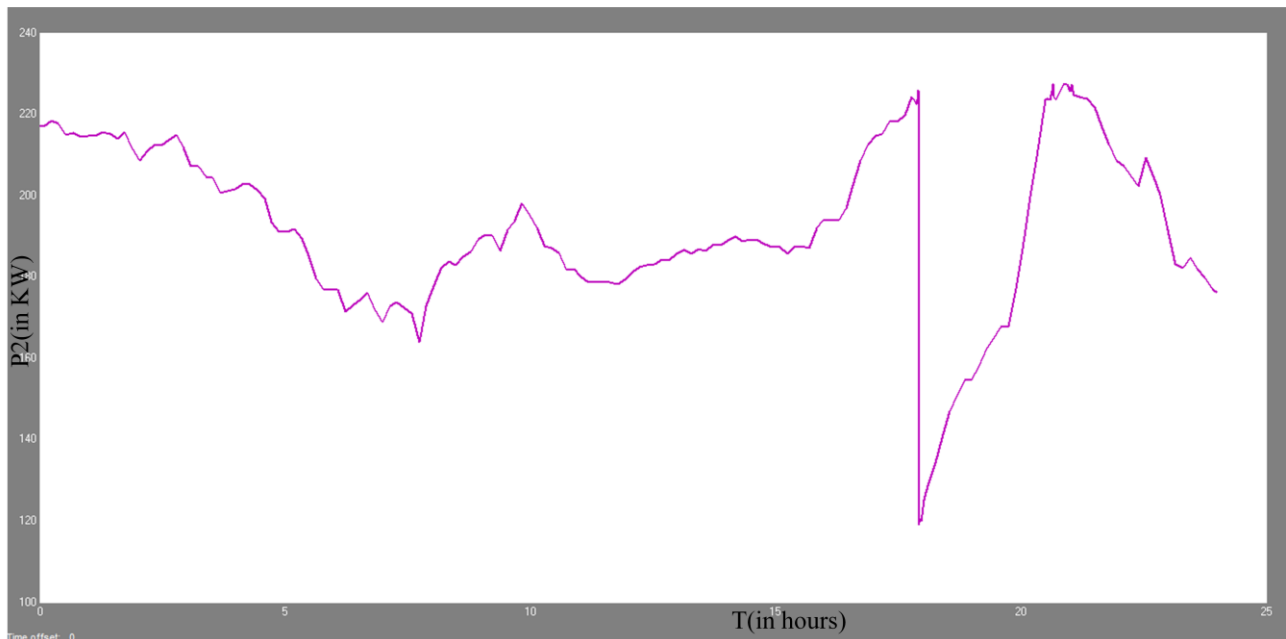
Fig 5.2.2 (d): The output result of the second compressor consuming power2 (in Kw) for Simulink and measurement values.
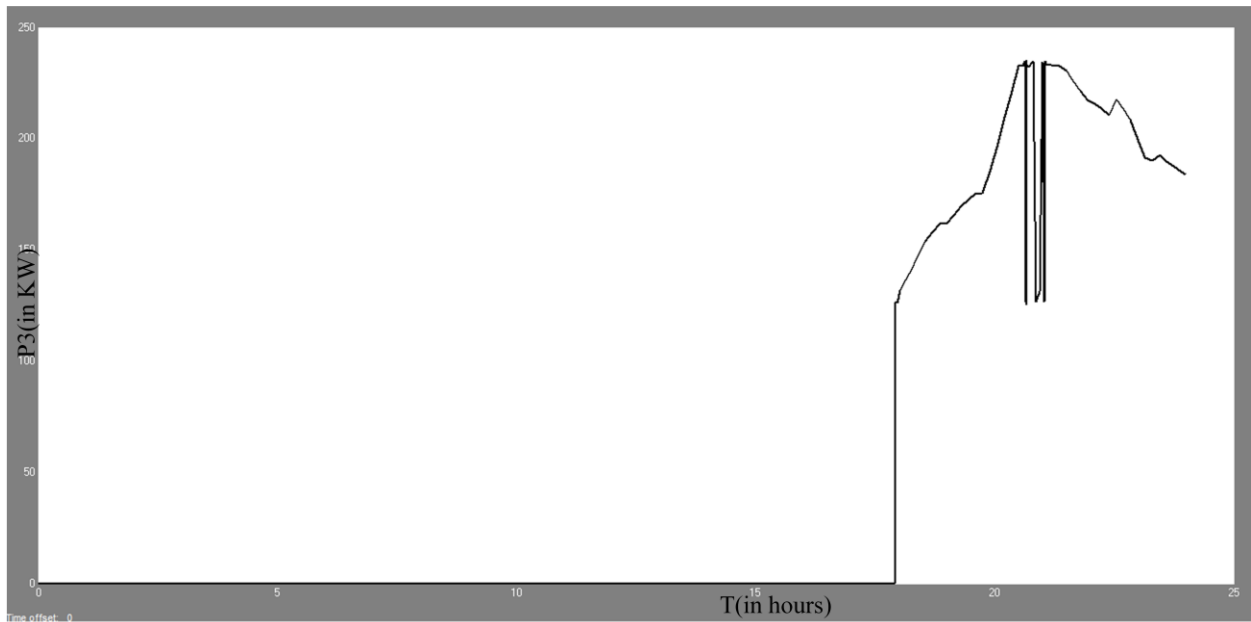
Fig 5.2.2 (e): The output result of the third compressor consuming power3 (in Kw) for Simulink and measurement values.

Energy values of Simulink:

The energy was consumed by the fourth compressor is:

For Simulink model values: 4842KWH.

The energy was consumed by the second compressor is:

For Simulink model values: 4173KWH.

The energy was consumed by the third compressor is:

For Simulink model values: 761KWH.

The total energy consumed by the all parallel compressors by using the second algorithm is:

$E_{second\ algorithm}$: 9776KWH.

6. **Conclusion:**

1) After observing the Matlab Simulink energy values for the different types of algorithm, the efficient is first algorithm because it has the energy values are less as compared with the other algorithm.

2) By using the Matlab Simulink model software, the power and energy values of each air compressors are identified.

3) By considering the volumetric flow rate should be produced by parallel air compressors, we have investigated the algorithms and the volumetric flow rate will splits depending upon the requirement.

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Appendix MATLAB Script:

A MATLAB Script was used to run the Simulink model for Model Application for Load. The script used the MATLAB Cell mode where the script was divided into functional parts and individual cells could be run alone or sequentially. The first part of the script involved the first algorithm and second part was second algorithm and the Command Window and Workspace to know the exact values and how it was executed.

```matlab
% For first algorithm% :
close all
clear all
clc
% To loao the data%
data=xlsread('air2.xlsx');
% Valve positions %
b=data(5763:end,32);
% Time for 72 hours%
a=data(5763:end,9);
%load vs Time %
c=[a b];
%power  vs Time %
d=data(5763:end,20);
P2=[a d];
f=data(5763:end,21);
P3=[a f];
h=data(5763:end,22);
P4=[a h];
j=data(5763:end,23);
P5=[a j];
% Energy Vs time %
w=data(5763:end,39);
E2=[a w];
x=data(5763:end,40);
E3=[a x];
y=data(5763:end,41);
E4=[a y];
z=data(5763:end,42);
E5=[a z];
% output power%
OP2=data(5763:end,34);
O2=[a OP2];
OP3=data(5763:end,35);
O3=[a OP3];
OP4=data(5763:end,36);
O4=[a OP4];
OP5=data(5763:end,37);
O5=[a OP5];

For second algorithm:
close all
clear all
clc
% To loao the data%
data=xlsread('one_day.xlsx');
% Valve positions %
```

```
L=data(3:5762,23);
% Time for 24hours %
a=data(3:5762,6);
Load=[a L];
% Temp %
T=data(3:5762,22);
Temp=[a T];
% flow%
f4=data(3:5762,33);
F4=[a f4];
%power%
P2=data(3:5762,25);
Power2=[a P2];
P3=data(3:5762,26);
Power3=[a P3];
P4=data(3:5762,27);
Power4=[a P4];
%Energy%
E2=data(3:5762,42);
Energy2=[a E2];
E3=data(3:5762,43);
Energy3=[a E3];
E4=data(3:5762,44);
Energy4=[a E4];
% Output power%
OP2=data(3:5762,37);
O2=[a OP2];
OP3=data(3:5762,38);
O3=[a OP3];
OP4=data(3:5762,39);
O4=[a OP4];

Load Program:
data2=xlsread('air.xls');
figure(1)
subplot(5,1,1)
plot(data2(3:end,3),data2(3:end,24),'k')
xlabel('Time(Hrs)');
ylabel('Flow1(m3/h)');
set(gca,'XTickLabel',[0 1.12 2.0 2.12 3.0 3.12 4.0 4.12 4.24] );
subplot(5,1,2)
plot(data2(3:end,3),data2(3:end,25),'k')
xlabel('Time(Hrs)');
ylabel('Flow2(m3/h)');
set(gca,'XTickLabel',[0 1.12 2.0 2.12 3.0 3.12 4.0 4.12 4.24] );
subplot(5,1,3)
plot(data2(3:end,3),data2(3:end,26),'k')
xlabel('Time(Hrs)');
ylabel('Flow3(m3/h)');
set(gca,'XTickLabel',[0 1.12 2.0 2.12 3.0 3.12 4.0 4.12 4.24] );
subplot(5,1,4)
plot(data2(3:end,3),data2(3:end,27),'k')
xlabel('Time(Hrs)');
ylabel('Flow4(m3/h)');
set(gca,'XTickLabel',[0 1.12 2.0 2.12 3.0 3.12 4.0 4.12 4.24] );
subplot(5,1,5)
plot(data2(3:end,3),data2(3:end,28),'k')
```

```
xlabel('Time(Hrs)');
ylabel('Flow5(m3/h');
set(gca,'XTickLabel',[0 1.12 2.0 2.12 3.0 3.12 4.0 4.12 4.24] );
```