CHAPTER 5

FREQUENCY STABILITY OF POWER SYSTEM USING MICROGRID WITH ENERGY STORAGE

5.1 INTRODUCTION

Active power output is controlled through the force or torque produced by the prime mover. This action is directly related to the electric power being supplied by the generator to the grid. This is because the magnetic field that provides the retarding effect is directly proportional to the current in the armature windings, while the same current also determines the amount of power generated. If the load on the generator suddenly increases, the reduction of load impedance results in an increased current in the armature windings, and the magnetic field associated with the increased current would slow down the generator.

Since the electrical power system operates under variable load condition, the load tracking problem will arise, which can cause the voltage and frequency instabilities. In order to maintain constant rotational frequency of the generator, the turbine must now supply an additional torque to match. Suppose if the load is suddenly reduced, the armature current and thus its magnetic field decreases, and the generator would speed up. To maintain equilibrium, the turbine must produce enough torque to stabilize the rotational frequency. The torque supplied by the prime mover is adjusted by a governor valve. In the case of steam turbine, the governor valve increases or decreases the steam flow, for a hydro turbine, it adjusts the water flow. In a
conventional power system, automatic governor control is employed for monitoring and controlling of the generator frequency. Such a governor system allows the generator to follow loads within the range of the prime mover’s capability and without operator intervention.

5.1.1 Background

In a conventional power system with a large number of synchronous generators as the main sources of energy, the mechanical energy in the generator rotors, in the form of kinetic energy, serves as the stored energy and feeds the grids in the event of any drastic load changes or disturbances. In the conventional way, the generation of electricity is based on fossil fuels and atomic energy. However, in recent years the rapid growth of demand and global concern over climate change and sustainability has led to the generation of electricity from renewable and sustainable resources. For power system security and stability to maintain frequency within a limit, continual balancing between active power generated and consumed is required.

Energy storage is a most promising technology. Reliable and affordable electricity storage is a prerequisite for using renewable energy in remote locations, for the integration of the electricity system and for the development of a future decentralised energy supply system. Energy storage has a pivotal role in combining a future sustainable energy supply. Energy storage alleviates the need to generate power at the same time as it is demanded. It has already wide variety of applications like supplying power to portable devices, UPS and recently in hybrid cars to reduce fuel consumption, etc. However, the addition of energy storage technology to store generated energy from renewable sources is not a widely explored area yet. Swierczynski et al (2010) have presented the complementarities between storage and renewable, that of particular interest, both in terms of capturing
enhanced value from such essentially intermittent resources and in maintaining stability in the electrical power system. Using storage technologies in combination with renewable resources is one of the proven solutions to balance the fluctuation of the power generation, consumption and complementing the primary generation (Vongmanee & Monyakul 2008).

Energy storage devices are able to balance the fluctuation of power generation and consumption. Storage devices can be used in a power grid to store the excess energy when the energy production is high and the demand is low and utilize the stored energy when the produced energy cannot meet the high demands of the consumers. Whenever there is an unbalance between active power production and active power load demand the frequency deviates from its nominal value. Therefore, the system should be able to maintain frequency in an acceptable operating range and to ensure power quality. This may be desirable both for economic reasons and to guarantee sufficient supply during times of peak demand or when resources are unavailable.

Lopes et al (2006) proposed that microgrid can usually be connected to an electrical distribution network in an autonomous way and can employ various distributed generation technologies such as micro-turbine, fuel cell, photovoltaic system together with energy storage devices such as battery, condenser and flywheel. Integration of microgrid with storage devices into the power system brings new challenges to the planning, operation, and control of the power system. The micro sources technologies like micro gas turbine, fuel cells, photovoltaic system and wind turbine used in the microgrid are not suitable for supplying energy to the grid directly (Vongmanee & Monyakul 2008, Daneshi et al 2010). When these sources are connected directly, the power pulsations present in the sources are almost directly transferred to the electrical grid. So, there is no control over active
and reactive power, which are the important control parameters to regulate the voltage and frequency. For a large-scale renewable generation, such as wind farms, energy storage will play a pivotal role in reaching reliability standards and meeting frequency and ramping requirements.

A range of power system characteristics, including system size, individual generator and load frequency response characteristics depends on the system parameters. The size and speed of a frequency deviation depend on the magnitude of the power imbalance and the power system size. The greater inertia of the system leads to a slower rate of change of frequency in the event of power imbalance. Large interconnected power systems have high inertia. In contrast, the small, isolated power system has much less inertia. Combined with the fact that large power imbalances relative to the system size are more frequent and frequency changes are faster. Therefore, maintaining system frequency at a nominal frequency for a power system with limited interconnection can be technically challenging as explained by Lalor (2005).

In microgrid, energy storage will have significant stabilizing effects on the system due to the low kinetic energy stored in the microgrid’s generators such as wind turbines and small synchronous generators. Consequently, the effective dynamic power flow control and stabilizing mechanisms, which engage energy storage are of paramount importance. In order to improve the transient stability, voltage regulators employed on the lines should be quick acting and the governors attached to the turbines driving alternators should be high speed so as to adjust the generator input quickly as per the demand of the load.

Apart from the different approaches to electricity storage technologies, Compressed Air Energy Storage (CAES) technology is newer technology, which is a preferred alternative to pumped hydro storage as
proposed by Bradshaw (2000). Absence of water reservoirs facilitates the use of compressed air as the storage medium. In CAES, electric energy is used to operate compressor motor that fill a confined space such as an underground cavern with air at high pressure. To retrieve the energy, the pumps are operated in reverse as generators. The CAES power plant produces power by storing energy during off-peak period in the form of compressed air. During peak period, the CAES utilize the stored energy during to generate electricity to meet the demand as presented by Vongmanee & Monyakul (2008), Sun et al (2010).

5.1.2 Significance of the Study

When a fault occurs in the system, frequency variation will cause a primary regulating action on the generating units. The units should automatically adjust their outputs to compensate for the variation in demand. Any departure from the set point is translated into a signal to the main valve to open or close by an appropriate amount. The power input to the turbine is controlled through the position of the control valves, which control the flow of air into the turbines. The valve position is influenced by the output signal of the PI controller. PI controller is one of the feedback controllers which calculate an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the control inputs to the valve, so that the generator operates at a fixed level of power output which would typically correspond to its maximum load.

5.1.3 Objective

The objective of this work is to maintain the generator power output corresponding to its peak load by controlling the flow of air for the energy storage in a microgrid to maintain stable frequency under various load
conditions. The focus of this work is on the potential of compressed energy storage technology to provide effective air flow control, stabilizing mechanism and demand response. Storage devices can provide the instantaneous active power required to support the dynamic stability of microgrid by varying the rate of absorbed power. In the proposed approach, the use of microgrid consists of conventional synchronous generator as well as renewable energy sources, energy storage systems and loads are considered, in order to investigate the effective frequency control under various load demands. The microgrid structure of the proposed work is shown in Figure 5.1.

![Microgrid structure](image)

Figure 5.1 Microgrid structure

Under variable load conditions, the stored compressed air from the CAES system will be utilized to meet the demand. During power generation an excess power is used to compress the air. An air flow controller is used to
control the air flow of CAES, so that the microgrid follows the various load demands to maintain the stable frequency.

The chapter is organized as follows: In section 5.2 various storage technologies are described. Process of air to energy conversion and the equipment used for that conversion are explained in section 5.3 and section 5.4 respectively. The proposed work is discussed in section 5.5. Section 5.6 briefs the results and discussion. Section 5.7 presents the conclusion about the work.

5.2 STORAGE TECHNOLOGIES

The rising problem of imbalance between energy production and demand presented by the sporadic nature of solar and wind resources can be resolved using energy storage. Sun et al (2010) described various storage technologies to fill the gap and accommodate the net demand variability. A number of major electric storage technologies are presented in Daneshi et al (2010) as given below:

- Pumped hydroelectric storage
- Batteries
- Flywheels
- Super Conducting Magnetic Energy Storage (SMES)
- Super Capacitors and Ultracapacitors
- Compressed Air Energy Storage (CAES)

5.2.1 Pumped Hydroelectric Storage

A pumped hydroelectric storage (PHS) described by Bradshaw (2000) is typically equipped with pumps to connect an upper and a lower
reservoir. During off-peak hours it pumps the water from the lower reservoir to the upper one to store energy. During peak hours, water is released from the upper reservoir to generate power at a higher price. Pumped storage hydroelectricity requires mountains, so opportunities are limited by geography. Building such storage also tends to be expensive and environmentally destructive.

5.2.2 Batteries

Batteries are energy storage devices which are used to provide active power to microgrid to compensate for fast load changes. A battery based energy storage unit is ideally suited to restore microgrid stability during transients. Energy is stored in a battery due to reactions generated by electrochemical components of the battery while charging. The battery can store energy in a chemical form and convert the stored chemical energy into electrical energy based on the demand. The development of advanced batteries (such as nickel-zinc, nickel-iron, zinc-chloride and sodium-sulphur) with characteristics superior to familiar lead-acid battery could result in the use of battery energy storage on a large scale. The only drawback of the battery is, it can be used only for a limited period of time (Lasseter & Erickson 2009, Chen et al 2009, Daneshi et al 2010).

5.2.3 Flywheels

It is an electromechanical energy conversion device which uses a type of kinetic energy storage. A rotor spinning at a very high velocity and an integrated motor-generator are two main components of flywheel storage device. The motor-generator operates either as a motor to turn the flywheel and store energy or as a generator to produce power. Though the efficiency of the flywheel is high, the discharge rate of flywheel makes it not suitable to be used for a long period as presented by Daneshi et al (2010).
5.2.4 Super Conducting Magnetic Energy Storage

A Super Conducting Magnetic Energy Storage (SMES) device consists of a super conducting coil, in which energy is stored as a magnetic field. The coil must be kept at a very low temperature to maintain its super conducting capabilities. SMES energy devices are able to follow the system load changes instantaneously and are capable of controlling both active and reactive power simultaneously. SMES is the only known technology to store electrical energy directly into electric current as discussed in Chen et al (2009), Daneshi et al (2010). It stores electric energy as direct electric current passing through an inductor (coil) made from a superconducting material so that current can circulate indefinitely with almost zero loss. SMES can also be used for storing energy as the magnetic field created by the flow of electric current. To maintain the inductor in its superconducting state, it is immersed in liquid helium contained in a vacuum-insulated cryostat.

5.2.5 Super Capacitor

Super capacitor is an electronic device that stores an electric charge using two conductive surfaces separated by an insulator. It uses a type of electrostatic energy conversion discussed by Chen et al (2009), Daneshi et al (2010). Energy is stored as electrostatic charges on opposing surfaces within the dielectric insulator. It can charge and discharge a large amount of power in a very short time. Self discharge rate of super capacitor is the main reason for being less suitable for long term storage. Ultra capacitor also uses the same principle and it is used to store a greater amount of energy and power in a small area.

5.2.6 Compressed Air Energy Storage System

Now a days effort for storing surplus power are being continually explored. Also currently these efforts have not involved in using a large scale
power storage method except for the pumped storage generation. For a pumped hydro storage system suitable locations are limited. Thus, the need for the more economical and efficient energy storage system was emphasized by Lee et al (2007).

Compressed Air Energy Storage (CAES) is one of the most efficient technologies used to balance the fluctuation of the power generation and consumption. Gas turbine generation/steam turbine generation units are used in fossil fuelled power plants. CAES works on the basis of conventional gas turbine generation. It decouples the compression and expansion cycles of a conventional gas turbine into two separate processes and stores the energy in the form of elastic potential energy of compressed air. The CAES power plant produces power by storing energy, during off-peak periods, in the form of compressed air and uses it on demand during the peak periods to generate power with a turbo-generator/gas turbine system. The conceptual representation of CAES and its schematic diagram proposed in Bradshaw (2000), Swider (2007), Vongmanee & Monyakul (2008) are shown in Figure 5.2 and Figure 5.3 respectively. Three types of technologies used to compress the air are given below:

- Adiabatic storage - retains the heat of compression and reuses this when the air is expanded to produce the power expected efficiency is around 70% (although theoretically 100% possible)

- Diabetic storage – takes the heat and dissipates it into the atmosphere via heat intercoolers. When the air is released through the turbines it needs to be heated and expected efficiency is around 70%.
- Isothermal storage – involves using heat exchangers to always keep the same internal and external temperature, so that as the air is compressed, heat dissipates into the atmosphere. Once the air is released to drive the turbine and produce the electricity, heat is bought in from the external environment.

**Figure 5.2 Conceptual representation of CAES**

**Figure 5.3 Schematic diagram of CAES system**
5.3 PROCESS OF AIR ENERGY CONVERSION

The energy conversion process of the proposed system consists of three main components: air compressor, storage vessel/underground salt cavern and compressed air generator. This process mainly involves thermodynamic energy conversion process at constant temperature. The energy conversion starts with the compressor, and the electrical power from renewable energy is converted into mechanical torque to suck and compress air from the atmosphere and store in the tank. Then, the compressed air power is converted back to torque to drive the prime mover coupled with the generator.

5.3.1 Air Compression/Expansion Process

The air compressor/expander uses mechanical energy from the rotational shaft to compress air for storage, and extracts energy from the compressed air through expansion to drive the rotating shaft. The thermodynamics of air energy conversion for both compression and expansion are considered as an isothermal process where the temperature is constant. As ideal gas law, \( PV = nRT \), which relates temperature \( T \), pressure \( P \) and volume \( V \), is used to derive the power and work. In thermodynamics, the work involved when a gas changes from initial state to final state is referred in Equations (5.1) and (5.2).

\[
W = \int_{V_{\text{initial}}}^{V_{\text{final}}} PdV = -\int_{V_{\text{initial}}}^{V_{\text{final}}} \frac{nRT}{V}dV = nRT(lnV_1 - lnV_2) \tag{5.1}
\]

\[
= nRT(lnP_2 - lnP_1) = P_1V_1(lnP_2 - lnP_1) \tag{5.2}
\]

where \( P \) is the pressure, \( V \) is volume, \( n \) is the number of mole and \( R \) is the gas constant, \( W \) is work done on the system. \( P_1, P_2 \) and \( V_1, V_2 \) are the pressure and volume of the atmospheric state and compressed air state, respectively.
However, power is work per unit time and air flow ($Q$) is volume per unit time ($Q = \frac{V}{t}$). The compression power ($P_c$) is expressed as Equation (5.3).

$$P_c = P_1 Q (\ln P_2 - \ln P_1)$$

(5.3)

The compressed air flow driven by electric power can be expressed by Equation (5.4).

$$Q = \frac{V \cdot I}{P_1 (\ln P_2 - \ln P_1)}$$

(5.4)

where $V$ and $I$ are voltage and current, respectively. The power directly depends on the pressure and air flow, which vary with the available power from renewable energy (Vongmanee & Monyakul 2008). When electricity is needed, the compressed air is expanded with turbo expanders or compressed air engines driving electrical generators to produce electricity. The process which transforms pneumatic energy into mechanical rotary movement with the possibility of continuous motion is known as compressed air expansion process.

### 5.4 AIR MOTORS

A device which is used in compressed air expansion process is called as compressed air engine or air motor. An air motor is a type of motor used to produce continuous rotary power from a compressed air system. Air motors can be used in volatile atmospheres. Common designs of air motors include axial piston, radial piston, gear motor, turbine, rotary vane motor, V-type, and diaphragm as explained in Air motor handbook (1987). Air motors generally convert the compressed air energy to mechanical work through either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor.
5.4.1 Piston Motors

Piston motors are most commonly used in hydraulic systems. It is same as hydraulic pumps except that they are used to convert hydraulic energy into mechanical energy. To ensure smooth running, it is used in a series of two, three, four, five, or six cylinders that are enclosed in housing. This allows for more power to be delivered by the pistons because several motors are in sync with each other at certain times of their cycle. The power of the motor depends on the input pressure, number of pistons, piston area, stroke and piston speed. The force from axially arranged cylinders is converted into a rotary motion.

5.4.2 Gear Motors

In this design, torque is generated by the pressure of the air against the teeth profiles of two meshed gear wheels. One of the gear wheels is secured to the motor shaft. Gear motors are produced with spur or helical gearing. Gear motors deliver high torque at low speed without additional gearing. When coupled with a 2-stage orbital planetary gear train, gear motor power elements provide torque at speeds down to 20 rpm. These motors are well suited to hazardous-environment applications where relatively high torque is needed in a limited space. Like vane motors, they are much less sensitive to mounting orientation than piston motors.

5.4.3 Turbine Motors

The efficiency of an air motor is defined as the ratio of the actual power output to the theoretical power available from the compressed air for the expansion ratio at which the machine is operating. Turbines convert pneumatic power to mechanical power at about 65% to 75% efficiency. Turbine efficiency is higher than other air motors because the sliding contact
of parts does not occur to cause internal friction. Recently turbine technology is being applied for starting small, medium and large reciprocating engines. Turbine motors are relatively compact and light, for their power delivery capability.

5.4.4 Rotary Vane Motors

Rotary vane motors are normally used in applications requiring low to medium power outputs. Because of their simple construction and low weight, sliding vane motors are used in a host of mixing, driving, turning, and pulling applications. Rotary vane air motors are available with three to ten vanes. There is a rotational drive shaft with four slots, each of which is fitted with a freely sliding rectangular vane. When the drive shaft starts to rotate, the vanes tend to slide outward due to centrifugal force and are limited by the shape of the rotor housing. Depending on the flow direction, this motor will rotate in either clockwise or counter clockwise directions. The rotor speed is between 3000 rpm and 8500 rpm and power range is 0.1 kW - 17 kW (0.14hp - 24 hp). The difference of air pressure provides force on the vanes, so that the motor can rotate in either direction. Torque is developed from pressure acting on one side of the vanes. Torque at the output shaft is proportional to the exposed vane area, the pressure, and the moment arm through which the pressure acts.

5.5 PROPOSED WORK

The energy conversion process of the proposed system consists of three main components: air compressor, energy storage vessel and compressed air generator. The electrical power from the grid is converted into mechanical torque is applied to suck and compress the air from the atmosphere and store it in the tank. Then the compressed air transmits the air power to drive the prime mover coupled to the generator, where the
mechanical power is converted back to electric power. The compressed air is released back into the atmosphere again. The functional block diagram of the proposed work and the proposed control system are shown in Figure 5.4 and Figure 5.5 respectively.

Figure 5.4 Functional block diagram of the proposed system

Figure 5.5 Proposed control system
5.5.1 PI Controller

PI (Proportional-Integral) controllers are commonly used to regulate the time-domain behaviour of many different types of dynamic plants. In this work PI controller is designed to control the pneumatic control valve. The output of the PI controller is used to adjust the valve position of the 5/3-way pneumatic control valve. PI controller works in the closed-loop system shown in Figure 5.5. The variable $e$ represents the tracking error, the difference between the desired frequency (set point) and the actual output frequency of the generator. This error signal will be sent to the PI controller, and the controller computes both the proportional and the integral of this error signal.

The output of the controller is defined in Equation (5.5),

$$u(t) = K[e(t) + \frac{1}{T_i} \int e(\tau) d\tau]$$

$$u(t) = Ke(t) + \frac{K}{T_i} \int e(\tau) d\tau$$

(5.5)

$$K_p = Ke(t), K_i = \frac{K}{T_i} \int e(\tau) d\tau$$

where $K_p$ and $K_i$ are the tuning parameters of PI controller and $T_i$ is the integral time constant of the system. PI controller signal generation is shown in Figure 5.6. The controller takes $e$ and compute proportional and integral gain.
Though 95% of the industrial controllers are PID type, most loops are actually PI control. Finding optimum parameters for a PI controller is a daunting task, so control engineers still use trial and error method for tuning. PI controller will eliminate forced oscillations and steady state error. PI controllers are very often used in industry, especially when the speed of the response is not an issue. The tuning procedure for a PI controller is given below,

- Set integral gain \( (K_i) \) to zero
- Set proportional gain \( (K_p) \) low for system stability
- Apply a step command
- Increase \( K_p \) to maximum value without overshoot
- Increase \( K_i \) approximately to 10% overshoot

Adjusting the weighting constants \( K_p \) and \( K_i \) continuously till the PI controller is set to give the desired performance (Patranabis 2012). In the
proposed work with $K_p = 10$ and $K_i = 20$ for PI controller, the desired response is achieved.

5.5.2 Pneumatic Control Valve

The directional control valves control the passage of air signals. The 5/3 valve has 5 working parts and 3 switching positions. Directional control valves with three positions have a mid-position offering additional options for cylinder actuation. With these valves, double-acting cylinders can be stopped within the stroke range. This means a cylinder piston under pressure in mid position is briefly clamped in normally closed position and in normally open position, the piston become unpressurised. If no signals are applied at either of the two control ports, the valve remains centered in mid position. In a 5/3 control valve the positions can either be, pressure is applied, pressure is exhausted or all 5 ports are blocked. The main reason for the last position would be to maintain high standards of safety. The flow control valve restricts or throttles the air in a particular direction to reduce the flow rate of the air and hence control the signal flow. Ideally, it is possible to infinitely vary the restrictor from fully open to completely close. The flow control valve is fitted close to the working element and must be adjusted to match the requirements of the application (Beater 2007). Figure 5.7 shows the pneumatic symbol of 5/3-way pneumatic control valve.

![Figure 5.7 Pneumatic symbol of 5/3-way pneumatic control valve](image_url)
5.5.3 Pneumatic Vane Motor

Pneumatic actuators convert the compressed air energy to mechanical energy through motion technology. They can be employed extensively for simple position and speed control applications in industry. The schematic diagram of pneumatic vane motor is shown in Figure 5.8.

![Schematic diagram of pneumatic vane motor](image)

**Figure 5.8 Schematic diagram of pneumatic vane motor**

If the storage facility is full of compressed air, the cavern pressure is higher and if the cavern is almost empty then the cavern pressure is low. Therefore, there are two operating modes considered for CAES system:

- Allow the pressure to change naturally as the air is released, which will mean that the turbine creates less electricity as time goes on.
- Control the speed at which the air is released from the cavern to ensure constant electricity supply from the turbine / generator.
The amount of energy produced by the compressed air energy storage facility is reflected by controlling the source of air driving the turbine.

5.6 SYSTEM SPECIFICATIONS

5.6.1 Generator Specifications

Synchronous Generator

Nominal power = 4 kW

Line to line Voltage = 400 V

Frequency = 50 Hz

5.6.2 Vane Air Motor Specifications

Power = 6.7 hp or 5 kW

Speed = 3000 Rpm

Flow rate = 4.7 m³/min

Pressure = 5 Bar

The dynamic performance of the proposed system is assessed through digital simulation. The MATLAB/Simulink model has been developed for the proposed work is shown in Figure 5.9.
Figure 5.9  Simulation diagram of CAES interconnected with electrical grid
5.7 SIMULATION RESULTS AND DISCUSSIONS

During sudden changes in load demand, two case studies have been considered in order to investigate the dynamic performance of the system to maintain frequency under variable load. In the first case study, the stabilization of frequency and the rate of air flow during load variation in grid connected mode is considered, and in the second case study, the stabilization of frequency and air flow rate under load variation in island mode of microgrid is considered. In case 1, the system is initially operated with load demand which is less than generated power, and in case 2, the system has more load demand than generated power. The simulation results are studied to observe the improvement in the behaviour of the power system dynamics due to variation in load.

5.7.1 Case 1

![Figure 5.10 Stabilized frequency response for load variations (Off-Peak load)](image)

The frequency of oscillations is investigated during off-peak load period. For this purpose, the load on the system is increased step by step. That is load ‘A’ is added at $t = 1$ sec and another load ‘$B$’ is added at $t = 8$ sec. In Figure 5.10, the grid frequency is fluctuating at $t = 8$ sec and after few seconds it has been slowly suppressed effectively.
Figure 5.11 Air flow rate (Off-Peak load)

The system frequency reaches a steady state operating point after few seconds from $t = 8$ sec which indicates the effective response of the controlling the air flow of CAES. Figure 5.11 shows the simulation results of the air flow rate.

Figure 5.12 Switching status of the compressor (Off-Peak load)

When the load demand is less than available grid power (Off-Peak Load Period), the excess unutilized grid power is used to run the compressor. The switching status of the compressor is shown in Figure 5.12.
From the Figure 5.13, it is observed that the grid voltage is fluctuating at $t = 8$ sec.

The grid voltage fluctuation is suppressed immediately by changing the rotor field excitation as shown in Figure 5.14. In case 1, the excess electrical power from the grid is converted into mechanical torque, and used to suck and compress the air from the atmosphere and store it in CAES.

5.7.2 Case 2

In the second case the frequency of oscillations is investigated during peak load period. For this purpose, the load on the system is increased
step by step. That is load ‘A’ is added at \( t = 1 \) sec and another load ‘B’ is added at \( t = 8 \) sec. In Figure 5.15, the grid frequency is fluctuating at \( t = 8 \) sec and after few seconds it has been slowly suppressed effectively. In this mode total load power is greater than the generated power.

![Stabilized frequency response for load variations (Peak load)](image)

**Figure 5.15** Stabilized frequency response for load variations (Peak load)

After few seconds the system frequency reaches a steady state operating point from \( t = 8 \) sec which indicate the effective response of controlling the air flow of CAES. Figure 5.16 shows the simulation results of the air flow rate.

![Air flow rate (Peak load)](image)

**Figure 5.16** Air flow rate (Peak load)
When the load demand is greater than available grid power (Peak Load period), the shortage of power is supplied by the stored compressed air from the CAES in order to generate additional electrical power to match the load demand. During that period the compressor should be in switch off mode. The switching status of the compressor is shown in Figure 5.17.

![Compressor ON and OFF timings](image)

**Figure 5.17 Switching status of the compressor (Peak load)**

The stabilized voltage response for load variation is shown in Figure 5.18. The change in grid voltage at $t = 8$ sec can be suppressed effectively after few seconds, by changing the rotor field excitation.

![Generated voltage (Peak load)](image)

**Figure 5.18 Generated voltage (Peak load)**
The grid voltage fluctuation is suppressed immediately by changing the rotor field excitation as shown in Figure 5.19. In case 2, the compressed air transmits the air to drive the prime mover of the generator through which the mechanical power is converted back to electric power.

![Graph showing change in rotor field excitation (Peak load)](image)

**Figure 5.19 Change in rotor field excitation (Peak load)**

### 5.8 SUMMARY

The impact of frequency control of power system combined with microgrid was examined. The complete process is implemented in MATLAB/SIMULINK environment. From the simulation results, it reveals that as the extra power from the air motor output, compensates the power shortfall during load variation. The proposed work improves the frequency stability and demand response by employing CAES. The CAES is used in a power grid to store the excess energy when the energy production is high and the demand is low and utilize the stored energy when the produced energy cannot meet the high demands of the consumers. During sudden load changes the effectiveness of controller to control the air flow from CAES is investigated. The simulation results demonstrated the microgrid with storage system can provide better frequency stability and demand response. The simulation results proved the stability performance of the grid under various load demands and showed the effective use of CAES system to balance the power generation and consumption.