PSO based Robust Frequency Control of Wind-Diesel Power Plant using BES

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Abstract

This paper presents a suitable mathematical model of Wind-Diesel hybrid power system is developed to study its response following a frequency disturbance on an island electric system. A robust controller is designed for the governor wind-diesel system to improve the system dynamic performance. Further to reduce system oscillations, a BES which will supply and absorb active power quickly. In addition, variation of system parameters, unpredictable power demand causes various uncertainties in the system. This paper focuses on a new robust controller design of BES for frequency control in a hybrid system. The co-prime factorization method is used to represent the unstructured uncertainties in the system modeling. The structure of BES controller is a first order lead lag compensator. To tune the controller parameters, the optimization problem is formulated based on PSO based $H_{\infty}$ loop shaping control is used for designing a robust controller.

Index Terms: Battery energy storage, frequency controller, $H_{\infty}$ loop shaping, particle swarm optimization, robust control, system uncertainties.

Introduction

A lot of work reported in the literatures to improve the performance of LFC. Fosa and
One alternative to improve the performance of LFC is the introduction of storage facilities during peak load period and specially BES facility. BES also improves the reliability of supply during peak load periods. Storage facilities possess additional dynamic benefits such as load leveling, spinning reserve, area regulation, long line stabilization, power factor correction and black start capability. Some of these applications have been successfully demonstrated at a 17MW BES facility in Berlin [5], (Kunish et al., 1986). Recently effect of BES system on LFC is also reported in [6] Kottick et al. (1993) and Chun-Feng Lu et al [7]. (1995).

Load perturbations in completely isolated power systems have a considerable effect on the network’s frequency. This is due to the fact that the kinetic energy stored in the rotating machines is usually the main source of immediate reserve available in the power system. Furthermore, the rapid output power variations required from thermal units result in cyclic fluctuations in steam pressure and temperature. Such fluctuations may adversely affect heat resisting alloy of super heaters thus shortening their life time. To overcome such problems, it may be necessary to reduce both the frequency fluctuations and the response required of the generating units. This may be achieved by means of BES facilities which would regulate the generating units response caused by load disturbances. This regulation is accomplished by discharging the energy stored in the batteries into the power network whenever there is a sudden frequency drop and charging them when the frequency increases sharply. Battery facilities are well suited for this task because it can provide fast active power compensation.

Wind power systems are considered economically for supply of electrical energy to remote and isolated areas where utility lines are uneconomical to install due to high costs, right of way difficulties or environmental impacts [8],[9]. Since wind power sources are naturally fluctuating or intermittent, they are generally integrated with the diesel generation [10], [11]. The hybrid wind-diesel power generation provides high reliability of the system to supply power to the isolated load. Different technologies such as flywheel [12], battery energy storage [13], superconducting Magnetic Energy Storage (SMES), etc., can be adopted to alleviate system frequency fluctuation in isolated systems [14],[15] and a grid connected systems [16],[17]. Among of them, a BES unit which is able to supply and absorb active power rapidly, has been highly expected as one of the most effective controller of system frequency [14],[15]. Especially, the application of BES to control frequency in a hybrid wind-diesel power system due to load changes has been presented in [5]-[7]. Even the BES shows satisfactorily frequency control effect, it may not be able to tolerate system uncertainties such as variation of system parameters, random load changes, fluctuating wind power input etc. As a result, the BES may lose control effect and fail to reduce frequency fluctuation. To enhance the robustness of the BES controller against system uncertainties, a robust frequency controller of BES is highly expected.

This paper proposes a new robust frequency controller of BES in a hybrid wind-diesel power system. To take system uncertainties mentioned above into account in the control design, the normalized co prime factorization [18], [19] is applied to represent all unstructured uncertainties in the system modeling. In this study, the
configuration of the frequency controller of BES is the first-order lead/lag compensator. The performance and stability conditions in the $H_\infty$ loop shaping method [18], [19] are applied to formulate the optimization problem. To achieve the controller parameters, the Particle Swarm Optimization (PSO) [20], [21] is used to solve the optimization problem. Simulation studies are carried out to confirm the superior robustness of the proposed BES against system uncertainties.

This paper is organized as follows. Section III describes the frequency control problem in the study system and the mathematical modeling of the study system. Subsequently, Section IV presents the proposed control design. In Section V, simulation studies are shown. Finally, Section VI the conclusion is given.

**Problem Formulation**

Fig. 1 shows the basic configuration of the hybrid wind-diesel power system which includes a BES unit [17]. In addition to the random wind energy supply, it is assumed that loads with sudden change have been placed in this isolated system. Variation of wind power and load change results in a serious problem of large frequency fluctuation in the system. Such frequency fluctuation severely affects the system stability. Furthermore, the life time of machine apparatuses on the load side is reduced. To tackle this problem, the BES is installed in the system to compensate for power variations and minimize frequency fluctuation.

Figure 1: Block Diagram of Wind-Diesel System with BES.
State Equation of Wind-diesel System

\[
\Delta f_w = \frac{1}{2H_w} [\Delta P_{\text{wind}}] + \frac{\Delta P_m}{2H_w} - \frac{K_w(\Delta f_d)}{2H_w} 
\]

\[
\Delta f_D = \frac{1}{2H_D} (K_w \Delta f_w - K_w \Delta f_D - \Delta P_{\text{load}} + \Delta P_d) 
\]

\[
\Delta P_m = (K_{p1} * K_{p2}) \Delta H_2 - \Delta P_m 
\]

\[
\Delta P_{f1} = K_D (\Delta f_{ref} - \Delta f_w) 
\]

\[
\Delta P_D = 40\Delta P_{D1} - 40\Delta P_{D1} + 40\Delta P_{f1} 
\]

\[
\Delta H_1 = \frac{1}{T_{p2}} \Delta x_i - \frac{1}{T_{p2}} \Delta H_2 
\]

\[
\Delta H_2 = (K_{f2} - K_{f1} \frac{K_{p2}^2 T_{p1}}{T_{p2}}) \Delta H_1 - \Delta H_2 + \frac{T_{p1}}{T_{p2}} \Delta x_i 
\]

\[
\Delta K_x = (-\frac{K_{p1} K_{p2}}{2H_w} \Delta P_{\text{wind}} - \frac{K_{p1} K_{p2}}{2H_w} \Delta P_m + \frac{K_{p1} K_{p2}}{2H_w} \Delta P_m + \frac{K_{p1} K_{p2}}{2H_w} \Delta P_D - \frac{K_{p1} K_{p2}}{2H_w} \Delta P_{\text{LOAD}} 
\]

The state equation of the system can be represented by

\[
\dot{\Delta X} = A\Delta X + B\Delta P_{\text{BES}} 
\]

As shown in fig. 2, the block diagram of BES [16] consists of two transfer function connected in series, i.e. the BES model and the frequency controller. The BES can be modeled by the first order transfer function with time constants $T_{\text{BES}} = 0.03$sec. For the frequency controller, it is practically represented by a lead lag compensator with first order. In the controller there are three parameters i.e., $K_{\text{BES}}$, $T_{\text{BES1}}$ and $T_{\text{BES2}}$. the input signal of the controller is only the frequency deviation.

**Figure 2:** Block diagram of BES with frequency controller.
**Proposed Method**

The objective of the control design is to optimize three control parameters, so that the resulted controller is robust to system uncertainties. Based on the $H_\infty$ loop shaping control the optimization problem can be formulated subsequently, the PSO is applied to solve the problem.

**i. Selection of the Weighing Functions**

Loop shaping weights $W_1$, $W_2$ are usually designed in to two stages. In the first stage, the desired loop-shape is determined. This usually involves translating time-response requirement and closed loop performance specification in to the frequency domain. In the second stage, the designer selects loop shaping weights $W_1$, $W_2$ so that $G_s$ has desired loop shape. All of these can be fairly time consuming; trial and error can never be guaranteed. But in this [20] paper it is done by a systematic procedure by first designing a lead compensator and then using its loop shaping weight which has given excellent result.

$$W_i = K_w \frac{S + a}{S + b} \text{ and } W_2 = 1 \quad (10)$$

Where $K_w$, $a$ and $b$ are positive values. Because, the frequency control problem is in a vicinity of low frequency ($< 1$Hz), $W_1$ is set as a high pass filter ($a<b$).

**ii. Formulate the Shaped Plant $G_s$**

In fig. 3 shows pre compensator $W_1$ and post compensator $W_2$ are employed to form the shaped plant $G_s = W_2*G*W_1$ is enclosed by the solid line. The proposed robust controller $K=W_1 K_\infty W_2$ is enclosed by the dotted line. $K_\infty$ is the $H_\infty$ controller.

**iii. Evaluate the Robust Stability Margin of the System**

In this work, variation of system parameters, generating and loading conditions Etc., are defined as unstructured system uncertainties. Because these uncertainties cannot
be clearly represented by mathematic equations, co-prime factorization is utilized to
represent these unstructured uncertainties. Shaped plant $G_s$ is expressed in form of
normalized left co-prime factor $G_s = M_s^{-1}N_s$, when the perturbed plant $G_{\Delta}$ is
determined as follows:

$$G_{\Delta} = (M_s + \Delta M_s)^{-1}(N_s + \Delta N_s); \|\Delta N_s \Delta M_s\| \leq 1/\gamma \quad (11)$$

Where $\Delta M_s$ and $\Delta N_s$ are stable unknown transfer functions which represent
unstructured uncertainties in the nominal plant model $G$. Based on this definition, the
robust control problem can be established by $G_{\Delta}$ and $K$ as depicted in figure 3. The
objective of robust control design is to stabilize not only the nominal plant $G$ but also
the family of perturbed plant $G_{\Delta}$. In (11), $1/\gamma$ is defined as the robust stability margin.
The maximum stability margin in the face of system uncertainties is given by the
lowest achievable value of $\gamma$, i.e. $\gamma_{\text{min}}$. Hence, $\gamma_{\text{min}}$ implies the largest size of system
uncertainties that can exist without destabilizing the closed-loop system in fig. 3. The
value of $\gamma_{\text{min}}$ can be easily calculated from.

$$\gamma_{\text{min}} = (1 + \lambda_{\text{max}}(XZ))^{1/2} \quad (12)$$

Where $\lambda_{\text{max}}(XZ)$ denotes the maximum eigen value of $XZ$. For minimal state space
realization $(A, B, C, D)$ of $G_s$, the values of $X$ and $Z$ are unique positive solutions to the
generalized control algebraic Riccati equation

$$(A - BS^{-1}D^T)X + X(A - BS^{-1}D^T) - XBS^{-1}B^TX + C^TR^{-1}C = 0 \quad (13)$$

and the generalized filtering algebraic Riccati equation:

$$(A - BS^{-1}D^T)Z + Z(A - BS^{-1}D^T)^T - ZC^TR^{-1}CZ + BS^{-1}B^T = 0 \quad (14)$$

Where $R = I + DD^T$ and $S = I + D^TD$. Note that no iteration on $\gamma$ is needed to solve
for $\gamma_{\text{min}}$. To ensure the robust stability of the nominal plant, the weighting function is
selected so that $\gamma_{\text{min}} \leq 4$. If $\gamma_{\text{min}}$ is not satisfied then go to step 1 and adjusts the
weighting functions.

iv. Formulate the objective function for PSO optimization

From the figure $K$ can be defined as

$$K_{w} = W_1^{-1}K(s)W_2 \quad (15)$$

$W_2=1$, the necessary and sufficient condition of the robust controller $K(s)$. In this
part, the performance and robust stability conditions in $H_{\infty}$ loop shaping design
approach are adopted to design a robust frequency controller $K$ for SMES. The
frequency controller is represented by

$$K = K_{\text{bes}} \left( \frac{I + ST_{\text{bes1}}}{I + ST_{\text{bes2}}} \right) \quad (16)$$

The control parameters $K_{\text{bes}}, T_{\text{bes1}}$ and $T_{\text{bes2}}$ are optimized by PSO. The
objective function is derived based on the following concept. As shown in figure 3, the designed controller $K$ is to be represented as

$$K = W_1 K_\infty W_2$$

(17)

$$K_\infty W_2 = W_1^{-1} K$$

(18)

Selecting $W_2 = 1$ yields

$$K_\infty = W_1^{-1} K$$

(19)

The necessary and sufficient condition of the designed robust controller $K$ is

$$\left\| \begin{bmatrix} 1 & \cdot & \cdot \\ \end{bmatrix} \right\| \left( I - G \cdot \right)^{-1} \left[ \begin{bmatrix} I & G_i \end{bmatrix} \right] \leq \gamma$$

(20)

Substituting (19) in to (20) yields

$$\left\| \begin{bmatrix} 1 & \cdot & \cdot \\ \end{bmatrix} \right\| \left( I - G W_1^{-1} K_\infty \right)^{-1} \left[ \begin{bmatrix} I & G_i \end{bmatrix} \right] \leq \gamma$$

(21)

$$K_{\text{BES,min}} < K_{\text{BES}} < K_{\text{BES,max}}$$

$$T_{\text{BES1,min}} < T_{\text{BES1}} < T_{\text{BES1,max}}$$

$$T_{\text{BES2,min}} < T_{\text{BES2}} < T_{\text{BES2,max}}$$

Where $K_{\text{BES}}$ Gain of BES, $T_{\text{BES1}}, T_{\text{BES2}}$ time constant of BES. The control parameters $K_{\text{BES}}, T_{\text{BES1}}, T_{\text{BES2}}$ are optimised by PSO. Equation (21) implies that if the $\infty$-norm of transfer function matrix in the left side is lower than $\gamma$, the robust controller $K$ can be obtained. As a result, the $\infty$-norm of the left side term in (21) can be used to formulate the optimization problem as

$$\text{Min} \left\| \begin{bmatrix} 1 & \cdot & \cdot \\ \end{bmatrix} \right\| \left( I - G W_1^{-1} K_\infty \right)^{-1} \left[ \begin{bmatrix} I & G_i \end{bmatrix} \right] \leq \gamma$$

(22)

Subject to

$$K_{\text{BES}} \leq 50.0,$$

$$0.001 \leq T_{\text{BES1}} \leq 1.0,$$

$$0.001 \leq T_{\text{BES2}} \leq 1.0,$$

This optimization problem is solved by PSO algorithm [20].

v. PSO Algorithm

The PSO algorithm [20], [21], Specify the parameters of PSO. Initialize a population of the particles with random position and velocity.
vi. Evaluate the objective function in (22) for each particle

vii. Compare the fitness value of each particle with its the best position for each particle (Pbest). The best fitness value among all the pbest is the best position of all particles in the group (gbest).

viii. Update the velocity $V_i$ and position of particle $x_i$ by

$$V_{i+1} = w \cdot v_i + c_1 \cdot \text{rand1} \cdot (p_{best} - x_i) + c_2 \cdot \text{rand2} \cdot (p_{best} - x_i)$$

$$X_{i+1} = x_i + v_{i+1}$$

Where $c_1$ and $c_2$ are the cognitive and social acceleration factors, respectively. rand1 and rand2 are the random numbers of range 0 to 1 respectively. $W$ is the inertia weight factor. $W_{\text{min}}$ and $W_{\text{max}}$ are the minimum and maximum of inertia weight factors, respectively. $\text{Iter}$ and $\text{Iter}_{\text{max}}$ are the iteration count and maximum iteration, respectively.

ix. When the maximum number of iteration is arrived, stop the process. Otherwise go to process (vi)

Simulation Results

Step 1: Selection of weighting functions. The linearized wind-diesel model is used in this simulation studies. System parameters are given in appendix. Here the designed results of the robust frequency controller of BES based on the proposed are explained as follows as given in equation (10). The shaped plant $G_s$ is established by weighting functions $W_1$ and $W_2$, the weighting functions are chosen as

$$W_2 = 1, \quad \kappa_w = 658, \quad a = 100, \quad b = 447$$

Where $\kappa_w$, a and b are positive values. Because, the frequency control problem is in a vicinity of low frequency ($<1$ Hz), $W_1$ is set as a high-pass filter ($a<b$).

Step 2: Formulate the shaped plant $G_s$ as shown in the fig. 3, a pre-compensator $W_1$ and a post-compensator $W_2$ are employed to form the shaped plant $G_s = W_2 G W_1$, which is enclosed by a solid line.

Step 3: Evaluate the robust stability margin of the system note that no iteration on $\gamma$ is needed to solve for $\gamma_{\text{min}}$. To ensure the robust stability of the nominal plant, the weighting function is selected so that $\gamma_{\text{min}} \leq 4$. If $\gamma_{\text{min}}$ is not satisfied, then go to step 1 process and adjust the weighting functions. From the program: Gain margin = 1.31 (for system without BES) Gain margin = 1.424 (for system with BES)
Step 4: Formulate the objective function for PSO optimization

Minimize

\[
\left\| \frac{1}{W_i^+K} \left( I - G_i^+K_i \right)^{-1} \left[ I \quad G_i \right] \right\| \leq \gamma
\]

Subject to

\[1.0 \leq K_{BES} \leq 50.0, \ 0.001 \leq T_{BES1} \leq 1.0, \ 0.001 \leq T_{BES2} \leq 1.0\]

Step 5: Initialize the search parameters for PSO. Define PSO parameters such as population Size = 100, Maximum Generation = 100, \( C_1 = 2 \), \( C_2 = 2 \), \( W_{min} = 0.4 \) and \( W_{max} = 0.9 \).

Step 6: Randomly generate the initial solution. Set the first generation, \( Gen = 1 \).

Step 7: Evaluate the objective function of each individual population.

Step 8: Select the best individual in the current generation. Check the maximum generation. If the current generation is the maximum generation, then stop. If the current generation is less than the maximum generation then go to step 9.

Step 9: Update the velocity factor.

Step 10: When the maximum number of iterations is reached stop the process. Otherwise go to step number 6.

The optimization is performed and the variables are obtained through Particle Swarm technique. The results obtained are given as \( K_{BES} = 49.8 \), \( T_{BES1} = 0.9547 \), \( T_{BES2} = 0.5680 \). The controller obtained is given by the following expression:

\[
K = 49.8 \left( \frac{1 + S \left( 0.9547 \right)}{1 + S \left( 0.5680 \right)} \right)
\]

Case 1: First, 0.01 pu kW step increase in the wind-diesel power input is applied to the system at \( t = 0.0 \) s figure 6 shows the frequency deviation of the wind-diesel side which represents the system frequency deviation without, with and proposed BES frequency controller, the system without BES controller frequency highly oscillates and the peak frequency deviation is very large. The frequency oscillation takes about 42 seconds to reach zero. This indicates that the frequency controller in the governor side control loop in the wind-diesel side is not able to work well. On the other hand, the peak frequency deviation is reduced significantly and returns to zero within shorter period in case of BES and the proposed BES. Similarly second, a 0.02 pu KW step increase in the wind-disel power input is applied to the system at \( t = 0.0 \) s. Fig. 7
shows the frequency deviation of the wind-diesel side which represents the system frequency deviation without, with and proposed BES frequency controller, the system without BES controller frequency highly oscillates and the peak frequency deviation is very large. The frequency oscillation takes about 50 seconds to reach zero. From this study, reveals that the proposed BES controllers are quite robust and the optimum BES gain once set for nominal condition need not be changed for +25% variations in system operating load condition from their nominal values.

**Case 2:** The power output deviations of both BESs are shown in fig. 8. The peak power output of the proposed BES is lower than that of the conventional BES. Next, a 0.01 pu kW step increase in the load power is applied to the system at \( t = 0.0 \) s. From the result the proposed BES are able to damp the power deviations quickly in comparison to without BES case.

**Case 3:** Random load change, the random load change as shown in fig. 9 is applied to the system. Fig. 10 depicts the system frequency deviation under normal system parameters. Clearly, the control effect of the proposed BES is better than that of the conventional BES. The values of IAE of system frequency deviation under the variation of \( K_{fc} \) from -30 % to +30 % of the normal values are shown in fig. 10. As \( K_{fc} \) decreases, the values of IAE in case of BES become larger. On the other hand, the values of IAE in case of the proposed BES are lower and rarely change. The proposed BES is more robust than the BES [15] against the variation of system parameters under this random load change.

\[ \text{Frequency deviation (Hz)} \]

\[ \text{Power deviations (pu)} \]

**Figure 4:** BODE Plot for System without BES.
Figure 5: BODE Plot for system with BES.

Figure 6: System Frequency Deviation against a 10% Load.
Figure 7: System Frequency Deviation against a 20% Load.

Figure 8: Power Output Deviation of BES against a Step Load.
Conclusion
The robust controller of BES for frequency control in the wind-diesel turbine has been presented. In the proposed controller design, unstructured uncertainties in the system such as variation of the system parameters, power variations due to load changes and power etc., are modeled by co-prime factorization. The structure of frequency controller is practically based on the first order lead lag compensator with a single input signal. Consequently, it is easy to implement in practical systems. To obtain the controller parameters, the optimization problem based on $H_\infty$ loop shaping technique
can be automatically solved by PSO. A simulation result clearly confirms that the proposed robust BES controller is much superior to the BES in [15] in terms of the robustness against uncertainties, random load change. Besides, the small power capacity of BES is required for robust frequency control.

Appendix

\[ P_r = 350 \text{ KW}, \quad H_W = 3.5 \text{ s}, \quad H_D = 8.5 \text{ s}, \quad K_{fc} = 16.2 \text{ Hz/puKW}, \quad K_D = 16.5 \text{ Hz/pu KW}, \]
\[ K_{p2} = 1.25, \quad K_{p3} = 1.4, \quad T_{p1} = 0.6 \text{ s}, \quad T_{p2} = 0.041 \text{ s}, \quad K_{pc} = 0.08, \quad K_{ps} = 4.0, \quad K_{pp} = 1.5, \quad K_p = 120, \]
\[ T_p = 20, \quad K_i = 0.5, \quad T_i = 10, \quad T_{g} = 0.08, \quad T_i = 0.3, \quad R = 2.4, \quad B = 0.425, \quad c_{bp} = 52497, \quad r_{bp} = 10, \quad c_{b1} = 1, \]
\[ r_{b1} = 0.001, \quad r_{b2} = 0.0167, \quad r_{be} = 0.013, \quad X_{co} = 0.0274, \quad I_{ben} = 4.426, \quad K_{bp} = 20, \quad T_{bp} = 0.026 \]

Symbols

- \( P_r \) area capacity
- \( H_W \) inertia constant for wind system
- \( H_D \) inertia constant for diesel system
- \( K_{fc} \) fluid coupling between wind and diesel system
- \( K_d \) governor gain
- \( K_{pi} \) integral controller gain of pitch controller
- \( K_{pp} \) proportional controller gain of pitch controller
- \( K_{p2} \) gain of hydraulic pitch actuator
- \( K_{p3} \) gain of data fit pitch response
- \( T_{p1} \) time constant of hydraulic pitch actuator
- \( T_{p2} \) time constant of hydraulic pitch actuator
- \( K_{pc} \) blade characteristic
- \( \Delta P_d \) power output deviation of diesel side
- \( \Delta P \) wind change in wind power
- \( \Delta P_w \) power output deviation of wind side
- \( \Delta f_w \) frequency deviation of wind generation side
- \( \Delta f_d \) frequency deviation of diesel generation side
- \( \Delta P_{BES} \) power output deviation of BES
- \( \Delta X \) state vector
- \( \Delta U_{BES} \) control signal deviation of SMES controller
- \( K_{BES} \) gain of frequency controller
- \( T_{BES1} \) time constant of frequency controller
- \( T_{BES2} \) time constant of frequency controller
- \( E_{b1} \) battery over voltage
- \( \Delta E_{co} \) BES of constant power mode
- \( K_{pb} \) Control loop gain
- \( T_{bp} \) Measurement time device constant
- \( E_i \) Line to neutral r.m.s voltage
- \( E_p \) Compensating power deviation
- \( E_{do} \) ideal no load maximum d.c. voltage
- \( E_{eo} \) d.c. voltage without overlap
PSO based Robust Frequency Control of Wind-Diesel Power Plant

$X_{co}$ Commutating reactance converter firing angle

$E_{boc}$ battery open circuit voltage

$E_{b1}$ battery overvoltage

$r_{b1}$ connecting resistance

$r_{bs}$ internal resistance

$I_{BES}$ d.c. current flowing into battery

$C_{b1}$ overvoltage capacitance

$r_{bp}$ self-discharge resistance

$c_{bp}$ battery capacitance

PSO Particle swarm optimization

BES Battery energy storage

LFC Load frequency control

References


Biographies

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**Tushar Kukreja** is a research student. His interested area broadly within Power System. Specifically his work focuses on assurance to be a more adaptive and balanced frequency load by designing a controller using Quantitative Feedback Theory. He received his B.E. from Bhagwan Mahaveer Institute of Engineering & Technology, Sonipat and presently pursuing his M.Tech (Power System) from Deenbandhu Chotturam University Of Science & Technology, Murthal, Sonipat.