

**Integrated Economic Dispatch and Automatic Generation  
Control for a Grid with High Penetration of Renewable and  
Energy Storage**

BY

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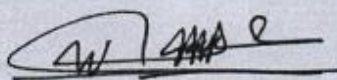
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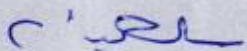
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This thesis is written by Hassan Ahmed Alsobaie under his thesis advisor's direction and approved by his thesis committee. It has been presented and accepted by the Dean of Graduate Studies in partial fulfillment of the **Masters in Science and electrical engineering**.



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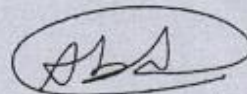
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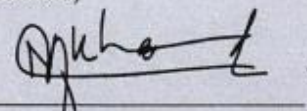
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*Dedicated to*

*All My Family and Friends*

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## LIST OF SYMBOLS

|             |                                         |
|-------------|-----------------------------------------|
| $TCB$       | Battery capital cost in $\$/MWh$        |
| $CAP$       | Battery capacity in $MWh$               |
| $DoD$       | Battery depth of discharge              |
| $Eff$       | Battery efficiency                      |
| $pf_i$      | Participation factor for each generator |
| $pf_b$      | Participation factor for Battery        |
| $P_{mech}$  | Mechanical power for generator          |
| $P_b$       | Battery power                           |
| $P_L$       | Frequency-sensitive load change power   |
| $P_{ele}$   | Electrical power                        |
| $P_v$       | Turbine prime mover                     |
| $P_g$       | Governor valve position                 |
| $P_{ref}$   | Reference set point of the load         |
| $P_{es}$    | Battery power input                     |
| $P_i$       | Generator power out from AGC            |
| $P_i^{min}$ | Minimum generator power out from AGC    |

|             |                                         |
|-------------|-----------------------------------------|
| $P_i^{max}$ | Maximum generator power out from AGC    |
| $P_b$       | Battery power out from AGC              |
| $P_b^{min}$ | Minimum battery power out from AGC      |
| $P_b^{max}$ | Maximum battery power out from AGC      |
| $P_{refi}$  | Power load set point for each generator |
| $P_{refb}$  | Power load set point for Battery        |
| $P_{basei}$ | Basepoint power for each generator      |
| $P_{baseb}$ | Basepoint power for Battery             |
| $P_{tie}$   | Power transferring                      |
| $E_b$       | Battery energy storage                  |
| $E_b^{min}$ | Minimum battery energy storage          |
| $E_b^{maz}$ | Maximum battery energy storage          |
| $M$         | Generator angular momentum              |
| $D$         | Load change to the frequency sensitive  |
| $T_t$       | Turbine time constant                   |
| $T_g$       | Governor valve time constant            |
| $T_b$       | Battery time constant                   |
| $R_g$       | Droop characteristic of the generator   |

|                      |                                                            |
|----------------------|------------------------------------------------------------|
| $R_b$                | Droop characteristic of battery energy storage             |
| $K$                  | Secondary control gain                                     |
| $f$                  | Objective function                                         |
| $C_i$                | Generator cost                                             |
| $C_b$                | Battery cost                                               |
| $a_i, b_i, c_i, d_i$ | Constant parameters for generator                          |
| $\Delta t$           | Time interval                                              |
| $L$                  | Lagrange function                                          |
| $\omega$             | Frequency response                                         |
| $\lambda_i$          | Lagrange multiplier associated with power balance          |
| $\beta_i$            | Lagrange multiplier associated with generator limit        |
| $\mu_1$              | Lagrange multiplier associated with battery power          |
| $\mu_2$              | Lagrange multiplier associated with battery energy storage |
| $t_{initial}$        | First time $t = 0$                                         |
| $t_{final}$          | Final time                                                 |

## THESIS ABSTRACT (ENGLISH)

**Full Name** : Hassan Ahmed Omar Alsobaie  
**Thesis Title** : Integrated Economic Dispatch and Automatic Generation Control for a Grid with High Penetration of Renewables and Energy Storage.  
**Degree** : Master of science  
**Major Field** : Electrical Engineering  
**Date of Degree** : May 2021

The generation of renewable energy (RE) in recent years is increased to minimize the nonrenewable resources, but renewable resources are having higher penetration of power generation compared to nonrenewable energy, which required a robust controller to minimize the error of deviation in the generation of electricity. The dynamic economic dispatch and automatic generation control (ED-AGC) monitor the generated electric power for grids. In this research, the power grid's storage energy is included in the ED-AGC system to improves the power generation's frequency response and steady-state error. This report proposes the real-time operation for a generation system in the AGC with battery energy storage using dynamic economic dispatch to supply electrical power to the grid. The conventional way of ED-AGC that considered energy storage is included in this report to have a better-regulated response in the AGC system. The battery power includes supplying the electric grid in the implementation process. The work transforms the conventional ED-AGC into an integrated feedback control system with battery energy storage and thermal generators to improve the frequency deviation response less than in the conventional ED-AGC. One and multi-period of integrated economic dispatch (ED) were implemented to provide a more economical cost of the AGC system. One area of the classic and integrated ED-AGC systems is comparing the responses and economical cost, including the ramp limit of generators in the Matlab simulation program. The look-ahead capability of the

optimization problem is considered in the simulation results for testing the performance of the ED-AGC. The considered work implements the two areas of classic and integrated ED-AGC in the simulation program. All of the simulation results are finding a better frequency regulation that leads to minimizing operation cost economically. The integrated feedback control of ED-AGC is more helpful to control the penetration of renewable resources and given an optimal cost compared to the conventional way of ED-AGC.

## THESIS ABSTRACT (ARABIC)

الاسم الكامل: حسن أحمد السبيعي

عنوان الرسالة: التوزيع الاقتصادي المتكامل والتحكم التلقائي في التوليد لشبكة ذات اختراق عالٍ لمصادر الطاقة

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التخصص: الهندسة الكهربائية

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زادت موارد الطاقة المتجدد في السنوات الأخيرة لتقليل الطاقة غير القابلة للتجدد، ولكن توليد الطاقة المتجددة عالية التغير مقارنة بالطاقة غير المتجددة التي تتطلب وحدة تحكم قوية لتقليل الخطأ في انحراف توليد الطاقة الكهربائية. يستخدم التوليد الاقتصادي الديناميكي والتحكم التلقائي للمولدات (ED-AGC) لتحكم في الطاقة الكهربائية التي يتم إنشاؤها للشبكات. في هذا البحث، تعمل طاقة التخزين للشبكات المتضمنة في نظام ED-AGC لتحسين استجابة تردد توليد الطاقة والحالة المستقرة لتوليد الطاقة. يهدف هذا التقرير إلى اقتراح التشغيل في الوقت الفعلي لنظام توليد في أي جي سي مع تخزين طاقة البطارية باستخدام التوزيع الاقتصادي الديناميكي لتزويد الطاقة الكهربائية للشبكة. الطريقة التقليدية لـ ED-AGC التي اعتبرت تخزين الطاقة للحصول على استجابة منظمة بشكل أفضل في نظام AGC المتضمنة في هذا التقرير والتي سوف تحدد طاقة البطارية لتزويد الشبكة الكهربائية. يحول هذا العمل التقليدي لـ ED-AGC إلى نظام تحكم متكامل عندما يكون لديه تخزين طاقة البطارية مع المولدات لتحسين استجابة انحراف التردد أقل من ED-AGC التقليدي. تم تنفيذ فترة واحدة ومتعددة من التوزيع الاقتصادي المتكامل (ED) لتوفير تكلفة أكثر اقتصادا لنظام AGC. المقارنة في مجال واحد بين نظام ED-AGC الكلاسيكي والمتكامل في استجابات النظام والتكلفة الاقتصادية عندما يشمل حد أقصى في تصاعد الطاقة للمولدات التي تعمل بالوقود باستخدام برنامج MATLAB. أيضا استخدام قدرة التطلع إلى تغيير الطاقة المطلوبة للإنتاج في نظام ED-AGC وبيان استجابة النظام للتردد والتكلفة المنتجة للطاقة. وأخيرا بيان كيفية استخدام هذه الأنظمة في منطقتين من النظام الاعتيادي والديناميكي. كل نتائج البحث تناقش التردد وطاقات المولدات والبطاريات مع تكلفة النظام. يعد التحكم المتكامل للمولدات لنظام ED-AGC أكثر فائدة لتحكم الطاقة المتجددة ويعطي التكلفة المثلى مقارنة بالطريقة التقليدية لنظام ED-AGC.

# **CHAPTER I INTRODUCTION**

## **1.1 THESIS BACKGROUND**

The generation power is increasing year by year, and the cost of generation is getting higher with the increasing power supply to the loads. Also, during a typical day, the industrial and nonindustrial loads vary from one hour to another because of the different equipment uses. So, the loads are changing depending on the customer's use of the power. This change is the reason for increasing cost because of generation increases and frequency response variation. When a load varies from one value to another, the frequency of generating power plant deviates from nominal value until generating power is equal to load power. When frequency differs from the expected value, it will cause the mechanical power to increase or decrease depending on the changing response of the frequency, whether it is positive or negative. If it is a negative value, the generation plant will require increasing mechanical power until it is equal to the electrical power. If the frequency deviation is positive, the generation plant will desire to decrease the mechanical power until it is equal to the electrical power [1-3].

The generation of renewable energy (RE) from the wind power and the solar photovoltaic power affects the frequency response. The automatic generation control (AGC) monitors the frequency response for the power generation and provides the needed power for the loads. This AGC system manages the cost of the generating power supply sources to the grids by minimizing the frequency when load and renewable generation changes. Thus, the AGC system keeps the needed electricity in an optimal manner [3-4].

The Kingdom of Saudi Arabia is planning to increase the use of renewable electrical energy by 2030. The kingdom intends to use 58.7 GW of renewable energy by 2030. This generation contains 40GW of solar photovoltaic (PV) and 16GW from wind, and 2.7 GW of concentrated solar power (CSP) [5]. This plan will lower of using non-renewable resources like thermal generators, and it will decrease the consumption of natural gas resources and reduce air pollution. Using renewable energy will create economic development and increase the investment cost of generating power, but it needs to improve the deviation responses of the power system generation. RE increases the number of deviation frequency responses from a steady-state value and affects generators' mechanical power by deviating from nominal power. So, it needs to eliminate the change in frequency and reach a steady-state value in a shorter time while generating renewable energy. In addition, the controller must minimize the error of frequency response and the cost of generation [6-7].

The automatic generation control (AGC) is a system that contains devices used to control the generator output power significantly when the load or renewable energy is changed. It reduces the deviation error of generating system response when the load or renewable power changes from its nominal value. However, this AGC system will not guarantee that the error comes with optimal operation because the system response deviates from steady state value when the load is changed [8]. The generating power source for the load should always be equal to the load power during generation. The system operator must ensure the loads are equivalent to the generation of electrical power and the cost of generation is minimal. For having an optimal response for generation power, it must be assigned a base point power for every generator working on the AGC system. This base point comes from the scheduling program, and this program is frequently performed every 5-15

min. This assignment is called economic dispatch (ED). The AGC responds every 2-4 seconds after setting the base point for raise or lower signal of generation power [9].

The ED determines individual generators' power frequently, and it depends on the load demand and the minimum fuel cost. To determine the cost of every generator available in the AGC, it requires some formulation equations to calculate the cost of generation loads. These formulations consist of the objective function for the total cost of generation. The objective function can contain another energy source like battery energy storage to support thermal generators in supplying grids and reduce the steady state errors of generation. The ED formulation has the constraints of power generation balance with load and the constraints limit of every generator and battery. In addition, the ED problem finds out the base point power for every generator and battery available in the AGC at an economical cost [10]. The ED-AGC system is required to have the minimum error of generating power when load or renewable is changed from its nominal value with the optimal cost. The conventional combined ED and AGC do not guarantee to reach the best optimal control operation of generation power.

## **1.2 THESIS OBJECTIVE**

This work will consider the ED problem that includes generators, battery energy storage, and renewable energy in the formulation problem to minimize the total cost of generation for the grids. The ED problem will consider one period and multi-period for ED-AGC. It will also utilize automatic generation control (AGC) to monitor the frequency response, and this AGC system uses three fuel generator units and one battery with RE. The testing results include the thermal generator mechanical power response, the battery power response, the battery energy response, the

renewable energy (RE) response, and the cost of the AGC system. The work will convert the classic (traditional) way of ED-AGC into an integrated feedback control system using one battery and multi-fuel generators. The battery can be sourcing the grids and can help control the frequency during load change. The AGC system will consider the scheduling transfer between two areas in the AGC system. The thesis millstones are the following:

1. Formulate the ED problem, find out the related equations, and solve the ED equations using the Lagrange function for one period to find the base point power for AGC. Then, implement the AGC system that includes a battery to control the frequency system of both generator and battery at optimal cost.
2. Develop the integrated feedback control of ED and include battery power and energy as a source of grids.
3. Implement two area systems for classic and integrated ED-AGC considering battery energy storage.
4. Generate a model for multiple periods in ED and integrate ED into a feedback controller to implement with AGC for optimal cost.
5. Include generator rate limit in the AGC system to control the generators ramping when the load increases suddenly to a higher value.
6. Include look-ahead capability in the classic and integrated ED-AGC to consider changing load demand in the generator control system.

### **1.3 THESIS CONTRIBUTION**

The following are the contributions of this report:

- Solving the multi-period optimization using three generators and one battery power and energy by using Lagrange multiplier.
- Convert the classical ED optimization considering three generators and one battery power with its energy into the feedback control loop (integrated ED system).
- Connect the integrated ED system with AGC and simulate the ED-AGC system in the Matlab Program.
- Simulate and compare the classical and integrated ED-AGC system for one and two areas.
- Discusses why an integrated ED-AGC system is better than classical ED-AGC in frequency, mechanical power, battery power, battery energy, and total generation cost.
- Include the ramp limit generators and look ahead capability for load demand in the ED-AGC one area system.

### **1.4 THESIS ORGANIZATION**

The thesis report is organized as follow:

Chapter 2 represents the comprehensive literature survey on automatic generation control (AGC) and the dynamic economic dispatch (ED) optimization used to control generation power. Also, this survey includes the conventional (classic) way of ED-AGC and the integrated way of the classical system. In addition, it contains battery energy storage and renewable resources (RE)

for AGC. Finally, part of the survey includes the generator ramp limit and look ahead capability demand load.

Chapter 3 depicts the AGC system model described with consideration of battery energy storage. First, the classical and integrated model for one-period optimization is illustrated in this chapter. In addition, the results of the simulation between the classic and the integrated ED-AGC are discussed in this chapter. This chapter will also cover the AGC that considers both battery and renewable in the simulation test for both systems.

Chapter 4 introduces the multi-period optimization for the classic and integrated ED systems. More explanation for improving the objective function and its constraints for finding the generators and battery power for the multi-period. The battery power and energy at each period are related together in multi-period optimization. The integrated feedback control loop develops and improves from a single period to a multi-period for the new objective function. This chapter includes testing classic and integrated ED optimization for comparison and connecting the ED system to AGC to study and simulate one ED-AGC system.

In chapter 5, the first part is implementing classic and integrated ED-AGC in two areas considering battery energy storage in the optimization problem. This work includes changing loads in testing simulation for area 1 of the ED-AGC system only, and area 2 keeps the load constant. The simulation results discuss the responses of both areas when changing power loads occur in area 1 considering battery energy storage. The second part is the proposed renewable source in the ED-AGC system. Wind generation is the source of renewable energy generation utilized in the work simulation.

The reality of generation source is limited to increase or decrease when the load is changing to another value quickly by the higher value of power. The limit rate of generator response is presented in chapter 6, contained in the AGC system. The look-ahead capability of optimization is presented in the second part of this chapter.

Chapter 7 is the conclusion of the thesis work and proposed future work.

## **CHAPTER 2    THESIS LITERATURE REVIEW**

### **2.1    INTRODUCTION**

This chapter summarizes several case studies related to power generation includes battery energy storage and renewable power resources. The studies provide several problems for control power generation in the ED-AGC system. The main discussions are on the frequency response and mechanical power that is driven by the generator. The cost of the generator output power is considered in some study cases. Generally, the literature survey divides into four main subjects.

The related latest studies of the ED optimization problem covers in the first part of the survey discussion. The following section discusses the classical AGC survey and the basic model for control generator and battery energy storage. Also, the renewable resource discussion includes in the second part. The integrated AGC system contains only generators is in part three. The last part proposes the generator ramp limit and looks ahead capability of ED.

### **2.2    ECONOMIC DISPATCH (ED)**

The optimal solution for the output power of every generator working on the plant determines by economic dispatch (ED) optimization that is using after the system operator deciding which generator is on or off during a day or week. The ED decides the best optimal power value for each generator depend on the load demand schedule for either quarter or one hour. In addition, the ED program gives the best economical cost for running generation to grids [11].

In [12], it presented the ED optimization problem for the generation unit of thermal generators. The objective function is to minimize the generation cost for every generator used, and the constraints are the power generation limit of active and reactive power. On the other hand, their work did not include renewable energy and battery energy storage in the formulation of ED. Using renewable resources and battery energy storage will allow having more saving costs in the ED optimization problem.

According to the implemented works in [13-15], the battery energy storage in ED was not including the battery cost model in the objective function. The battery supplies power to the grid when needed without considering the operation cost of the battery energy storage. The limit constraint of the battery is formulated in the optimization problem to ensure the power given value is inside the limitation of the battery power. These papers considered the energy storage limit in the optimization problem to ensure charging and discharging capacity are satisfied.

As in [17-19], the authors included the cost of battery energy storage in the objective function of the optimization problem in ED and considered the constraints of all generator's limits, battery power limit, and energy storage limits. The dynamic programming solver utilized to solve the problem with multi-time periods includes different loads at each time. The same researchers presented a method to control the power in microgrids as a discrete-time system. Finally, their implemented work was solved the optimization problem considering infinite time.

These days, renewable energy sources are widely utilized in the power system generation because they reduce nonrenewable resources and allow for more economical costs in generation power. In [20], the authors solved the ED by considering multi generators, one battery system, and renewable energy. The optimal cost comes from the consideration of generator units, batteries, and renewable energy. They calculated the reserve cost from the generation of renewable sources and

minimized cost using fuel generation in their ED optimization formulas and got power from renewable energy considering optimal cost solutions. The battery is used in the constraints equation of their ED formulation to limit the source of battery power and battery energy. They solved the optimization in multi-time periods using dynamic and linear programming [20-21].

The ED problem for one-period optimization can be solved using the Lagrange function as illustrated in [22-23]. This function contains variables for each constraint available in the formulation of ED called the Lagrange multiplier. Each multiplier is associated with one of the constraints. In [24-26] described the function using the cost of energy storage and included the battery and energy constraints in their formulation. The Lagrange function is the best solver used for optimization ED problems as in [26]. This function gives the best optimal power generator and fuel cost solution where the generators run during a day schedule.

In this report, the one-period and multi-period ED optimization have to solve the Lagrange function's formulation problem, including multi generators and battery energy storage. This problem is solved economically in an optimal manner. The results of the generator and battery are the base point power for the classical (conventional) system of automatic generation control (AGC). To improve the AGC system response, the conventional way of ED optimization converts to an integrated feedback control loop to help the AGC controller provide smaller errors in the frequency response and mechanical power for every generator than classical AGC.

## **2.3 CLASSICAL SYSTEM OF AUTOMATIC GENERATION CONTROL (AGC)**

The AGC system needs to have a base point power value for every generator to provide the correct output power needed for the load. The AGC controls the generator output to regulate frequency while the system continuously runs after ED decides the base point power for every generator, as illustrated in [27]. The modeling of AGC basic blocks is to control frequency generator units and reduce frequency deviation while loading changes during running machines. This control will minimize frequency response error until it reaches a steady-state value after load change [28]. In addition, the AGC system can control multi-generators to supply the source to the loads [29].

The classical way of solving ED optimization helps the system operators to maintain the required generation power plant to get the necessary frequency and minimize the deviation system's error when the load changes to a different value. It is a good system for using a classical ED and connected to AGC to have generator power. Generator power results from ED are the base point power for AGC. The model of conventional classical ED with AGC is used to let generators follow the load variance for maintaining the acceptable value of frequency economically. A lot of traditional classic ED discussions with AGC are in [30-31].

Renewable energy (RE) is an economical saving cost of generating power. Using renewable energy will minimize the use of nonrenewable energy like a fuel generator. The RE sources are always variable-generated power that is changing values most of the time. According to [32-34], the source of renewable energy can be controlled and minimize the fuel cost of generating electricity throughout the AGC controller. The AGC can consider the RE variability

generating power while controlling the generators' frequency response [35]. The battery energy storage and renewable resources can be used together in the AGC controller to regulate a frequency response by battery power when renewable power is deviated [36].

According to [37-38], the work presented the conventional AGC with battery energy storage in two-area power system model. The work was to control the frequency deviation by minimizing the error when the load system is changed. As in [39-42], they used capacitor energy storage connected in AGC. The battery power output affected the generation response optimally when there is a frequency deviation. In [43-44], the authors used a superconducting magnetic energy storage system in their study work to simulate the response of frequency deviation. They did not include the battery as a source of generation in ED and only used the battery to decrease frequency error when the load changed. Minimizing frequency response using the illustrated approach in these papers [37-44] with only a battery to control frequency will not reach the optimal cost economically.

In this thesis, two classic AGC areas have been investigated considering Li-ion battery energy storage cost in ED optimization. A renewable resource like wind generation includes in the simulation. The battery power and energy will help the AGC system control all required output responses for generation power electricity. The AGC has considered a Li-ion battery as a power generating source for supplying the grid. The other advantage of using the battery is to help AGC control minimize the error of the deviation response when the load is changed and save more generation cost due to reducing the frequency response error.

## **2.4 INTEGRATED SYSTEM OF AUTOMATIC GENERATION CONTROL (AGC)**

The classical ED approach does not ensure the optimal frequency solution when running the generator at all times to the power grid. Due to the high penetration of renewable energy in the grid, the generation must have great control to obtain an optimal solution for frequency regulation during load or renewable power changes. One of the solutions is organized in [45-46]. This solution is to convert the classical way of ED into a feedback controller.

The integrated ED-AGC is used to determine the accepted results for the optimal solution in a power grid with a more economical cost of generating power. In [47], a generation scheduling of ED can be converted to a feedback control strategy for AGC. This feedback control provides the individual generator's base point in each second, depending on loads. The base point power will change directly to a new value when the load changes in minor seconds. Integrated ED-AGC gets better system response like frequency and mechanical power response compared to classical ED-AGC. The integrated ED-AGC will provide a better optimal solution for frequency deviation during load or renewable power variation at different times [46]. In [47-48], they provided the integrated ED-AGC for one area of the AGC system. They explained the difference between classic and integrated ED-AGC and compared cost and frequency deviation in one area of ED-AGC [49].

This paperwork includes the one area integrated ED-AGC considering battery energy storage with renewable resources. Also, the integrated ED-AGC implements in two areas considering the battery and wind generation in area 1 while area 2 is integrated ED-AGC without load changed in this area. This implementation illustrates the system response of integrated ED-

AGC when the load is changing in an area that includes battery and wind. Also, this research studies the effective system response for the second area that does not consider battery energy storage, wind resource, and load change.

## **2.5 GENERATORS RAMP LIMIT AND LOOK AHEAD CAPABILITY.**

### **2.5.1 ED-AGC Considered Generators Ramp limit**

With the increase of power consumption, the economic dispatch of automatic generation control (AGC) units becomes a critical issue in frequency control. In some large industries, the power load consumption when operating a large machine will suddenly consume around 100 *MW* of power electricity. Higher operating electricity will affect the frequency control of AGC for getting faster in the steady-state values. Many studies in [50-52] considered the ramping limit of fuel generators in economic dispatch (ED) for the traditional way of AGC to solve the deviation of frequency when load consumption varies to a high level of power in a shorter time. This thesis work will consider the ramping limit of generators in classic ED-AGC and the proposed integrated ED-AGC that looks into this issue.

### **2.5.2 ED-AGC Considered Look Ahead Capability**

Look ahead capability in ED, whose idea began during the 1980s [53], aims to manage operational uncertainties over the following several times [54-56]. Look ahead capability displays an improved exhibition in economy and security over day-ahead dynamic ED when updating and using the most accurate load demand. Look ahead capability leads to more utilization of renewable resources as these resources are not predictable for a long time due to some conditions. Like wind

power, it depends on daily weather. So, updating the load demand when the operation of generation equipment is running will benefit the AGC controller for minimizing error and saving cost. The benefits of considering load ahead capability in the ED-AGC will reduce the error of the frequency response and generating electricity.

In this report, the integrated ED-AGC considers demand power implementation to investigate the AGC response when the load demand is changed in the middle of running generation and between the two running ED optimizers. The comparison of the responding generation power of the classic and integrated ED-AGC is explained in this report.

## CHAPTER 3 CLASSICAL AND INTEGRATED ED-AGC SYSTEM CONSIDERING ENERGY STORAGE

### 3.1 CLASSICAL AGC MODELING WITH ENERGY STORAGE

The classical AGC system of implemented work consists of one fuel generator and one battery storage [6-9]. Figure 3.1 shows the AGC system model and the modeling equations of this system described in equations (3.1) to (3.8). The modification of this model is colored orange. Figure 3.1 illustrates the blocks for the generator, battery, and their connection of the AGC model. If the load is changed, the frequency response of AGC deviates from the steady value and affects the other system responses. In equation (3.1),  $\Delta\omega$  represents the frequency response, and it is equal to the mechanical power of the generator  $\Delta P_{mech}$  and battery power of energy storage  $\Delta P_b$  subtracted from electrical power  $\Delta P_{ele}$  where  $M$  is the angular momentum of the generator. According to equation (3.2), the electrical power output comes from two major parts: a frequency sensitive load change power  $\Delta P_L$  and a non-frequency sensitive load change power  $D\Delta\omega$ .  $D$  is the load change to the frequency sensitive component  $KW/H_z$ . Note that the generator's electrical output power and the battery are equal to the electrical system load. As given in (3.3), the mechanical power output represents the generator's prime turbine mover movement. The input is the governor valve position  $\Delta P_v$  and  $t_t$  is the turbine time constant. In (3.4), the governor valve position input is a function of the governor actuating signal  $\Delta P_g$  where  $t_g$  is the governor valve time constant. Equation (3.5) shows the input signal of governor actuating equal to the difference between reference set point of the load  $\Delta P_{ref}$  and frequency deviation where  $R_g$  is the generator's droop characteristic. Equation (3.6) illustrates the battery power input  $\Delta P_b$  and it is equal to a

function of energy storage actuating signal  $\Delta P_{es}$  where  $t_b$  is the battery time constant. According to equation (3.7), the energy storage actuating signal is equal to the difference between the reference set point and frequency deviation.  $R_b$  is the droop characteristic of the battery energy storage. To ensure the system gives zero steady-state error for frequency, the load reference setpoint is driven by the frequency integrator. The gain  $K$  is the supplementary (secondary) control gain (3.8).

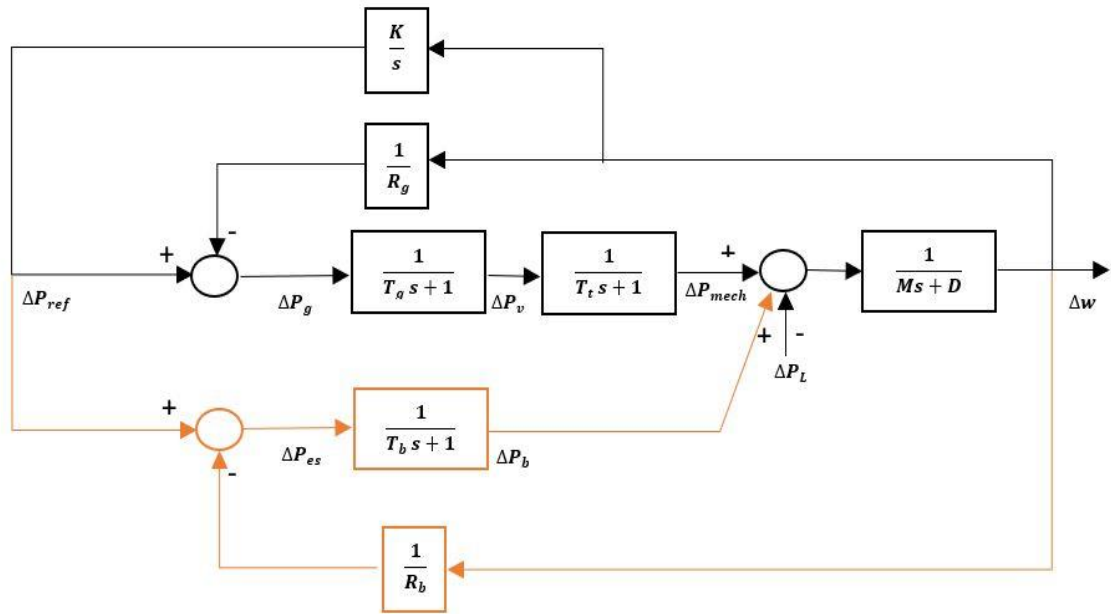


Figure 3.1 Block diagram for AGC.

$$\Delta\omega(s) = \frac{1}{Ms} (\Delta P_{mech}(s) + \Delta P_b(s) - \Delta P_L(s)) \quad (3.1)$$

$$\Delta P_{ele}(s) = \Delta P_L(s) + D\Delta\omega(s) \quad (3.2)$$

$$\Delta P_{mech}(s) = \frac{1}{T_t s + 1} \Delta P_v(s) \quad (3.3)$$

$$\Delta P_v(s) = \frac{1}{T_g s + 1} \Delta P_g(s) \quad (3.4)$$

$$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R_g} \Delta \omega(s) \quad (3.5)$$

$$\Delta P_b(s) = \frac{1}{T_b s + 1} \Delta P_{es}(s) \quad (3.6)$$

$$\Delta P_{es}(s) = \Delta P_{ref}(s) - \frac{1}{R_b} \Delta \omega(s) \quad (3.7)$$

$$\Delta P_{ref}(s) = \frac{K}{s} \Delta \omega(s) \quad (3.8)$$

Figure 3.1 illustrates the block diagram of the AGC system that contains the generator and battery. Each of the droop characteristics is part of the primary control stage for frequency deviation in the AGC. When the load changes, the generator and battery power outputs will change from their base point powers to upper or lower values until generation power equals the total loads. When they are equal power, it means the frequency reaches a steady-state error. The primary control will not be enough to get the response needed for frequency. The integral controller inserted in the AGC system as a secondary control helps the primary control to eliminate errors and attain zero steady-state error.

Figure 3.2 shows the multiple generators used in the AGC system with one battery energy storage. In this situation, when the load is varying from nominal value to another value, the mechanical power for every generator online on the AGC system and battery storage will participate in the load changing. Each one of these machines will have a participation percentage on the load change called the participation factor. Equations (3.9) to (3.11) represent the equality of total load change need in the AGC system where  $pf_i$  represents the percentage of each generator

and  $pf_b$  is the battery participation factor. Note that the total of all participation factors is equal to one.  $\Delta P_{refi}(s)$  is the power load set point for each generator, and  $\Delta P_{refb}(s)$  is the power load set point for the battery. Both of  $\Delta P_{refi}(s)$  and  $\Delta P_{refb}(s)$  are available in the secondary control. The  $P_{basei}$  and  $P_{baseb}$  come from ED programming set at different times. Based on these values and frequency deviation, the secondary control of AGC will decide the new  $\Delta P_{refi}(s)$  and  $\Delta P_{refb}(s)$  values.

$$\Delta P_i(s) = pf_i * \Delta P_{refi}(s) \quad (3.9)$$

$$\Delta P_b(s) = pf_b * \Delta P_{refb}(s) \quad (3.10)$$

$$\sum_{i=1}^N pf_i + pf_b = 1 \quad (3.11)$$

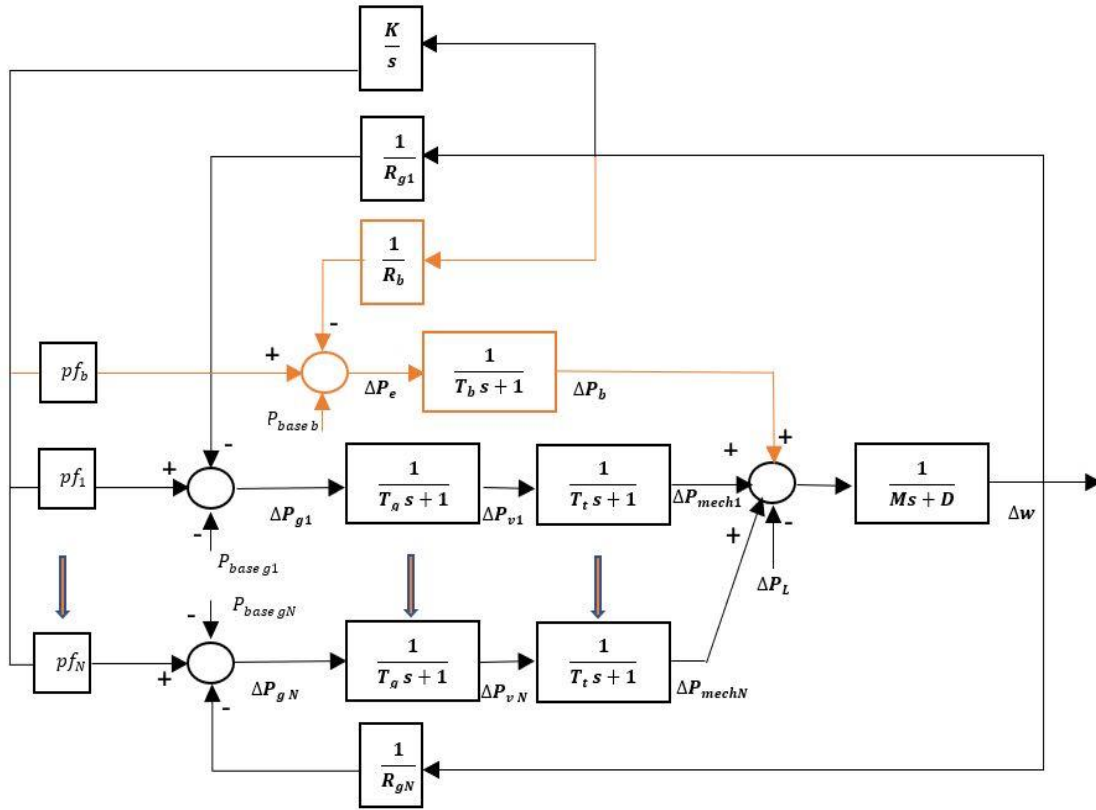


Figure 3.2 Block diagram for multi-generator and one Battery in AGC.

### 3.2 CLASSICAL ED MODEL FOR ONE PERIOD

The formulation of economic dispatch (ED) in an isolated system for generators and battery energy storage is available in equations (3.12) to (3.21).

**Objective function:**

$$\text{Min} \quad f = \sum_{i=1}^N C_i(P_i) + C_b(E_b) \quad (3.12)$$

**The cost for individual generator:**

$$C_i(P_i) = a_i + b_i * P_i + c_i * P_i^2 + d_i * P_i^3 \quad (3.13)$$

**The cost for battery energy storage:**

$$C_b(E_b) = \frac{TCB}{CAP * lifecycle * DoD * Eff} \quad (3.14)$$

$$lifecycle = 694 * (DoD)^{-0.795} \quad (3.15)$$

$$DoD = 1 - \frac{E_b}{E_b^{max}} \quad (3.16)$$

Where  $f$  is the objective function of the total cost for all generators and one battery used,  $i$  represent the generator unit, and  $P_i$  is the base point power for generator  $i$ .  $C_i$  is the generator  $i$  cost function with constant parameters  $a, b, c$ , and  $d$ .  $E_b$  is the energy storage of the battery, and  $C_b$  is the cost function of battery energy.  $TCB$  represents the total cost of the installed battery, and this cost will be a divide on each cycle of using the battery as in equations (3.15) and (3.16).  $CAP$  is the energy-rated battery capacity.  $lifecycle$  is the life cycle of battery energy storage due to  $DoD$  change, which is the battery's depth of discharge.  $DoD$  is the capacity

percentage that has been removed from fully charge battery.  $Eff$  is the efficiency of the battery energy storage.  $E_b^{max}$  is the maximum energy storage in the battery. The constraints of the objected function are the following:

**Power balance equality constraints:**

$$P_L - \sum_{i=1}^N P_i + P_b = 0 \quad (3.17)$$

**Generator limit constraints:**

$$P_i^{min} \leq P_i \leq P_i^{max} \quad (3.18)$$

**Battery power limit constraints:**

$$P_b^{min} \leq P_b \leq P_b^{max} \quad (3.19)$$

**Battery energy limit constraints:**

$$E_b^{min} \leq E_b \leq E_b^{max} \quad (3.20)$$

$$E_b = E_b (\text{previous stored energy}) - P_b * \Delta t \quad (3.21)$$

Where  $P_L$  represents the load demand that needs to generate power from generators and batteries. Note that the battery could be a load when charging and could be a generator when discharging.  $P_b$  is the base point power for the battery.  $P_i^{max}$  and  $P_i^{min}$  is the maximum and minimum limit of generation power of the individual generator.  $P_b^{max}$  and  $P_b^{min}$  are the maximum and minimum limit of battery base point power given to the AGC. If the  $P_b$  is positive means the battery is discharging, and if it reaches the maximum value, it means that the battery gets the limit value of discharge. However, if the  $P_b$  is negative, which indicates the battery is charging, and if

it reaches the minimum  $P_b$  value, this represents the battery is fully charging power.  $E_b^{min}$  is the minimum energy storage in the battery.

The Lagrange function  $L$  in equation (3.22) is used to solve this kind of mathematics formulation in ED. The first and second term of this function is the objective function which indicates the total cost. The third term illustrates the power equality constraint for load, all generators, and battery.  $\lambda$  is the Lagrange multiplier proposed the incremental cost associated with a power equality constraint.  $L$ 's other terms indicate the limit constraints for all generator powers, battery power, and energy storage in the battery.  $\beta_i$ ,  $\mu_1$  and  $\mu_2$  represent the Lagrange multiplier connected with generator limits, battery limits, and energy storage limits. To get the optimal solution in ED optimization, it needs to set all partial derivatives of  $L$  to zero in equations (3.23) to (3.25). Equation (3.26) to (3.28) defines the complementary slackness condition to handle the inequality constraints.

$$L = \sum_{i=1}^N C_i(P_i) + C_b(P_b) + \lambda \left( P_L - \sum_{i=1}^N P_i \right) + \beta_i(P_i - P_i^{limit}) + \mu_1(P_b - P_b^{limit}) + \mu_2(E_b - E_b^{limit}) \quad (3.22)$$

$$\frac{\partial L}{\partial P_i} = \frac{\partial C_i(P_i)}{\partial P_i} - \lambda + \beta_i = 0 \quad (3.23)$$

$$\frac{\partial L}{\partial P_b} = \frac{\partial C_b(P_b)}{\partial P_b} - \lambda + \mu_1 - \mu_2 = 0 \quad (3.24)$$

$$\frac{\partial L}{\partial \lambda} = P_L - \sum_{i=1}^N P_i = 0 \quad (3.25)$$

$$\beta_i = \begin{cases} 0, & \text{if } P_i^{min} \leq P_i \leq P_i^{max} \\ > 0, & \text{if } P_i^{min} = P_i \text{ or } P_i^{max} = P_i \end{cases} \quad (3.26)$$

$$\mu_1 = \begin{cases} 0, & \text{if } P_b^{min} \leq P_b \leq P_b^{max} \\ > 0, & \text{if } P_b^{min} = P_b \text{ or } P_b^{max} = P_b \end{cases} \quad (3.27)$$

$$\mu_2 = \begin{cases} 0, & \text{if } E_b^{min} \leq E_b \leq E_b^{max} \\ > 0, & \text{if } E_b^{min} = E_b \text{ or } E_b^{max} = E_b \end{cases} \quad (3.28)$$

### 3.3 INTEGRATED ED-AGC MODELING

The conversion of the economic dispatch (ED) optimization problem as given in (3.12) to (3.28) into an integrated feedback control loop is presented in this part. Figure 3.3 illustrates the feedback control loop's block diagram for the Lagrange function formulated in equations (3.21) to (3.28). This control scheme's outputs are the partial derivatives of Lagrange variables, and the inputs are the different values between the outputs and zero. These differences are the inputs to the integrator, whose outputs are the base point power of the AGC that represent generators and battery  $P_i$ ,  $P_b$  and the incremental cost  $\lambda, \beta_i, \mu_1$ , and  $\mu_2$  values will deviate from zero if generators and battery reach their limits. In the steady-state operation in the AGC, the partial derivatives are all zero, and the operating base point powers are in optimal values. Suppose the load varies from the base value at any time. In that case, the partial derivatives will change from zero value, and the proportional-integral (PI) will deviate the base points to the new optimal values.

The values of  $P_i$ ,  $P_b$  and  $\lambda$  in the integrated ED is connected directly to the base point power for the AGC system to let integrated ED directly provide feedback to the generators and battery. The participation factors are set to zero to have integrated ED effective, eliminating the response integral of secondary control. So, the model of integrated ED cancels the supplementary control of the AGC.

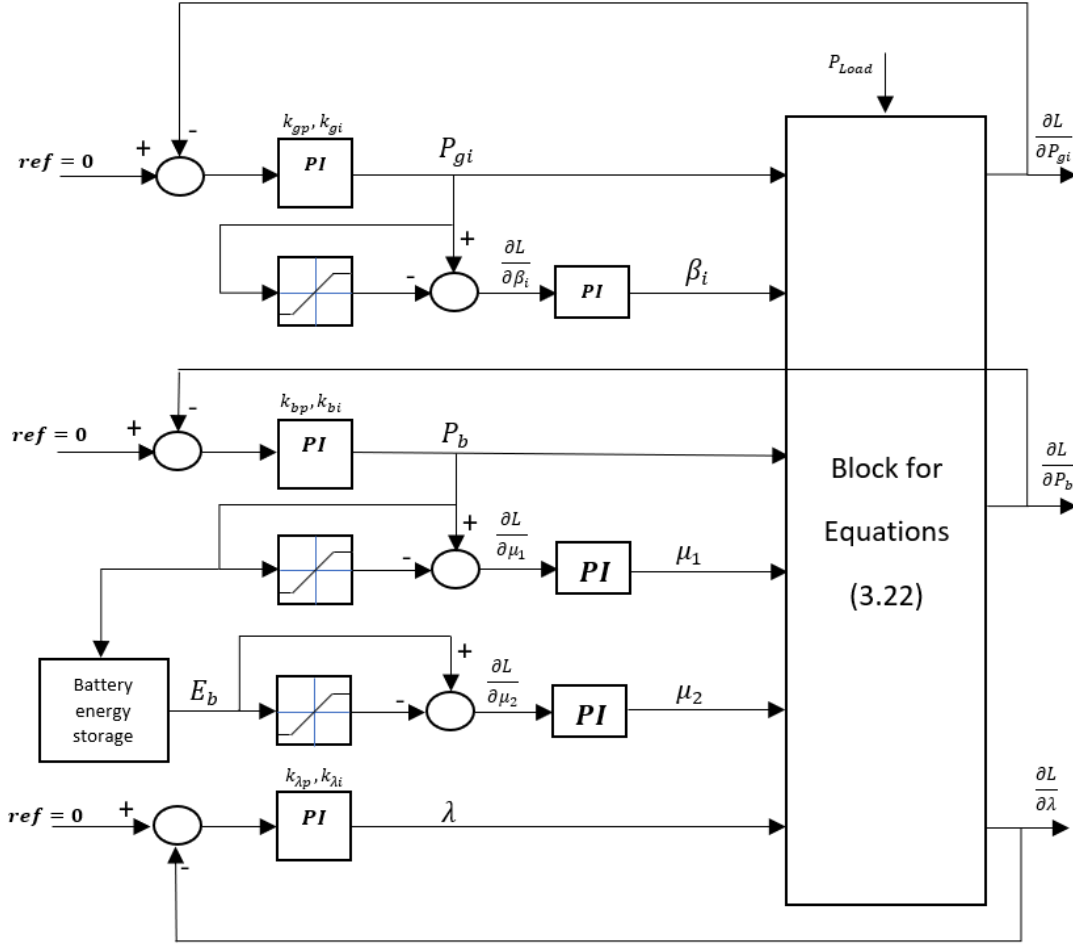


Figure 3.3 Block diagram for integrated feedback control.

### 3.4 CLASSICAL AND INTEGRATED TESTING FOR ONE PERIOD ED - AGC

The work proposes the classical and integrated ED-AGC for one area simulated in Matlab using three thermal generators. The constant parameters for every generator used in the simulation for classical and integrated ED-AGC are available in Table 3.1. Thus, the ED-AGC area has the same generator parameter values. In addition, table 3.2 shows the classical droop characteristics

and participation factor values of ED-AGC. Moreover, table 3.3 illustrates the exact number of each PI parameter considered in the simulation.

### 3.4.1 Classical ED-AGC Compared With or Without considering Battery Energy Storage

In this part, Matlab is used to run the ED programming optimization for multiple periods. This optimization determines the base point power for every generator and battery based on the formulation equations. The AGC simulation system includes three thermal generators and one battery. Table 3.1 illustrates the constant parameters values for all generators [43-44]. Table 3.2 shows the parameter values of battery energy storage [11]. The regulation gain  $R$  and participation factor  $p_f$  for generators and one battery used in the Classical ED-AGC control strategy are available in table 3.3. These values are set according to [43-44]. The participation factor of the battery is set to zero to keep battery power as scheduled and to have battery energy equal to the base start value.

**Table 3.1 Generator Parameters.**

| Generator     | $P_{g1}$ | $P_{g2}$ | $P_{g3}$ |
|---------------|----------|----------|----------|
| $a$           | 213.1    | 200      | 240      |
| $b$           | 7.669    | 4.833    | 8.833    |
| $c$           | 0.0533   | 0.00889  | 0.00741  |
| $d * 10^{-3}$ | 0.0665   | 0.4445   | 0.1705   |
| $P_g^{min}$   | 50 MW    | 37.5 MW  | 45 MW    |
| $P_g^{max}$   | 400 MW   | 500 MW   | 500 MW   |
| $t_t$         | 0.2 sec  | 0.2 sec  | 0.2 sec  |
| $t_g$         | 0.2 sec  | 0.2 sec  | 0.2 sec  |

**Table 3.2 Battery energy storage parameters.**

| Parameters             | Values                    |
|------------------------|---------------------------|
| Capital cost ( $TCB$ ) | 250 k\$/MWh               |
| Capacity (CAP)         | 50 MWh                    |
| $P_b^{min}$            | -16 MW (16 MW charging)   |
| $P_b^{max}$            | 16 MW (16 MW discharging) |
| $E_b^{min}$            | 0.15 * Capacity           |
| $E_b^{max}$            | 0.95 * Capacity           |
| $t_b$                  | 0.02 sec                  |

**Table 3.3 Classical ED-AGC control Parameters.**

| Items | $R$  | $pf$ |
|-------|------|------|
| Gen 1 | 0.01 | 0.43 |
| Gen 2 | 0.02 | 0.26 |
| Gen 3 | 0.02 | 0.31 |
| Batt  | 0.01 | 0    |

**Table 3.4 Classical ED optimization without Battery.**

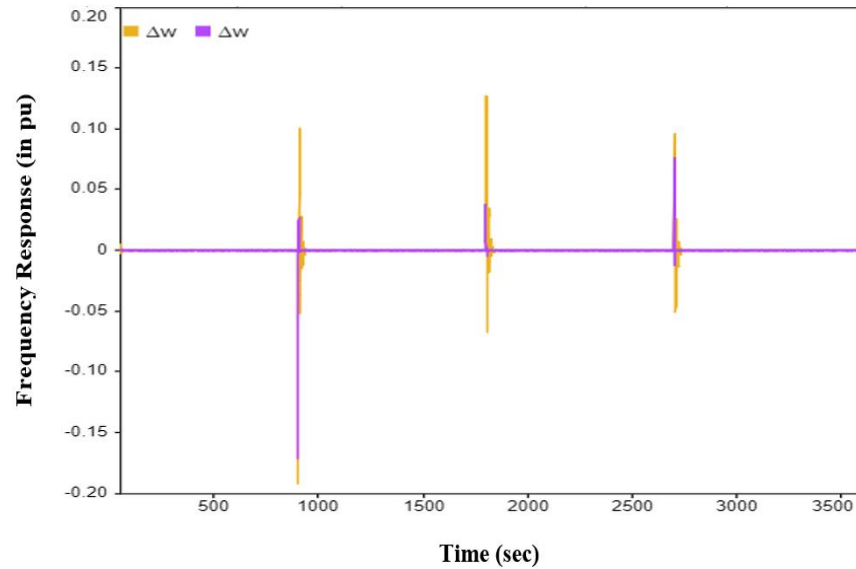
| Load   | $P_{g1}$   | $P_{g2}$   | $P_{g3}$   | Gen cost    |
|--------|------------|------------|------------|-------------|
| 580 MW | 284.377 MW | 121.954 MW | 173.669 MW | 2243.204 \$ |
| 640 MW | 314.275 MW | 132.832 MW | 192.893 MW | 2674.441 \$ |
| 620 MW | 294.343 MW | 125.567 MW | 180.089 MW | 2380.500 \$ |
| 570 MW | 279.394 MW | 120.152 MW | 170.454 MW | 2176.888 \$ |

**Table 3.5 Classical ED optimization with Battery.**

| Load   | $P_{g1}$   | $P_{g2}$   | $P_{g3}$   | $P_b$  | Gen cost    | Batt cost |
|--------|------------|------------|------------|--------|-------------|-----------|
| 580 MW | 292.350 MW | 124.843 MW | 178.806 MW | -16 MW | 2352.537 \$ | 8.741 \$  |
| 640 MW | 306.302 MW | 129.920 MW | 187.777 MW | 16 MW  | 2553.699 \$ | 8.397 \$  |
| 620 MW | 296.337 MW | 126.291 MW | 181.372 MW | 16 MW  | 2270.162 \$ | 8.120 \$  |
| 570 MW | 287.367 MW | 123.036 MW | 175.597 MW | -16 MW | 2283.734 \$ | 8.397 \$  |

In the first simulation, the classical ED ran for 1 hour and used 4-time optimization changed every 15 minutes. The results work connected to the base points of every generator and battery in the AGC system. Table 3.4 shows the optimization results of optimal cost for non considerable batteries, and table 3.5 illustrates the effect of running ED with battery in economical price. Tables 3.4 and 3.5 are particular periods running optimization in ED. In single-period optimization, the

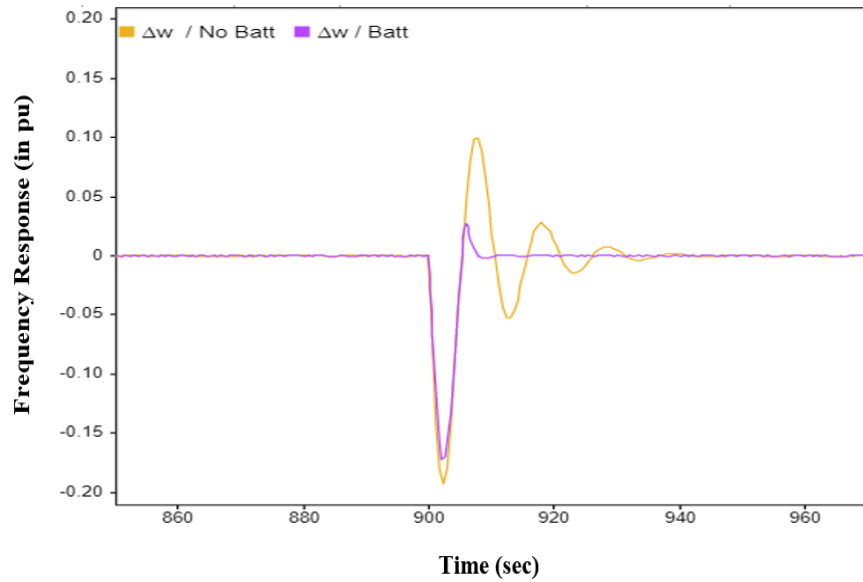
system operator must decide which period is charging or discharging. At each optimization period, the battery will result in the maximum or minimum power because low power is used with the battery compared to generator power, and the cost of the battery is significantly less. So, battery power schedules every period to supply the maximum power capacity in the classic ED-AGC system. Here in the first simulation, battery power is charging in the first and fourth periods and discharging in the second and third periods. The load changes consider every 15 minutes in each period with high load demand change to represent the maximum load frequency change and the restorable steady-state error.



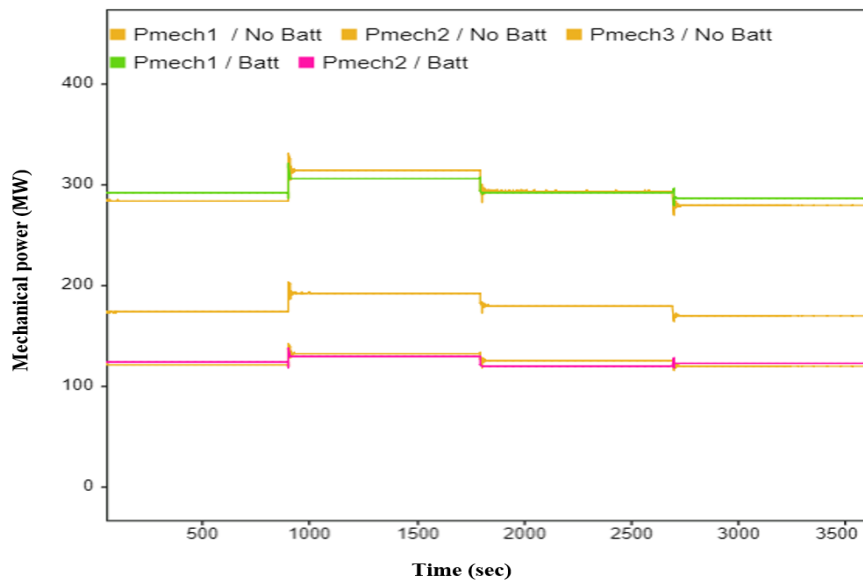
**Figure 3.4 Frequency response for four periods.**

The frequency response considering battery storage is better than the frequency response without including energy storage as figures 3.4 and 3.5 illustrates. The time taken to return the frequency to steady-state for the AGC system considering the battery is a quarter-time for not considering the battery in the same system. The response of the mechanical output of the generators is illustrated in figures 3.6 and 3.7. When the load is changed, each generator's mechanical power

goes to the expected new steady-state value in a shorter time when considering the battery in AGC than without considering the battery.



**Figure 3.5 Frequency response for the First Period.**



**Figure 3.6 Mechanical power response for four periods.**

Figures 3.8, 3.9, and 3.10 show the battery power in both systems and the battery energy saving while charging and discharging power in a one-hour running simulation. When the load changes to another value, the battery will deviate from its expected value to another steady-state

value. Also, the deviation will fluctuate until the required frequency is back to zero steady-state value. However, the battery is not a wave signal like a generator due to the limited power of the battery. The starting battery energy is 25 *MWh*, and it is equal to the final value of battery energy, as illustrated in figure 3.10. The maximum stored energy reaches around 29 *MWh* while the minimum stored value is approximately 21 *MWh*.

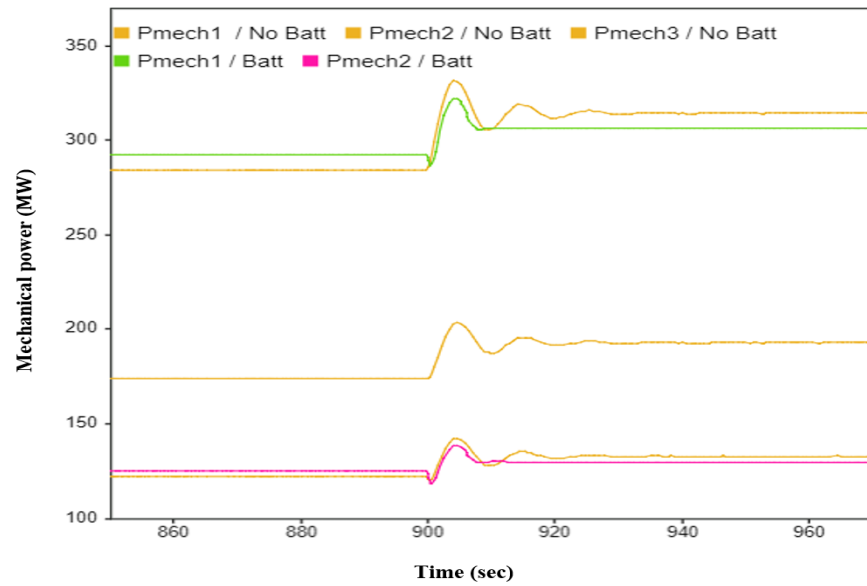


Figure 3.7 Mechanical power response for first periods.

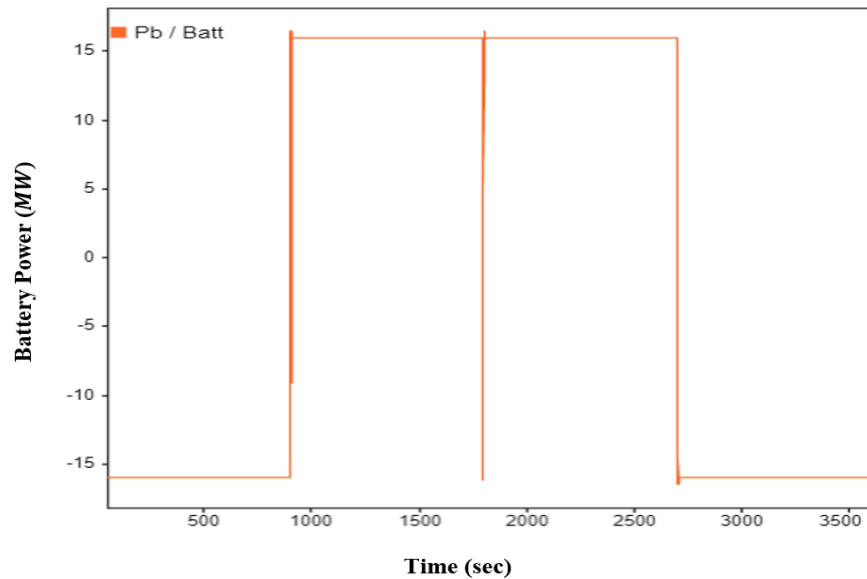
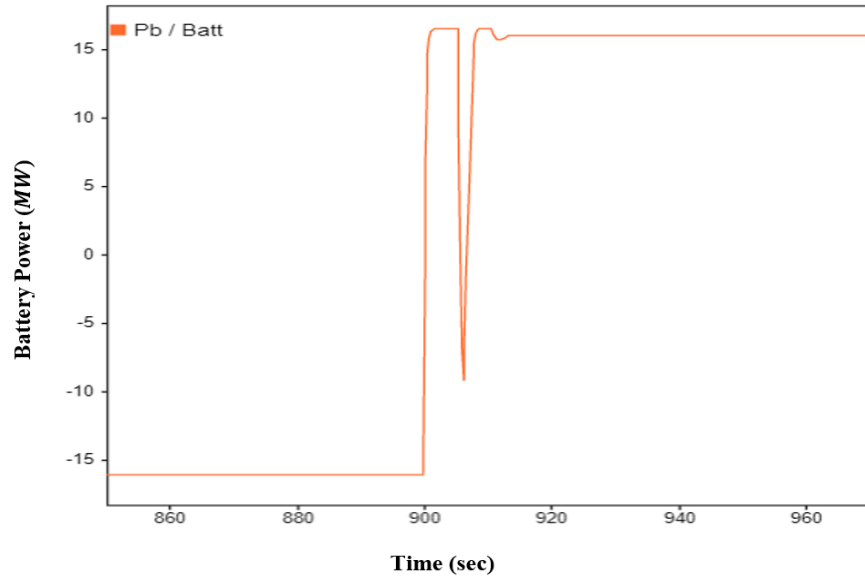
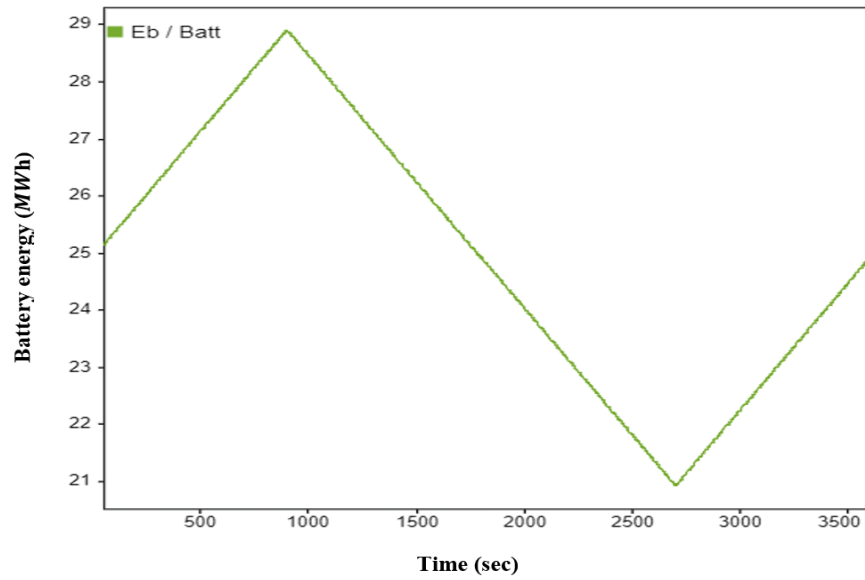


Figure 3.8 Battery power response for four periods.



**Figure 3.9 Battery power response for first periods.**



**Figure 3.10 Energy storage response.**

The total cost of considering the battery and not considering the battery in the AGC system is represented in figure 3.11. Due to the battery regulates the frequency response faster to reach a steady-state, the ED-AGC considering battery has the lower cost than the system without using battery. So, the total cost difference is \$8.4. However, this saving is only for one hour running AGC, and the estimated yearly cost for running AGC considering the battery is around \$73584.

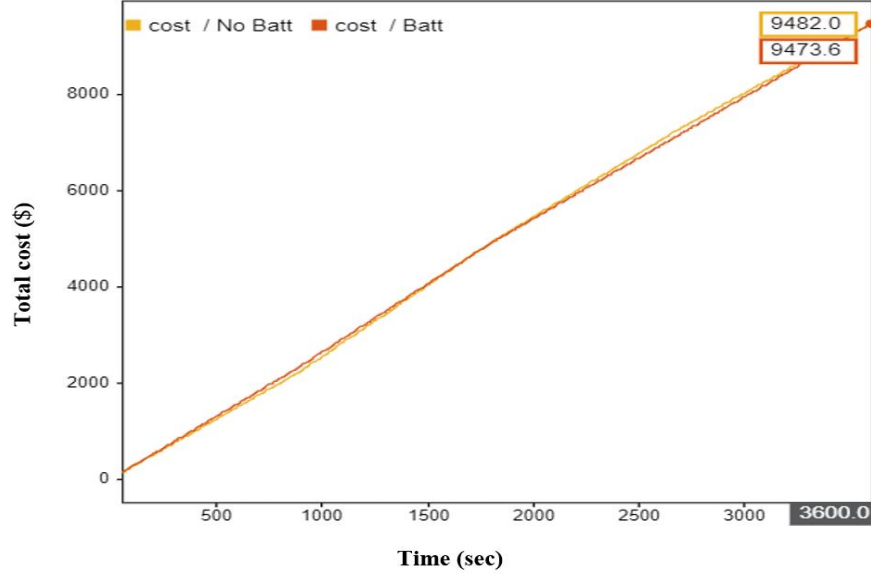


Figure 3.11 Total cost for considering and non considering battery.

### 3.4.2 Classical and Integrated ED-AGC Using Battery

The constant PI parameters in the integrated ED block shown in figure 3.3 are available in table 3.6. These are used for *PI* controller to determine the generators and battery base point power  $P_{gi}$ ,  $P_b$ , the incremental cost  $\lambda$  and the Lagrange multiplier associated with the generator power limit  $\beta_i$ , battery power limit  $\mu_1$  and battery energy limit  $\mu_2$ . These parameters are chosen carefully to obtain the net load change needed. These are tuned values to ensure reaching zero state errors. To make simulation easy,  $k_{gp} = k_{bp}$  and  $k_{bp} = k_{\lambda p}$ . The response time of the system running should be reasonable with a steady-state error. The system utilizes high integral gains to make sure frequency deviation gives zero error in optimal time. The *PI* controller's parameters value for  $\beta_i$ ,  $\mu_1$ , and  $\mu_2$ . are set up and found integral parameters ( $P_{\beta i}$ ,  $P_{\mu_1 i}$  and  $P_{\mu_2 i}$ ) need to be set to zero. However, the proportional parameters ( $P_{\beta p}$ ,  $P_{\mu_1 p}$  and  $P_{\mu_2 p}$ ) values are above zero. Hence,

unacceptable performance occurs when these set values parameters are more than zero. Table 3.6 shows all parameter values for *PI* controllers.

**Table 3.6 Integrated ED-AGC control Parameters.**

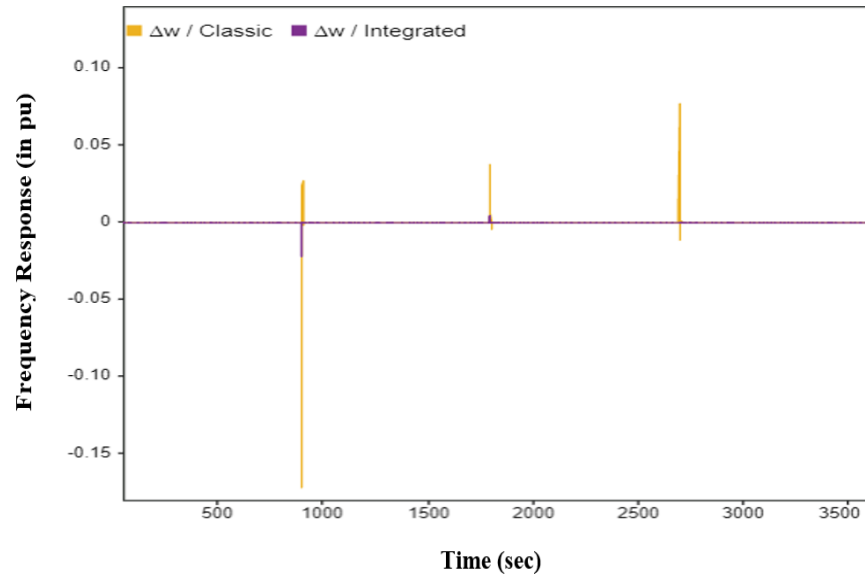
|                                            | Parameter       | value |
|--------------------------------------------|-----------------|-------|
| <i>PI</i> controller that drives $P_i$     | $k_{gp}$        | 262.5 |
|                                            | $k_{gi}$        | 1500  |
| <i>PI</i> controller that drives $P_b$     | $k_{bp}$        | 262.5 |
|                                            | $k_{bpi}$       | 1500  |
| <i>PI</i> controller that drives $\lambda$ | $k_{\lambda p}$ | 262.5 |
|                                            | $k_{\lambda i}$ | 1500  |
| <i>PI</i> controller that drives $\beta_i$ | $k_{\beta p}$   | 18    |
|                                            | $k_{\beta i}$   | 0     |
| <i>PI</i> controller that drives $\mu_1$   | $k_{\mu 1p}$    | 18    |
|                                            | $k_{\mu 1i}$    | 0     |
| <i>PI</i> controller that drives $\mu_2$   | $k_{\mu 2p}$    | 18    |
|                                            | $k_{\mu 2i}$    | 0     |

The PI controllers are available in ED-AGC to control the generator's power, battery power, battery energy, and limit power for all generators and batteries. The PI's that drive the  $\beta_i, \mu_1$  and  $\mu_2$  are used to control the limit power for the generator and battery together with the battery energy limit. The best operating integrated system is finding the best values of the parameters as in table 3.6. Before connecting the integrated economic dispatch ED to AGC, it is tested to ensure the output values are equal to classical economic dispatch and make sure that when the load is changed, the output base power is similar to the load changed. The output power values of the integrated ED system must be equal to the output power of the classic ED system when the integrated ED system does not connect to AGC. So, the integrated PI control parameter values are carefully tuned until all base point power between traditional economic dispatch calculations is equal to the integrated system and load changed is equal to all base point power.

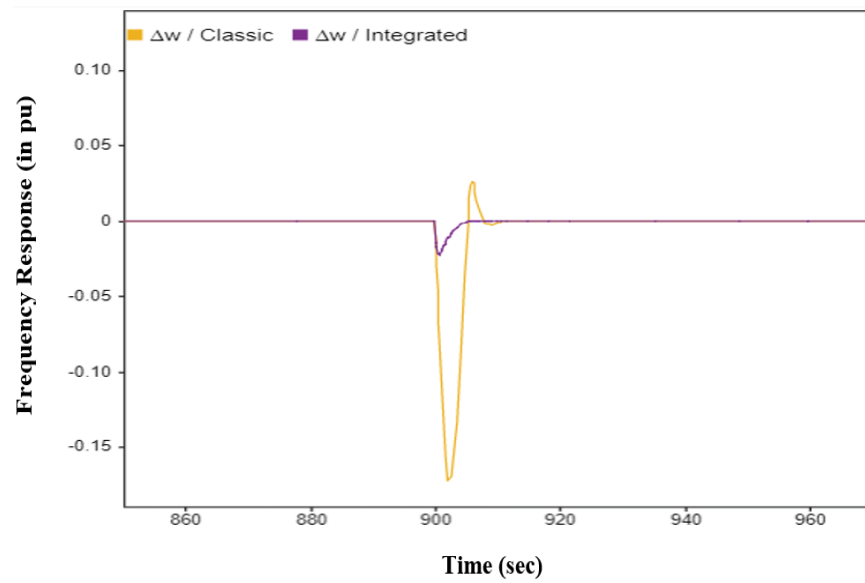
It should be noted that  $R$  values for every generator and battery in the primary control of AGC are still available in integrated ED, but the  $p_f$  is set to zero. Due to a complicated system of using battery energy storage in a single ED programming, the Lagrange function in a single period can not decide whether the battery is charging or discharging. The battery values in the optimization program give discharging mode in every scheduling period of ED because the equation of the initial and final energy value is not included in a single period optimization. The system operator must decide when the battery needs to charge or discharge. For a classic ED, the system operator needs to identify which period is charging or discharging based on the demand load. The higher value of demand load for an hour optimization is the discharging period for the battery and the lower value of the demand load for the same hour is the charging period. It should be informed that each hour has four demand loads for optimization.

On the other hand, the battery parameter connects with  $PI$  controllers' output that drives the  $P_b$  in the integrated feedback control. This parameter connects with the partial output derivative of  $P_b$ . These parameter values consist of an integer number of -1, 0, 1, charging, pausing, and discharging the battery. These values multiply individually in different running ED with  $P_b$  and every ED optimization will have to change the sign of  $P_b$  depending on the system operator decision as in the classic system.

The result of integrated ED-AGC is illustrated in figures 3.12 to 3.19. The classic ED-AGC is shown in figures with the color orange. The frequency response in an integrated system gets better than the classic system. Figures 3.12 and 3.13 show the deviation frequency response when the load is changed and occurs in only one direction in the integrated system. In contrast, the classic system deviation fluctuates on positive or negative y axes, making the system have more disturbance than the integrated ED-AGC.



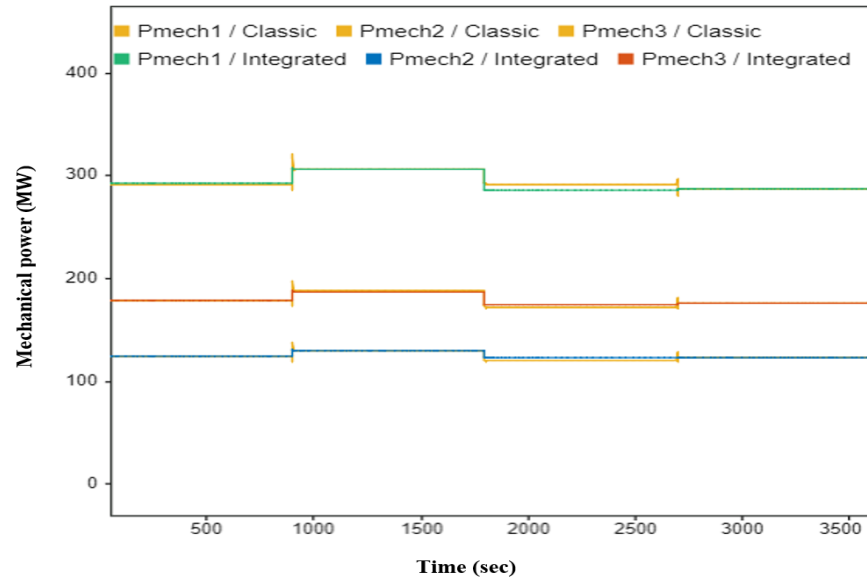
**Figure 3.12 Frequency response 1 for classic and integrate.**



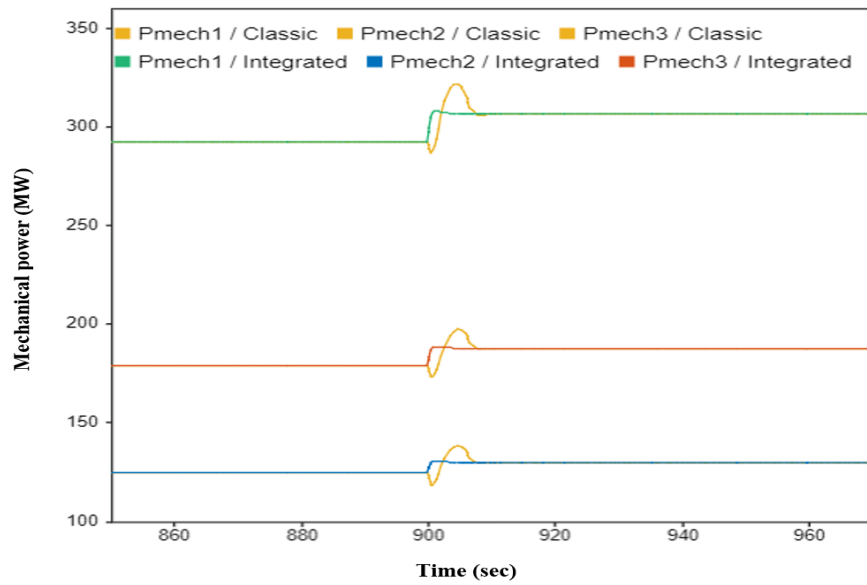
**Figure 3.13 Frequency response 2 for classic and integrate.**

The mechanical response is almost the same except when the load is changed as per figures 3.14 and 3.15. When it is changed to a different variable, the mechanical power of the integrated system deviates in only one direction because the integrated system frequency response moves in one direction when it deviates from steady states. So, if the load increases, the mechanical power will increase, and if the load decreases, the mechanical power will decrease. In a classical system,

the deviation of mechanical power is a wave signal until it reaches a steady-state value due to frequency response.



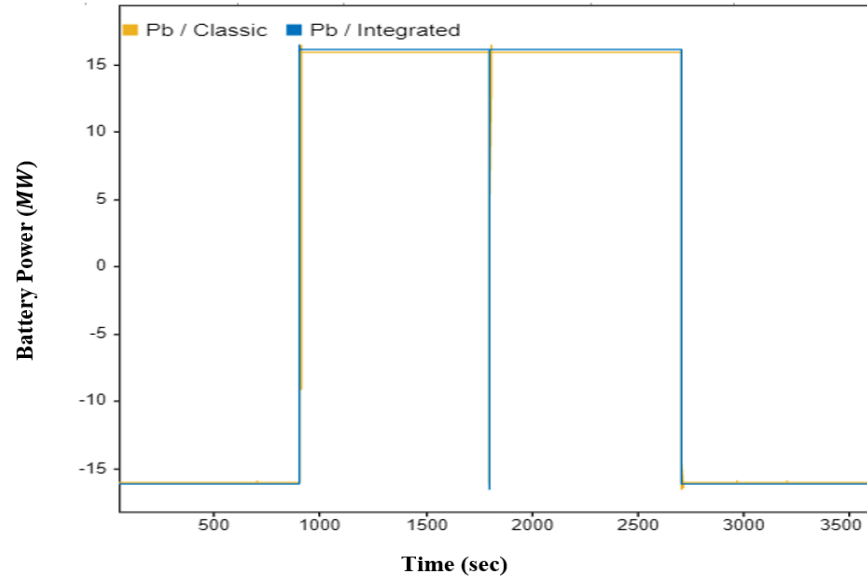
**Figure 3.14 Mechanical power response 1 for classic and integrate.**



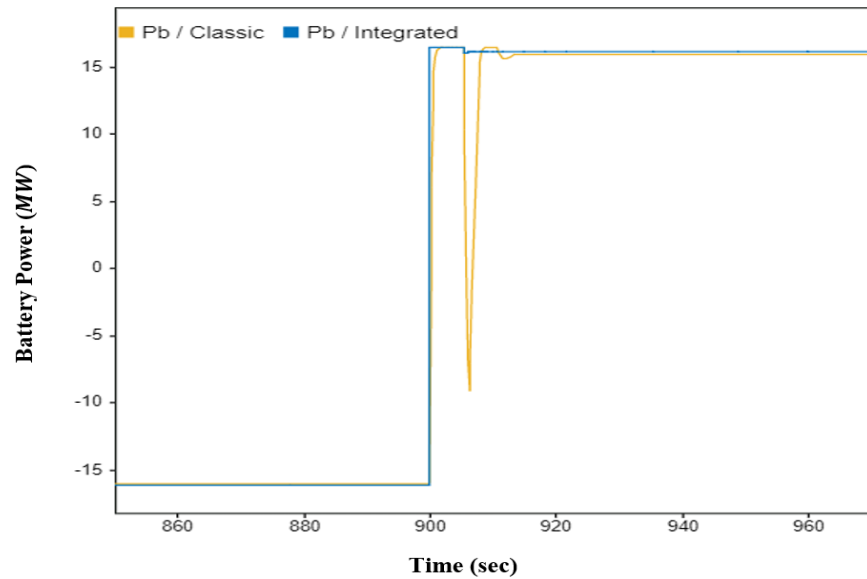
**Figure 3.15 Mechanical power response 2 for classic and integrate.**

The battery power is illustrated in figures 3.16 and 3.17. The signal of battery power in an integrated system moves in one direction. It stays in a new steady-state value after the load is changed, which is better than the battery response in a classical (traditional) way. The time it

reaches the steady-state value of battery power in an integrated system is earlier than the response of the classic approach.



**Figure 3.16 Battery power response 1 for classic and integrate.**



**Figure 3.17 Battery power response 2 for classic and integrate.**

The battery energy saving is 25 MWh at the start of the simulation, and it ends with the same energy value. Figure 3.18 shows the battery energy response for both ED-AGC systems. This test saves cost when implementing integrated one area ED-AGC and is equal to \$5.3. Figure 3.19

shows the cost result of running classic and integrated ED-AGC. The estimated yearly saving cost of using the integrated system is \$46428.

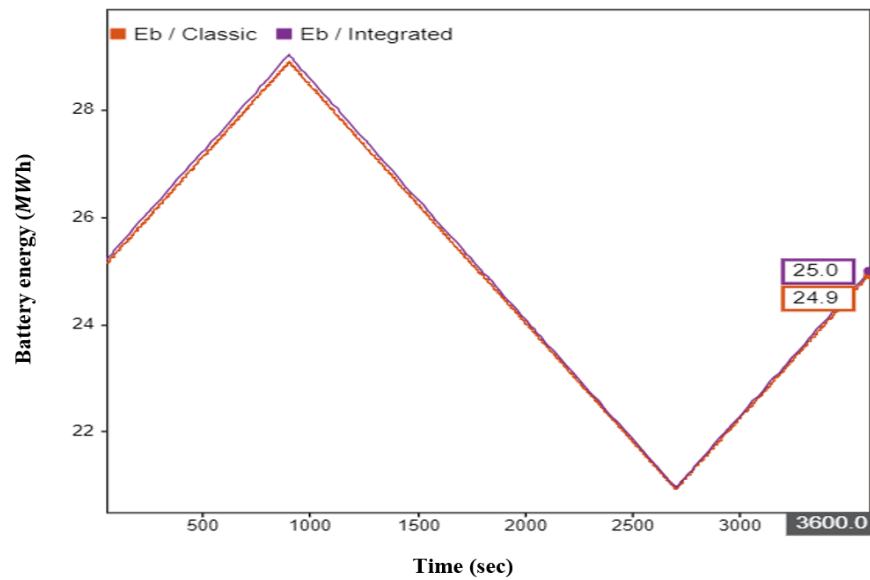


Figure 3.18 Energy storage response.

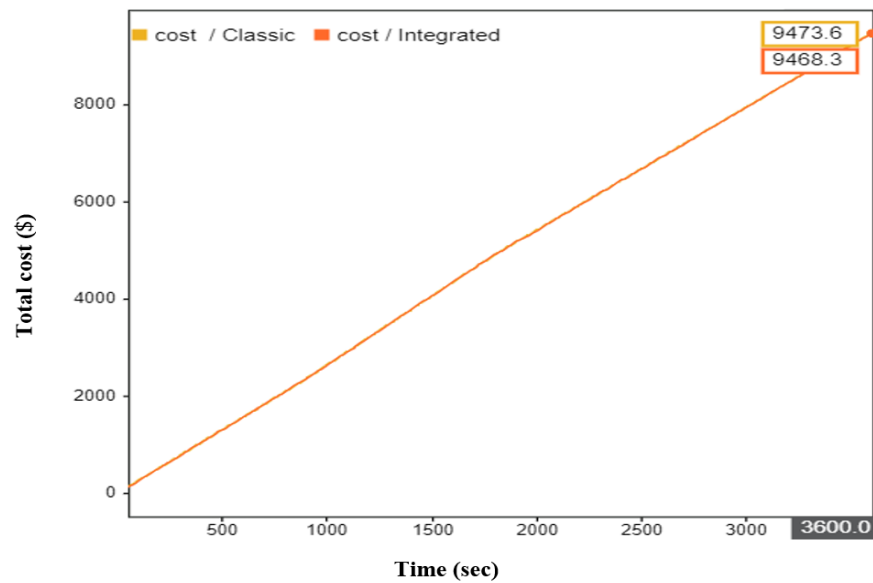


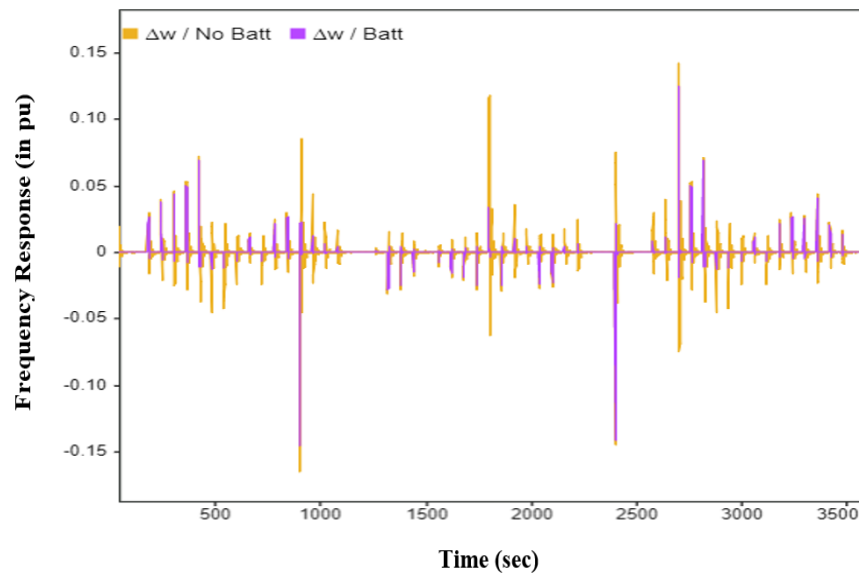
Figure 3.19 Cost for the classic and integrated system.

### 3.4.3 Testing simulation with wind penetration

Wind generation is a mechanical power source generated from wind movement to move a mechanical turbine to turn mechanical energy to an electrical source through generators to create

electrical power. Wind power is a renewable energy source that impacts daily on wind speed. So, wind power is an intermittent source of electricity, and it cannot be dispatchable while generating electricity. Typically, it gives a variable power source in the grids. Therefore, wind generators must be with the thermal generators to supply the grid.

In the Matlab testing program simulation, the wind source utilizes the AGC system to generate power to decrease power from thermal generators and keep demand loads as required. As a result, in figure 3.20, the response of frequency as before in section 3.4.2 is deviating from the nominal value, and it reaches faster to the steady-state value when include battery in the AGC system and that is a reason to have more saving cost in the operation of AGC as shown in figure 3.23.



**Figure 3.20 Frequency response for wind generation used in AGC with and without battery.**

The mechanical power of all generators is in figure 3.21. When wind generation increases, the mechanical power of thermal generators decreases, and if the wind decreases, the mechanical power increases. The battery power responds when the wind generation gets different values, but the battery has limited resources. Therefore, the change should not exceed the minimum and

maximum value of battery power. The total saving cost of this implementation when considering the battery is \$5.3 compared with not considering the battery in the AGC. Figure 3.23 illustrates the cost generated from simulation for one hour. So, if wind generation is included in a year generation of AGC, the saving cost estimated will be around \$46428.

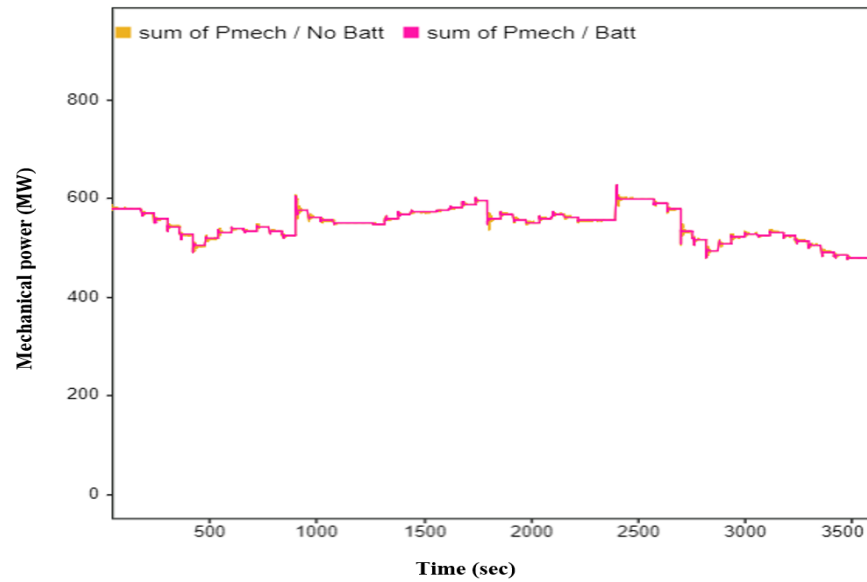


Figure 3.21 Mechanical power for wind generation used in AGC with and without battery.

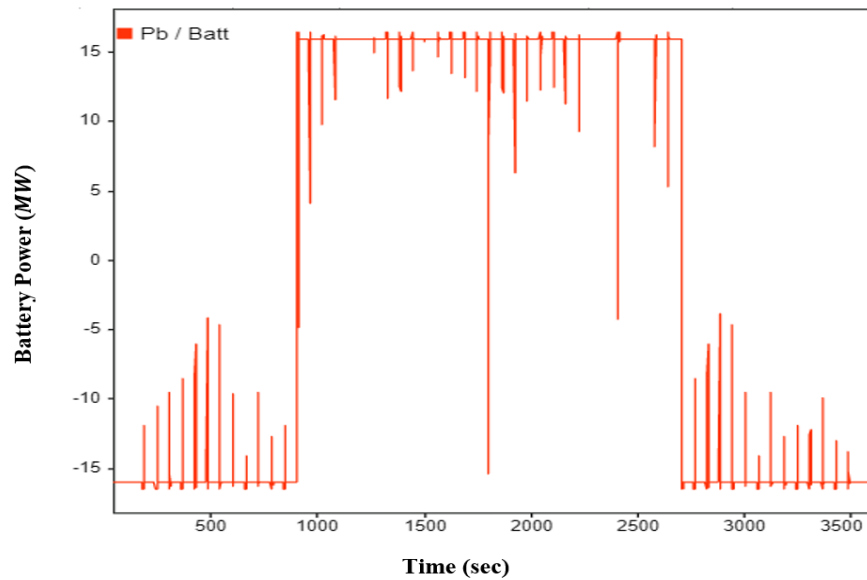
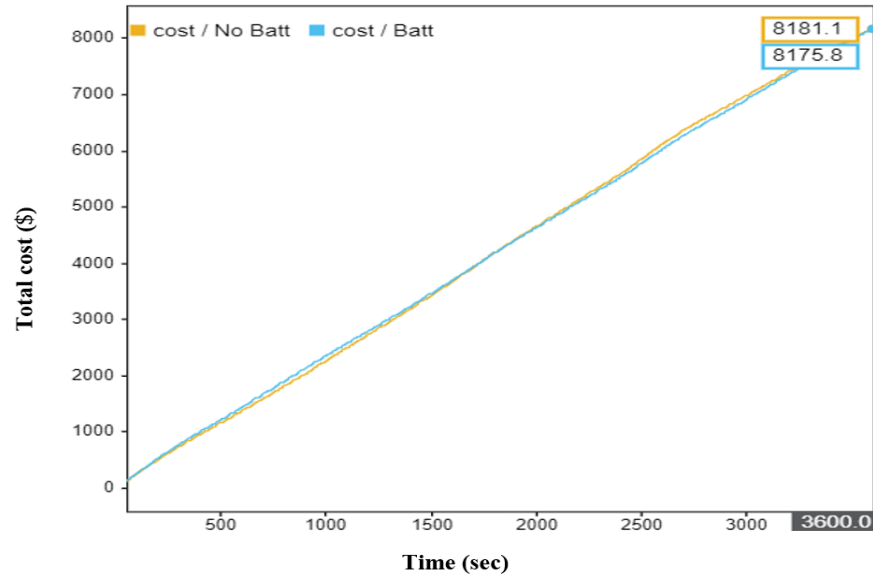
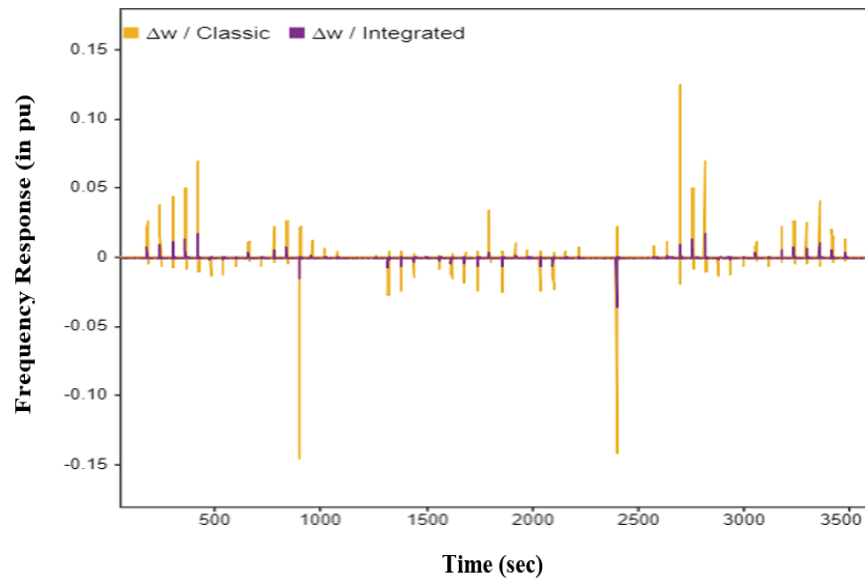


Figure 3.22 Battery response for wind generation used in AGC.

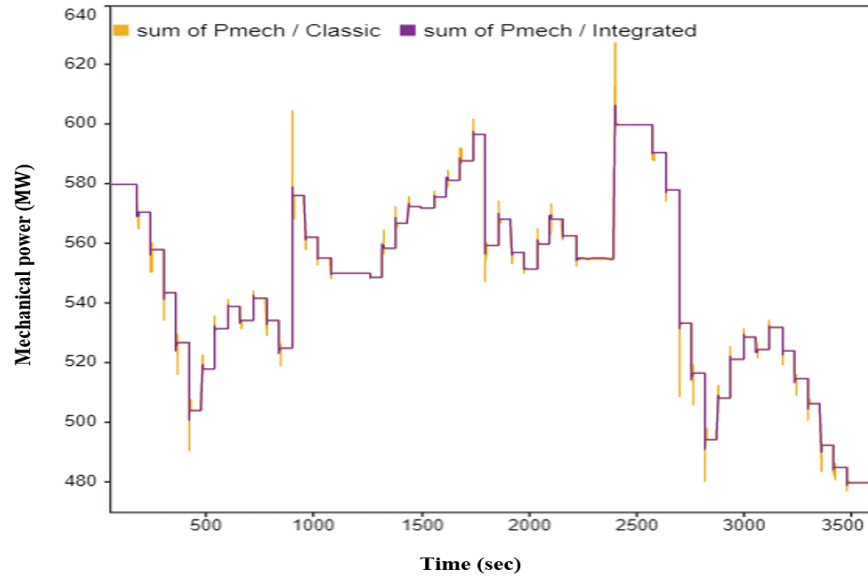


**Figure 3.23 Cost for wind generation used in AGC with and without battery.**

The second simulation test has used the wind in integrated ED-AGC and compares results with the classic system. The frequency response will deviate less magnitude as in figure 3.24, and it reaches a steady-state value after the load changes by wind generation. It should be noted that the wind directly connects to supply the load. So, it seems like a load on the AGC system. The AGC will sense the total subtraction of load and wind generation.

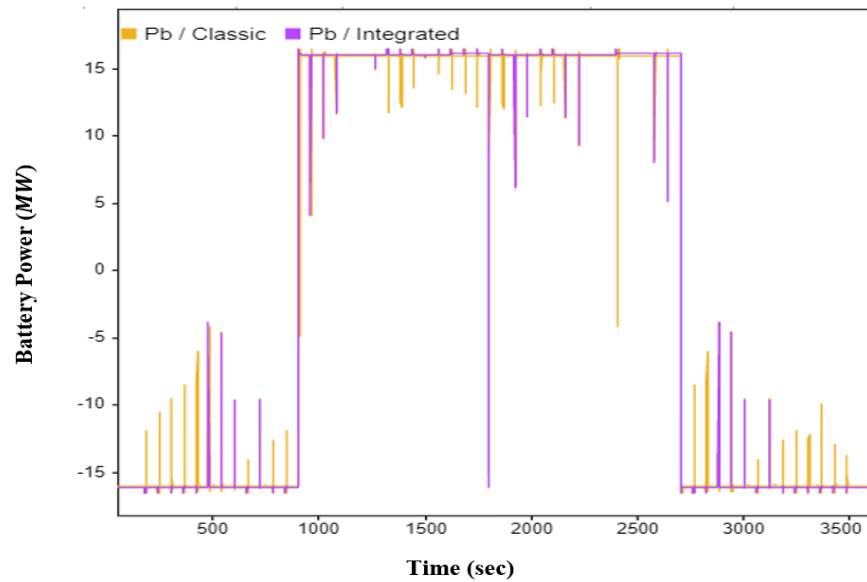


**Figure 3.24 Frequency response for classic and integrated AGC using wind.**



**Figure 3.25 Total mechanical power for classic and integrated AGC using wind.**

The total mechanical power is illustrated in figure 3.25. The battery in the integrated system will have a more negligible effect than the classic system during turbine wind generate source, as shown in figure 3.26. The battery in the integrated system has less impact than the classic system because it moves only in one direction, either positive or negative value in the deviation response when wind or load is changed.



**Figure 3.26 Battery for classic and integrated AGC using wind.**

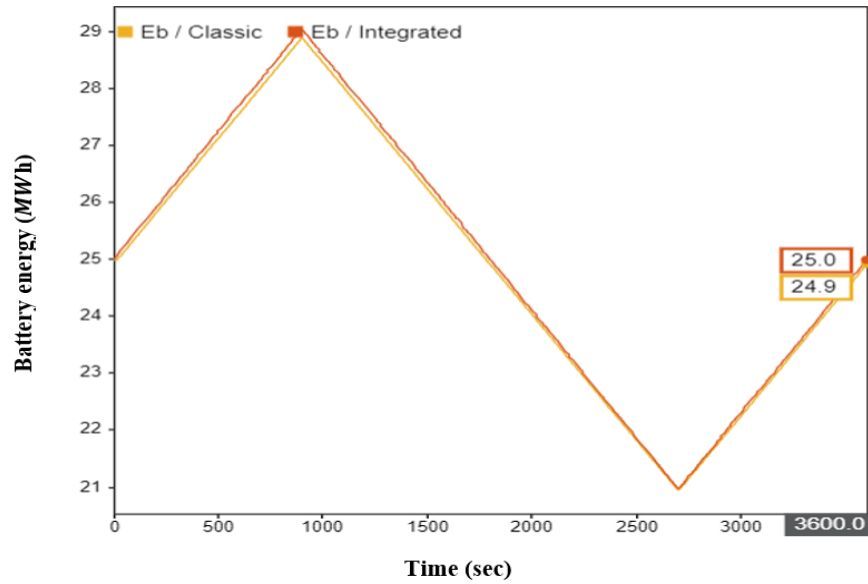


Figure 3.27 Energy for classic and integrated AGC using wind.

The energy end value is the same as in the start value when using integrated ED-AGC, while traditionally, it has little difference. Figure 3.27 shows the end value for classic and integrated ED-AGC. All these reasons affect the total cost. The total saving cost by using the integrated way is \$1.2. The total yearly estimating saving cost is \$10512.

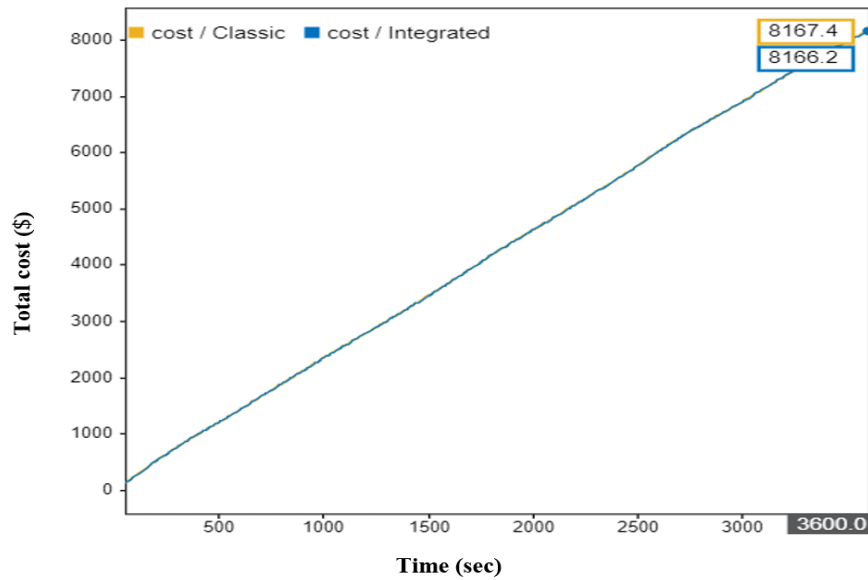


Figure 3.28 Cost for classic and integrated AGC using wind.

## **CHAPTER 4    MULTI-PERIOD OF ONE AREA INTEGRATED ED-AGC SYSTEM**

### **4.1    MULTI-PERIOD INTEGRATED SYSTEM FOR ECONOMIC DISPATCH**

The multi-period integrated ED is a control loop system that optimizes the economic dispatch problem with multi periods, and it has variables connected from past to future time. In this work, the optimization is conducted in four periods. Each period has 15 minutes, so the proposed work is implemented in GAMS and Matlab for classic and integrated ED.

In the previous chapter, the battery decided to supply the maximum and minimum value during the single period optimization. The optimizer is the one that decides which time interval is charging or discharging. Also, the system operator decides the best way to implement each cycle of ED optimization when he is looking at the demand load for the integrated ED. Another problem is the battery energy storage, in which energy value must be placed in the base energy at integrated ED for each optimization period.

In this chapter, the multi-period integrated ED system is solved for the previous chapter's problems, and it connects each period by using the battery. The following formulation equations describe the multi-period ED optimization:

**Objective function:**

$$\text{Min} \quad \sum_{t=1}^T \sum_{i=1}^N C_{ti}(P_i) + C_{bt}(E_{bt}) \quad (4.1)$$

**The cost for individual generator:**

$$C_{ti}(P_{ti}) = a_i + b_i * P_{ti} + c_i * P_{ti}^2 + d_i * P_{ti}^3 \quad (4.2)$$

**The cost for battery energy storage:**

$$C_{bt}(E_{bt}) = \frac{TCB}{CAP * lifecycle_t * DoD_t * Eff} \quad (4.3)$$

$$lifecycle_t = 694 * (DoD_t)^{-0.795} \quad (4.5)$$

$$DoD_t = 1 - \frac{E_{bt}}{E_b^{max}} \quad (4.6)$$

**Power balance equality constraints:**

$$\sum_{t=1}^T (P_{Lt} - \sum_{i=1}^N P_{ti} + P_{bt}) = 0 \quad (4.7)$$

**Generator limit constraints:**

$$P_{ti}^{min} \leq P_{ti} \leq P_{ti}^{max} \quad (4.8)$$

**Battery power limit constraints:**

$$P_{bt}^{min} \leq P_{bt} \leq P_{bt}^{max} \quad (4.9)$$

**Battery energy limit constraints:**

$$E_{bt}^{min} \leq E_{bt} \leq E_{bt}^{max} \quad (4.10)$$

Where  $t$  represents the time for each period in the optimization.  $t$  includes all variables for all generators and one battery. The Lagrange function is used to solve multi-period ED optimization. The following equations are representing the Lagrange function with time  $t$ :

$$L = \sum_{t=1}^T \sum_{i=1}^N C_{ti}(P_i) + \lambda_t \left( P_{Lt} - \sum_{i=1}^N P_{ti} \right) + \beta_{ti}(P_{ti} - P_{ti}^{limit}) + \mu_{t1}(P_{bt} - P_{bt}^{limit}) + \mu_{t2}(E_{bt} - E_{bt}^{limit}) \quad (4.11)$$

$$\frac{\partial L}{\partial P_{ti}} = \frac{\partial C_{ti}(P_i)}{\partial P_{ti}} - \lambda_t + \beta_{ti} = 0 \quad (4.12)$$

$$\frac{\partial L}{\partial P_{bt}} = \frac{\partial C_{bt}(E_{bt})}{\partial P_{bt}} - \lambda_t + \mu_{t1} - \mu_{t2} = 0 \quad (4.13)$$

$$\frac{\partial L}{\partial \lambda_t} = P_{Lt} - \sum_{i=1}^N P_{ti} = 0 \quad (4.14)$$

$$\beta_{ti} = \begin{cases} 0, & \text{if } P_{ti}^{min} \leq P_{ti} \leq P_{ti}^{max} \\ > 0, & \text{if } P_{ti}^{min} = P_{ti} \text{ or } P_{ti}^{max} = P_{ti} \end{cases} \quad (4.15)$$

$$\mu_{t1} = \begin{cases} 0, & \text{if } P_{bt}^{min} \leq P_{bt} \leq P_{bt}^{max} \\ > 0, & \text{if } P_{bt}^{min} = P_{bt} \text{ or } P_{bt}^{max} = P_{bt} \end{cases} \quad (4.16)$$

$$\mu_{t2} = \begin{cases} 0, & \text{if } E_{bt}^{min} \leq E_{bt} \leq E_{bt}^{max} \\ > 0, & \text{if } E_{bt}^{min} = E_{bt} \text{ or } E_{bt}^{max} = E_{bt} \end{cases} \quad (4.17)$$

Where  $L$  is the total cost of the objective function for all periods, and time  $t$  includes all variables for the Lagrange function and all associated multipliers. The connection between period  $t$  and the previous period  $t - 1$  The objective function is related to battery energy and power. Equation (4.18) illustrates the battery power and energy equivalent where  $\Delta\tau$  is the time interval on each period.  $E_{bt}$  at  $t = 0$  is the initial stored energy for the battery system. To ensure the

battery energy storage stored at the beginning of the time  $t = 0$  is equal to the final time  $t_f$ , equation (4.19) is using as a constraint of the objective function  $f$ . Equation (4.20) is using in the Lagrange function, and  $\lambda_5$  is the Lagrange multiplier associated with the energy equality between the initial value and final value energy stored. The updated Lagrange function of equation (4.11) is in equation (4.21). The partial derivatives of  $\lambda_5$  illustrate in equation (4.22).

$$E_{bt} = E_{b(t-1)} - \Delta\tau * P_{bt} \quad (4.18)$$

**Battery energy balance:**

$$E_{b0} = E_{b \text{ final}} \text{ or } E_{base} - E_{b \text{ final}} = 0 \quad (4.19)$$

$$\lambda_5(E_{base} - E_{b \text{ final}}) \quad (4.20)$$

$$L = \sum_{t=1}^T \sum_{i=1}^N C_{ti}(P_i) + \lambda_t \left( P_{Lt} - \sum_{i=1}^N P_{ti} \right) + \lambda_5(E_{base} - E_{b \text{ final}}) + \beta_{ti}(P_{ti} - P_{ti}^{limit}) + \mu_{t1}(P_{bt} - P_{bt}^{limit}) + \mu_{t2}(E_{bt} - E_{bt}^{limit}) \quad (4.21)$$

$$\frac{\partial L}{\partial \lambda_t} = E_{base} - E_{b \text{ final}} = P_{b1} + P_{b2} + P_{b3} + P_{b4} = 0 \quad (4.22)$$

The integrated feedback control loop of the Lagrange function for equations (4.11) to (4.22) is illustrated in figure 4.1. The base point power for AGC is connected directly to the power output of integrated ED at each time interval. As before in chapter 3, the participation factor for all generators and batteries is equal to zero.

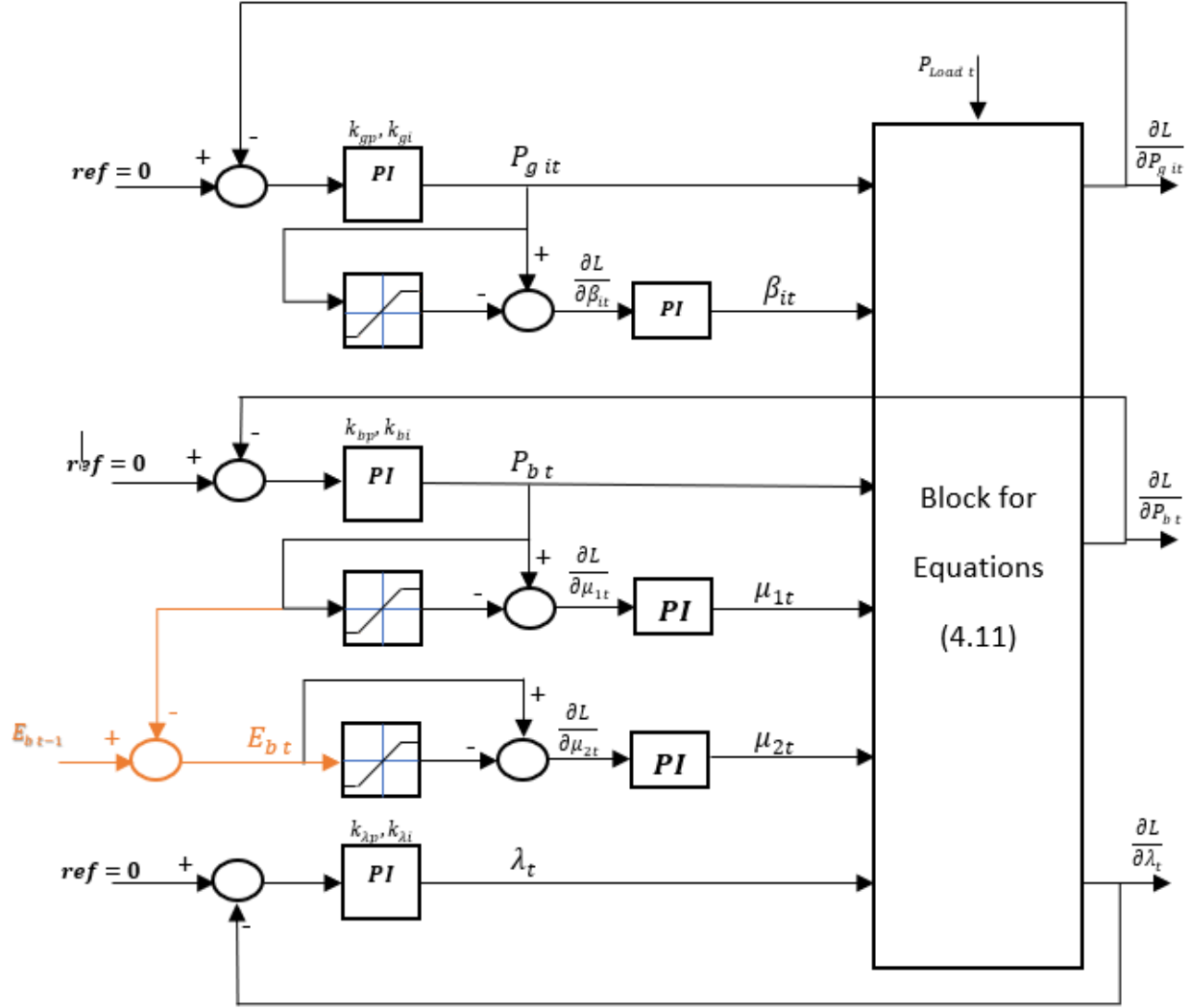


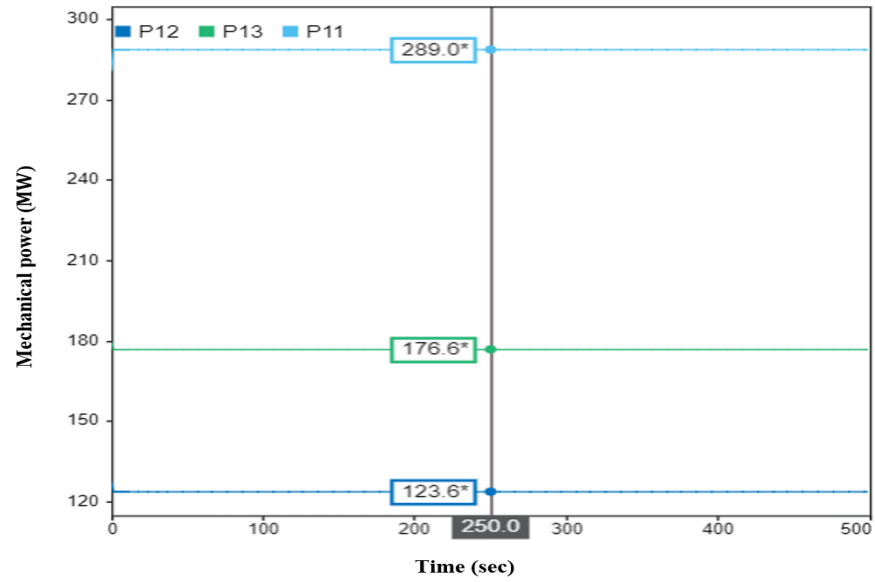
Figure 4.1 Multi-Period integrated ED.

## 4.2 INTEGRATED FOUR PERIOD OF ED-AGC SYSTEM

In this part, the work discusses the dynamic ED and the integrated ED conducted in four optimization periods. Each period uses 15 minutes in the simulation programs, which means optimization conduct as a one-hour ED at optimal cost. Table 4.1 illustrates the dynamic ED using the GAMS program to find the classic base point power for AGC. The demand loads are 580, 640, 600, and 570.

**Table 4.1 ED optimization from the classic optimizer.**

| Load               | $P_{g1}$ | $P_{g2}$ | $P_{g3}$ | $P_b$   | $E_b$  | Gen cost | Batt cost |
|--------------------|----------|----------|----------|---------|--------|----------|-----------|
| 580                | 288.741  | 123.534  | 176.482  | -8.757  | 27.189 | 2302.546 | 8.575     |
| 640                | 306.302  | 129.920  | 187.777  | 16.000  | 23.189 | 2553.699 | 8.265     |
| 600                | 289.980  | 123.983  | 177.280  | 8.757   | 21.000 | 2319.612 | 8.120     |
| 570                | 287.367  | 123.036  | 175.597  | -16.000 | 25.000 | 2283.734 | 8.397     |
| Total dynamic cost |          |          |          | 9492.9  |        |          |           |



**Figure 4.2 Mechanical power at period  $t = 1$  for integrated ED.**

Figures 4.2 to 4.11 show the results of an integrated ED system before being connected to AGC. Figures 4.2 to 4.5 illustrate the mechanical power for the integrated ED. The integrated mechanical power values have minor differences from the classic ED due to some differences in

the battery power, as in figure 4.6. Figure 4.7 shows the battery energy storage from the integrated testing and illustrates the final period  $E_{b4}$  equal to the base energy stored as it is 25 MW.

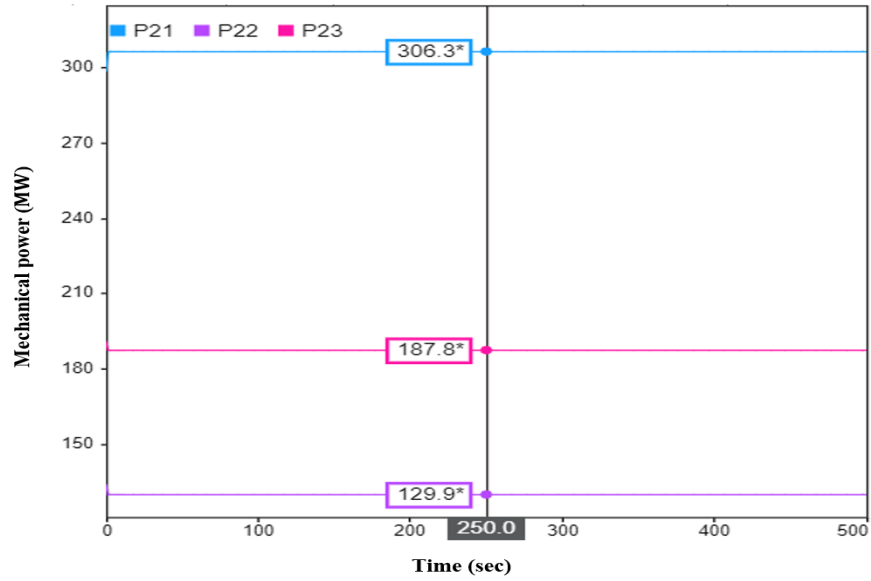


Figure 4.3 Mechanical power at period  $t = 2$  for integrated ED.

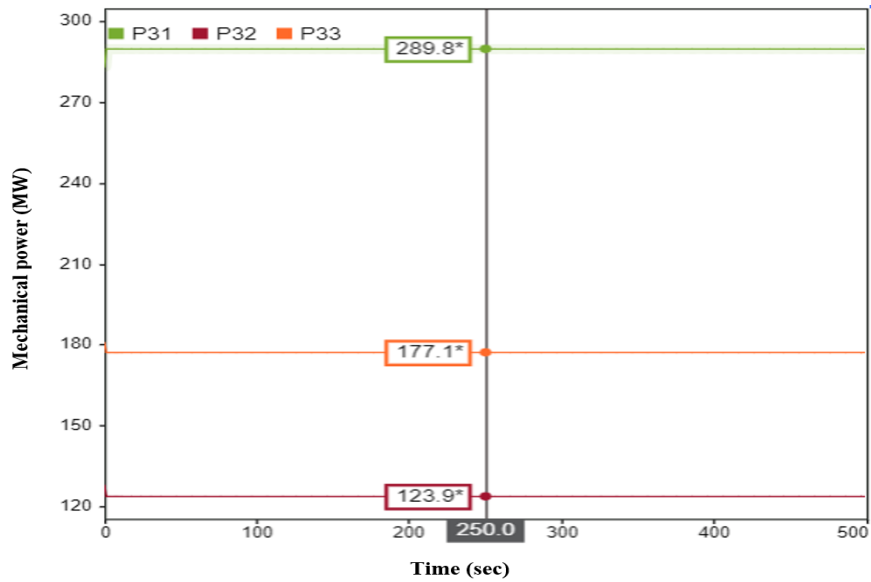


Figure 4.4 Mechanical power at period  $t = 3$  for integrated ED.

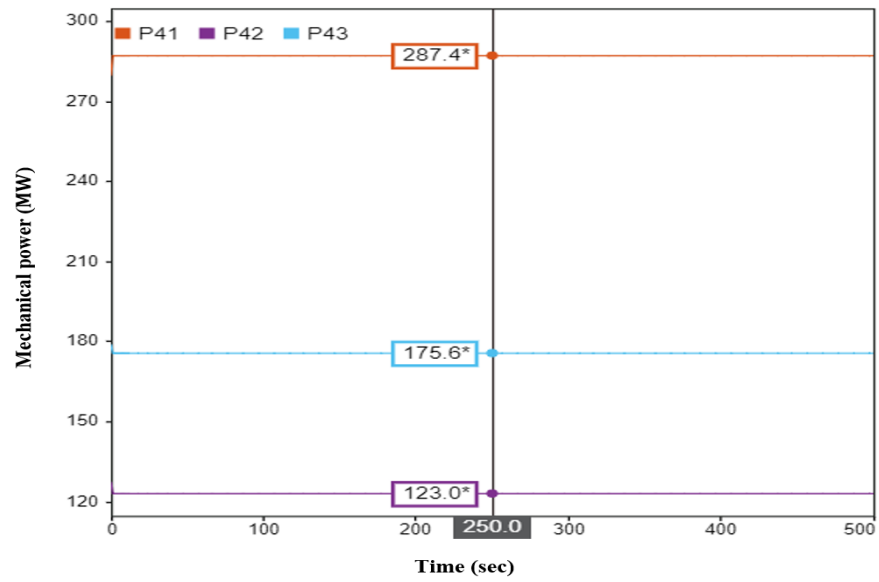


Figure 4.5 Mechanical power at period  $t = 4$  for integrated ED.

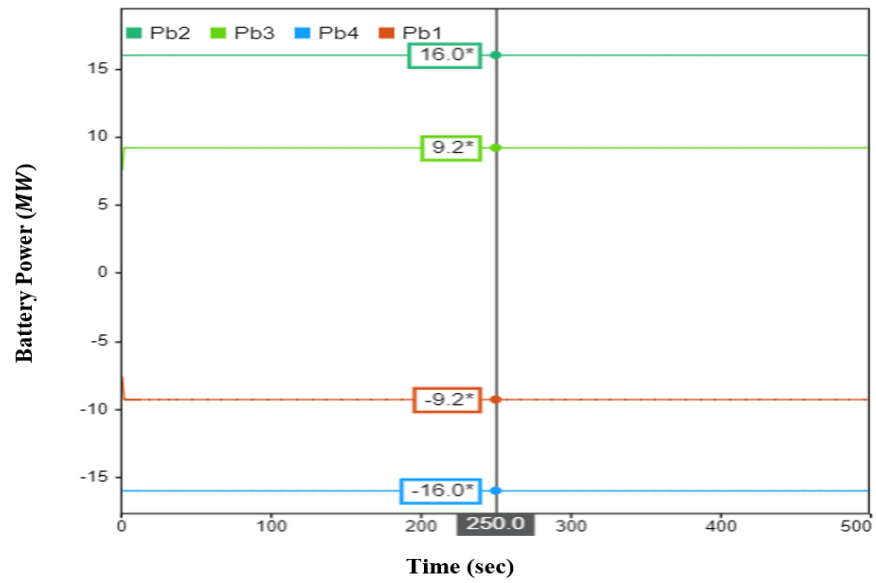


Figure 4.6 Battery power at all periods for integrated ED.

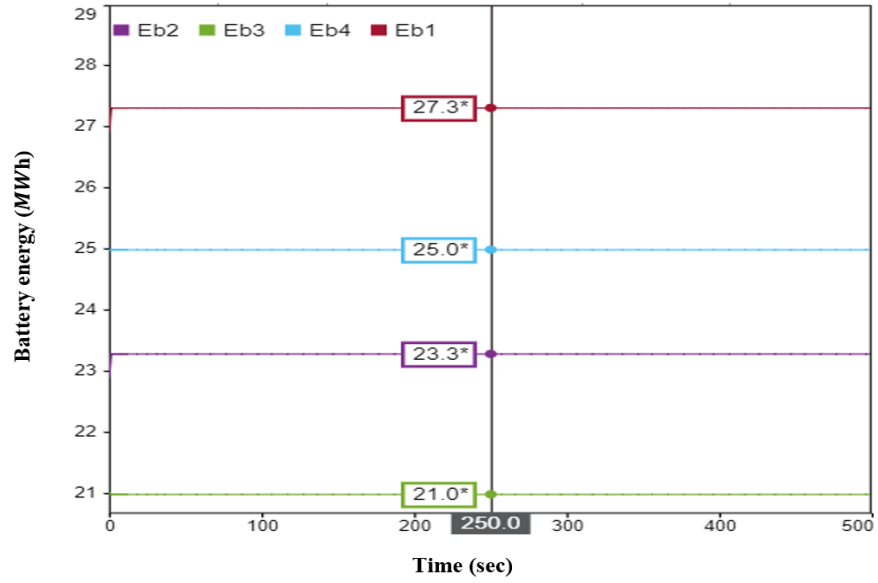


Figure 4.7 Battery Energy at all Periods for integrated ED.

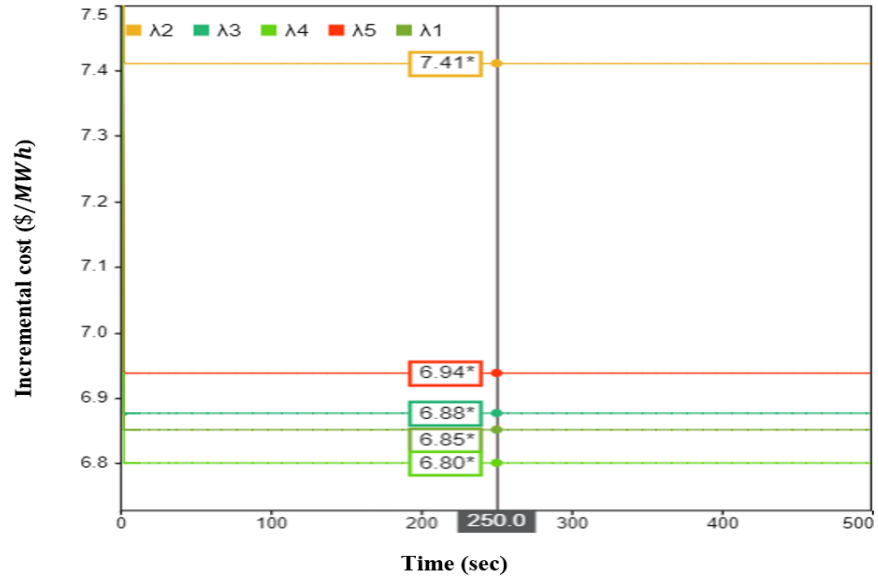


Figure 4.8 Incremental cost and energy multiplier for integrated ED.

The values of the incremental cost  $\lambda_1$  to  $\lambda_4$  are shown in figure 4.8.  $\lambda_5$  value is the multiplier associated with the energy balance, as illustrated before in equation (4.22). From figure 4.9 and table 4.1, the total cost of the integrated ED is equal to the total cost in dynamic ED. The cost of

generators and battery at each interval are illustrated in figures 4.10 and 4.11. These values are almost very similar to the cost values in table 4.1. So, from these results, they confirm that the integrated ED works great before connecting to AGC.

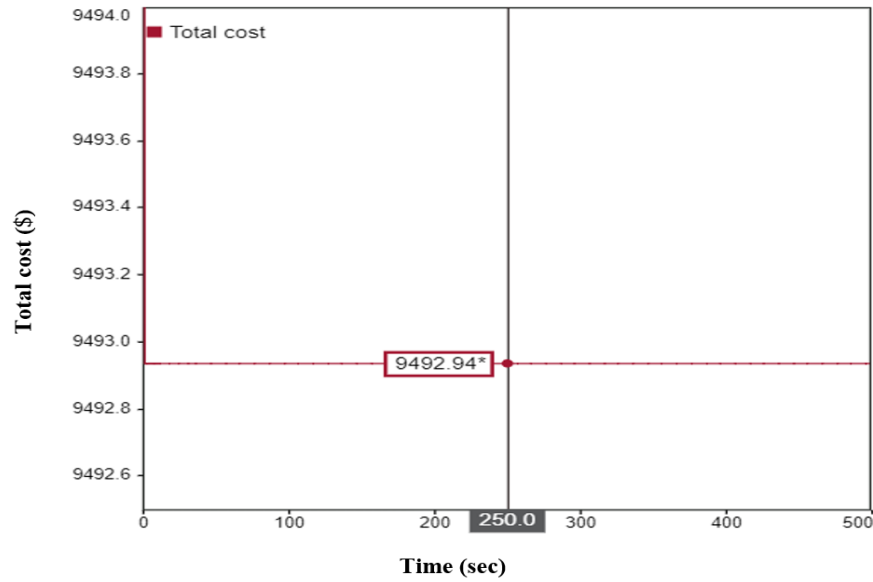


Figure 4.9 Total cost for integrated ED.

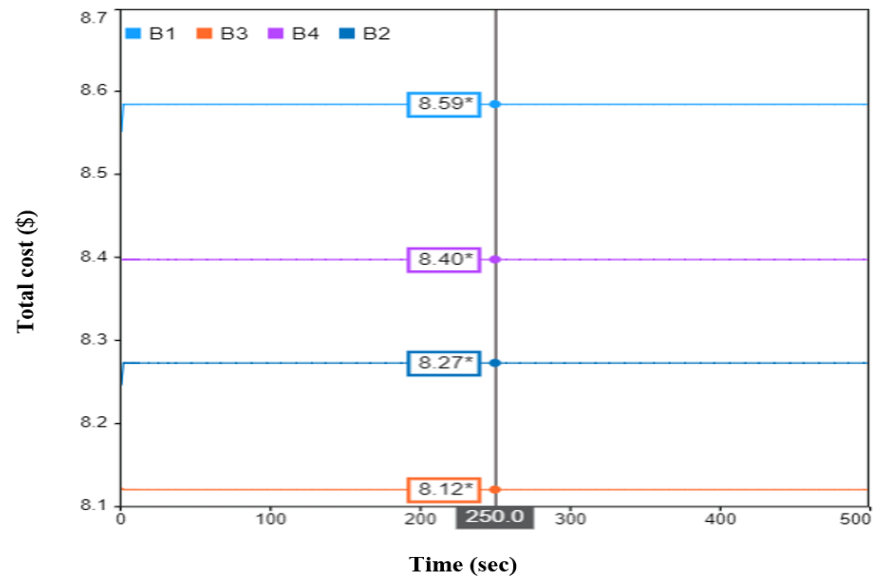


Figure 4.10 Battery cost for integrated ED.

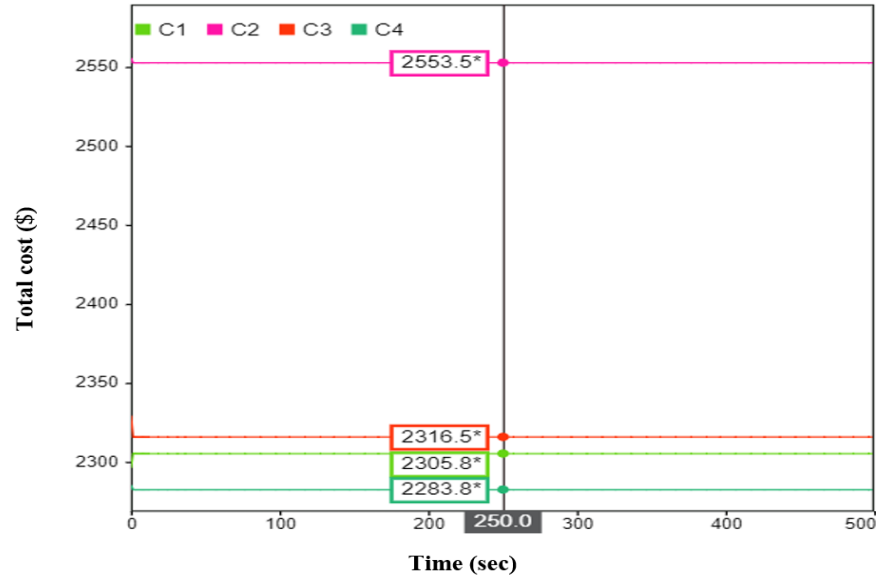


Figure 4.11 generator cost for integrated ED.

Table 4.2 shows the Lagrange multiplier values from integrated ED associated with generators, battery power, and energy. The multiplier associated with the generator power limit is equal to zero, which means that the generator power values are within their boundaries. Also, the battery energy limit is in between their limit capacity value for storing energy which drives  $\mu_{t2}$  equal to zero at each period. However, the battery power reaches the limit at periods 2 and 4. So,  $\mu_{21}$  and  $\mu_{24}$  are not zero while  $\mu_{11}$  and  $\mu_{31}$  are zero because batteries at periods 1 and 3 are in between the battery power limit.

Table 4.2 Lagrange multiplier values for integrated ED.

| parameters | $\beta_{it}$ | $\mu_{11}$ | $\mu_{21}$ | $\mu_{31}$ | $\mu_{41}$ | $\mu_{t2}$ |
|------------|--------------|------------|------------|------------|------------|------------|
| values     | 0            | 0          | 0.54       | 0          | -0.06      | 0          |

## 4.3 COMPARISON BETWEEN CLASSIC AND INTEGRATED SYSTEM RESULTS FOR ONE AREA

### 4.3.1 ED-AGC System Include Battery Energy Storage.

The base point power for all generators and batteries in the AGC system for the traditional way is determined from multi-period dynamic ED optimization using the GAMs program. The base point powers are available in table 4.1. The base points power for the integrated ED-AGC system is determined from integrated ED simulation blocks. The integrated ED gives the output power values for all periods together at all-time in the simulation as from the previous part description. Thus, at any period of AGC, power generation and the battery in integrated ED at the same period will supply directly to base point power in AGC. In contrast, the other power of other periods in integrated ED does disconnect with AGC. The implementation of the simulation ED-AGC system in the Matlab program for classic and integrated ED-AGC is illustrates in figures 4.12 to 4.16.

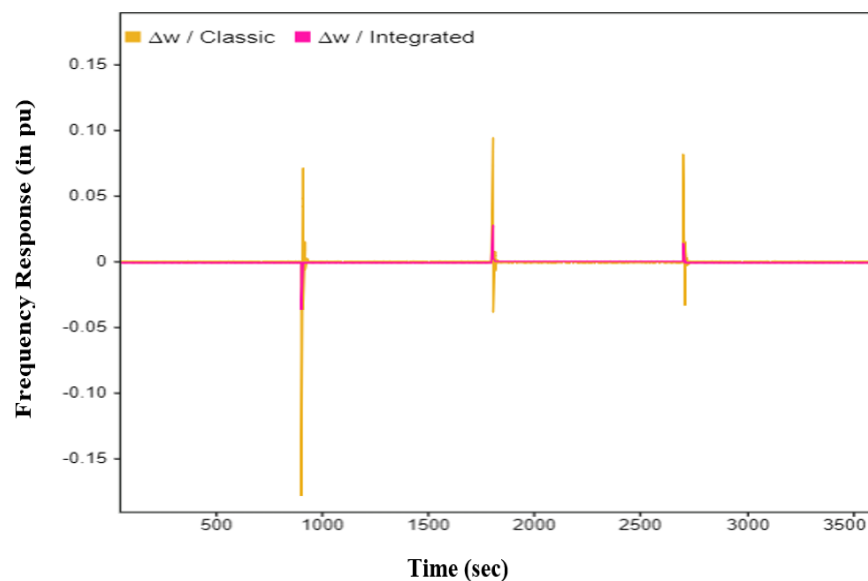
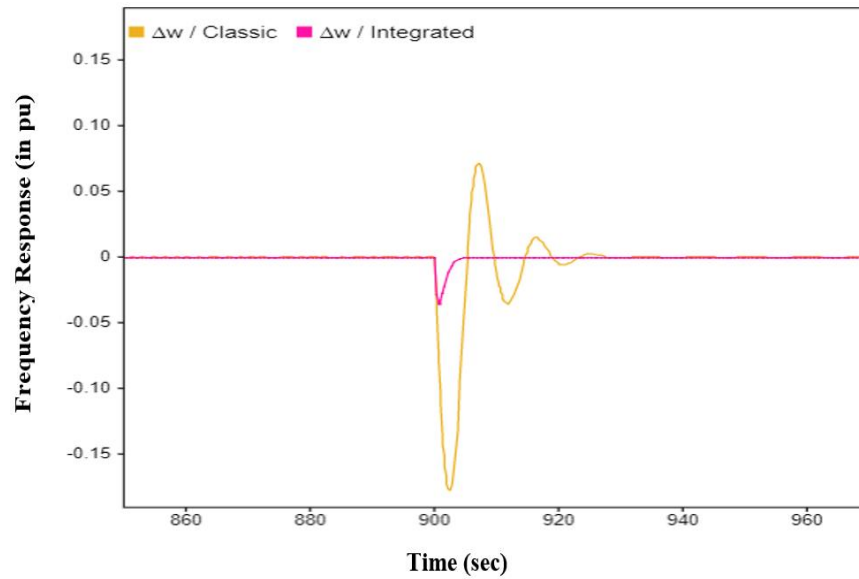


Figure 4.12 Frequency response of four periods for one area classic and integrated ED-AGC.

In figures 4.12 and 4.13 show the frequency response of the classic and integrated system. When the load changes to other values, the integrated system frequency is better than the traditional system because the frequency of integrated ED-AGC reaches a steady-state earlier time, which is about a quarter-time of the classic response. Figure 4.14 shows the total mechanical power of the different types of ED-AGC.



**Figure 4.13 Frequency response of period 1 for one area classic and integrated ED-AGC.**

The results of battery power values in the integrated system are in table 4.3. The battery energy values during all times for the simulation as in figure 4.15. There is some difference between classic and integrated battery energy due to some battery power differences as in table 4.1 and 4.3. The final energy value for both systems is equal to 25 MWh, equal to the initial energy value. The equality of initial and end energy value will keep energy saving as a constant value for the next generator hour.

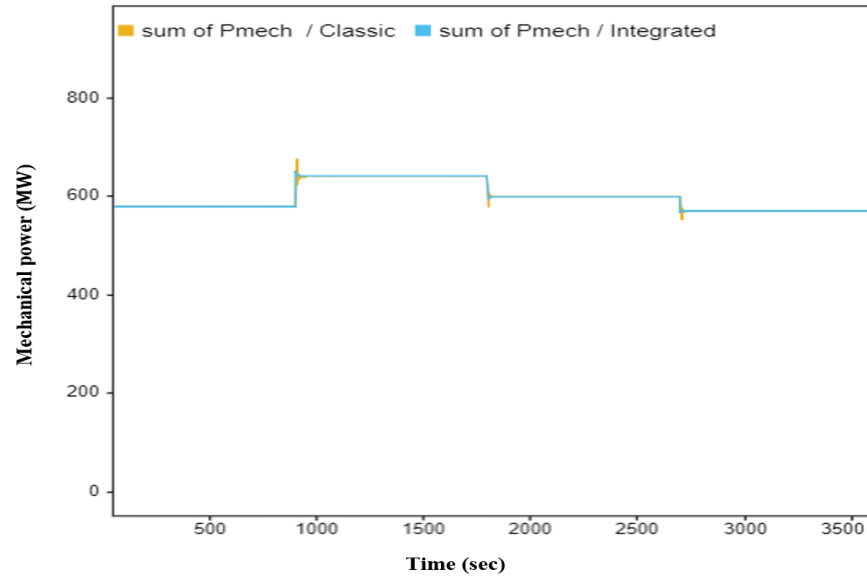


Figure 4.14 Sum of all mechanical power for one area classic and integrated ED-AGC.

Table 4.3 Integrated results for ED-AGC system.

| Load | $P_{g1}$ | $P_{g2}$ | $P_{g3}$ | $P_b$   |
|------|----------|----------|----------|---------|
| 580  | 288.994  | 123.628  | 176.643  | -9.213  |
| 640  | 306.298  | 129.920  | 187.773  | 16.000  |
| 600  | 289.752  | 123.900  | 177.133  | 9.213   |
| 570  | 287.383  | 123.044  | 175.605  | -16.000 |

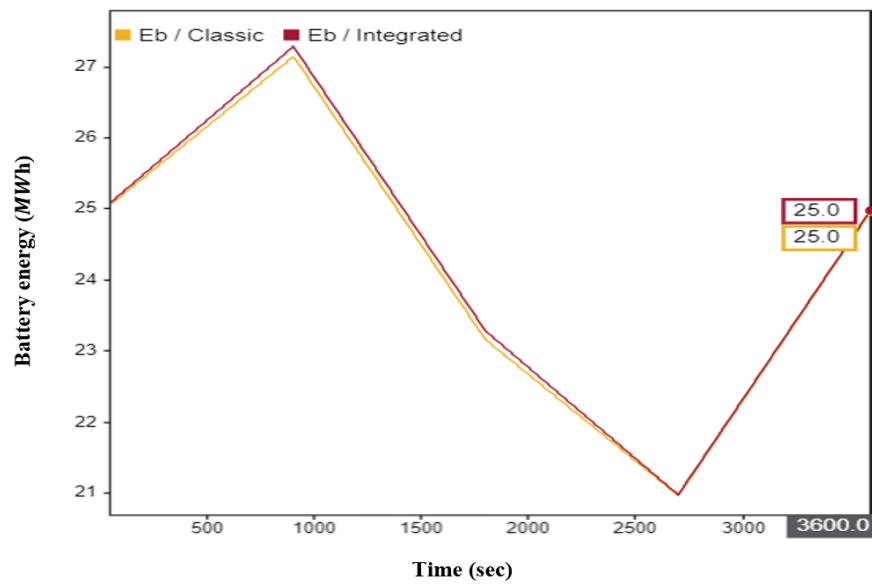


Figure 4.15 Energy for one area classic and integrated ED-AGC.

The total cost of classic and integrated ED-AGC is available in figure 4.16. The total saving cost is \$5.2 when using an integrated system in the ED-AGC. Therefore, the total estimated saving cost per yearly running generation of the ED-AGC system is around \$45552.

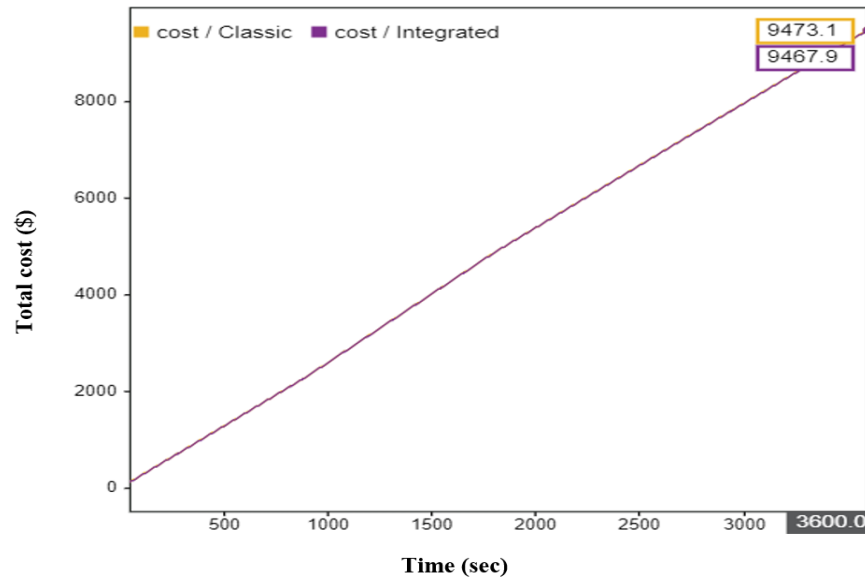


Figure 4.16 Total cost for one area classic and integrated ED-AGC.

#### 4.3.2 ED-AGC System Include Battery Energy Storage and Wind Generation.

Wind generation and battery energy storage are utilized to have better test simulation results for classic and integrated ED-AGC. In the previous chapter, the integrated ED feedback control loop for one period does not connect the wind generation in design blocks for the integrated ED. In this section, the source of wind generation and load consumed are related together. Both of them are connected to supply integrated ED as an input source to give the correct output generators and battery power for the base point power needed in the AGC system. So, the wind power generated will decrease the load consumed and send the subtraction value to integrated ED as source input. These new blue color connections in figure 4.17 were inserted to prevent keeping the battery charging most of the time. The implementation of the new connections decides after take different design connection blocks and test simulations.

On the other hand, suppose the wind does not connect in ED. The integrated ED system keeps the battery charging most of the time during the whole period, which will violate the energy starting and ending equality. Figure 4.17 shows how wind generation connects in the integrated ED.

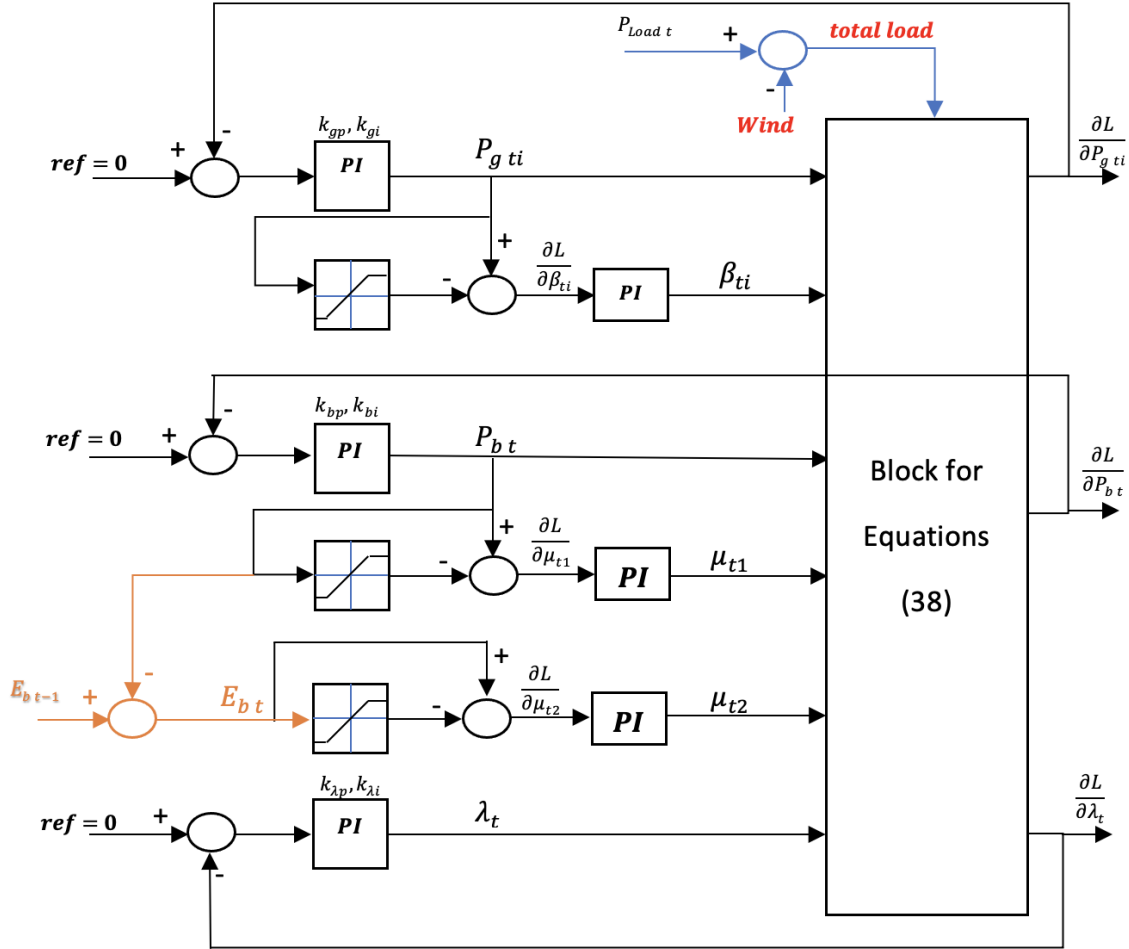


Figure 4.17. Multi-Period integrated ED-AGC system using wind generation.

Figure 4.18 represents the different frequency responses of testing classic and integrated ED-AGC systems considering battery energy storage and wind generation. The classic response has a high value of deviation in frequency when the load and wind are fluctuating compared to the

integrated response. At the same time, the integrated ED-AGC has a low magnitude in deviation frequency when high wind penetration generates. Therefore, wind generation affects the total mechanical power of thermal generators for the AGC, which will cause more saving costs than without using renewable resources. Figure 4.19 shows the total mechanical power for classic and integrated ED-AGC.

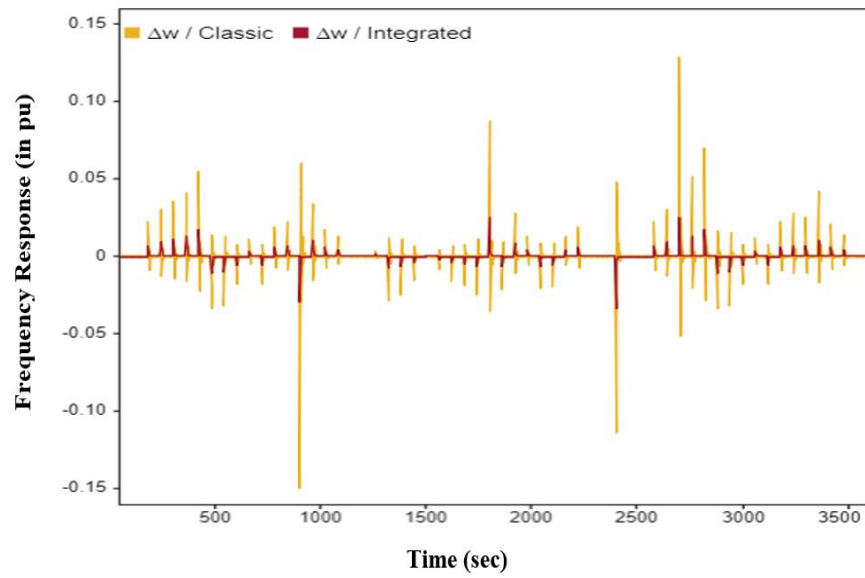


Figure 4.18 Frequency response for one area classic and integrated ED-AGC with the wind.

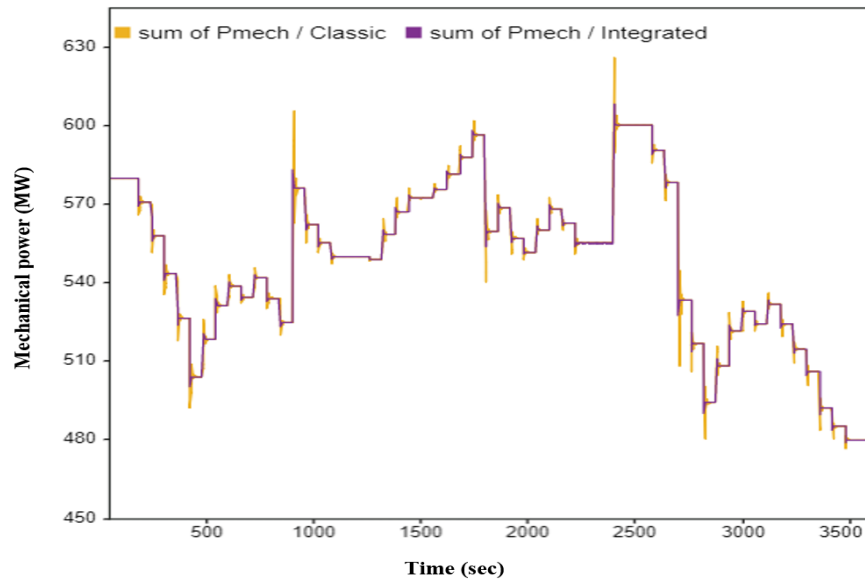
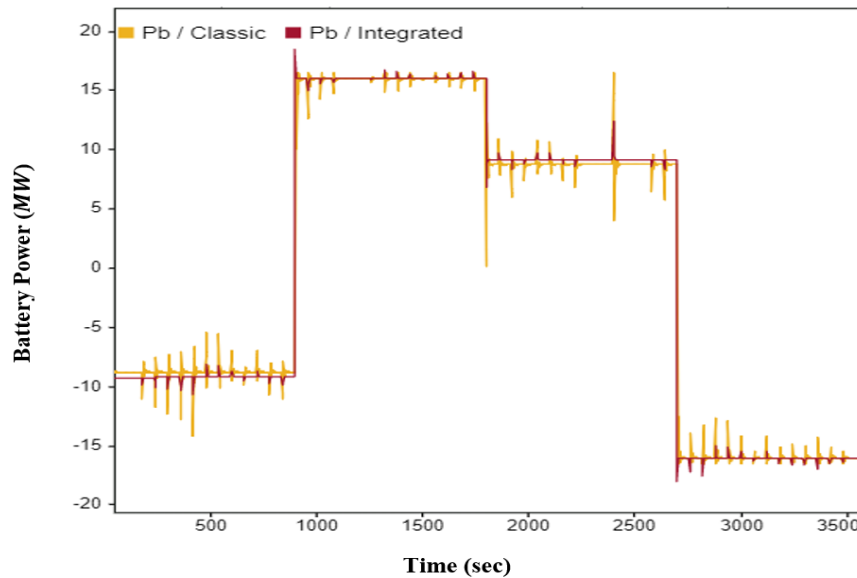


Figure 4.19 Mechanical power for one area classic and integrated ED-AGC with the wind.

From figure 4.20, the battery power will not change when the AGC in the steady-state generation. Steady-state means the load and renewable generation have stable power value (no change in power). However, when load or wind power varies, it affects the frequency to change from the nominal power. The variation of the wind power is not affecting the battery power during steady-state value, and only small values can be considered a deviation from its nominal value when the frequency is changing due to wind generation. The initial energy equals the final energy when using wind in ED-AGC for both classic and integrated. The energy of the battery is shown in figure 4.21. The total saving cost in this simulation is \$9.2 when subtracting the integrated and classic total cost of simulation as in figure 4.22. So, the yearly estimated saving cost of running integrated ED-AGC is around \$80592, equal to  $365 \text{ days} * 24 \text{ hours} * \$9.2$ .



**Figure 4.20 Battery power for one area classic and integrated ED-AGC with the wind.**

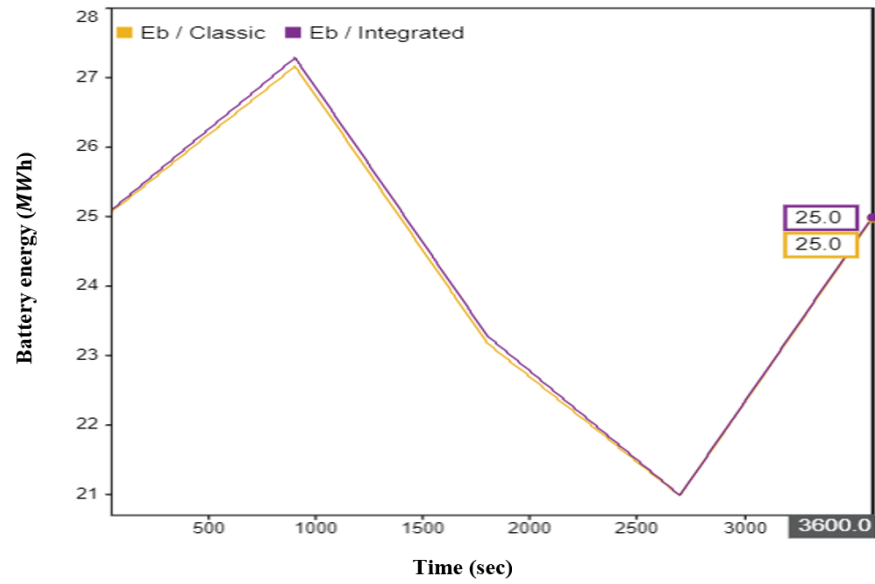


Figure 4.21 Battery energy for one area classic and integrated ED-AGC with the wind.

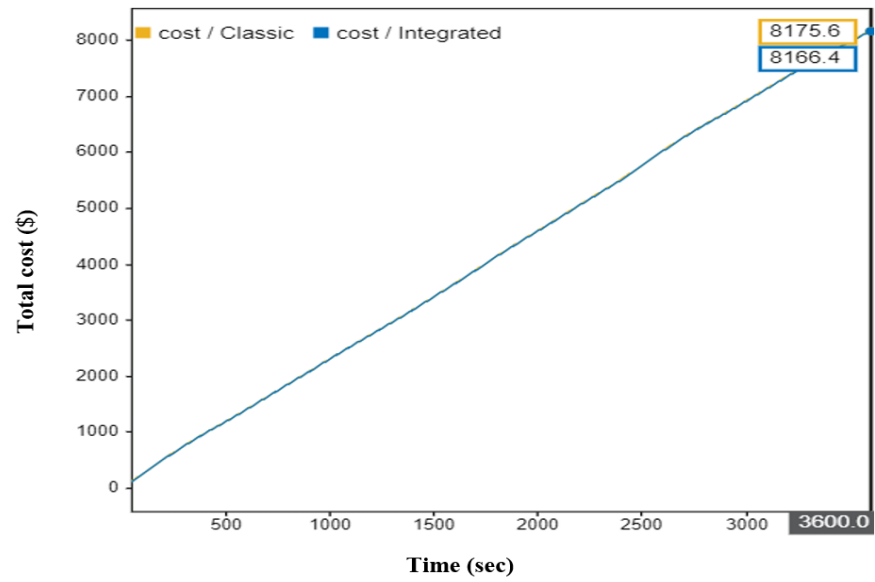


Figure 4.22 Total cost for one area classic and integrated ED-AGC with the wind.

## CHAPTER 5 MULTI-PERIOD OF TWO AREA INTEGRATED ED-AGC SYSTEM

In this chapter, the two classic and integrated ED-AGC areas are present in the first part using battery energy storage. In the second part, both wind generation and battery are considered in the simulation testing.

### 5.1 TWO AREA ED-AGC WITH BATTERY ENERGY STORAGE

The two-area system of ED-AGC is required to have a power transfer between them. Figure 5.1 shows the connection of two-area ED-AGC with consideration of the transferring power from area 1 to area 2. The  $\Delta P_{tie}$  is a tie line power effect by the frequency response difference as illustrated in equation (5.1), where  $T$  is the tie line stiffness, and  $X_{tie}$  is the tie line impedance.  $\Delta P_{tie}$  is changing the transferring power schedule when the load is changing to another value in any area. If  $\Delta P_{tie}$  is positive, it means the power is transferring from area 1 to area 2, and if  $\Delta P_{tie}$  is negative, the power will transfer from area 2 to area 1.  $ACE$  is the area control error representing the generating power required for ED-AGC to restore the frequency response and tie-line power into steady-state value.  $ACE$  for both areas represents in equations (5.2) and (5.3), where  $\beta_1$  and  $\beta_2$  are the frequency bias factors.

$$\Delta P_{tie} = \frac{2\pi T}{s} (\Delta\omega_1 - \Delta\omega_2) \quad (5.1)$$

$$ACE_1 = -\Delta P_{tie} - \beta_1 \Delta\omega \quad (5.2)$$

$$ACE_2 = \Delta P_{tie} - \beta_2 \Delta\omega \quad (5.3)$$

$$T = \frac{377}{X_{tie}} \quad (5.4)$$

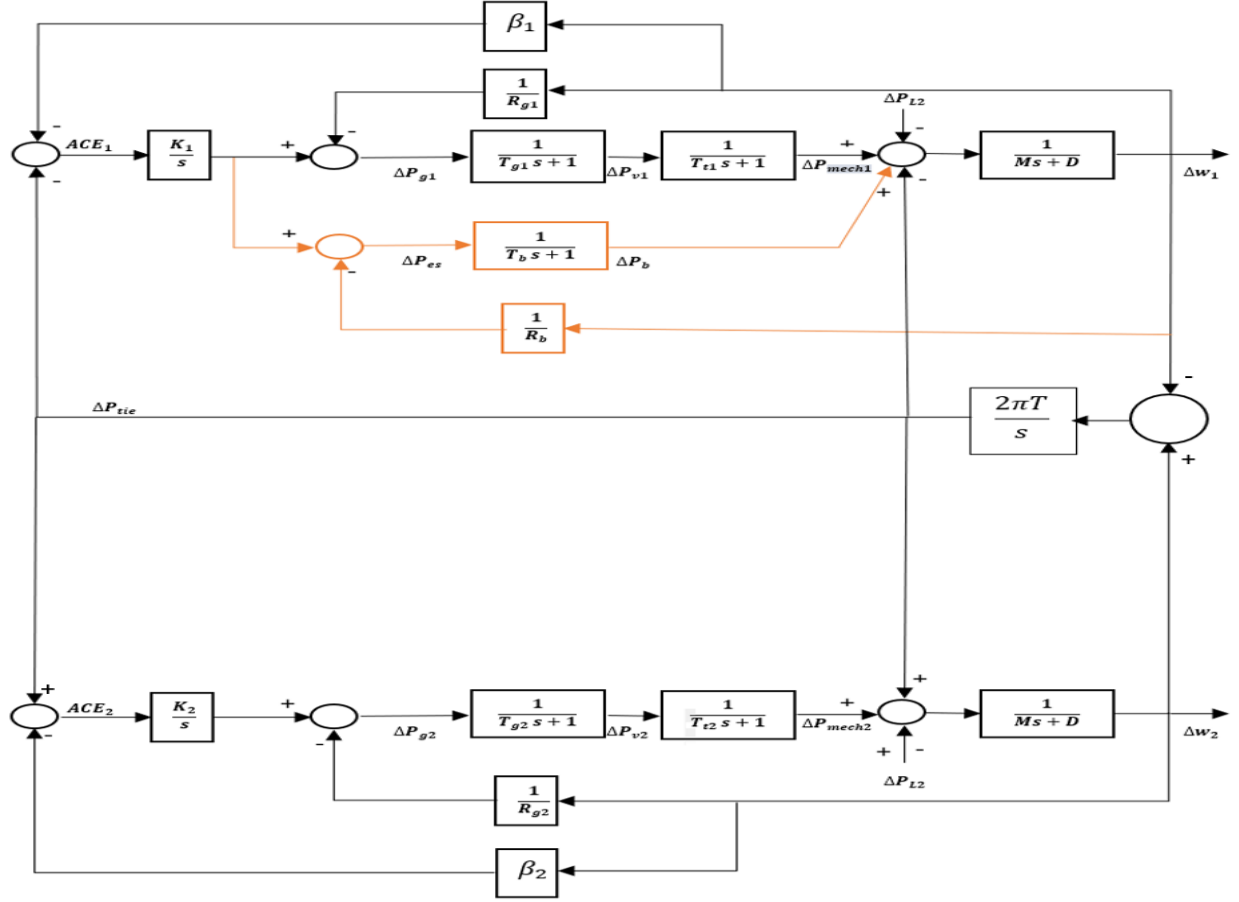


Figure 5.1 Two areas AGC model.

This chapter simulation test consists of battery energy storage in area 1 while keeping area 2 without using the battery. Also, the load change only happens in area 1, and area 2 load is constant. The simulation is implemented to check both areas' influence when the load is changing to another magnitude on area 1 only. Table 5.1 illustrates the classical ED-AGC control parameters, and table 5.2 shows the parameter's value for both areas in an integrated system. The parameters of integrated ED are tested before connecting to AGC to ensure the tuned parameter values fit with the results needed. The integrated ED test results are compared with dynamic ED to make sure the output values are equal.

**Table 5.1 Classical ED-AGC control Parameters.**

| Items | area | $R$  | $pf$ |
|-------|------|------|------|
| Gen 1 | 1    | 0.01 | 0.43 |
| Gen 2 |      | 0.02 | 0.26 |
| Gen 3 |      | 0.02 | 0.31 |
| Batt  |      | 0.01 | 0    |
| Gen 1 | 2    | 0.01 | 0.43 |
| Gen 2 |      | 0.02 | 0.26 |
| Gen 3 |      | 0.02 | 0.31 |

**Table 5.2 Integrated ED-AGC control Parameters.**

|                                       | Area | Parameter       | value |
|---------------------------------------|------|-----------------|-------|
| $PI$ controller that drives $P_i$     | 1    | $k_{gp}$        | 262.5 |
|                                       |      | $k_{gi}$        | 1500  |
| $PI$ controller that drives $P_b$     |      | $k_{bp}$        | 262.5 |
|                                       |      | $k_{bpi}$       | 1500  |
| $PI$ controller that drives $\lambda$ |      | $k_{\lambda p}$ | 262.5 |
|                                       |      | $k_{\lambda i}$ | 1500  |
| $PI$ controller that drives $\beta_i$ |      | $k_{\beta p}$   | 18    |
|                                       |      | $k_{\beta i}$   | 0     |
| $PI$ controller that drives $P_i$     | 2    | $k_{gp}$        | 262.5 |
|                                       |      | $k_{gi}$        | 1500  |
| $PI$ controller that drives $P_b$     |      | $k_{bp}$        | 262.5 |
|                                       |      | $k_{bpi}$       | 1500  |
| $PI$ controller that drives $\lambda$ |      | $k_{\lambda p}$ | 262.5 |
|                                       |      | $k_{\lambda i}$ | 1500  |
| $PI$ controller that drives $\beta_i$ |      | $k_{\beta p}$   | 18    |
|                                       |      | $k_{\beta i}$   | 0     |

The frequency response for the two classic and integrated ED-AGC areas are available in figures 5.2 to 5.4. These figures show the deviation response for ED-AGC when the load is changing to another value. The frequency in area 1 is higher than in area 2 due to load change in area 1. The difference between classic and integrated ED-AGC illustrates that integrated area systems get better data to lower the frequency response error. Frequency response in area 2 has

little effect when the load changes at the other area and affects by less than 0.01, keeping generators as scheduled for area 2. Therefore, area 1 has less frequency deviation when using integrated ED-AGC than the classic system.

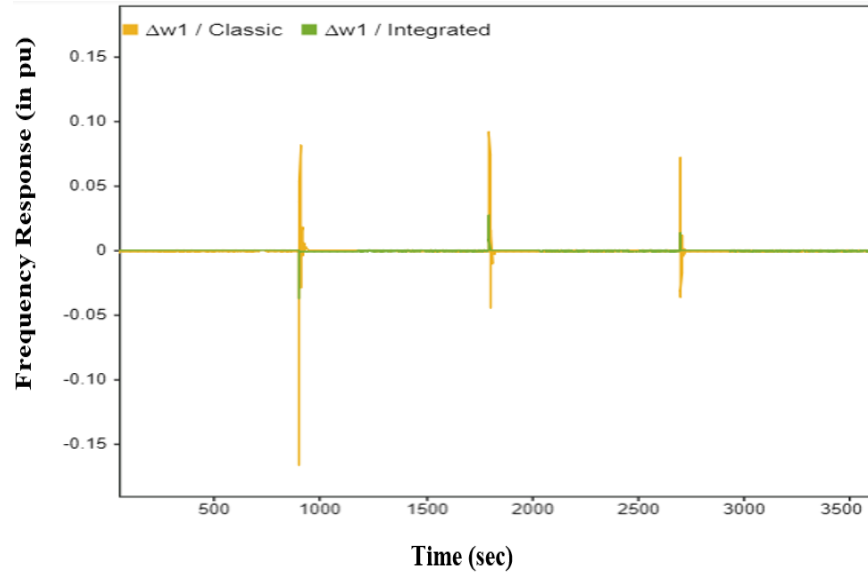


Figure 5.2 Frequency response of 4 periods for two area classic and integrated ED-AGC.

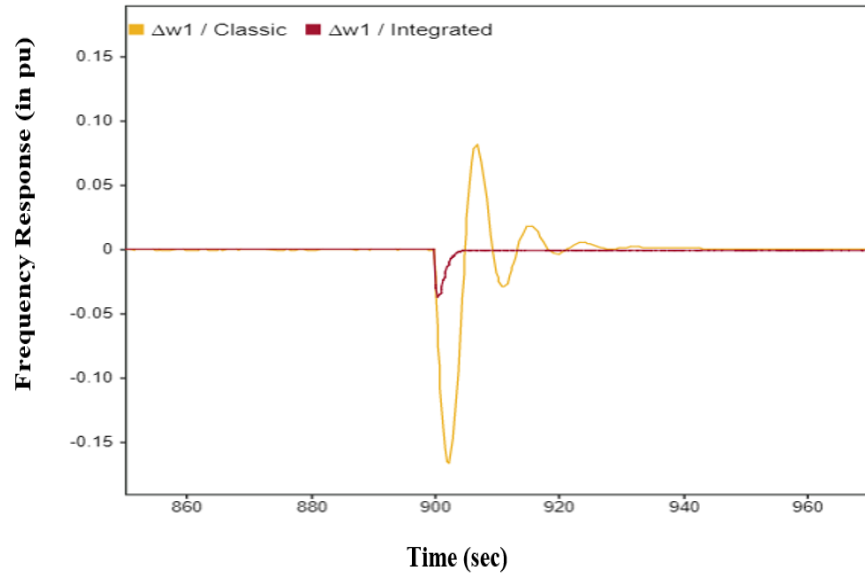
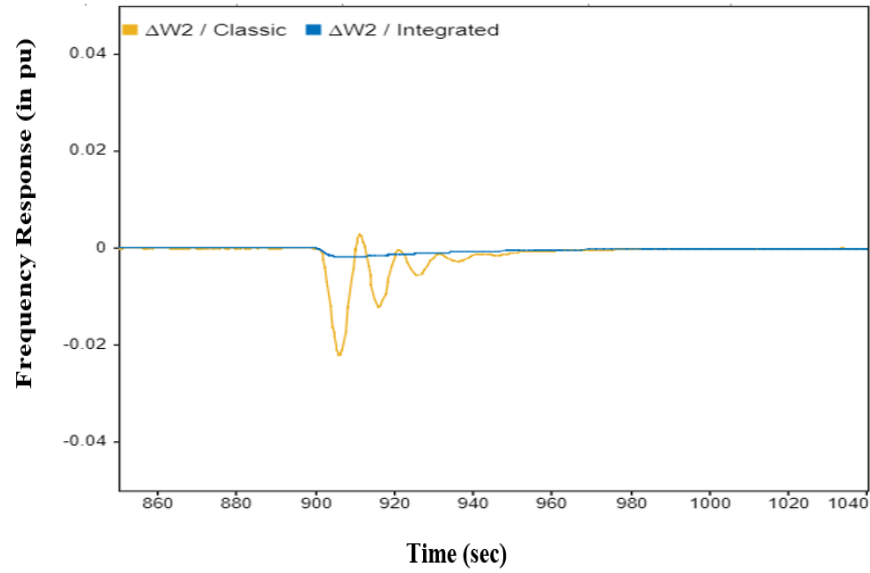
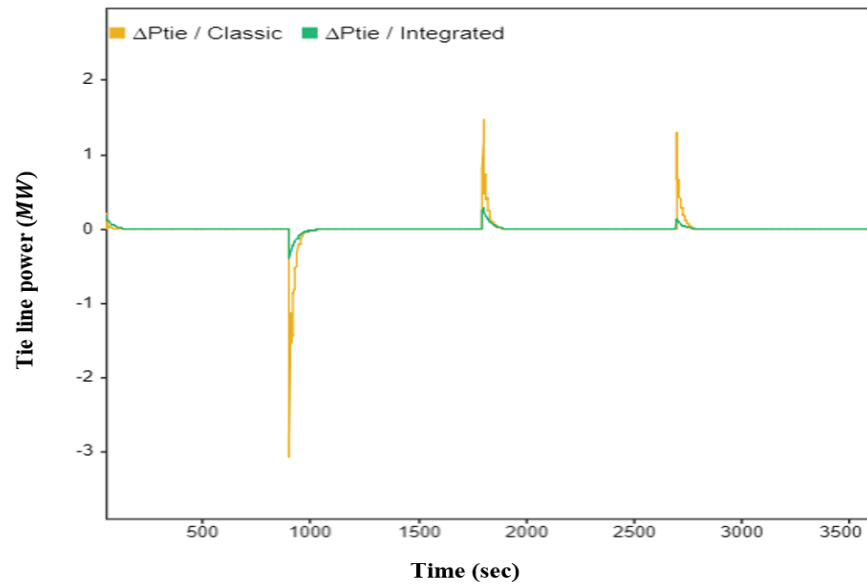


Figure 5.3 Frequency response of period 1 for two area classic and integrated ED-AGC.



**Figure 5.4 Frequency response of area 2 for classic and integrated ED-AGC.**

Because of changes in frequency in both areas, the transfer power schedule is changing to another value when frequency changes. Figure 5.5 shows the difference in transferring power values between classic and integrated ED-AGC between both areas. The integrated system let transferring power value less than the classic system.



**Figure 5.5 Power transfer for two area classic and integrated ED-AGC.**

Figures 5.6 and 5.7 represent the total mechanical power for areas 1 and 2. The integrated ED-AGC in area 1 has little effect when total mechanical power moves to another value than the traditional way and reaches an earlier time to the new steady-state value after the load is changing. In area 2, the total mechanical power of the thermal generator in the integrated system has significantly less value in deviation power compare to the traditional way. This because the value of transferring power is less than one  $MW$  at the integrated system.

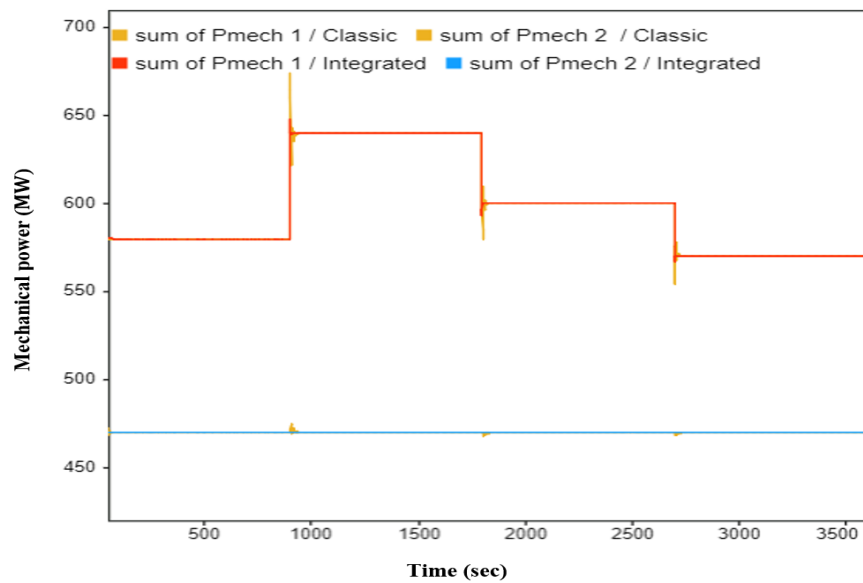


Figure 5.6 a) Total mechanical power for two area classic and integrated ED-AGC.

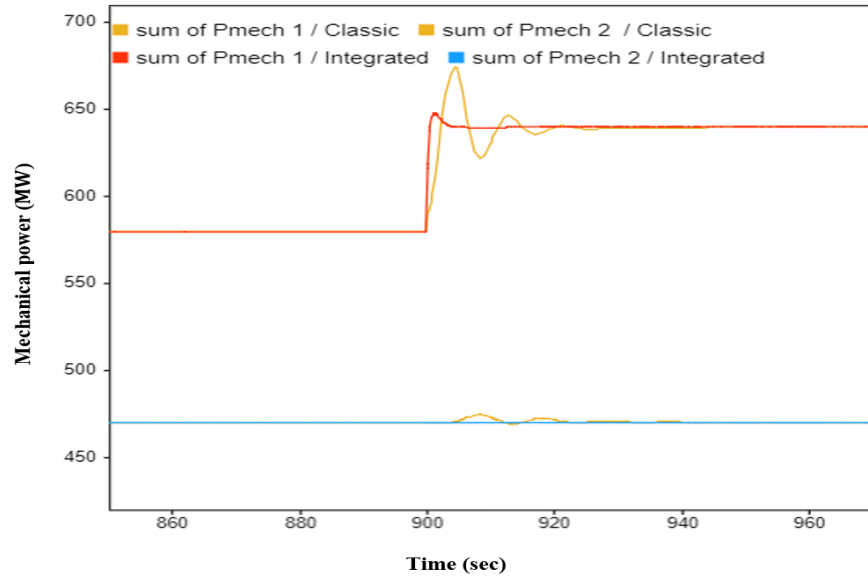


Figure 5.7 b) Total mechanical power for two areas classic and integrated ED-AGC.

The battery power values are presented in figure 5.8, and these values are almost the same as in table 4.3. Figure 5.9 shows the battery energy that is available in area 1. The initial value is equal to the final value, which is needed in the ED-AGC system.

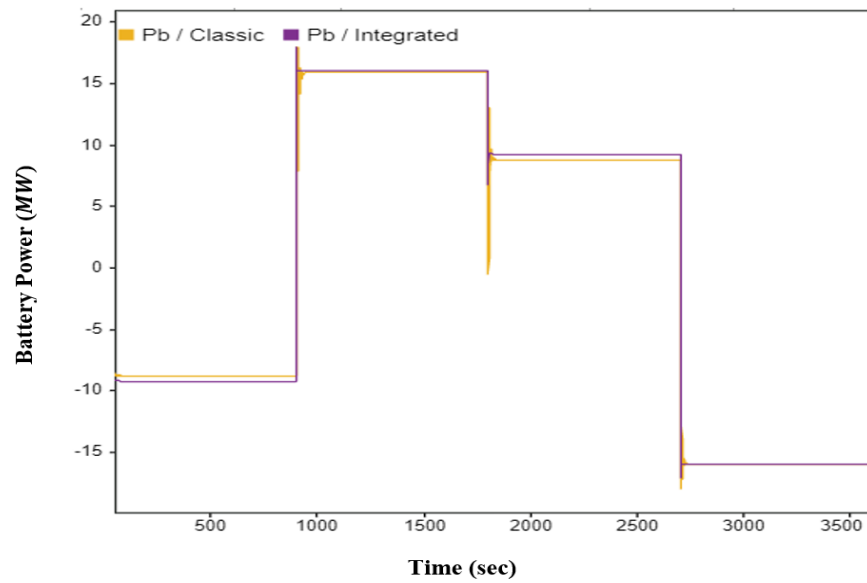


Figure 5.8 Battery power for two area classic and integrated ED-AGC.

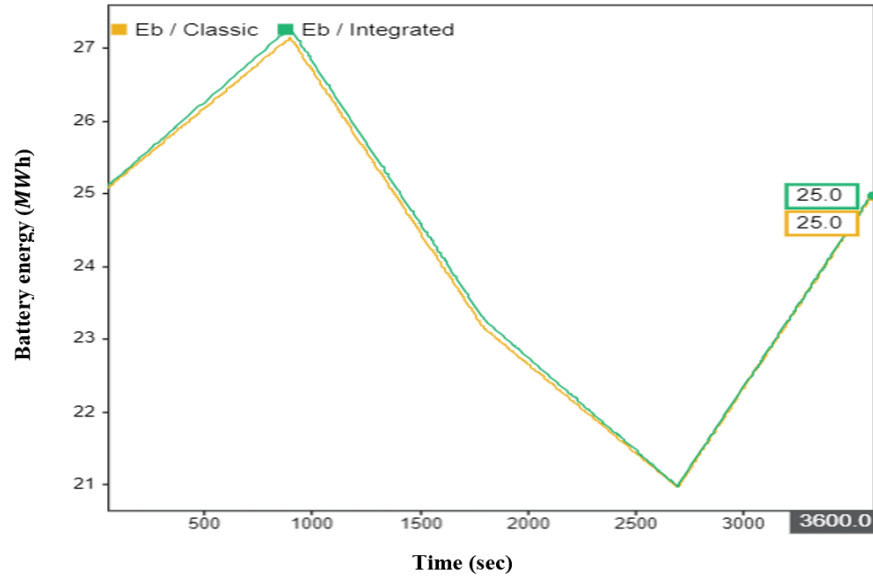


Figure 5.9 Battery energy for two area classic and integrated ED-AGC.

The total cost for both systems in both areas is available in figure 5.10. The saving cost in area 1 is \$4.8, and area 2 is \$3.8. The total saving cost in both areas is \$8.6. So, the estimated saving yearly running generation of integrated ED-AGC is \$75336.

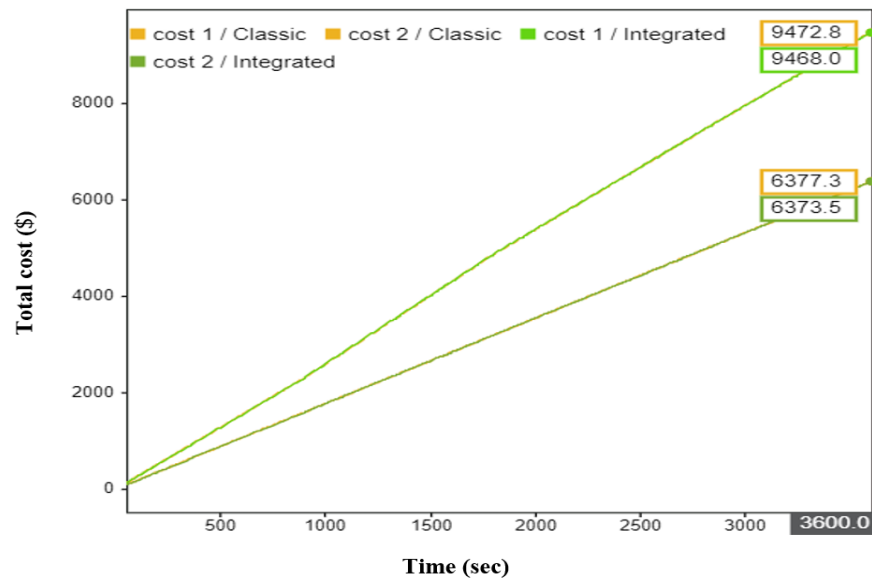


Figure 5.10 Total cost for two area classic and integrated ED-AGC.

## 5.2 TWO AREA ED-AGC WITH BATTERY ENERGY STORAGE AND WIND GENERATION

The integrated ED-AGC considers wind generation and battery energy storage in area 1, as illustrated in the previous chapter for the integrated feedback control loop in the ED-AGC. Area 2 considers no change on load and wind for classic and integrated ED-AGC and only using thermal generators. Battery energy storage and renewable resources like the wind are not included in area 2. The results of testing simulation for both areas of the classic and the integrated ED-AGC are present in this part.

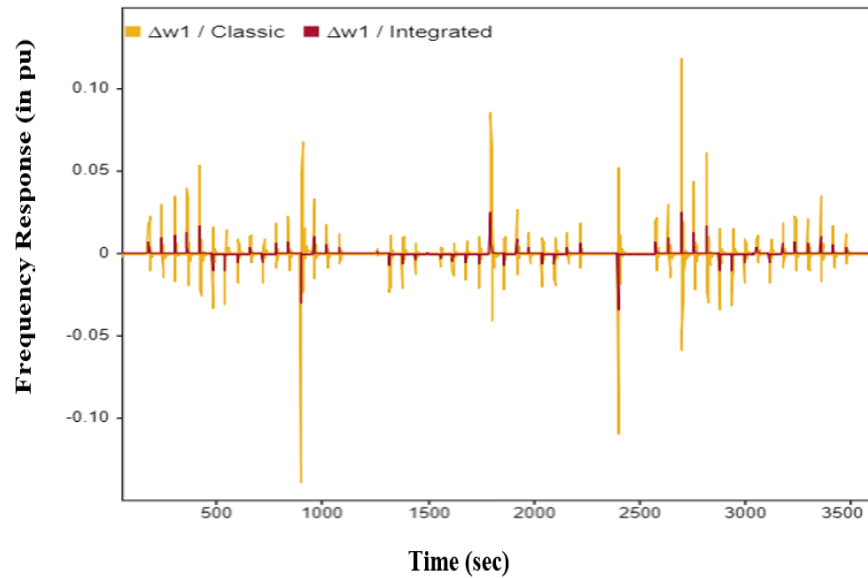


Figure 5.11 Frequency response for area 1 classic and integrated ED-AGC with the wind.

The differences in deviation of frequency response in each area can be found in figures 5.11 and 5.12. The classic has a lot of higher magnitude in deviation from steady-state when load or wind change from their nominal power, which affects the responding of generators. In contrast, the integrated system deviates with a minimum value of around a quarter of classical values as in

area 1 frequency response. The deviation of frequency in area 2 is near zero for the integrated system, while in the classic system, it reaches around 0.02, which causes more power deviation in area 2 generators. It also affects transferring power. The power transfer in the traditional way goes more than  $2MW$  while the integration is not reaching  $1MW$  in the whole simulation.

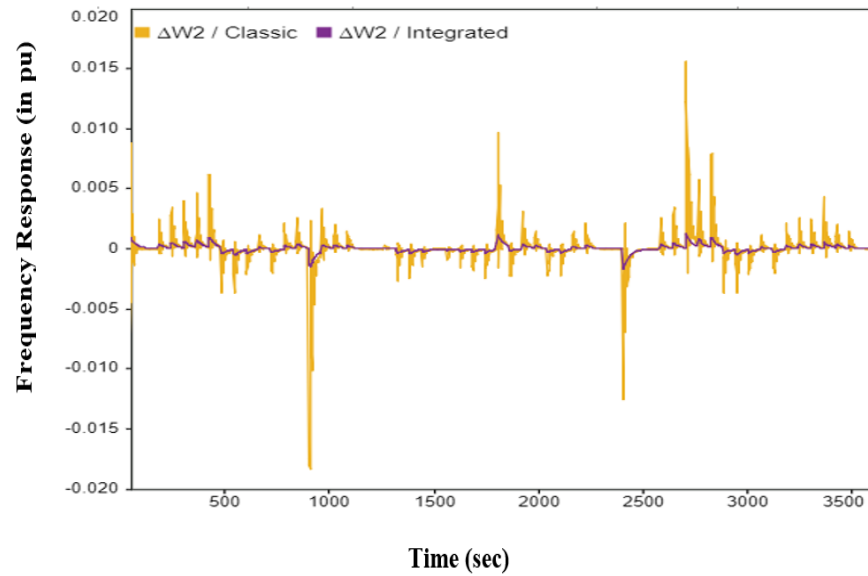


Figure 5.12 Frequency response for area 2 classic and integrated ED-AGC with the wind.

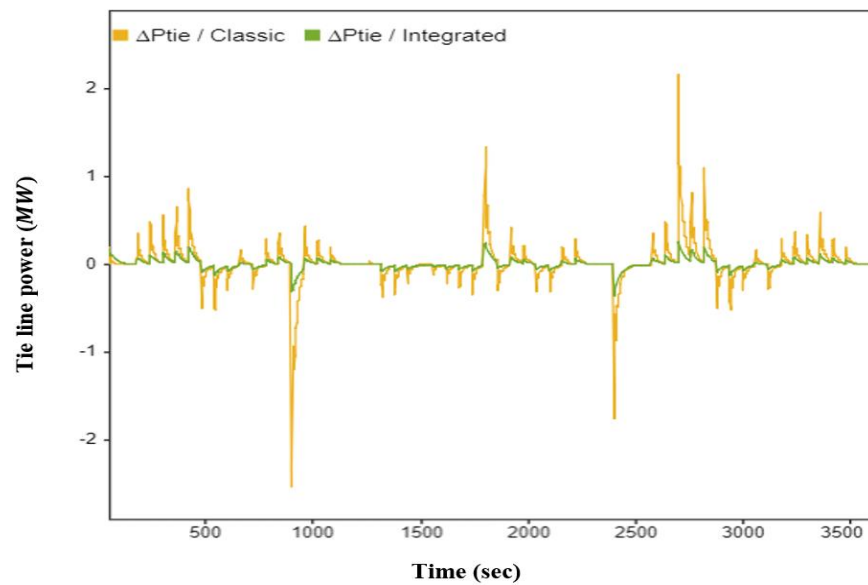
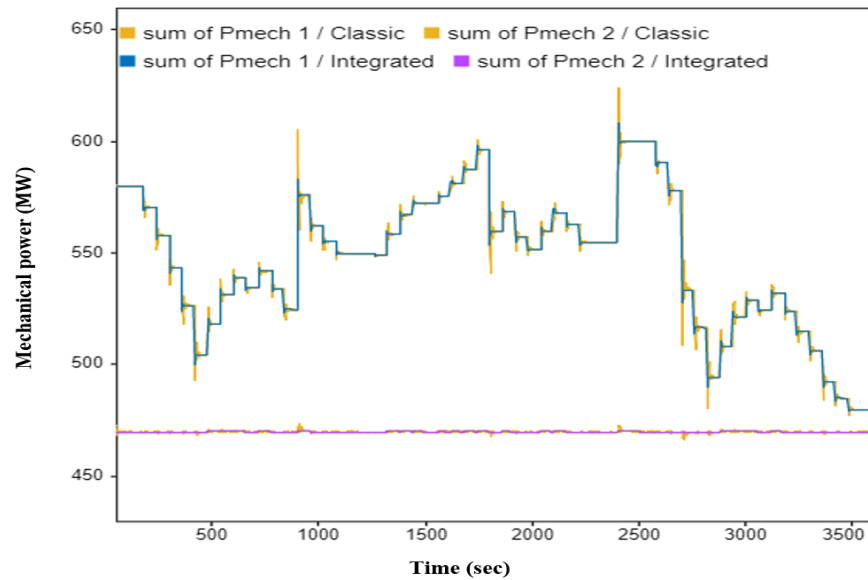


Figure 5.13 Power transfer for two area classic and integrated ED-AGC with the wind.

The mechanical power generators in both classic areas have fluctuations and errors in control generators due to high deviation frequency and transferring power response. However, the mechanical power of the thermal generator in integrated ED-AGC is not deviation higher value like the classic system.



**Figure 5.14 Mechanical power for two area classic and integrated ED-AGC with the wind.**

The battery power and energy are kept as scheduled optimization without using wind generation, but only the deviation response affects the battery power due to changes in frequency. Therefore, the final value of battery energy is equal to the initial value. The battery power and energy are illustrated in figures 5.15 and 5.16.

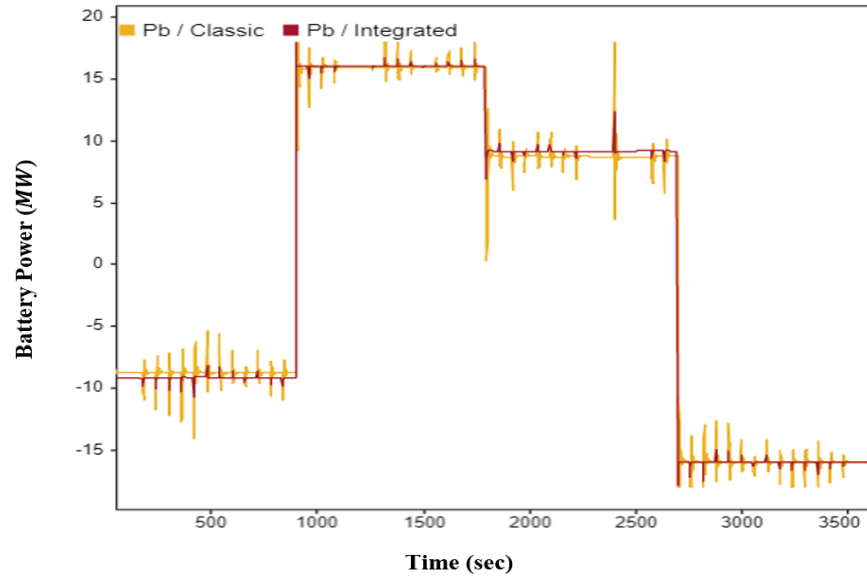


Figure 5.15 Battery power for area 1 classic and integrated ED-AGC with the wind.

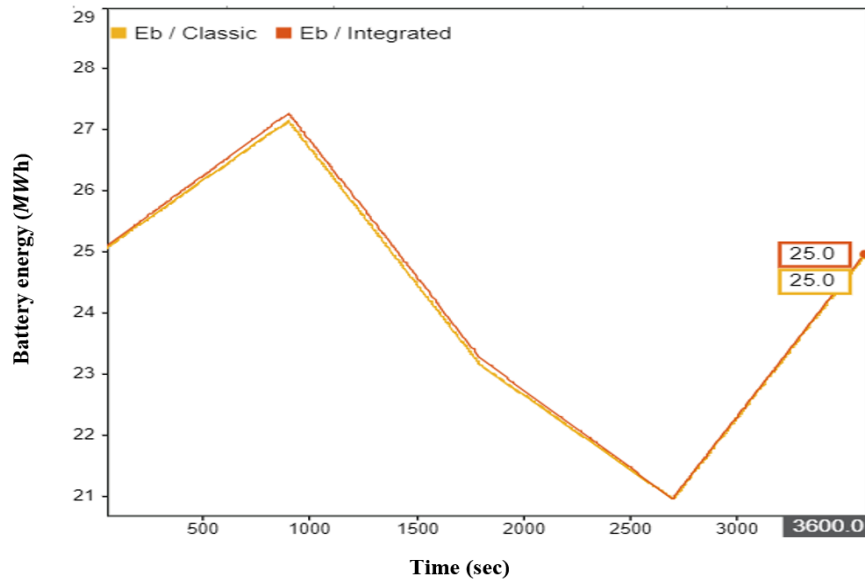


Figure 5.16 Battery energy for two area classic and integrated ED-AGC with the wind.

From figure 5.17, the total cost of the two areas simulation for the integrated system using battery and wind is equal to \$14540.0, and the classic system's total cost is equal to \$14552.7. The saving cost is equal to \$12.7. The estimated running yearly of integrated ED-AGC is around \$111252.

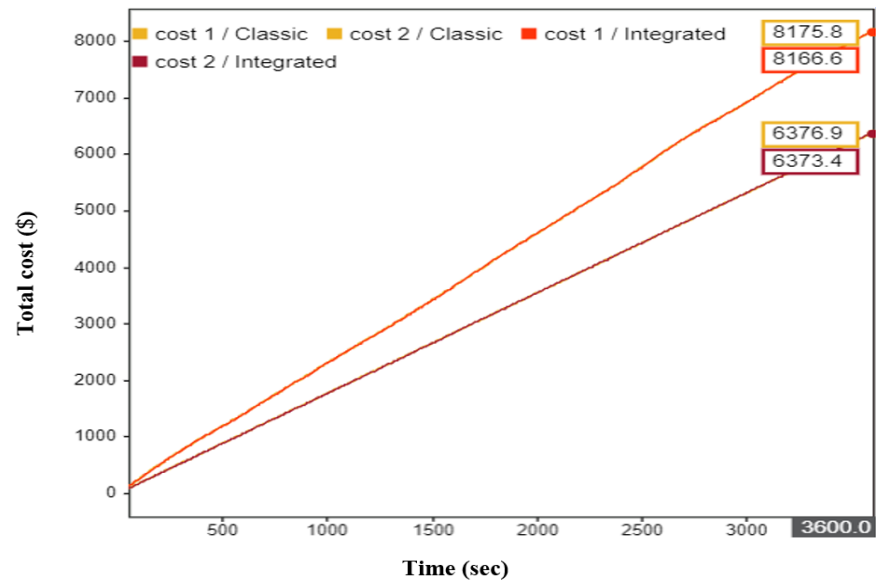


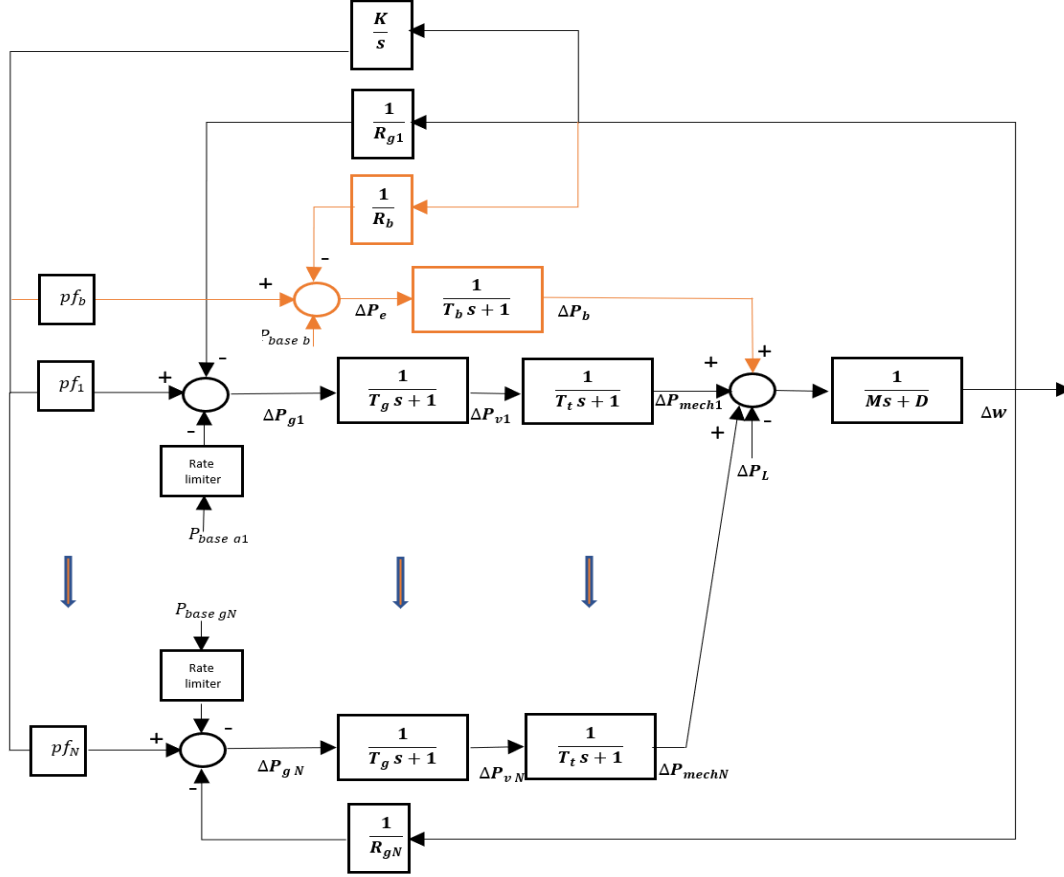
Figure 5.17 Total cost for two area classic and integrated ED-AGC with the wind.

## **CHAPTER 6 RAMP LIMIT GENERATION AND LOOK AHEAD CAPABILITY**

### **6.1 RAMP LIMIT CONTROL GENERATORS IN ED-AGC**

#### **6.1.1 Classical ED-AGC With and Without Ramping Limit Integrated ED-AGC With Ramping Limit.**

Power generation increases any time during the day, and sometimes in a day, the load is increasing or decreasing to a very high power value. For example, in some industry the load change to  $100MW$  when start or stop one machine. The generators may not respond fast due to higher load change because of the limitation of thermal generators' ramping rate. Battery power has a higher limitation value for ramping rate. Due to the battery's limited power rate, the higher load change cannot be covered by batteries. In the previous chapter, the AGC control system does not include the ramping rate of the generators. In this part of this chapter, Rate limit generators consider to control the ramping rate of the AGC system power outputs after the base point power is determined. This ramping limit will allow the system to increase gradually when the demand load changes to a higher value. Figure 6.1 shows the connection of the AGC model with the rate limiter.



**Figure 6.1.** AGC system includes a rate limiter for generators.

The simulation results for having a rate limiter on each generator of one area for the classic and integrated ED-AGC system are available in figures 6.2 to 6.9. Figures 6.2 and 6.3 illustrate the transient frequency response for AGC. Each response reaches a steady-state simultaneously while the integrated system has a lower deviate magnitude from the steady-state valve than the classic system. The deviation of integrated ED-AGC is fluctuating on either positive or negative frequency response. However, the time take for reaching a steady state value after load change is almost the same for all the simulation tests. Therefore, considering a rate limiter for the generator does not affect the reaching steady state value. However, the magnitude of the frequency deviation has different from each test as in figure 6.3.

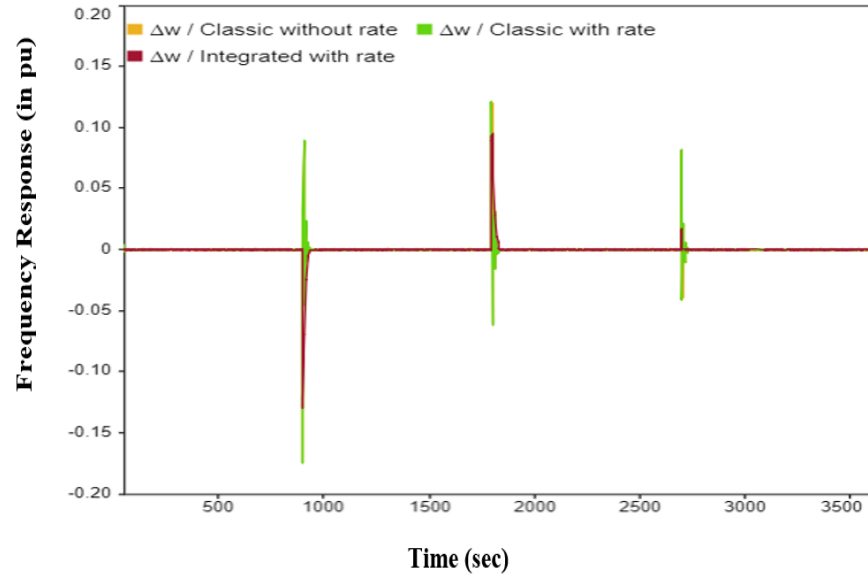


Figure 6.2 Frequency response for one area ED-AGC with the rate limit for all periods.

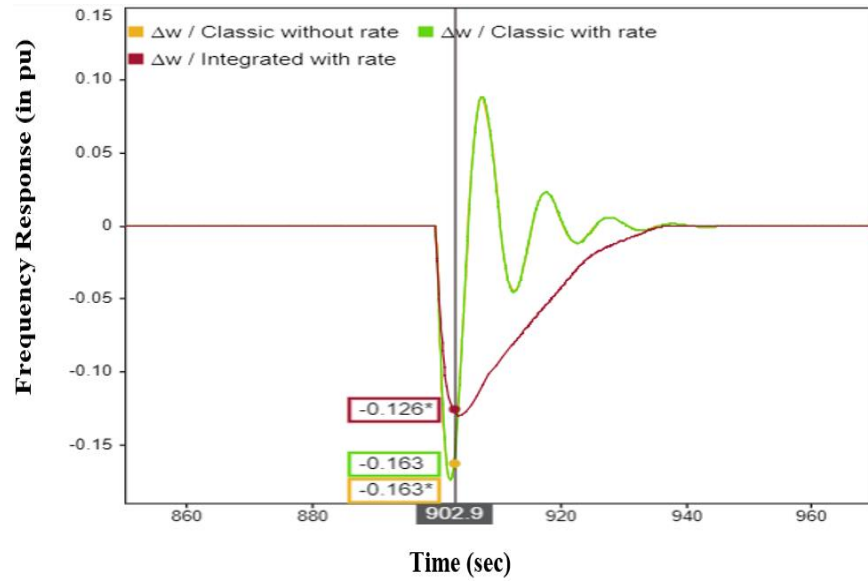


Figure 6.3 Frequency response for one area ED-AGC with rate limit.

The mechanical power of the generators gradually increases or decreases for the integrated part until it reaches the steady-state value while the classic fluctuates. As in figures 6.4 and 6.5, the integrated system has a lower deviation in mechanical power compare with the classic system.

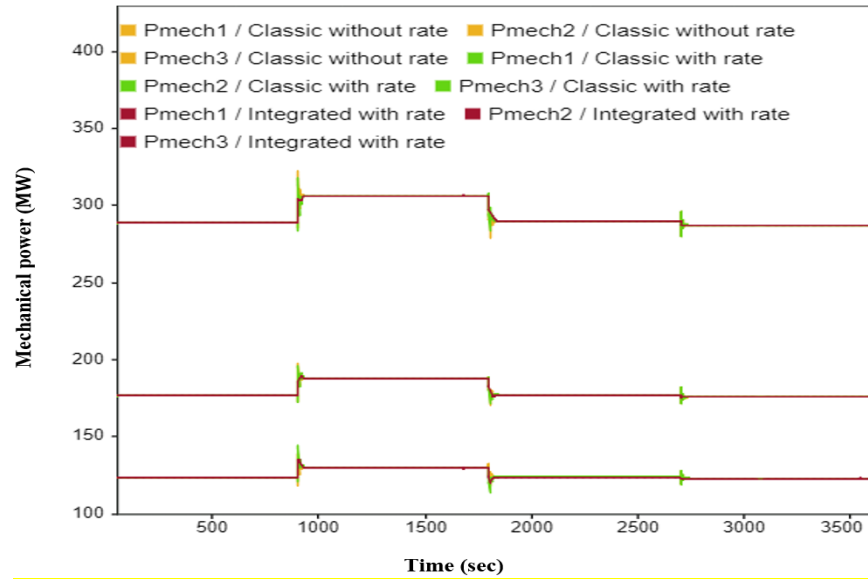


Figure 6.4 Mechanical power for one area ED-AGC with rate limit for all periods.

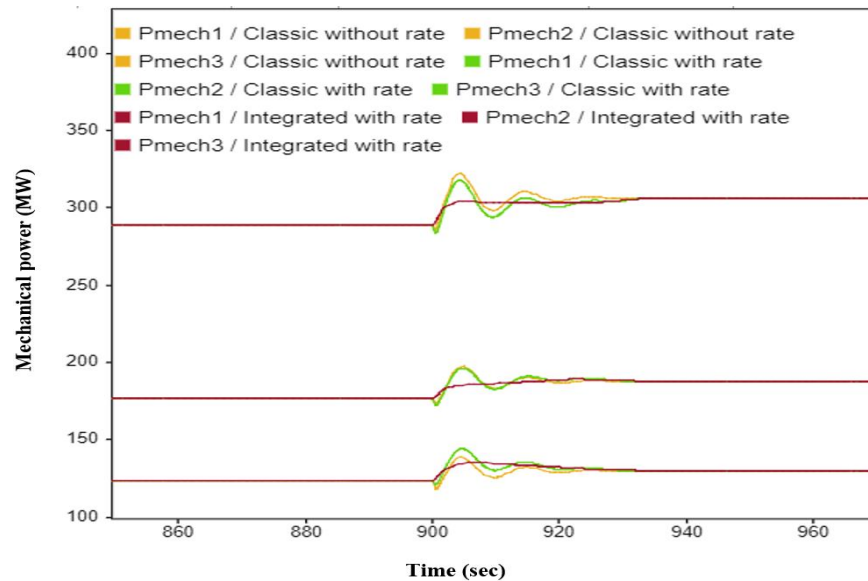


Figure 6.5 Mechanical power for one area ED-AGC with rate limit.

In figures 6.6 and 6.7, the battery power responds higher when the load changes in the integrated system due to high-frequency change and generators have no fast response. A saturation limiter is connected to the value of battery power in AGC to control battery power from deviation to out of the limit. The battery system's output limit value is desired to be  $\pm 18 \text{ MW}$ . The battery

power in the classic system has a wave signal while the integrated system has only a straight line.  
The below figures represent battery power for all systems.

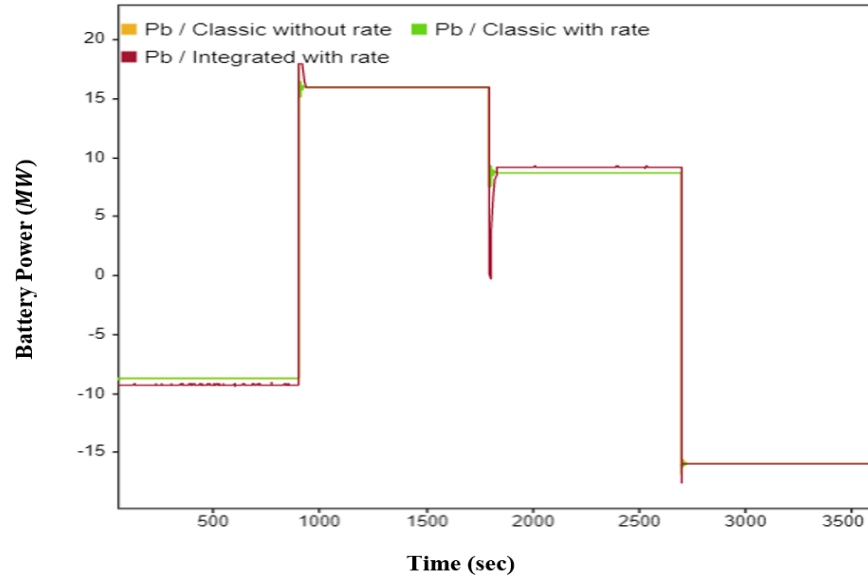


Figure 6.6 Battery power for one area ED-AGC with rate limit for all periods.

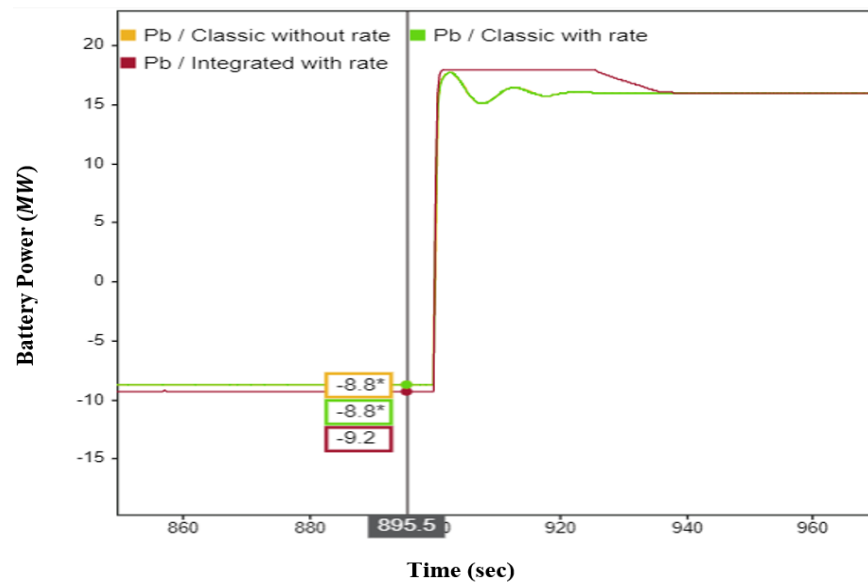
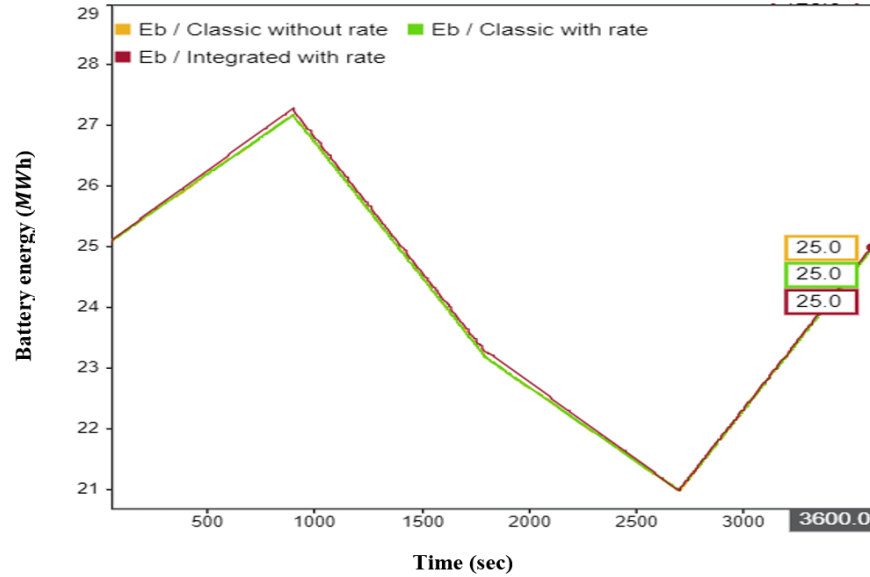


Figure 6.7 Battery power for one area ED-AGC with rate limit.

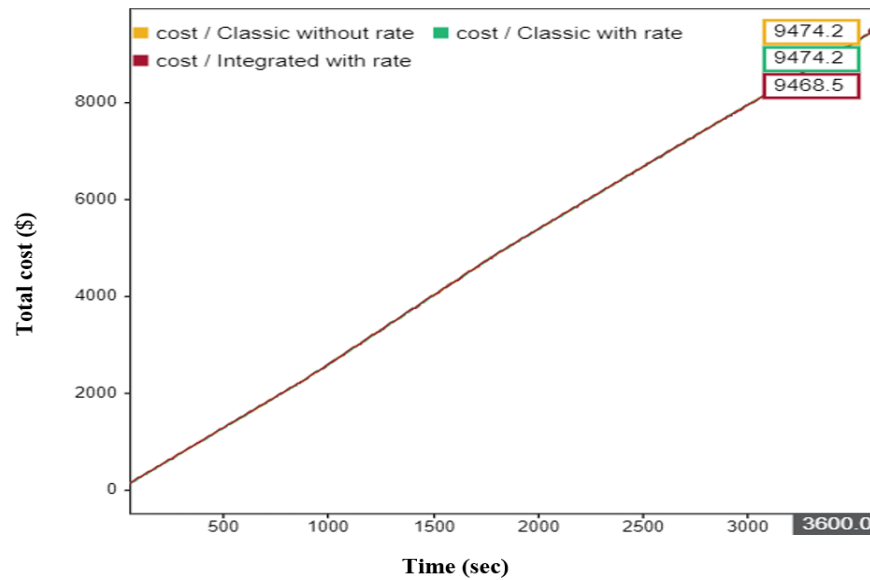
The final and initial battery energy are equal as expected for all systems as in figure 6.8. It is a little different in stored energy value between classic and integrated ED-AGC during running

simulation, but these differences keep the final value for energy as required. Figure 6.8 represents the battery power and energy.



**Figure 6.8 Battery energy for one area ED-AGC with the rate limit.**

From figure 6.9, the total cost for integrated ED-AGC using a rate limiter is \$9468.5 while the other system is \$9474.2. Therefore, the saving cost is \$5.7. So, the estimated cost for using an integrated system rather than using the classic system is around \$49932.



**Figure 6.9 Total cost for one area ED-AGC with the rate limit.**

## 6.2 LOOK AHEAD CAPABILITY FOR OPTIMIZATION CONTROL SYSTEM

### 6.2.1 Integrated ED Include Look Ahead Capability

Look ahead capability in ED is to find a solution of ED optimization in the next scheduling program after load demand is changed while the ED-AGC system is running. The traditional way of multi-period ED optimization obtains every 15 minutes while AGC is running. However, when the optimizer's load demand changes to another value, the optimizer should fix the demand load following schedule optimization [43]. In this section, the integrated ED considers look-ahead capability and investigates the simulation results after a demand load update at a specific time in the simulation program.

The simulation implements the demand load as in previous chapters 3 to 4 and this demand load changes to another demand load at  $t = 601s$ . The integrator will directly update the integrated demand loads. The system response is directly affected as per the following figures 6.10 to 6.23. The second demand loads are used at  $t=601$  to  $t= 3600$ , as illustrated in table 6.1. The updated load record happens in periods 2 and 3. The other periods keep the same values.

**Table 6.1 Demand load change at  $t = 601s$  to  $t = 3600s$ .**

| Period | Load demand at $t = 0$ to 600 | Load demand at $t = 600$ to 3600 |
|--------|-------------------------------|----------------------------------|
| 1      | 580                           | 580                              |
| 2      | 640                           | 650                              |
| 3      | 600                           | 630                              |
| 4      | 570                           | 570                              |

Figures 6.10 to 6.23 represent the output of the integrated ED without using the AGC system, and it is considering look-ahead capability in the demand load as in table 6.1. Figures 6.10

and 6.11 show the load demand inserted in the integrated ED and the load updates values after  $t = 600s$ . Figures 6.12 and 6.13 show the battery power at each interval. The battery powers change directly when the load changes to other values. Figure 6.12 shows the output value of battery power from integrated ED before load changed at  $t = 600s$  at periods 2 and 3. Figure 6.13 illustrates the output values of battery power after load demand desired changes after  $t = 600s$ .

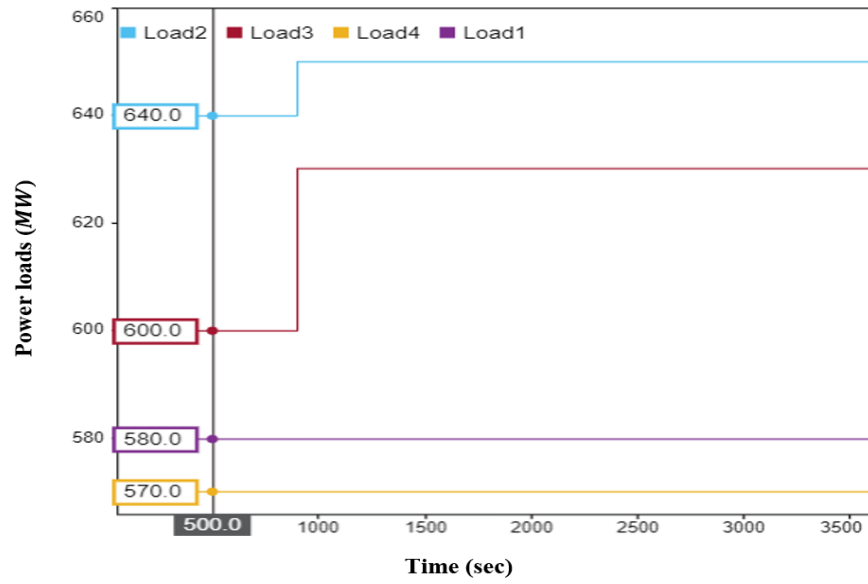


Figure 6.10 Loads used in integrated ED include look-ahead capability before load demand change.

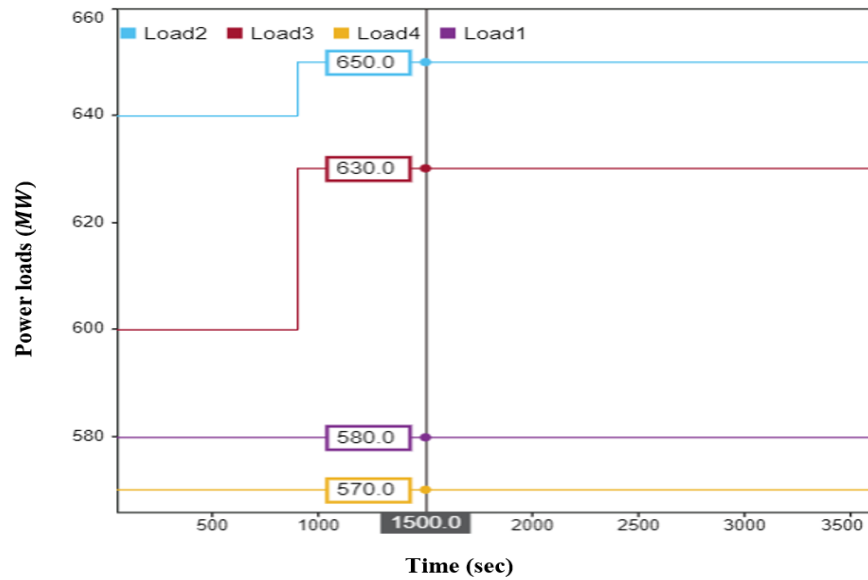


Figure 6.11 Loads used in integrated ED include look-ahead capability after load demand change.

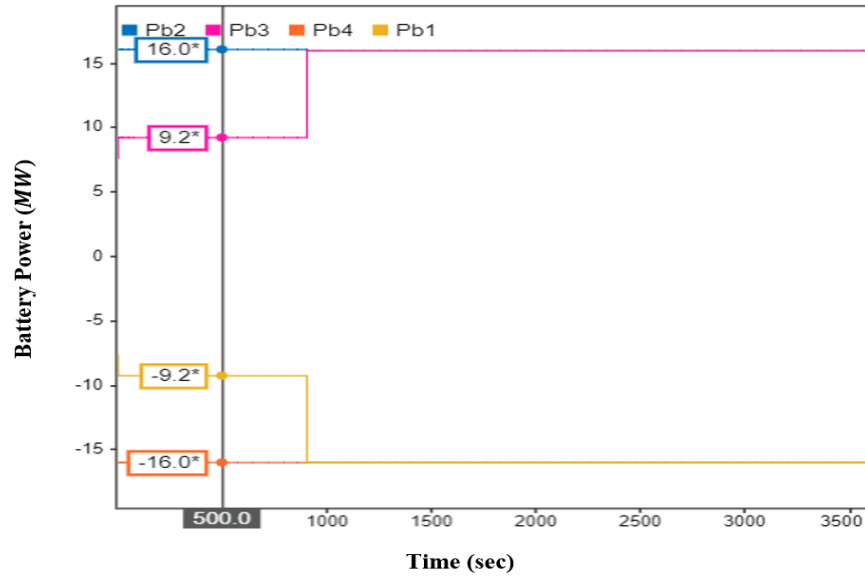


Figure 6.12 Battery power for integrated ED includes look-ahead capability before load demand change.

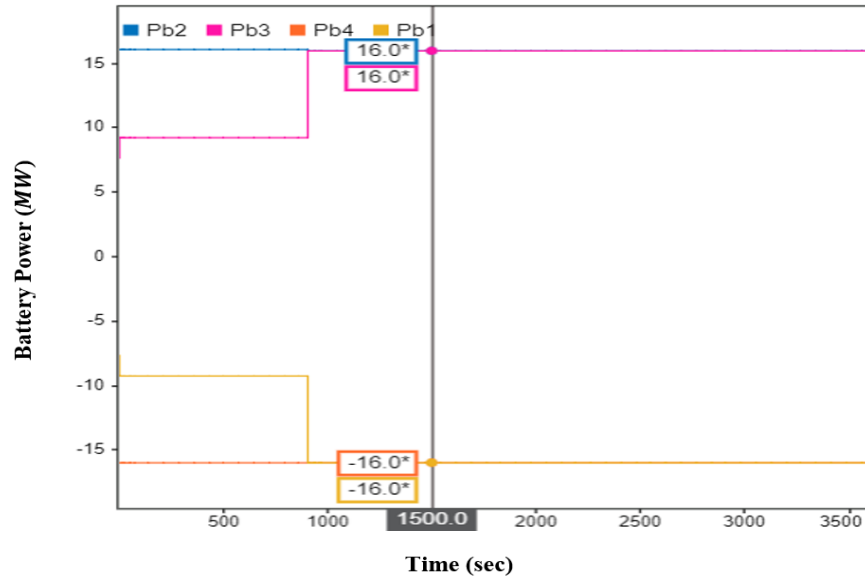


Figure 6.13 Battery power for integrated ED includes look-ahead capability after load demand change.

Changing in battery has affected the mechanical power for all generators and battery energy because they depend on each other. So, periods 1 and 3 change the mechanical power and battery energy change to the new values in figures 6.14 to 6.19. Thus, the final value of energy integrated ED does not violate the energy final requirement. Figure 6.14 shows the battery energy values before load demand changes to another desired value, while figure 6.15 illustrates the battery when

the load is changed. The same thing happens to mechanical power as it generates from integrated ED that uses it for the base point power of AGC. Figures 6.16 to 6.19 represent the output mechanical power for each interval used as base point power for AGC.

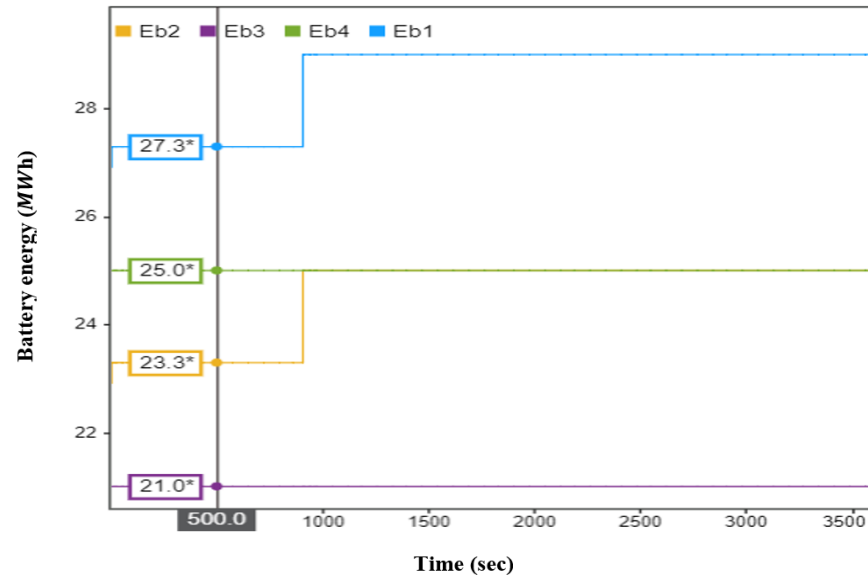


Figure 6.14 Battery energy for integrated ED includes look-ahead capability before load demand change.

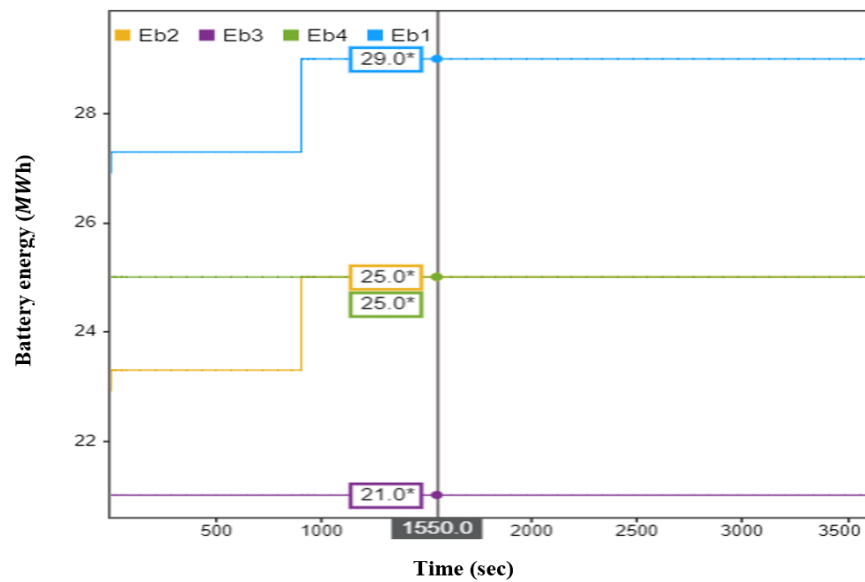


Figure 6.15 Battery power for integrated ED includes look-ahead capability after load demand change.

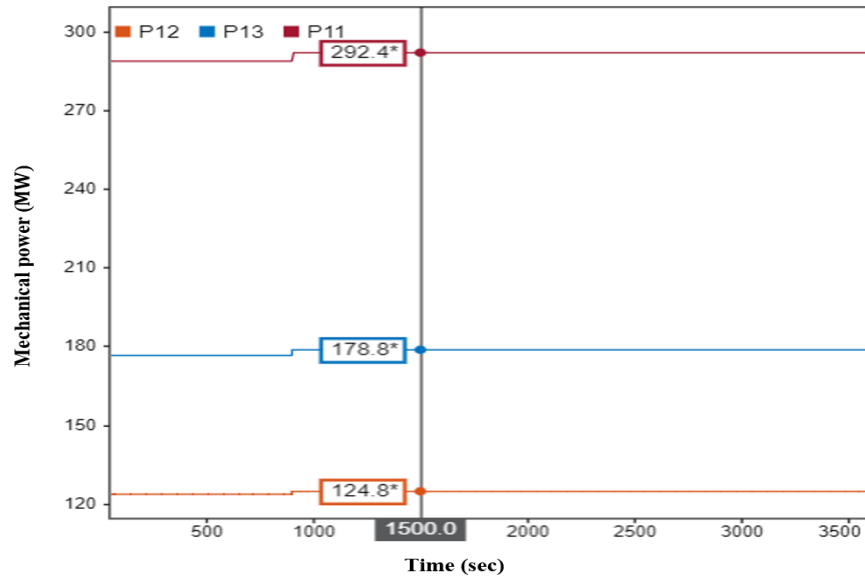


Figure 6.16 Mechanical power for period 1 of integrated ED includes looking ahead capability.

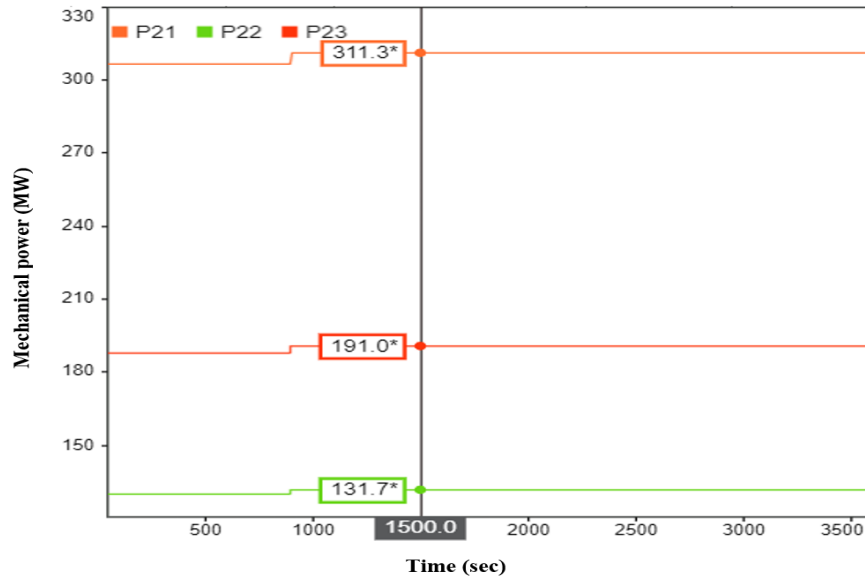


Figure 6.17 Mechanical power for period two integrated ED includes look-ahead capability.

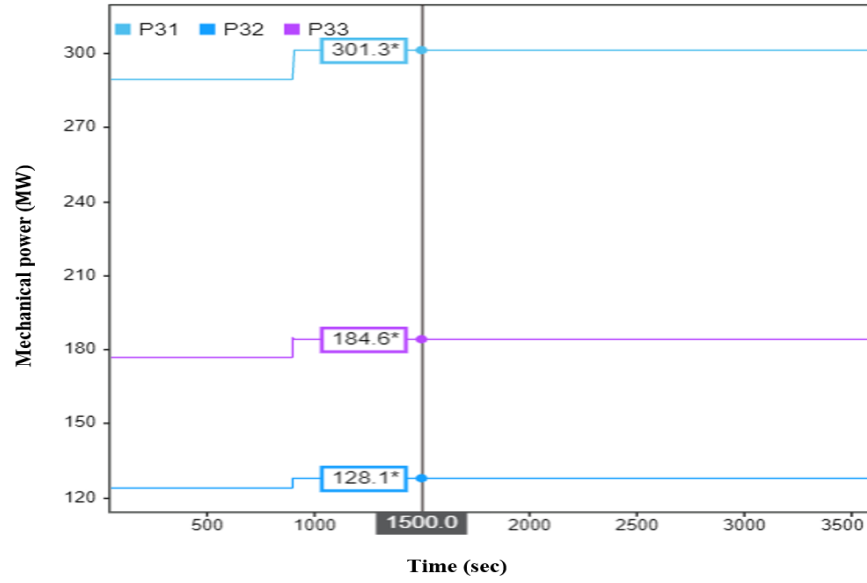


Figure 6.18 Mechanical power for period 3 of integrated ED includes looking ahead capability.

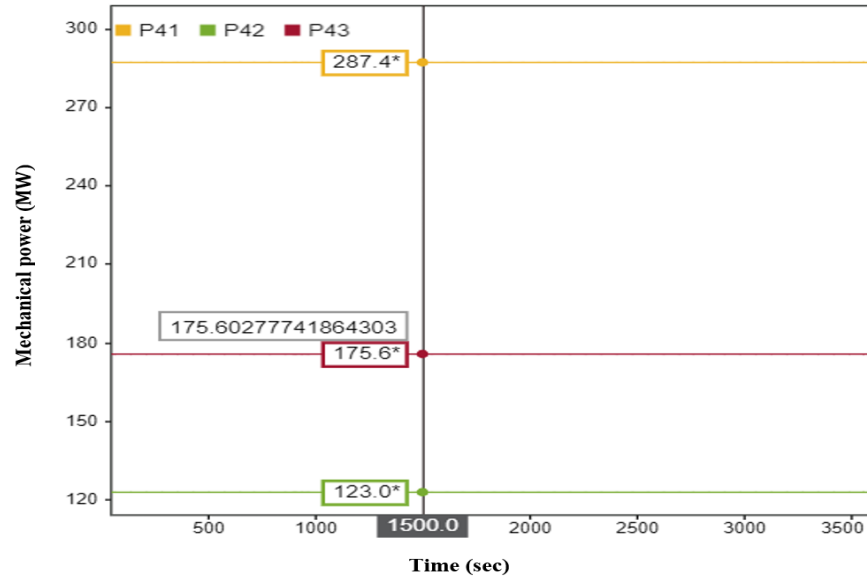


Figure 6.19 Mechanical power for period 4 of integrated ED includes look-ahead capability.

The incremental cost of each period updates when loading changes as per figures 6.20 and 6.21. The multiplier  $\lambda_5$  changed due to energy change at periods 1 and 2 as per figures 6.14 and 6.15.  $\lambda_5$  is associated with the energy battery balance, which equals the total battery at all periods. So, changing in all  $\lambda$  is expected.

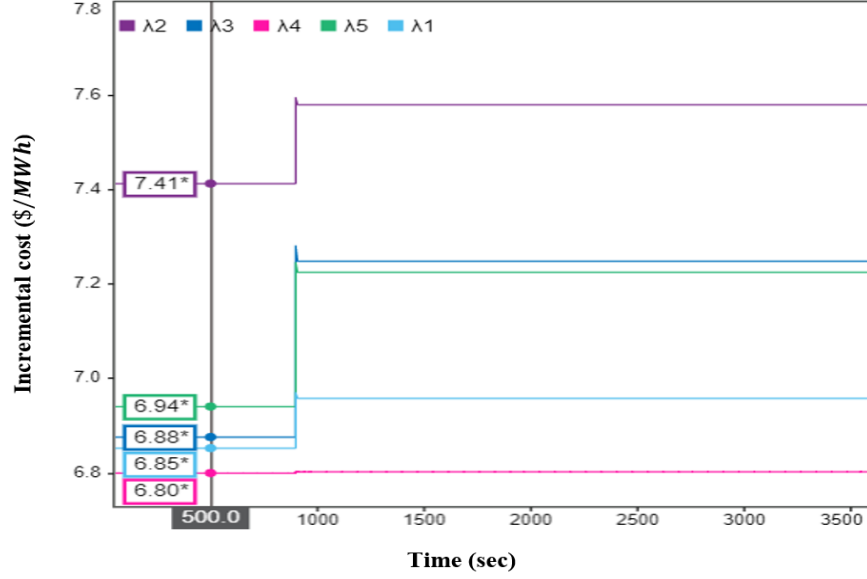


Figure 6.20  $\lambda$ 's for integrated ED includes look-ahead capability before load demand change.

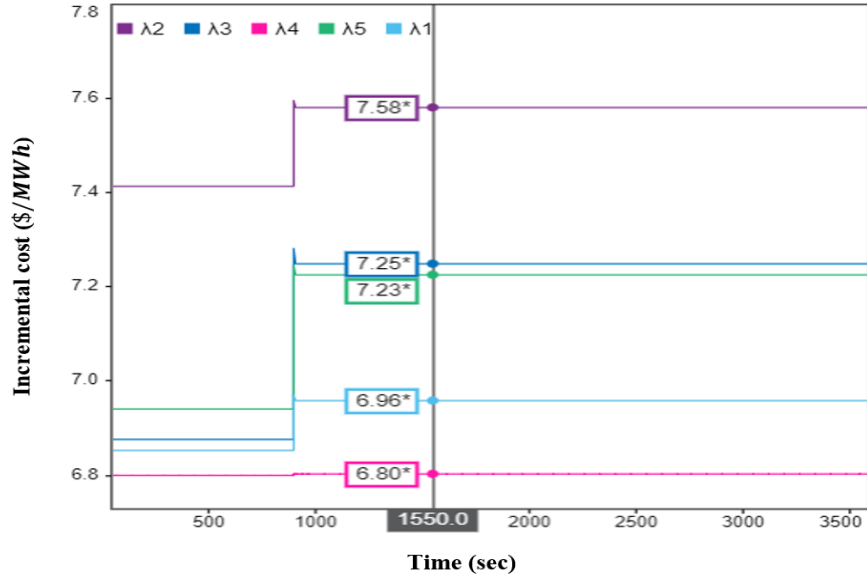


Figure 6.21  $\lambda$ 's for integrated ED includes look-ahead capability after load demand change.

The  $\beta_{ti}$ 's are all zero due to all mechanical power values are in between their limits. The  $\mu_{t1}$  values for battery power limits are all changed due to optimization variable values for the battery powers are all on the limit side. The  $\mu_{t2}$  values are all zeros since battery energy values are in between their limit values.

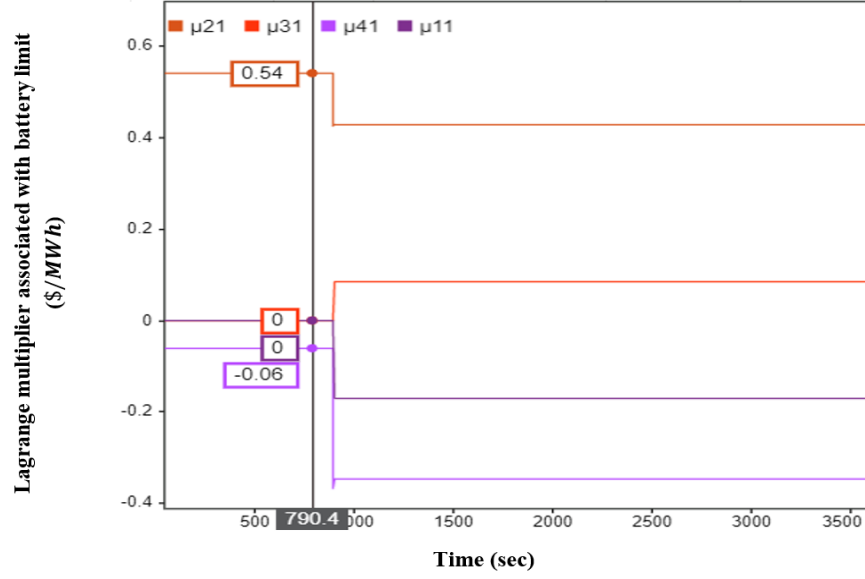


Figure 6.22  $\mu$ 's for integrated ED includes look-ahead capability before load demand change.

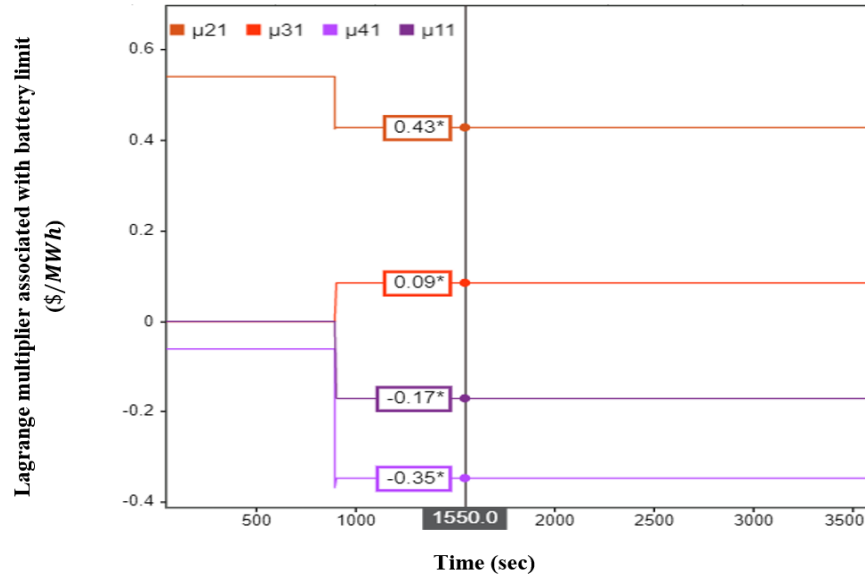


Figure 6.23  $\mu$ 's for integrated ED includes look-ahead capability after load demand change.

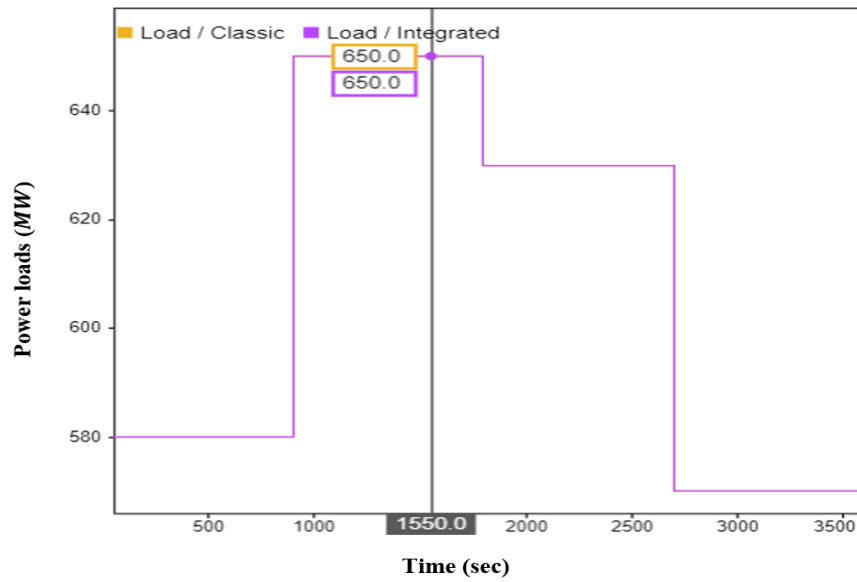
### 6.2.2 Classic and Integrated ED-AGC Include Look Ahead Capability with Same Time Directly Effect in Integrated Response.

From section 6.2.1, the integrated ED system connects to the AGC and simulation compared with classic ED-AGC. Table 6.2 shows the classical optimization ED values that include looking ahead to capability. The simulated optimizer gets the new demand load at  $t = 600s$  in the

first period. The optimizer uses the new updated values in the optimization schedule at periods 2, 3, and 4. However, the integrated ED directly affects when demand load is updated.

**Table 6.2 Dynamic ED using look-ahead capability.**

| Period | Load demand | Load demand change at $t = 600$ s | $P_{g1}$ | $P_{g2}$ | $P_{g3}$ | $P_b$  |            |
|--------|-------------|-----------------------------------|----------|----------|----------|--------|------------|
| 1      | 580         | 580 No changed                    | 288.741  | 123.534  | 176.482  | -8.757 | As table 7 |
| 2      | 640         | 640 changed                       | 311.285  | 131.739  | 190.976  | 16     | New values |
| 3      | 600         | 630 changed                       | 301.320  | 128.104  | 184.576  | 16     | New values |
| 4      | 570         | 570 No changed                    | 287.367  | 123.036  | 175.597  | -16    | New values |

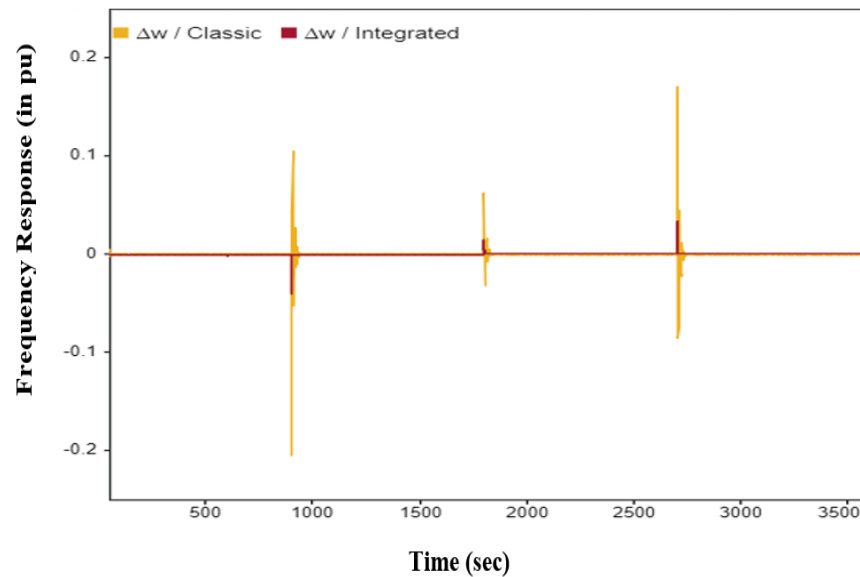


**Figure 6.24 loads for classic and integrated ED-AGC include look-ahead capability.**

The simulation results for classic and integrated ED-AGC implements in the Matlab program. The load power of the ED is illustrated in figure 6.24, and the frequency response in an integrated system is better than the classic system. However, the mechanical power of thermal generators and battery power for the classic and integrated system are different power values at the interval time from  $t = 601$  to  $t = 900$  due to the classic system optimization schedule at  $t = 900$ s. The base point power is not directly changed when load demand is changed, while the

integrated is directly update base point power at  $t=600s$ . The results of the ED integrated system are discussed in section 6.2.1.

The classic and integrated ED-AGC frequency response is represented in figure 6.25. The integrated way has a minimum value of around 0.001 changed when the load demand varies from the nominal value at  $t = 600s$ . This lower value of frequency response happens because load demand directly changes in the integrated system. Figure 6.26 shows the mechanical power of both systems at all periods, and it illustrates the integrated mechanical power change after load demand change to another desired value.



**Figure 6.25 Frequency response for classic and integrated ED-AGC includes looking ahead capability.**

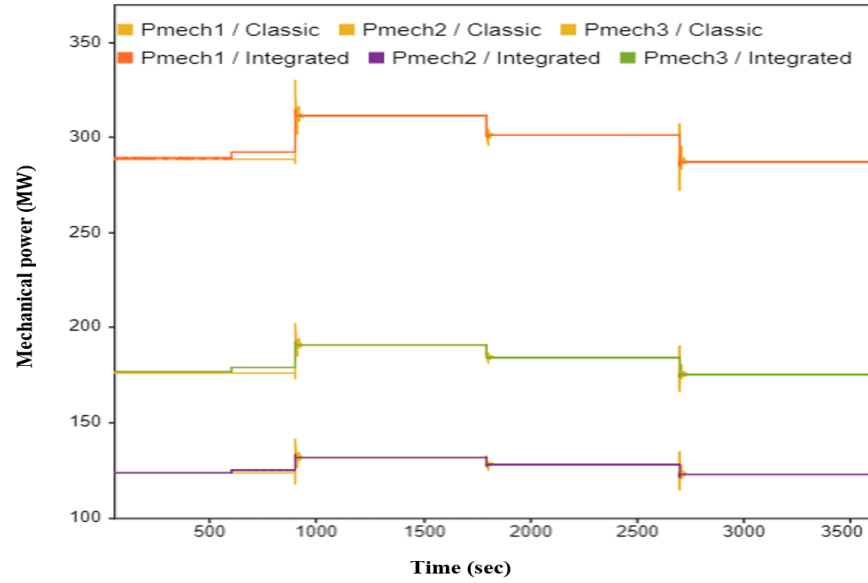


Figure 6.26 Mechanical power for classic and integrated ED-AGC includes looking ahead capability.

The battery power for this simulation is in figure 6.27. The battery power value is changed at the minimum value at  $t = 600s$  due to changes in load demand. It reaches the minimum value because of the optimization ED to get a better optimal cost.

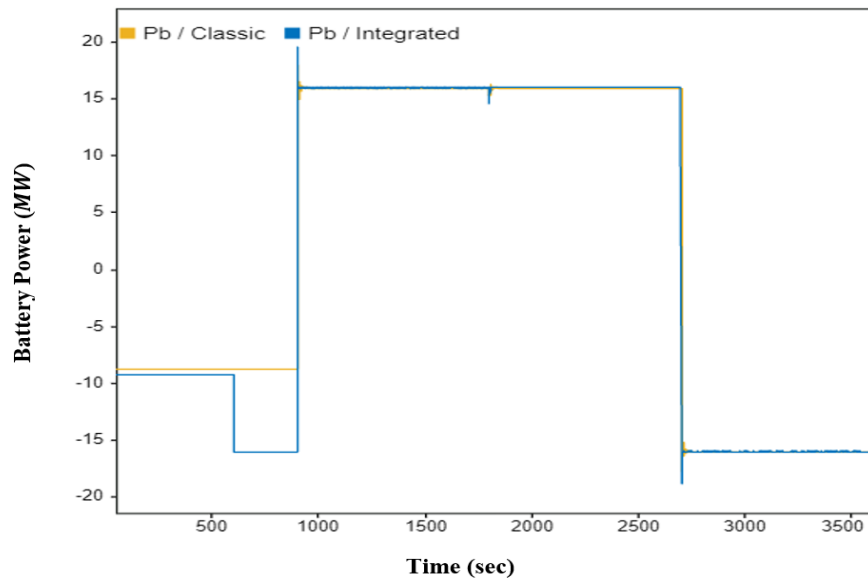


Figure 6.27 Battery power for classic and integrated ED-AGC includes looking ahead capability.

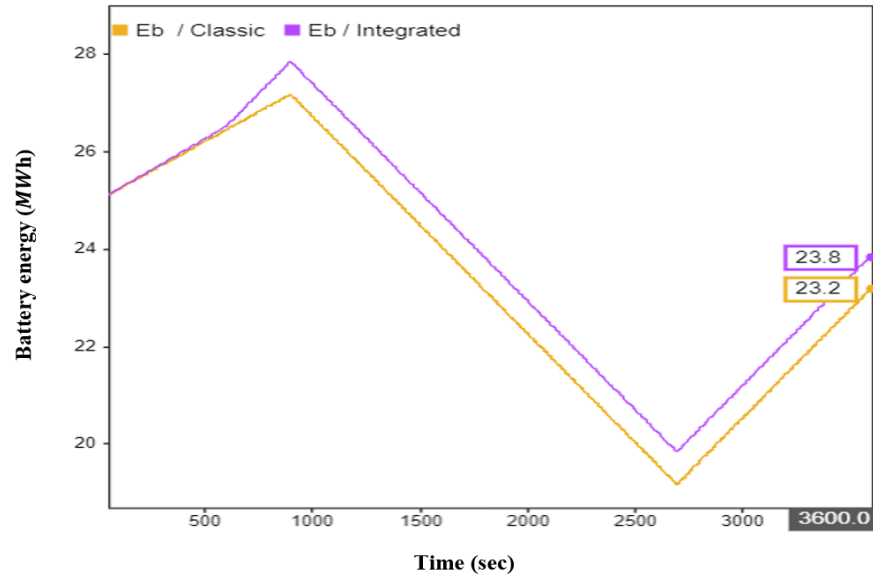


Figure 6.28 Battery energy for classic and integrated ED-AGC includes looking ahead capability.

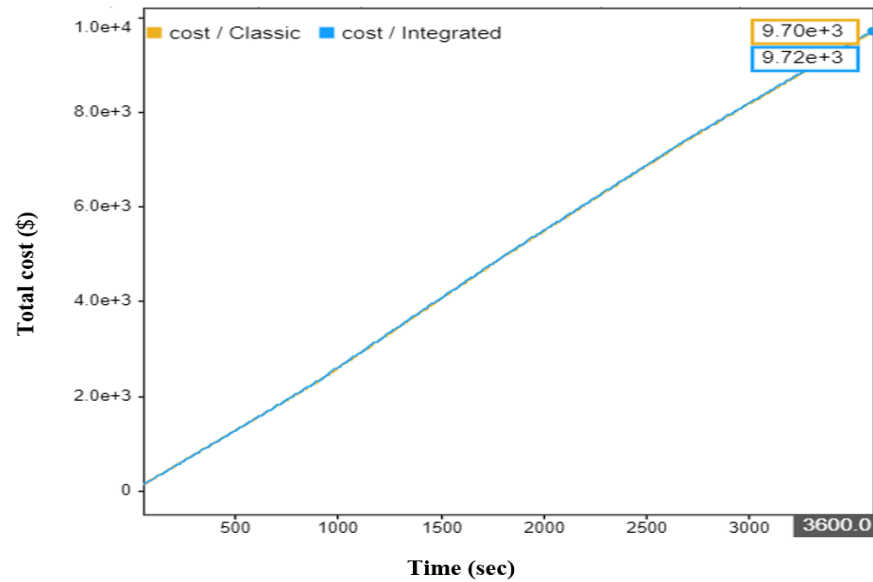


Figure 6.29 Total cost for classic and integrated ED-AGC include look-ahead capability.

The battery energy is illustrated in figure 6.28. The final energy in both systems violates due to changes in demand load. But the integrated system has fewer minor value violation errors from the required final energy value than the classic. In addition, the classic system has less cost than the integrated system because generation increased from  $t=600s$  up to  $t=900s$ . The battery has

an increasing charging power at this time interval. The classic cost is \$9709.97, and the integrated cost is \$9722.44. The difference in cost is \$12.47.

### 6.2.3 Classic and Integrated ED-AGC Include Look Ahead Capability and Effect Response in the next Period.

In this section, the integrated system simulation will wait when the load demand changes to another desired value until the next optimization period to update the new demand load. Figures 6.30 to 6.33 are the results of these simulations. No change happens at  $t = 600s$  for the frequency response for the classic and integrated ED-AGC because of the updated load demand at  $t = 900s$  for both systems. The battery power in an integrated system is nearly the same as a classic system with a slight change. The battery energy in an integrated way is better than the traditional way. The error of the final violation value of energy in integrated is getting higher than in the previous simulation due to updating load data to the next period. The cost in the integrated is better than the classic, and it has \$9706.82 while the classic is \$9709.94. The total saving cost is \$3.12. The yearly estimated running generation ED-AGC of this simulation is equal to \$27331.2.

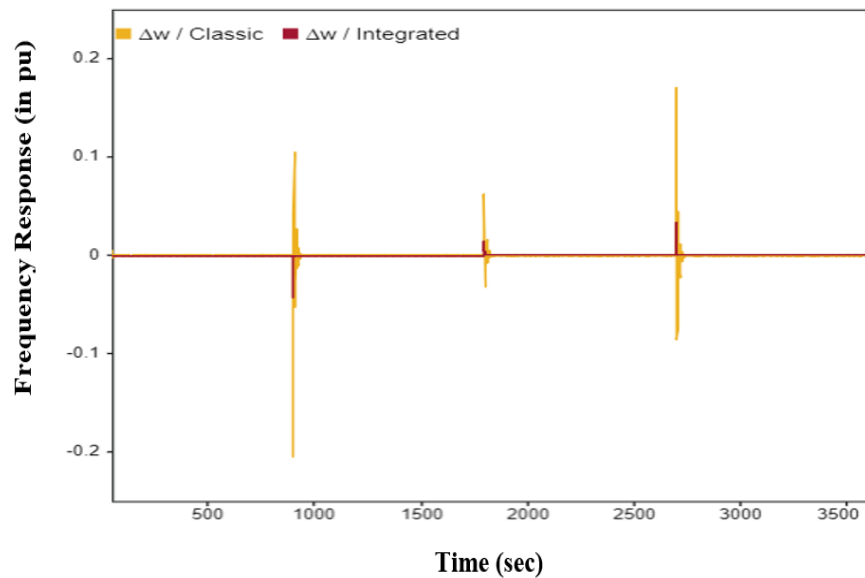


Figure 6.30 Frequency response for ED-AGC includes new load demands at  $t = 900$ .

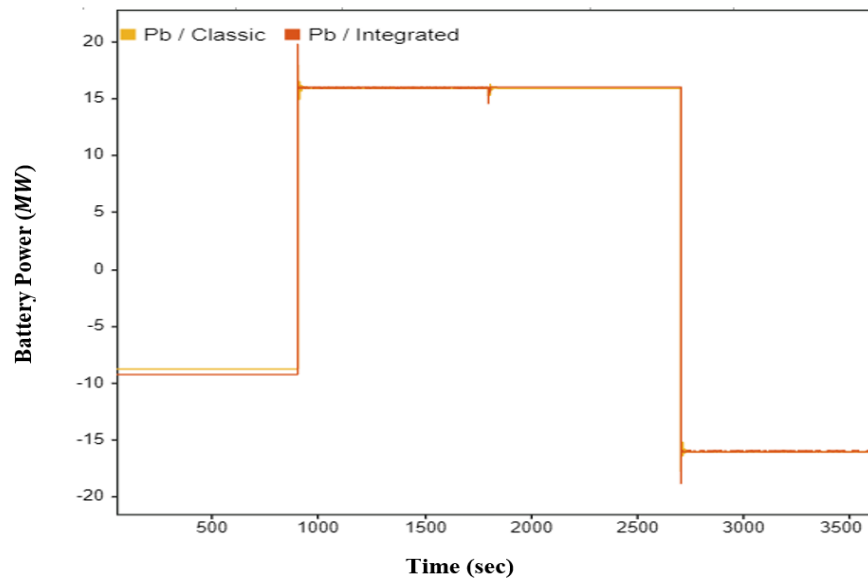


Figure 6.31 Battery power for ED-AGC includes new load demands at  $t = 900$ .

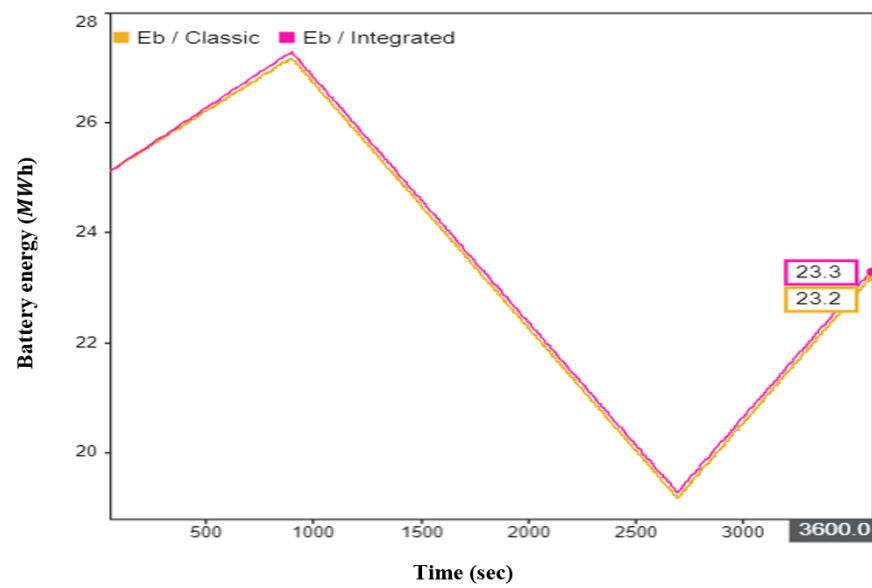


Figure 6.32 Battery energy for ED-AGC includes new load demands at  $t = 900$ .

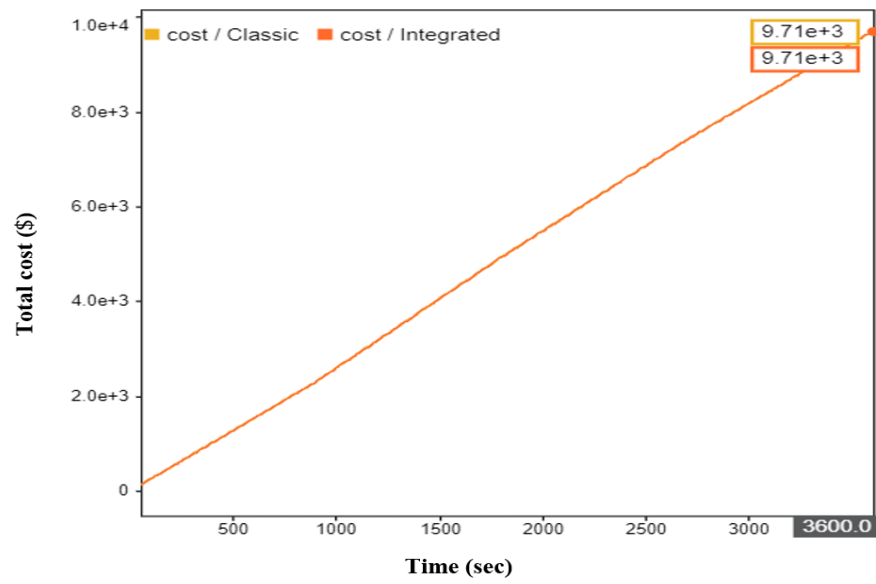


Figure 6.33 Total cost for ED-AGC includes new load demands at  $t = 900$ .

## **CHAPTER 7      THESIS CONCLUSION**

### **7.1 CONCLUSION**

In conclusion, the integrated economic dispatch optimization and automatic generation control are implemented for single-period optimization and multi-period optimization to find the best optimal cost for generating electricity to the grid. The models and equations of the AGC system are illustrated in the study cases in this report. The ED-AGC model included battery energy storage in the automatic generation control to improve system responses and support system control to their requirement loads. The battery power and energy are considered in the classic and integrated economic dispatch optimization to get better cost optimization for generation ED. The ED scheduling was deciding the base point power of generators and battery. Renewable resources included in the studying responses of ED-AGC for improvement of generation by using penetration resources in the AGC control system. Wind generation is the renewable generation source of energy used in all study cases for getting the improvement cost of generating electricity.

The classic and integrated of two areas ED-AGC are explained in this report. It illustrated the responses of frequency deviation, mechanical power, battery power, battery energy, and transferring power while considering battery energy storage and wind generation source. Also, this study included the optimization cost of the simulation ED-AGC system. The different responses between the classic and integrated ED-AGC of the two areas system are illustrated in the result discussion. The total optimization is found with the optimal cost using an integrated way. The work implemented in the ED-AGC system contained the load changes and wind generation

that happened in area 1 while keeping area 2 as constant demand load to study the system responses when the load changed on area 1.

Ramp limit control in the fuel generation is considered in the AGC system to ensure generators respond well when the load changes to a very high magnitude. The classic and integrated ED-AGC system included ramp limit generation in the simulation program for one area of generation AGC. It supported the generators to give more efficient results. The last study case was on a look-ahead capability included in the economic dispatch optimization. The optimizer gets an updated load demand while the system is running. The implementation study included the changing demand loads during the first period of the simulation control system. All case study has improved the cost of the generators and battery in an optimal cost using integrated ED-AGC.

## **7.2 FUTURE WORK**

The following items can be included in future work:

- First, consider many periods in classic and integrated economic dispatch rather than four periods in one optimization. For example, include 24 periods for a one-day optimization.
- Include battery energy storage in both areas of automatic generation control.
- Include ramp limit generation in two areas of automatic generation control and testing simulation using many renewable energy sources.

- Include renewable energy in AGC and look ahead to consider the uncertainty of renewable resources in the operation control system.

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