Demand Response in the Day-Ahead Market

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Abstract

Demand response (DR) is an essential tool in energy management systems, playing a significant role in optimizing power systems and reducing energy production costs. In the day-ahead market, large companies and consumers can adjust their consumption patterns to balance supply and demand. This program facilitates proactive planning, aiming to improve the efficiency and behavior of both consumers and producers, making it a valuable approach for achieving market stability.

This simulation includes accurate modeling of load responsiveness and the impact on network price and stability. Using advanced algorithms and historical data, various strategies can be examined for optimal participation in DR programs. This approach not only aids in cost reduction and operational efficiency but also plays a critical role in managing price fluctuations and ensuring uninterrupted production and consumption.

Ultimately, the simulation results of demand response programs can support decision-makers in the electricity market in formulating suitable policies. Utilizing DR as a tool can enhance the balance between supply and demand, improving both the stability and efficiency of the power system.

Introduction

In today's world, rising energy demands and the need for efficient resource utilization have driven the development of energy management tools. One of the key methods, known as Demand Response (DR), is gaining importance in the day-ahead electricity market. DR enables consumers to adjust their consumption in response to price signals or other incentives, helping to reduce energy costs and improve grid stability. This program can mitigate price fluctuations and support risk management by balancing supply and demand.

A primary reason for the significance of DR is its ability to help balance supply and demand in the electricity market. In power systems, balancing demand and supply in real-time is essential for system stability. With increasing demand and limited production capacity, DR can manage demand effectively, aiding in system equilibrium.

DR also plays a vital role in reducing electricity production costs. In electricity markets, prices are determined based on demand and supply, often increasing during peak demand periods. By implementing DR programs, consumers can shift their consumption to non-peak hours, reducing demand and thus lowering costs for all users.

Additionally, DR improves the resilience and flexibility of power systems. By responding to sudden demand changes, DR enhances the system's ability to avoid major blackouts, which is particularly beneficial during emergencies or network disturbances. This capability supports environmental goals by reducing reliance on high-emission, inefficient power plants.

Demand Response

Demand Response (DR) refers to a set of actions and strategies that allow consumers to adjust their electricity usage to balance supply and demand. In DR, consumers modify their consumption patterns in response to price signals, financial incentives, or requests from network operators. Typically, these adjustments include reducing usage during peak periods, shifting consumption to off-peak times, or even increasing usage when there is surplus energy.

The main objective of DR is to enhance the efficiency and stability of power systems, reduce energy production and distribution costs, and manage energy resources more effectively. This concept is particularly valuable in renewable and smart grids, where production and consumption are more variable. DR can be implemented in various ways:

1. **Price-Based DR:** Consumers adjust their consumption in response to changes in electricity prices. For example, consumers reduce usage during high-price periods to lower their costs.
2. **Event-Based DR:** During specific situations, such as grid crises, network operators send requests to consumers to reduce or increase their consumption as needed.
3. **Program-Based DR:** Consumers follow a pre-scheduled plan to adjust their usage at specified times, aiding in system stability and efficiency.

DR not only helps balance supply and demand more effectively but also delays the need for new investments in production and distribution capacity. Ultimately, this tool contributes to economic efficiency, cost reduction, and environmental benefits.

In summary, DR supports balancing supply and demand, reducing energy production and distribution costs, and enhancing grid stability and flexibility. By supporting environmental objectives, DR helps create a more resilient power system. The accurate modeling, simulation, and analysis of DR programs are crucial for optimizing consumer behavior and supporting policymakers in making informed decisions.

Impact of Demand Response on the Day-Ahead Market

Demand response in the day-ahead market allows consumers to adjust their electricity usage in response to pre-determined prices for the following day. The impacts of demand response include:

1. **Supply and Demand Balance:** Demand response helps balance supply and demand by reducing consumption during peak hours and increasing it during off-peak periods, contributing to a more stable power system.
2. **Price Reduction:** By reducing demand during peak hours, electricity prices decrease, resulting in lower costs for consumers.
3. **Reduction in Extra Capacity Needs:** Adjusting consumption can reduce the need for building additional backup power plants, minimizing investment and operational costs.
4. **Enhanced Stability and Flexibility of the Grid:** Consumers who adjust their consumption contribute to increased grid stability, helping manage fluctuations and avoid disturbances.
5. **Support for Renewable Resources:** Demand response can manage fluctuations from renewable sources, especially by increasing consumption during periods of high renewable energy generation.

6. **Improved Economic Efficiency:** Adjusting consumption patterns based on price signals can reduce costs for both consumers and producers, enhancing economic efficiency.

Overall, demand response in the day-ahead market contributes to grid efficiency, cost reduction, and enhanced stability, supporting environmental and sustainability goals.

Simulation and Technical Explanations

In the demand response problem for the day-ahead market, three approaches are considered to examine the various impacts of different demand response programs. These approaches are described below:

Approach 1: Traditional Market

- **1-1 Traditional Environment with Load Shedding:** In this approach, the power system operates traditionally. Load shedding is applied temporarily in emergency situations to prevent network collapse and maintain system reliability.

- **1-2 Traditional Environment with Demand Response:** In this environment, the power system operates traditionally with the integration of demand response programs. Consumers adjust their consumption patterns based on signals from the network, leading to improved operational efficiency and reduced costs.

Approach 2: Market Environment

- **2-1 Market with Load Shedding:** In this scenario, the electricity market operates competitively, and load shedding is implemented in emergency situations to balance supply and demand.

- **2-2 Market with Demand Response:** Here, demand response programs are applied in a competitive market, where consumers adjust their consumption based on price signals, resulting in price stabilization and improved power market stability.

Approach 3: Market with Various Load Types

This environment considers different types of loads:

- **Fixed Loads:** Consumers with a fixed consumption pattern that does not change.

- **Elastic Loads:** Consumers who can adjust their consumption based on market prices and conditions.

- **Interruptible Loads:** Consumers who can reduce or interrupt their consumption during peak periods or critical conditions.

- **Shiftable Loads:** Consumers who can shift their consumption from one time period to another.

This approach provides a comprehensive analysis of various consumer behaviors and their impacts on the power market and grid stability, identifying optimal solutions for balancing supply and demand.

Objective Function and Constraints for Approach 1

First Part

The objective function and constraints for Approach 1 are as follows:

$$\min \sum_{t=1}^{24} \sum_{i=1}^{39} \left(a_i P_g(i,t)^2 + b_i P_g(i,t) + c_i u(i,t)\right) + \sum_{t=1}^{24} \sum_{i=1}^{39} \mathrm{VOLL}(i,t) \cdot P_{sh}(i,t) \tag{1}$$

$$P_g^{\min}(i) \cdot u(i,t) \le P_g(i,t) \le P_g^{\max}(i) \cdot u(i,t) \tag{2}$$

$$0 \le P_{sh}(i,t) \le P_L(i,t) \tag{3}$$

$$D_L(i,t) = P_L(i,t) - P_{sh}(i,t) \tag{4}$$

$$P_g(i,t) - D_L(i,t) = \sum_{j=1}^{39} B_{ij} \delta(j,t) \tag{5}$$

$$F(i,j,t) = B_{ij} \left(\delta(i,t) - \delta(j,t)\right) \tag{6}$$

$$-\,\mathrm{Flow}_{\max}(i,j) \le F(i,j,t) \le \mathrm{Flow}_{\max}(i,j) \tag{7}$$

Second Part

The second part includes additional bidding terms:

$$\min \sum_{t=1}^{24} \sum_{i=1}^{39} \left(a_i P_g(i,t)^2 + b_i P_g(i,t) + c_i u(i,t)\right) + \sum_{t=10,3,39} (\mathrm{bid}_c)\left(-P_c(c,t)\right) + \sum_{\mathrm{df}=4,8,20} \mathrm{bid}_{\mathrm{df}} P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \tag{8}$$

$$P_g^{\min}(i) \cdot u(i,t) \le P_g(i,t) \le P_g^{\max}(i) \cdot u(i,t) \tag{9}$$

$$-\sum_{t=10}^{12} \sum_{c=1}^{12} P_c(c,t) \le 0 \tag{10}$$

$$P_{\mathrm{df}}(\mathrm{df},t) = \mathrm{coef}_{\mathrm{df}}(\mathrm{df},t) \cdot P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \tag{11}$$

$$D_L(i,t) = P_L(i,t) + P_{\mathrm{df}}(\mathrm{df},t) + P_c(c,t) \tag{12}$$

Objective Function and Constraints for Approach 2

First Part

The objective function and constraints for Approach 2 are similar but include different values:

$$\min \sum_{t=1}^{24} \sum_{i=1}^{39} \left(\mathrm{bid}_g(i) P_g(i,t) u(i,t)\right) + \sum_{t=10,c=3,39} (\mathrm{bid}_c)\left(-P_c(c,t)\right) \tag{13}$$

$$\mathrm{VOLL}(i,t) = 300\$/\mathrm{MWh} \quad 1 \le t \le 24,\ 1 \le i \le 39 \tag{14}$$

Additional constraints are set as follows:

$$P_g^{\min}(i) \cdot u(i,t) \leq P_g(i,t) \leq P_g^{\max}(i) \cdot u(i,t) \tag{15}$$

$$P_L(i,t) = P_L(i,t) - P_{sh}(i,t) \tag{16}$$

$$P_g(i,t) - D_L(i,t) = \sum_{j=1}^{39} B_{ij}\delta(j,t) \tag{17}$$

$$F(i,j,t) = B_{ij}\left(\delta(i,t) - \delta(j,t)\right) \tag{18}$$

$$-\,\mathrm{Flow}_{\max}(i,j) \leq F(i,j,t) \leq \mathrm{Flow}_{\max}(i,j) \tag{19}$$

Second Part

$$\min\left(\sum_{t=1}^{24}\sum_{i=1}^{39}\mathrm{bid}_g(i)P_g(i,t)u(i,t) + \sum_{t=10}^{12}\sum_{c=3,39}\mathrm{bid}_c(c)\left(-P_c(c,t)\right) + \sum_{\mathrm{df}=4,8,20}\mathrm{bid}_{\mathrm{df}}P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df})\right) \tag{20}$$

Subject to: $$P_g^{\min}(i)u(i,t) \leq P_g(i,t) \leq P_g^{\max}(i)u(i,t) \tag{21}$$

$$-\,\mathrm{amount}(c) \leq \sum_{t=10}^{12}\{P_c(c,t)\} \leq 0 \tag{22}$$

$$P_{\mathrm{dr}}(\mathrm{df},t) = \mathrm{coef}_{\mathrm{df}}P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \tag{23}$$

$$-\,P_c(c,t) \leq P_{\mathrm{dr}}(\mathrm{df},t) \leq 0 \quad \text{if } \mathrm{coef}_{\mathrm{df}}(df,t) \leq 0 \tag{24}$$

$$-\,D_L(c,t) \leq P_{\mathrm{dr}}(\mathrm{df},t) \leq 0 \quad \text{if } \mathrm{coef}_{\mathrm{df}}(df,t) \leq 0 \tag{25}$$

$$0 \leq P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \leq \mathrm{amount}(\mathrm{df}) \tag{26}$$

$$D_L(i,t) = P_L(i,t) + P_{\mathrm{dr}}(\mathrm{df},t) + P_c(c,t) \tag{27}$$

$$P_g(i,t) - D_L(i,t) = \sum_{j=1}^{39} B_{ij}\delta(j,t) \tag{28}$$

$$F(i,j,t) = B_{ij}\left(\delta(i,t) - \delta(j,t)\right) \tag{29}$$

$$-\,\mathrm{Flow}_{\max}(i,j) \leq F(i,j,t) \leq \mathrm{Flow}_{\max}(i,j) \tag{30}$$

Objective Function and Constraints for Approach 3

The third approach integrates both bidding and stability functions:

$$\max \mathrm{SW} = \max\left\{\mathrm{VOLL}(i,t) + \sum_{i=1}^{19}P_L(i,t) + \sum_{i=30}^{39}P_L(i,t) + \sum_{t=20}^{24}\sum_{\mathrm{el}=20}^{29}[\mathrm{MU}(\mathrm{el})D_{\mathrm{el}}(el,t)](el,t)\right\} \tag{31}$$

The extended objective function and constraints for Approach 3 are as follows:

$$P_g^{\min}(i) \cdot u(i,t) \leq P_g(i,t) \leq P_g^{\max}(i) \cdot u(i,t) \tag{32}$$

$$D_L(i,t) = P_L(i,t) + D_{\{el\}}(el,t) \tag{33}$$

$$P_g(i,t) - D_L(i,t) = \sum_{j=1}^{39} B_{ij}\delta(j,t) \tag{34}$$

$$F(i,j,t) = B_{ij}\left(\delta(i,t) - \delta(j,t)\right) \tag{35}$$

$$-\,\mathrm{Flow}_{\max}(i,j) \leq F(i,j,t) \leq \mathrm{Flow}_{\max}(i,j) \tag{36}$$

The maximization of social welfare (SW) is given by:

$$\max \mathrm{SW} = \max\left\{\sum_{t=1}^{24}\mathrm{VOLL}(t) + \sum_{i=1}^{39} P_L(i,t) + \sum_{i=1}^{19} P_L(i,t) + \sum_{\mathrm{el}=1}^{24}\left[\mathrm{MU}(\mathrm{el})D_{\mathrm{el}}(el,t)\right]\right\} \tag{37}$$

$$-\sum_{t=1}^{24}\sum_{i=1}^{39}\left[\mathrm{MC}(i,t)P_g(i,t)u(i,t)\right] - \sum_{c=10}^{12}\mathrm{bid}_c(-P_c(c,t)) - \sum_{\mathrm{df}=4,8,20}\mathrm{bid}_{\mathrm{df}}P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \tag{38}$$

Subject to the following constraints:

$$P_g^{\min}(i) \cdot u(i,t) \leq P_g(i,t) \leq P_g^{\max}(i) \cdot u(i,t) \tag{39}$$

$$P_c(c,t) \leq P_c(i,t) \leq 0 \quad \text{if } c \in \mathrm{eel} \quad 10 \leq t \leq 12 \tag{40}$$

$$-\,D_L(c,t) \leq P_c(i,t) \leq 0 \quad \text{if } c \in \mathrm{eel} \quad 10 \leq t \leq 12 \tag{41}$$

$$-\,\mathrm{amount}(c) \leq \sum_{c=10}^{12} P_c(c,t) \leq 0 \tag{42}$$

$$P_{\mathrm{df}}(\mathrm{df},t) = \mathrm{coef}_{\mathrm{df}}(\mathrm{df},t)P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \tag{43}$$

$$-\,P_c(c,t) \leq P_{\mathrm{df}}(\mathrm{df},t) \leq 0 \quad \text{if } \mathrm{coef}_{\mathrm{df}}(df,t) \leq 0 \tag{44}$$

$$-\,D_L(c,t) \leq P_{\mathrm{df}}(\mathrm{df},t) \leq 0 \quad \text{if } \mathrm{coef}_{\mathrm{df}}(df,t) \leq 0 \tag{45}$$

$$0 \leq P_{\mathrm{df}}^{\mathrm{tot}}(\mathrm{df}) \leq \mathrm{amount}(\mathrm{df}) \tag{46}$$

Additional constraints include load demands and flows:

$$D_{\{L\}}(i,t) = P_{\{L\}}(i,t) + D_{\{px\}}(pt,t) + P_{\{c\}}(c,t) + P_{\{df\}}(df,t) \tag{47}$$

$$D_L(i,t) - D_L(i,t) = \sum_{j=1}^{39} B_{ij}\delta(j,t) \tag{48}$$

$$F(i,j,t) = B_{ij}\left(\delta(i,t) - \delta(j,t)\right) \quad 1 \leq i,j \leq 39 \tag{49}$$

$$-\,\mathrm{Flow}_{\max}(i,j) \leq F(i,j,t) \leq \mathrm{Flow}_{\max}(i,j) \quad 1 \leq i,j \leq 39 \tag{50}$$

Instructions for Code Usage

To run the code, first place the files in the specified directory and then execute the program.

Input Data

In this section, we observe the input data for the problem.

- Figure 1 shows the installation location of units. From this diagram, we can identify which bus each unit is connected to.

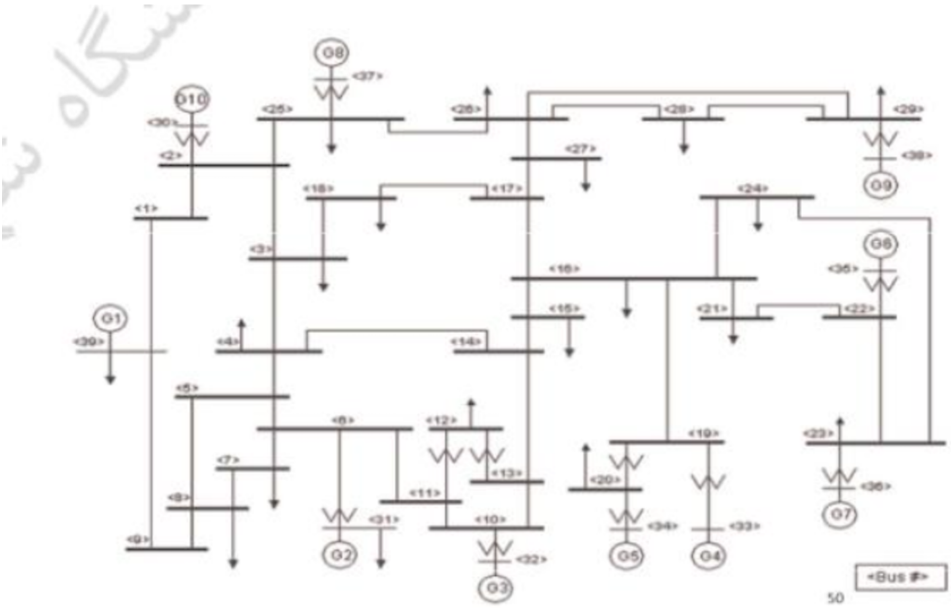


Figure 1: Diagram of the 39-Bus System

The base power and voltage values for the system are:

$$S_{\text{base}} = 33.67 \text{ MVA}, \quad V_{\text{base}} = 230 \text{ kV}$$

Table 1: Generator Information

The table below lists the information for each generator, including the maximum and minimum power outputs (Pmax, Pmin, Qmax, Qmin) and the cost coefficients (a, b, c, MC).

Table 1: Generator Specifications

Generator	Pmax	Pmin	Qmax	Qmin	a	b	c	MC
g1	1040	0	400	140	0.0384	25/93	34/76	29/92
g2	646	400	300	-100	0.0333	14/30	80	14/663
g3	725	500	300	150	0.0087	13/33	81/14	14/6524
g4	652	200	250	0	0.0078	13/22	0	14/9.63
g5	600	200	167	0	0.0062	18	217/89	19/44
g6	700	450	300	-100	0.0062	10/69	142/73	12/116
g7	680	200	240	0	0.0056	12/7	40	14/716
g8	564	400	250	0	0.0015	10/86	107/05	0/059
g9	865	600	300	-150	0.0019	7/5	211/91	9/02
g10	1100	0	300	-100	0.0045	6/6	100	11/64

The total installed capacity exceeds 3000 MW.

Table 2: Fixed and Shiftable Loads

The table below shows the values for fixed and shiftable loads across various scenarios.

Table 2: Fixed and Shiftable Loads

Load	sm1	sm2	sm3	sm4	sm5
3	32	27	22	17	12
39	35	30	25	20	15

Table 3: Cost of Control Loads

The table below provides the cost per megawatt-hour for control loads across different scenarios.

Table 3: Control Load Costs in $ per MWh

Amount	sm1	sm2	sm3	sm4	sm5
50	28	24	18	14	8
150	29	25	20	15	10
200	30	26	20	16	10

Code Explanation

The problem includes five scenarios, and each section of this report details one scenario. Each scenario is based on specific conditions and constraints, adding or removing certain elements to optimize the objective function and constraints.

Indices and Sets

The indices and sets are defined as follows:

- t: Time index, representing a 24-hour period.
- g: Generator index, indicating the number of generators in the network.
- bus: Index representing the number of buses in the network.
- slack: Index for the slack bus.
- t1 to t3: Indices for different time periods with varying costs.
- GB(bus, g): Indicates the connection of each generator to each bus.

```
Set
   t 'time'              / 1*24   /
   g 'generators indices' / g1*g10  /
   bus         / 1*39   /
   slack(bus) / 1      /
   t1(t) /1*9/
   t2(t) /12*24/
   t3(t) /10*12/
;
Alias (t,tt);
Alias (bus,node);

Set GB(bus,g) 'connectivity index of each generating unit to each bus'
/
30.g1
31.g2
32.g3
33.g4
34.g5
35.g6
36.g7
37.g8
38.g9
39.g10
```

Figure 2: Code snippet defining indices and sets

```
parameter  gendata(g,*) Information on the Generators ;
$call GDXXRW INdata.xlsx maxDupeErrors=100000000 par=gendata rng=Gen!a1
$GDXIN INdata.gdx
$load gendata
$GDXIN
;
parameter  Xij(bus,node) Inductance of transmission lines  ;
$call GDXXRW INdata.xlsx maxDupeErrors=100000000 par=Xij rng=Xij!a1
$GDXIN INdata.gdx
$load Xij
$GDXIN
;
parameter  Bij(bus,node) Suspedance of transmission lines ;
$call GDXXRW INdata.xlsx maxDupeErrors=100000000 par=Bij rng=Bij!a1
$GDXIN INdata.gdx
$load Bij
$GDXIN
;
parameter  Limit(bus,node) Transmission capacity ;
$call GDXXRW INdata.xlsx maxDupeErrors=100000000 par=Limit rng=Limit!a1
$GDXIN INdata.gdx
$load Limit
$GDXIN
```

Figure 3: Input data code for generators, transmission line inductance, and constraints

Input Data

The following code snippet demonstrates how the input data, including generator information, transmission line inductance, and other relevant system constraints, are retrieved from an Excel file.

- **Parameter** `gendata(g,*)`: Contains information on the generators.
- **Parameter** `Xij(bus, node)`: Represents the inductance of the transmission lines.

- **Parameter** `Bij(bus, node)`: Represents the susceptance of the transmission lines.
- **Parameter** `Limit(bus, node)`: Defines the transmission capacity of each line.

In Figure 3, we see the parameters being loaded from an Excel file using specific ranges and sheets.

```
Scalar
Voll /500/
;

parameter  Price(t,*) Price ;
$call GDXXRW INdata.xlsx maxDupeErrors=100000000 par=Price rng=Price!a1
$GDXIN INdata.gdx
$load Price
$GDXIN
;
```

Figure 4: Scalar parameter for price scaling to account for penalty costs in electricity pricing

- **Scalar** `Voll`: A penalty multiplier applied as a scalar value in the continuation of electricity pricing to handle varying penalty costs at different hours.

Decision Variables

The decision variables are categorized as follows:

- **Positive Variables:** Represent active and reactive power generation, load shedding amount, and consumption levels.
- **Binary Variables:** Used to determine generator states.

```
Variable
OF
delta0(bus,t)
Pij(bus,node,t)
;

Positive Variable
Pg(g,t)
Phs(bus,t)
DL(bus,t)
;
Binary Variable
u(g,t)
;
```

Figure 5: Code snippet showing decision variables

Modeling Equations and Objective Functions

The following equations define the objective functions and constraints for the system:

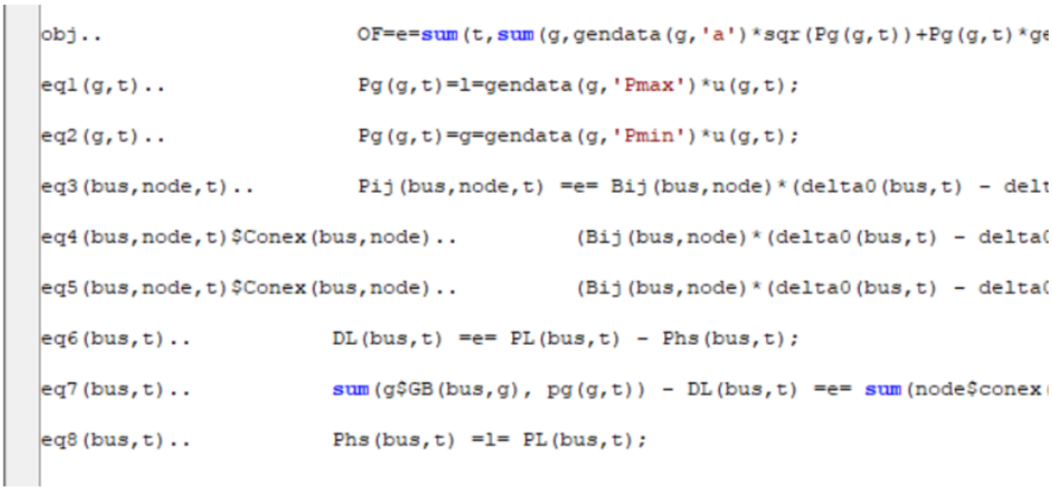
$$\text{obj} = \sum_{t,g} \left(a_g \cdot P_g(t)^2 + b_g \cdot P_g(t) \right) + \sum_{t} \text{VOLL}(t) \cdot \text{Load Shedding} \tag{51}$$

$$\text{eq1} : P_g(t) \geq \text{Pmin} \cdot u(g,t) \tag{52}$$

$$\text{eq2} : P_g(t) \leq \text{Pmax} \cdot u(g,t) \tag{53}$$

$$\text{eq3} : P_{\text{trans}}(bus, node, t) = B_{ij} \left(\delta(bus,t) - \delta(node,t) \right) \tag{54}$$

$$\vdots \tag{55}$$



```
obj..                          OF=e=sum(t,sum(g,gendata(g,'a')*sqr(Pg(g,t))+Pg(g,t)*ge
eq1(g,t)..                     Pg(g,t)=l=gendata(g,'Pmax')*u(g,t);
eq2(g,t)..                     Pg(g,t)=g=gendata(g,'Pmin')*u(g,t);
eq3(bus,node,t)..              Pij(bus,node,t)  =e= Bij(bus,node)*(delta0(bus,t)  - delt
eq4(bus,node,t)$Conex(bus,node)..          (Bij(bus,node)*(delta0(bus,t)  - delta(
eq5(bus,node,t)$Conex(bus,node)..          (Bij(bus,node)*(delta0(bus,t)  - delta(
eq6(bus,t)..                 DL(bus,t)  =e=  PL(bus,t)  - Phs(bus,t);
eq7(bus,t)..                 sum(g$GB(bus,g), pg(g,t))  - DL(bus,t)  =e= sum(node$conex
eq8(bus,t)..                 Phs(bus,t)  =l= PL(bus,t);
```

Figure 6: Modeling equations and constraints

Results

The simulation results are saved in an Excel file under NUM1, NUM2, NUM3, NUM4, and NUM5.

Biography

Amirreza Shafiei received the B.Sc. degree from Amirkabir University of Technology, Tehran, Iran, in 2022, in Electrical Engineering. He is currently a junior graduate student of Electrical Engineering at Shahid Beheshti University, Tehran. His main research interests include in the Transient Stability Assessment, Operation and Planning of Power Systems combined with Renewable Energy and Smartgrids.