DYNAMIC SIMULATION OF A PV-DIESEL-BATTERY HYBRID PLANT FOR OFF GRID ELECTRICITY SUPPLY

By:
Basem Idlbi

A Thesis Submitted To The Faculty Of Electrical Engineering And Computer Science At The University Of Kassel And Faculty Of Engineering At Cairo University
In Partial Fulfillment Of The Requirements For The Degree Of
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In
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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{acap}$</td>
<td>Annualized capital cost</td>
<td>[$]</td>
</tr>
<tr>
<td>$c_{arep}$</td>
<td>Annualized replacement cost</td>
<td>[$]</td>
</tr>
<tr>
<td>$C_{cap}$</td>
<td>Initial capital cost</td>
<td>[$]</td>
</tr>
<tr>
<td>$C_{rep}$</td>
<td>Capital cost of the replaced components</td>
<td>[$]</td>
</tr>
<tr>
<td>CRF</td>
<td>Capital recovery factor</td>
<td>-</td>
</tr>
<tr>
<td>$d$</td>
<td>Depth of discharge</td>
<td>[%]</td>
</tr>
<tr>
<td>$F$</td>
<td>Number of cycles to failure of a battery</td>
<td>[cycle]</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
<td>[HZ]</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>Maximum value of frequency to disconnect the PV field</td>
<td>[HZ]</td>
</tr>
<tr>
<td>$f_{min}$</td>
<td>Minimum value of frequency to disconnect the PV field</td>
<td>[HZ]</td>
</tr>
<tr>
<td>$f_r$</td>
<td>The value of frequency to start regulation of PV field</td>
<td>[HZ]</td>
</tr>
<tr>
<td>$f_{rep}$</td>
<td>Factor to compensate the difference between the component lifetime and the project lifetime</td>
<td>-</td>
</tr>
<tr>
<td>$i$</td>
<td>Real interest rate</td>
<td>[%]</td>
</tr>
<tr>
<td>$i'$</td>
<td>Nominal interest rate</td>
<td>[%]</td>
</tr>
<tr>
<td>$J$</td>
<td>Moment of inertia</td>
<td>[kg.m$^2$]</td>
</tr>
<tr>
<td>$K_{pj}$</td>
<td>Power sharing factor of the secondary control</td>
<td>-</td>
</tr>
<tr>
<td>$K_{pf,i}$</td>
<td>Primary control gain of generator</td>
<td>-</td>
</tr>
<tr>
<td>$N_{bat}$</td>
<td>Number of batteries in the battery bank</td>
<td>[cell]</td>
</tr>
<tr>
<td>$P$</td>
<td>Active power</td>
<td>[W]</td>
</tr>
<tr>
<td>$Q_{lifetime}$</td>
<td>Lifetime throughput of a battery</td>
<td>[kWh]</td>
</tr>
<tr>
<td>$q_{max}$</td>
<td>Maximum capacity of battery</td>
<td>[Ah]</td>
</tr>
<tr>
<td>$Q_{thrpt}$</td>
<td>Annual battery throughput</td>
<td>[kWh/year]</td>
</tr>
<tr>
<td>$R_{bat}$</td>
<td>Battery bank lifetime</td>
<td>[year]</td>
</tr>
<tr>
<td>$R_{bat,f}$</td>
<td>Battery float life</td>
<td>[year]</td>
</tr>
<tr>
<td>$R_{comp}$</td>
<td>Lifetime of component</td>
<td>[year]</td>
</tr>
<tr>
<td>$R_{rep}$</td>
<td>Replacement cost duration</td>
<td>[year]</td>
</tr>
<tr>
<td>$R_{proj}$</td>
<td>Project lifetime</td>
<td>[year]</td>
</tr>
<tr>
<td>$S$</td>
<td>Salavage at the end of the project lifetime</td>
<td>[$]</td>
</tr>
<tr>
<td>$SFF$</td>
<td>Sinking fund factor</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>$S_n$</td>
<td>Generator nominal apparent power</td>
<td>[VA]</td>
</tr>
<tr>
<td>$T_{ags}$</td>
<td>Acceleration time constant</td>
<td>[s]</td>
</tr>
<tr>
<td>$U_{DC}$</td>
<td>Terminal DC voltage of the battery</td>
<td>[V]</td>
</tr>
<tr>
<td>$U_{max}$</td>
<td>Cell voltage of fully loaded cell</td>
<td>[V]</td>
</tr>
<tr>
<td>$U_{min}$</td>
<td>Cell voltage of discharged cell</td>
<td>[V]</td>
</tr>
<tr>
<td>$\dot{V}_f$</td>
<td>Volume flow rate of fuel</td>
<td>[litre/h]</td>
</tr>
<tr>
<td>$V_{nom}$</td>
<td>Nominal voltage of the battery</td>
<td>[V]</td>
</tr>
<tr>
<td>$\omega_{FL}$</td>
<td>Speeds of generators at full load</td>
<td>[rad/sec]</td>
</tr>
<tr>
<td>$\omega_{NL}$</td>
<td>Speeds of generators at no load</td>
<td>[rad/sec]</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>Rated angular velocity</td>
<td>[rad/sec]</td>
</tr>
<tr>
<td>$Z_i$</td>
<td>Internal resistance of the battery</td>
<td>[ohm]</td>
</tr>
</tbody>
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**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic voltage regulator</td>
</tr>
<tr>
<td>BB</td>
<td>Bus bar</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery energy storage system</td>
</tr>
<tr>
<td>COE</td>
<td>Cost of energy</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DSL</td>
<td>Dlgsilent simulation language</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage level</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated gate bipolar transistor</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage level</td>
</tr>
<tr>
<td>MENA</td>
<td>Middle East and North Africa</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum power point</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and maintenance</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>sfc</td>
<td>Specific fuel consumption</td>
</tr>
<tr>
<td>SOC</td>
<td>State of charge of the battery</td>
</tr>
<tr>
<td>VCO</td>
<td>Voltage controller</td>
</tr>
<tr>
<td>VP-controller</td>
<td>Voltage and power controller</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage sourced converter</td>
</tr>
</tbody>
</table>
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ABSTRACT

Hybrid plants, which are composed of combinations of diesel generators, battery energy storage system and renewable energy resources such as photovoltaic, are outlined as a recommended approach for off grid power supply options for remote areas applications. According to frequency control of stand-alone grids, the output power of the diesel generators and the battery energy storage system are susceptible to variations in order to compensate power fluctuations, which are caused by the variations of the load and power of the PV field. The variations in the loading of diesel generators can have adverse effects on the operation, such as increase of fuel consumption, maintenance and slobbering problems.

This thesis analyzes different control strategies to improve the operation of stand-alone PV-diesel generator-battery plants, and to reduce the operation cost accordingly. Therefore, four control strategies are proposed according to primary and secondary control of frequency. Each control strategy provides different loading patterns of the diesel generators and the storage system. Dynamic simulations of the plant operation are performed according to each control strategy. The effects of the control strategy are analyzed according to four criterions: the frequency deviations, fuel consumption, lifetime of the batteries and the performance of the diesel generators. Finally, the cost of energy is calculated by considering the difference in fuel consumption according to each control strategy.

The simulation results show that the control strategy, which covers the power fluctuations mainly from the battery system, demonstrates more constant output power of diesel generators, lower frequency deviations, less fuel consumption, better performance of the diesel generators and less cost of energy, but less expected lifetime of the batteries compared to the other analyzed control strategies. On the other hand, the control strategy, which covers the power fluctuations from the diesel generators and the battery system in parallel, demonstrates higher variation in output power of the diesel generators, higher frequency deviations, higher fuel consumption, less favorable performance of the diesel generators and higher cost of energy, but higher expected lifetime of the battery compared to the other analyzed control strategies.
CHAPTER ONE:

INTRODUCTION
1. INTRODUCTION

Public interconnected power grids are composed of complex combinations of generation plants, substations, transformers and transmission lines, which supply electricity to cities, businesses and industry. In addition, there are smaller independent power grids that provide power to islands or remote areas, which have limited or no access to public interconnected grids [1]. Connecting these areas and regions to the public grid is a time and money consuming process or in some cases physically impossible [2]. Traditionally, small stand-alone grids are electrified by diesel generators [1]. However, the renewable energy resources are attractive sources of power, since they can provide sustainable and clean power. Hybrid plants can be an integration of diesel generators with renewable energy resources such as photovoltaic. In addition, integrating a battery energy storage system (BESS) with the hybrid plant provides significant dynamic operation benefits such as higher stability and reliability of power supply [3]. Hybrid plants are outlined as an optimum approach for off grid power supply options for remote areas applications [4].

The hybrid plant must continually manage the fluctuations of the load and output power of the PV field to maintain the nominal frequency of the grid, which is a requirement for the satisfactory operation of power systems [5], [1]. According to the frequency control, the components of the plant are susceptible to variations in active power loading, because the frequency is dependent on the active power of the grid [5]. However, the variations in the output power of the diesel generators can lead to adverse effects on the operation such as increase of fuel consumption, maintenance, slobbering problems etc [6].

The objective of this thesis is to analyze different control strategies in order to study options for improving the operation of PV-diesel generator-battery hybrid plants in stand-alone applications. The studied options focus on reducing the adverse effects of the variations in the load and the power of PV field. Accordingly, the operation cost can be reduced. Therefore, the active power control is analyzed, and the effects of the control strategy on the operation and costs of the plant are studied according to four criterions. The criterions are the frequency deviations, fuel consumption, expected lifetime of the batteries and the performance of the diesel generators.
Active power control is analyzed according to primary control, which provides regulation in terms of few seconds, and secondary control, which provides much slower regulation [5].

In order to analyze the operation of the plant, the dynamic operation is run in the software PowerFactory. Firstly, a model of diesel plant is implemented by integrating built-in models of diesel generator with its controllers and a load model, and then the models of three diesel generators are integrated with the load. Moreover, a model of fuel consumption measurement is developed in the thesis and integrated. Then, a model of battery energy storage system is integrated with the diesel plant and load, and then a model of PV field is integrated with the plant. After that, the model is integrated with supplementary components such as lines and transformers. Finally, a model of secondary controller is developed in this thesis and integrated with the model of the plant.

Four control strategies in relation to primary and secondary control of active power are proposed. Each control strategy leads to different performance and variations in the output power of the diesel generators and the BESS. The operation of the hybrid plant is analyzed according to each control strategy according to the results of the simulations. The simulation is run for an example day according to each control strategy. Furthermore, the four control strategies are compared according to the four criterions. Finally, an economical overview is performed by considering the difference of fuel consumption between the proposed control strategies.
CHAPTER TWO:
ACTIVE POWER – FREQUENCY CONTROL
2. ACTIVE POWER - FREQUENCY CONTROL

2.1. PARALLEL OPERATION WITH DROOP CONTROL

The frequency of a grid is dependent of active power and the voltage of the grid is dependent of reactive power. For the satisfactory operation of power systems, it is important to keep the frequency and voltage close to their nominal values. In the simple case of one source of power in an island grid (i.e. one generator), the automatic voltage regulators (AVR) suffice to keep the voltage on target. For the frequency control, the speed governor of the generator suffices to keep the frequency close to the nominal value by accommodating changes in load demand as needed. For multiple sources of power in parallel, it is important to recognize that there are two essential control loops; the frequency control loop, which controls the active power sharing and the voltage control loop, which controls the reactive power sharing [5], [7].

In this thesis we will focus on the control of active power. Therefore, it is important to firstly define the following terms:

**Droop:** when a prime mover has a droop governor, the speed of the prime mover decreases as more load is applied. The droop value is the rate of frequency decrease to the load increase [7].

\[
Droop = \frac{\Delta f}{\Delta P} \ [pu/pu]
\]

\(\omega_{NL}, \omega_{FL} \): are the speeds at no load and full load respectively [5].
**Isochronous**: when a prime mover has an isochronous governor, the prime mover maintains its speed at the set value throughout the entire range of load. An isochronous governor has a zero droop [7].

![Figure 2: Isochronous characteristics of a governor](image)

“...The isochronous governors cannot be used when there are two or more units connected to the same grid since each generator would have to have precisely its same speed setting. Otherwise, they would fight each other, each trying to control system frequency to its own setting” [5].

With two or more parallel sources of power, the load demands the required power as long as the frequency and the voltage of the connected bus bar are maintained close to the nominal values. For the control of active power, the parallel power sources must have the ability to adjust their output power according to the load demand. The most common way, and the oldest technique is to use the droop control of frequency. The droop characteristics define the power sharing of different parallel power sources [5].

To clarify the technique of starting up two generators in parallel with droop control, we consider one slack generator (lead machine) with zero droop, and one generator with droop characteristics. If the slack machine is supplying power to a load and the second generator should operate in parallel, the second generator should be synchronized with the same frequency, voltage and phase angle of the first generator, then the switch can be closed. Initially the generator is rotating without providing power, but the operator adjusts the speed of the governor up that the second generator shares the load with the first generator. After starting up, both generators share the power of load changes according to their droop characteristics [7].
In PowerFactory, the slack machine is the reference machine which is selected in the tab of (load flow) of the model of synchronous generator (ElmSym). And the set value of power share between the paralleled machines is the dispatch value which is configured also in the same tab. However, the dispatch value determines only the initial value of power share. During the simulation, the share of active power is determined by the droop value of the governors of each machine, which determines the sharing of active power with load variations [8].

2.2. INERTIAL RESPONSE

When the load of one or more generators changes, it is reflected directly as a change in the electrical torque of the generators. This causes an unbalance between the mechanical torque and the electrical torque on the shaft of the generators. Consequently, the rotation speed of the generators varies. In stand-alone grids, this load change probably causes a deviation in the grid frequency. In the absence of governor, the system responds to a load change by the inertia of all the rotating machines which are connected to the grid. The inertial response represents the instantaneous active power delivered by the kinetic energy of the rotating parts in the grid. In this case the frequency drop is related to the inertia of the generators in the grid [5], [9].

In PowerFactory the inertia of the generators is represented in the generator model (ElmSym) in the tab of RMS simulation by the acceleration time constant of the generator ($T_{ags}$) [9].
The inertia of the machine is provided in the data sheet of the generator [Appendix A]. The acceleration time constant is calculated by the following equations [9]:

\[ J = S_n \frac{T_{ags}}{\omega_n^2} \]

\( J \) : is the moment of inertia;
\( \omega_n \) : is the rated angular velocity, which equals \( 2\pi f \);
\( S_n \) : is the generator nominal apparent power;
\( T_{ags} \) : is the acceleration time constant rated to \( S_n \);

In the datasheet of the simulated generator: \( J = 20 \text{ kg.m}^2 \).

By calculation, the acceleration time constant is: \( T_{ags} \approx 2 \text{ seconds} \).

**Note:** Battery inverters do not have inertial response, because they do not have rotating parts.

### 2.3. PRIMARY CONTROL AND GOVERNOR ACTION

The governor of a generator determines the active power primary control of the generator. The governors of the generators connected to the grid react shortly after a load change according to their primary control characteristics. The governor reaction decreases/increases the output power of the generators in order to retrieve a balance in the active power. On the other hand, the primary control of the battery energy storage system (BESS) is regulated by the frequency controller which is integrated with its controller. According to the primary control of load change, the frequency drops and stabilizes close to the nominal value after a short while. The frequency deviation is proportional to the value of load increase/decrease and the droop value of the primary control [5], [9].
The output power change of each generator and BESS is a function of the load change and the droop value, which is configured in the governor of the diesel generators or the frequency controller of the BESS in the studied grid. The modified output power of the diesel generator or BESS can be calculated according to the following equations [9]:

\[ P_i' = P_i + \Delta P_i \]

\( P_i' \) is the modified active power of the power source \( i \);

\( P_i \) is the initial active power value of power source \( i \);

\( \Delta P_i \) is the active power change in the power source according to primary control, which is determined by the total frequency deviation and the corresponding primary control gain \( K_{pf,i} \) (i.e. the inverse of the droop value) [9]:

\[ \Delta P_i = K_{pf,i} \times \Delta f \]

\( K_{pf,i} \) is the primary control gain of generator \( i \): [MW/HZ];

\( \Delta f \) is the total frequency deviation, which can be calculated as follows [9]:

\[ \Delta f = \frac{\Delta P_{Tot}}{\sum K_{pf}} \]

\( \sum K_{pf} \) is the summation of the primary control gain of all generators and BESS;
\( \Delta P_{Tot} \): is the total active power change by the primary control, which can be calculated according to [9]:

\[
\Delta P_{Tot} = \sum_{i=1}^{n} \Delta P_i
\]

Figure 5: Power sharing by parallel units with droop characteristics [5].

The typical value of the overall droop of grids is related to the grid codes in different countries. In the thesis, the droop value is changed to obtain different power sharing.

2.4. SECONDARY CONTROL

According to primary control, a change in the load of the grid causes a steady state frequency deviation. Restoration of the frequency to the nominal value requires supplementary control action, which adjusts the power reference set points. The secondary control is the automatic control of the set points of the power sources to maintain the frequency at the nominal value. The secondary control regulates the frequency and defines the interchanged power by adjusting the output power of the power sources. The secondary control action is much slower than the primary action, and it compensates the deviation after the primary control stabilizes the frequency. In other words, the secondary control overrides the frequency deviations which occur after the primary control. The power sources, which are not providing secondary control, restore the initial generation before the load change [5], [9]. More details about the secondary control of the studied hybrid plant are explained in the section of (developing of model of secondary controller).
CHAPTER THREE:
MODELING OF THE PLANT
3. MODELING OF THE PLANT

3.1. POWERFACTORY SIMULATION SOFTWARE

The software which is used to achieve the simulation is PowerFactory-version14.1 from the company DIgSILENT. The name **DIgSILENT** stands for "**DIGital SImuLation and Electrical NeTwork calculation program**" [10]. The simulation method is the balanced RMS simulation, which considers dynamics in electromechanical, control and thermal devices in symmetrical operation. [9]. The modeling is formed by the basic hierarchical levels of time-domain models:

• The DSL block definitions, based on the (DIgSILENT Simulation Language), form the basic building blocks to represent transfer functions, differential equations and primitive controllers in order to be implemented in more complex transient models. These models have the entity of (BlkRef) in PowerFactory [9].

• The built-in models or elements are the transient PowerFactory models for standard power system equipment, i.e. for generators, motors, static generators, etc. Only these models appear in the single line diagram, which shows the grid elements in PowerFactory. Each model has its own entity in PowerFactory. For example, the model of a synchronous generator has the entity of (ElmSym) in PowerFactory [9].

• The common models are based on the DSL block definitions and are the front-end of the user-defined transient models, which combine a model definition with specific parameter settings. The common models have the entity of (ElmDsl) in PowerFactory [9].

• The composite models are based on composite frames and are used to combine and interconnect several elements (built-in models) and/or common models. The composite frames enable the reuse of the basic structure of the composite model. This composite frame is basically a schematic diagram containing various empty slots, in which controller or elements can be assigned. The composite models have the entity of (ElmComp) in PowerFactory [9].

• A common model has a reference to the Model Definition (BlkDef), which looks similar to the composite frame. Here different blocks are attached together according to the diagram [9].
3.2. MODEL OF DIESEL GENERATORS

3.2.1. PHYSICAL DESCRIPTION OF DIESEL GENERATORS

A diesel generation unit is composed mainly of a diesel engine and a synchronous generator rotating on one shaft. The diesel engine provides the active power by converting the chemical energy of the fuel into mechanical energy, which is represented by the mechanical torque on the rotating shaft. On the other hand, the excitation system of the synchronous generator determines the reactive power by the excitation current in excitation windings of the rotor [2].

![General structure of diesel generators](image)

Figure 6: General structure of diesel generators [2].

The diesel engine is a reliable source of power that can provide power whenever it is needed according to its rated power, provided that the fuel is available. The diesel engine needs a governor to control the output power and the speed of the generator. The governor adjusts the fuel valve (throttle) in order to control the fuel rate according to load variations on the shaft [2].

3.2.2. MODEL OF SYNCHRONOUS GENERATOR IN POWERFACTOR

Synchronous generators have a built-in model in PowerFactory (ElmSym), which represents the equivalent circuit and the describing equations of the synchronous generator. The parameters and the rated values of the generator can be entered in the model in the edit dialog after copying the model from the global library to the user library [8]. The used generator for the thesis is 1.02 [MVA] with nominal power of 0.816 [MW], whose datasheet is attached in [Appendix A].
3.2.3. MODEL OF DIESEL GOVERNOR IN POWERFACTORY

The analyzed model of governor in this thesis is a built-in model in PowerFactory with the name “DEGOV1”, which can be found in the standard models of the global library of PowerFactory. The model is based on IEEE model, which is developed by Woodward Company [8].

The model contains three main blocks. The electric control box is an analogue controller type PT1, which gives the control signal. The actuator converts the control signal into a signal of fuel flow rate (throttle). The engine block represents the delay of the combustion to convert the fuel signal into torque signal [8].

The analyzed governor has droop characteristics, which are determined by the parameters of the model. The parameters should be configured in order to approximately simulate the actual performance of the diesel engine.

Calibration of parameters of the diesel governor:
The parameters of controllers in PowerFactory are the values of gains, time constants or nominal values of the blocks in the controllers. The parameters determine the characteristics of the controllers and the performance of its operation. However, tuning the parameters is a difficult process, since the mathematical methods can be too complicated for complex paths of the control signals. In addition, some models can interfere with the signals indirectly such as the models of lines, bus bars and transformers. Therefore, the parameters in the thesis are mainly calibrated by try-and-error method. Accordingly, the governor is configured according Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>[pu/pu]</td>
<td>Actuator gain</td>
<td>9</td>
</tr>
<tr>
<td>T4</td>
<td>[s]</td>
<td>Actuator derivative time constant</td>
<td>0.35</td>
</tr>
<tr>
<td>T5</td>
<td>[s]</td>
<td>Actuator first time constant</td>
<td>0.002</td>
</tr>
<tr>
<td>T6</td>
<td>[s]</td>
<td>Actuator second time constant</td>
<td>0.015</td>
</tr>
<tr>
<td>TD</td>
<td>[s]</td>
<td>Combustion delay</td>
<td>0.024</td>
</tr>
<tr>
<td>Droop</td>
<td>[pu/pu]</td>
<td>Frequency deviation / active power change</td>
<td>0.02</td>
</tr>
<tr>
<td>TE</td>
<td>[s]</td>
<td>Time const. power feedback</td>
<td>0.5</td>
</tr>
<tr>
<td>T1</td>
<td>[s]</td>
<td>Electric control box first time constant</td>
<td>0.018</td>
</tr>
<tr>
<td>T2</td>
<td>[s]</td>
<td>Electric control box second time constant</td>
<td>0.0001</td>
</tr>
<tr>
<td>T3</td>
<td>[s]</td>
<td>Electric control box derivative time constant</td>
<td>0.38</td>
</tr>
<tr>
<td>Droop_Control</td>
<td></td>
<td>(0=Throttle feedback, 1=Elec. Power feedback)</td>
<td>1</td>
</tr>
<tr>
<td>PN</td>
<td>[MW]</td>
<td>Prime mover rated power (PN=Pgnn)</td>
<td>0.816</td>
</tr>
<tr>
<td>Tmin</td>
<td>[pu]</td>
<td>Minimum torque (at minimum position of throttle)</td>
<td>0</td>
</tr>
<tr>
<td>Tmax</td>
<td>[pu]</td>
<td>Maximum torque (at maximum position of throttle)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the model of the diesel governor.

3.2.4. MODEL OF VOLTAGE CONTROLLER IN POWERFACTORY

The voltage controller controls the excitation current by adjusting the excitation voltage of the rotor windings. The excitation system controls the reactive power of the generator and thus the voltage [5]. Although the thesis does not focus on the voltage control in the grid, a model of voltage controller must be implemented to run a simulation with realistic values of voltage.

The implemented model is an IEEE model from global library of PowerFactory [8].
Figure 8: Common model of the voltage controller [8].

The model receives the actual voltage and set point to provide the excitation voltage accordingly.

**Calibration of voltage controller parameters:**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tr</strong></td>
<td>[s]</td>
<td>Measurement delay</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Ka</strong></td>
<td>[pu]</td>
<td>Controller gain</td>
<td>150</td>
</tr>
<tr>
<td><strong>Ta</strong></td>
<td>[s]</td>
<td>Controller time constant</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Ke</strong></td>
<td>[pu]</td>
<td>Excitor constant</td>
<td>1</td>
</tr>
<tr>
<td><strong>Te</strong></td>
<td>[s]</td>
<td>Excitor time constant</td>
<td>0</td>
</tr>
<tr>
<td><strong>Kf</strong></td>
<td>[pu]</td>
<td>Stabilization path gain</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Tf</strong></td>
<td>[s]</td>
<td>Stabilization path time constant</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>E1</strong></td>
<td>[pu]</td>
<td>Saturation factor 1</td>
<td>6</td>
</tr>
<tr>
<td><strong>Se1</strong></td>
<td>[pu]</td>
<td>Saturation factor 2</td>
<td>1</td>
</tr>
<tr>
<td><strong>E2</strong></td>
<td>[pu]</td>
<td>Saturation factor 3</td>
<td>10</td>
</tr>
<tr>
<td><strong>Se2</strong></td>
<td>[pu]</td>
<td>Saturation factor 4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Vrmin</strong></td>
<td>[pu]</td>
<td>Controller output minimum</td>
<td>0</td>
</tr>
<tr>
<td><strong>Vrmax</strong></td>
<td>[pu]</td>
<td>Controller output maximum</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2: Parameters of the model of the voltage controller of the diesel generator.
Note: the implemented composite model frame of the diesel generator, which represents the signal flow between the common models, is the built-in IEEE model frame from the global library of PowerFactory [8].

3.2.5. SIMULATION OF PRIMARY CONTROL OF DIESEL GENERATOR
In order to analyze the primary control of the diesel generator, a diesel generator is simulated with a load, when the load changes by a step of 10%. The primary control of active power is determined by the characteristics of the diesel governor. The governor is responsible on regulating the torque at the rotating shaft in order to provide the balancing active power in short term [5]. The characteristics of the governor are determined by the parameters of the common model of the diesel governor, which is configured according to the parameters in the Table 1, but the droop here is set to the value of 0.04 [pu/pu].

Figure 9: The grid components for the simulation of primary control of diesel generator.

Figure 10: Simulation results of primary control of a diesel generator with a load step of 10% increase (normal regulation).
The initial value of the load is 0.75 [MW], which is defined as dispatch value in the (load flow) tab of the load model. Figure 10 shows that the increase of power demand by the load is supplied adequately by the generator. The frequency drops rapidly after the load step, until the governor controls the active power and stabilizes the frequency. The settling time (the time interval between the load step and the steady state operation [11]) is about 6 seconds, and the steady state frequency deviation is about 0.004pu.

In order to obtain a faster reaction of the governor, the value of the parameter (T4: actuator derivative time constant) is reduced to the value of 0.05 second. Also, (K: actuator gain) should be changed to the value of 57 [pu/pu]. The results of frequency and active power for the same load step applied are simulated again.

![Simulation results of primary control of a diesel generator with a load step of 10% increase (fast regulation).](image)

Figure 11 shows that the reaction of the governor is faster than in Figure 10. The settling time is about 2 seconds. Nevertheless, the steady state frequency deviation is the same as in Figure 10, because the value of the droop is the same in both simulations.

The first case of simulation is closer to reality, since the time delay of the reaction of the diesel engine is considerable. The diesel engine needs time to regulate the output power because of the
delay of the throttle reaction and the delay of combustion [12]. Therefore, the configuration of the first simulation case is adopted in the following simulations.

3.2.6. SIMULATION OF PRIMARY CONTROL OF PARALLEL DIESEL GENERATORS

Three diesel generators in parallel are simulated with a load and the load increases in a step of 10%. The dispatch value of active power is at the nominal value for all the generators (0.816 [kW]). The three generators have the same type of governor and voltage controller, which are configured according to Table 1 and Table 2 respectively. Also, the same droop value is configured in all the governors (0.04 [pu]).

![Diagram of grid components](image)

**Figure 12:** The grid components for the simulation of primary control of parallel diesel generators.

![Simulation results](image)

**Figure 13:** Simulation results of primary control of parallel diesel generators with load step of 10%.
Figure 13 shows that the active power of all generators equally increases after the load step. The three generators share the same value of primary control of active power, since they have the same value of the droop. In addition, the frequency signal is similar to the frequency in the case of one diesel generator with normal regulation.

**Note:** in the following simulations, only the output of one diesel generator is shown in the simulation results, because the parallel generators have the same characteristics and output.

### 3.2.7. ADJUSTING THE MODEL OF DIESEL GENERATORS TO APPLY DISPATCHING

In order to minimize the fuel consumption of the plant, diesel generators should be disconnected or connected according to the need of power supply in the grid. The scheduling of the generators switching is expressed as the dispatch control. The simulation of disconnection and connection of the diesel generators models in PowerFactory cannot be applied with built-in commands, because there is no built-in model of synchronization unit. Therefore, the disconnection is applied by some adjustments to the model of the diesel governor to get zero output power.

![Figure 14: Model of the governor after the adjustment for dispatching.](image)
The set point of the governor is multiplied by a constant (called dispatcher), which equals 1 at normal operation. In order to switch off the generator, a parameter event is defined to change the constant to 0. To reconnect the generator, a parameter event is defined to change the constant to 1 again. The parameter event can be defined in the simulation event window of PowerFactory. In addition, the same method is applied with the voltage controller for disconnecting or connecting the generator.

**3.2.8. DEVELOPING A MODEL OF FUEL CONSUMPTION MEASUREMENT**

The fuel consumption is measured as a volume flow rate or mass flow rate per unit time. An important parameter is the specific fuel consumption, which represents the fuel flow rate per unit output power. It reflects how efficiently an engine is consuming the fuel to produce energy. Lower values of $sfc$ are apparently desirable and represent more efficient operation [12].

\[
sfc = \frac{\dot{V}_f}{P}
\]

$sfc$ : is the specific fuel consumption [litre/kWh];

$\dot{V}_f$ : is the volume flow rate [litre/h];

$P$ : is the output power [kW].

The reference volume flow rate is usually mentioned in the datasheet as a function of engine loading [Appendix B]. The reference flow represents the fuel consumption under steady state operation. For the implemented model of engine, the reference volume flow rate is obtained from the data sheet of an engine which has the same capacity (1 [MVA]). The data sheet provides three values of fuel flow with different loading levels.

<table>
<thead>
<tr>
<th>Level of loading</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference fuel flow [litre/h]</td>
<td>216.9</td>
<td>171.7</td>
<td>122.3</td>
</tr>
</tbody>
</table>

*Table 3: Reference flow rate of fuel [Appendix B].*
The throttle signal in the model of the governor represents the fuel flow rate in [pu], which is the source of mechanical torque. The actual torque after this signal is subject to the transport delay of combustion of the throttle signal (Figure 14) [8].

In order to simulate the instantaneous values of fuel consumption, a simple model is built, in which the signal of throttle is multiplied by the corresponding reference flow rate from the datasheet. The instantaneous values of specific fuel consumption are simply obtained by dividing the fuel flow rate by the output power of the generator.

![Diagram of fuel measurement model](image)

**Figure 15: Common model of fuel measurement.**

The inputs of the model are the throttle signal from the model of the governor, and the output power from the model of the generator. The signal of the throttle is multiplied by the reference fuel flow to get the instantaneous flow. The output power is multiplied by 1000 to convert the unit into [kW], and the fuel flow is divided by the output power resulting in the specific fuel consumption.

The following notes should be considered in relation to the fuel measurement model:
• The model is built for short-term simulations, since the reference fuel flow has a specific value according to the loading level of the engine. If the diesel generator operates at the nominal power, the throttle is multiplied by the reference flow rate at 100% loading.

• For the long term simulations, the loading of the engine can vary considerably so that the reference flow needs to be changed with the loading level. Therefore, the reference flow is obtained instantaneously by cubic interpolation of the mentioned flow rates in the datasheet with the instantaneous value of output power. The signal of fuel consumption and specific fuel consumption are processed in Matlab program in order to change the reference fuel flow according to look-up table with cubic interpolation.

![Figure 16: Reference fuel flow rate.](image)

The reference flow is not linearly proportional to the output power, since the efficiency of the engine can vary according to the loading.

• There are two if-switches in the model in order to prevent simulation errors in case the generator is disconnected. A mathematical error occurs if the specific fuel consumption is divided by zero output power when the generator is switched off. Therefore, the signal of specific fuel consumption is switched to zero when the throttle is zero.

• Diesel consumption under steady state conditions is primarily function of load. The efficiency of diesel engines is higher when the loading is close to 100%. Variations of the PV output power or the load drives the efficiency of the diesel engine down, causing the diesel to operate at lower overall specific fuel consumption. Load ramping of the diesel engine leads to rapid or extreme diesel throttle variations, which dynamically increase fuel consumption [13].
3.3. MODEL OF BATTERY ENERGY STORAGE SYSTEM (BESS)

3.3.1. PHYSICAL DESCRIPTION OF THE BESS

The battery energy storage system consists of two main parts; the electrochemical storage part and the rectifier/inverter, which transform the voltage from DC to AC and vice versa. The rectifier/inverter is usually based on a voltage source converter (VSC), whose model is available in PowerFactory. The model of the rechargeable battery depends on the actual application, because different battery technologies have diverse characteristics. Therefore, there is no easy accurate model, which is valid for all types of batteries. The battery model used in the studied plant is lead-acid, which is the most common type of batteries for most applications, especially with high capacities, because of the relatively lower cost compared to other types [14].

![Diagram of BESS in PowerFactory](image)

Figure 17: General structure of the battery energy storage system in PowerFactory [14].

3.3.2. ADVANTAGES OF THE BESS IN OFF GRID OPERATION

The BESS are implemented in parallel with different applications of renewable energy in order to improve the frequency, voltage, oscillatory and transient stability, and hence to increase the reliability of the grid. The implementation of the BESS can replace or reduce the need of spinning reserve in the network, which are the rotating generators. The importance of the BESS
increases considerably in small or island power systems, with rather low spinning reserve, when load perturbation has a serious effect on the frequency of the grid [3].

In the analyzed hybrid plant in this thesis, the BESS has a significant role in covering the power change in the network. The BESS is always connected to the network even when the PV field or the diesel generators provide the power demand adequately. The BESS can cover the power unbalance between the supplied power and the load of the grid by storing the excess energy or supplying the residual demand. The BESS charges when the frequency increases, and discharges when there is a frequency drop. An advantage of implementing the BESS is the faster provision of power compared to the diesel generators. In addition, the BESS stores the excess energy in the grid, in particular when the output power of the PV field is higher than the demand [3].

3.3.3. MODEL OF THE BATTERY IN POWERFACTORY

The analyzed model of the battery storage system is obtained from a built-in template in PowerFactory. The model of the battery is described by the terminal voltage and the internal resistance, which are functions of different characteristics and variables of the battery, such as the state of charge (SOC), the age and temperature of the battery. The battery is fully loaded if the SOC is one and it is zero if the battery is empty [14].

![Simple equivalent circuit of battery](image)

**Figure 18: Simple equivalent circuit of battery [14].**

Figure 18 shows a simple electrical equivalent of the battery, which consists of a voltage source and an internal resistance. The resistance and the voltage are dependent on the state of charge. The battery voltage has non-linear values if the value of state of charge is under 0.5 [14].
Figure 19: Typical discharge profile of lead-acid battery [14].

Figure 19 shows that the battery voltage increases non-linearly with the SOC, while the internal resistance decreases non-linearly with the SOC of the battery.

Some assumptions are made to get a simple, but functional model. At first, it is assumed, that the SOC battery does not reach less than 20%. In that case the voltage could be assumed as linearly dependant on the SOC. Additionally, the internal resistance is assumed as constant, because it has to be very small due to the high current applications. The battery capacity is assumed as constant. This is valid if the discharge current is determined in advance. So the expected capacity could be calculated and inserted in the parameters of the model. According to these assumptions the model of the battery is similar to the model of Figure 18. The internal resistance is constant and the voltage source is dependent on the SOC. The battery model is built according to [14]:

\[
U_{DC} = U_{max} \cdot SOC + U_{min} \cdot (1 - SOC) - I \cdot Z_i
\]

\(U_{DC}\) : is the terminal DC voltage of the battery [V];

\(U_{max}\) : is cell voltage of fully loaded cell [V];

\(U_{min}\) : is cell voltage of discharged cell [V];

\(SOC\) : is state of charge of the battery [dimensionless];

\(I\) : is the current of charging/discharging [A];

\(Z_i\) : is the internal resistance of the battery [ohm].
The SOC is calculated with an integrator, by integrating the current of the battery. The integrator \(\frac{1}{sT}\) needs an initial condition (SOC0). This value is configured in the model as a parameter.

![Image of the battery model](image)

**Figure 20: Common model of the battery [8].**

Only the DC-current is needed as input signal to the model. The model gives out the outer DC-voltage, the SOC and also the DC-cell-voltage, which are needed for the charge controller.

![Image of the composite model frame](image)

**Figure 21: Composite model frame of the battery [8].**
In the single line diagram of PowerFactory, the battery is represented with DC voltage source. The voltage source provides terminal voltage according to the received value from the model of the battery [14].

**Calibration of the parameters of the battery model:**

The battery model in this thesis is configured according to the parameters in Table 4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC0</td>
<td>[int]</td>
<td>State of charge at initialization</td>
<td>0.5</td>
</tr>
<tr>
<td>CellCapacity</td>
<td>[Ah]</td>
<td>Capacity per cell</td>
<td>480</td>
</tr>
<tr>
<td>u_min</td>
<td>[V]</td>
<td>Voltage of empty cell</td>
<td>12</td>
</tr>
<tr>
<td>u_max</td>
<td>[V]</td>
<td>Voltage of full cell</td>
<td>13.85</td>
</tr>
<tr>
<td>CellsParallel</td>
<td>[int]</td>
<td>Amount of parallel cells</td>
<td>60</td>
</tr>
<tr>
<td>CellsInRow</td>
<td>[int]</td>
<td>Amount of cells in row</td>
<td>65</td>
</tr>
<tr>
<td>Unom</td>
<td>[kV]</td>
<td>Nominal voltage of source</td>
<td>0.9</td>
</tr>
<tr>
<td>RiCell</td>
<td>[ohm]</td>
<td>Internal resistance per cell</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Table 4: Parameters of the battery common model.**

The corresponding rated terminal DC voltage of the battery is 800 [V]. However, the DC voltage is changeable according to the SOC of the battery. The total capacity of the battery bank is 23 [MWh]. The calculated voltage and capacity of the battery bank is calculated according to the following equations:

Nominal voltage = voltage of one cell × number of cells in the row

Total capacity = nominal voltage × capacity per cell × number of parallel rows

**Note:** sizing of the battery is complicated, and it takes in consideration many criterions such as the dispatch strategy of the plant, which is not analyzed in details in this thesis. However, it is assumed that the capacity of the battery bank is enough for the objectives of study.
3.3.4. MODEL OF VOLTAGE SOURCED CONVERTER IN POWERFACTORY

In order to convert the DC-voltage from the battery to AC-voltage, VSC is implemented to convert to AC voltage through fast switching of IGBT-valves. Therefore, a model of PWM converter, whose built-in model is available in PowerFactory, is implemented.

![PWM Converter Diagram](image)

**Figure 22: Equivalent circuit of PWM converter [14].**

The model of PWM converter in PowerFactory has two inputs; the (id_ref), which represents the real part of reference current, and (iq_ref), which represents the imaginary part of the reference current. (id_ref) determines the active power output of the converter, while (iq_ref) determines the reactive power of the converter [14].

3.3.5. MODEL OF BESS CONTROLLER IN POWERFACTORY

The frequency of the grid is controlled by the active power, which is controlled by the value of (id_ref) in the PWM converter. Also, the voltage is controlled by the reactive power, which is controlled by the value of (iq_ref) [14].

The BESS controller has three controllers; frequency controller, voltage and power controller (VP_controller) and the charge controller.
Figure 23: Composite model frame of the BESS controller [8].

Figure 23 shows the signal flow between the three controllers with the common model of the PWM converter and the measurement devices. The input signals of the composite model are:

(id_ref) & (iq_ref): are the currents in the dq-components in [pu], which are received by the PWM-converter;

fmeas: is the frequency in [pu], which are obtained by a (ElmPhi) measurement device;

vin: is the absolute AC-voltage in [pu], which are obtained by a (StaVmea) voltage measurement;

pin: is the output active power in [pu], which is obtained by a (StaPqmea) power measurement;

3.3.6. MODEL OF FREQUENCY CONTROLLER IN POWERFACTORY

The frequency controller is a proportional controller with a dead band. In the case of frequency deviation the frequency controller defines the activated active power according to the value of the droop. The reference value of frequency (f0) is usually 1 [pu] [14].
Calibration of the parameters of the frequency controller model:

The frequency controller is configured according to the parameters in Table 5. However, the parameters in the thesis are changed according to different control strategies.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>droop</td>
<td>[pu/pu]</td>
<td>the droop value of active power</td>
<td>0.004</td>
</tr>
<tr>
<td>db</td>
<td>[pu]</td>
<td>dead band for frequency control</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 5: Parameters of the frequency controller of the BESS.

3.3.7. MODEL OF VOLTAGE AND POWER CONTROLLER IN POWERFACTORY

In the active and reactive power control, the control deviation is filtered with a PT1 element. After that, the signals are used as an input to a proportional-integral-controller. In the active path the signal (delta_i) is added, which is received from the charge controller. The voltage (or reactive power) controller has a very slow integral-controller for set point tracing, and proportional voltage support with dead band [14].
Figure 25: Common model of voltage and power controller of the BESS [8].

Calibration of the parameters of VP controller:

The controller of the active and reactive power is configured according to Table 6. However, for explanations in the coming sections, some parameters can be changed.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr</td>
<td>[s]</td>
<td>Filter time constant, active path</td>
<td>0.0001</td>
</tr>
<tr>
<td>Trq</td>
<td>[s]</td>
<td>Filter time constant, reactive path</td>
<td>0.1</td>
</tr>
<tr>
<td>Kp</td>
<td>[pu]</td>
<td>Proportional gain - id-PI-controller</td>
<td>2</td>
</tr>
<tr>
<td>Tip</td>
<td>[s]</td>
<td>Integrator time constant (id) PI-control</td>
<td>0.1</td>
</tr>
<tr>
<td>AC_deadband</td>
<td>[pu]</td>
<td>dead band for proportional gain</td>
<td>0</td>
</tr>
<tr>
<td>Kq</td>
<td>[pu]</td>
<td>Proportional gain for AC-voltage support</td>
<td>3</td>
</tr>
<tr>
<td>Tiq</td>
<td>[s]</td>
<td>Integrator time constant (iq) I-control</td>
<td>0.004</td>
</tr>
<tr>
<td>id_min</td>
<td>[pu]</td>
<td>Minimum real part of current</td>
<td>-0.4</td>
</tr>
<tr>
<td>iq_min</td>
<td>[pu]</td>
<td>Minimum imaginary part of current</td>
<td>-1</td>
</tr>
<tr>
<td>id_max</td>
<td>[pu]</td>
<td>Maximum real part of current</td>
<td>1</td>
</tr>
<tr>
<td>iq_max</td>
<td>[pu]</td>
<td>Maximum imaginary part of current</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6: Parameters of the voltage and power controller of the BESS.
3.3.8. MODEL OF CHARGE CONTROLLER IN POWERFACTORY

The battery can consume power if the (SOC<1) or supply power if the (SOC>0) according to the available power in the grid. However, the value of the consumed/supplied apparent power cannot exceed the rated value. In addition, the battery should be recharged if the SOC of the battery is under a certain level. This operation is controlled by the charge controller [14].

![Figure 26: Common model of charge controller of the BESS [8].](image)

The charge controller consists of two parts; the charging control, which controls the charging logically according to the value of SOC, and the current limiter, which limits the value of the current according to the rated apparent power. The signal (delta) is the difference of the (id_ref) between the VP-controller and the modified id from the charging logic. The feedback of that signal to the VP-controller prevents a windup of the PI-controller [14].

Calibration of the model of charge controller:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChargeCur</td>
<td>[pu]</td>
<td>minimum charging current</td>
<td>0.05</td>
</tr>
<tr>
<td>minSOC</td>
<td>[pu]</td>
<td>minimal SOC, discharging will be stopped</td>
<td>0.5</td>
</tr>
<tr>
<td>maxSOC</td>
<td>[pu]</td>
<td>maximal SOC, charging will be stopped</td>
<td>1</td>
</tr>
<tr>
<td>maxAbsCur</td>
<td>[pu]</td>
<td>maximal absolute current</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7: Parameters of charge controller of BESS.
3.3.9. DESCRIPTION OF THE IMPLEMENTED BESS IN THE HYBRID PLANT

After the implementation of the model of the BESS, the PWM is configured from the single line diagram of PowerFactory. The rated AC voltage is 400 [V] and the rated DC voltage is 800 [V]. In the (load flow) tab, it is also possible to determine the dispatch value of active and reactive power of the PWM converter, which is the initial value of power in the simulation. The nominal apparent power of the BESS is 3 [MVA]. The power of the BESS is equal to the peak power of the PV field, because the battery must be able to compensate a loss of the output power of the PV when all the generators are disconnected. This can occur if a cloud causes a sudden sharp drop of the irradiation during a day, when the solar irradiation is so high that only the PV field supplies power, while the diesel generators are off.

3.3.10. SIMULATION OF PRIMARY CONTROL OF THE BESS

The primary control of the BESS is regulated by the common model of frequency controller, which is included in the composite model frame of BESS controller. The model provides the demanded power change according to primary control in order to achieve the balance after a load change. The input of the model is the frequency signal and the frequency set value. The output signal is the power change according to primary control (dpref). The model does not include any component of time delay. Therefore, it does not control the speed of the active power reaction. However, the model of VP-controller (i.e. active and reactive power controller), which is included in the composite model frame BESS, contains the time delay of output power (Tip). Actually, the value of (Tip) controls the speed of primary control reaction.

In order to study the primary control of the BESS, a model of BESS and one load is integrated, and the frequency and active power output are simulated when the load increases by 10%.

Note: it should be in consideration that the model of the PWM converter represents a static generator. Therefore, the simulation cannot be initialized when the BESS is the slack machine in the grid (i.e. the grid forming element). In order to simulate the BESS as slack machine with one load, we initialize the model with one generator connected with the grid, then we disconnect it.
shortly after the initialization. However, the simulation results are shown regardless the period when the generator was connected.

Figure 27: The grid components for the simulation of primary control of the BESS.

Figure 28: Simulation results of primary control of the BESS with a load step of 10% increase (fast regulation).

Figure 28 shows that the primary control provides the balance of active power by increasing the output power of the BESS. The frequency signal shows that the primary control is fast compared to the diesel generator. The settling time is less than one second, and the steady state deviation is about 0.0007 [pu], which corresponds to the droop value of the BESS.

In order to obtain a slower speed of primary control reaction of the BESS, the simulation is run after changing the parameter (Tip: integrator time constant of PI-control) to the value of 1 second.
Figure 29: Simulation results of primary control of the BESS with a load step of 10% increase (slow regulation).

Figure 29 shows that the reaction speed of the BESS is much slower than in Figure 28. The settling time is about 4 seconds whereas it is less than 1 sec in Figure 28.

The primary control of the BESS is supposed to be fast compared to the diesel generator, since the time delay of power control in the PWM converter is much less than the time delay in the diesel engine [3]. Therefore, the configuration of the first simulation case is adopted in the following simulations.

3.3.11. SIMULATION OF PRIMARY CONTROL OF BESS AND DIESEL GENERATORS IN PARALLEL

The simulation includes three diesel generators operating in parallel with the BESS to cover a load. A load step of 10% increase is simulated to analyze the sharing of primary control of active power. The diesel generators have the same configuration of controllers, and their dispatch values of active power are at the nominal power (0.816 [kW]). However, the dispatch value of the BESS is zero, since the BESS provides only the primary control of active power in this case. All the generators and the BESS have a droop value of 0.02 [pu/pu].
Figure 30: The grid components for the simulation of primary control of the BESS and diesel generators in parallel.

Figure 31: Simulation results of primary control of the BESS and 3 diesel generators with a load step of 10% increase and droop value of 0.02 [pu/pu] of all the components.

Figure 31 shows that the diesel generators and the BESS share the primary control equally at the steady state case. However, the BESS reacts faster than the diesel generators to the load step. Shortly after the load step, the output power of the BESS increases more than the diesel generators, then it drops until it reaches the steady state value. On the other hand, the output power of the diesel generators increases gradually until it reaches the steady state value. Moreover, instantaneously at the load step, there is a sharp fluctuation, which represents the inertial response of the generator.
Note: In the following simulations, this primary control configuration is considered as the case, where the primary control is provided by the BESS and the diesel generators in parallel.

Another configuration of primary control is to provide a constant output power of the diesel generators. In order to simulate this case, the droop of the BESS is decreased and the droop of the diesel generators are increased. As suggested values, the droop of the diesel generators is set at 0.1 [pu/pu], and the droop value of the BESS is set at 0.004 [pu/pu].

Figure 32: Simulation results of primary control of the BESS (droop=0.004 [pu/pu]), and 3 diesel generators (droop=0.1 [pu/pu]) with a load step of 10% increase.

Figure 32 shows that the BESS provides almost all the primary control whereas the diesel engines provide very low primary control of active power. Therefore, the output power of the diesel generators is approximately constant.

Note: In the following simulations, this primary control configuration is considered as the case, where primary control is mainly provided by the BESS.

Note: although a lower droop value of the BESS and higher droop values of the diesel generators can provide more constant output power of the diesel generators [5], the power system becomes unstable, and PowerFactory does not show the simulation results.
3.4. MODEL OF PV FIELD

3.4.1. PHYSICAL DESCRIPTION OF THE PV FIELD

The PV field is the renewable energy power source of the plant. It is mainly composed of the PV modules and the electrical inverters. The PV modules convert the solar energy to electrical energy in the shape of DC current. The output power of the PV modules is a function of the solar irradiation on the field and the nominal peak power [15].

Figure 33: Performance characteristics of PV modules [15].

Figure 33 shows the current and power characteristics of a PV module. The module has a value of voltage and current at each irradiation level, at which the module provides its maximum power (MPP) [15].

The inverters of the PV field convert the DC current into AC current at the frequency of the grid. The inverters can also control the output power by changing the operation point of the PV field. However, it is not possible to increase the output power to more than the maximum power point at a certain irradiation [15].

3.4.2. ACTIVE POWER REGULATION OF THE PV FIELD

Power sources of renewable energy must be able to control the active power output according to the requirements of the grid operators. The PV field does not provide primary or secondary control, because it is required to harness all the available green energy. However, the power controller of the PV field should react to a power unbalance in the grid which leads to a critical frequency disturbance. When the frequency of the grid increases to exceed a predefined value
(\(f_r\)), the inverters start the regulation by reducing the output power proportionally to the increase of the frequency deviation, but without disconnecting from the grid. Nevertheless, when the frequency of the grid decreases to less than a predefined value (\(f_{\text{min}}\)), or increases to exceed a predefined value (\(f_{\text{max}}\)) the PV field should be disconnected from the grid. The values of \(f_r\), \(f_{\text{min}}\) and \(f_{\text{max}}\) are defined by the grid operators (i.e. they are defined in the grid codes) [16].

When: \(f_r \leq f \leq f_{\text{max}}\)

\[
P = P' - \Delta P
\]

\[
\Delta P = \frac{f - f_r}{f_{\text{max}} - f} P'
\]

\(P\) : is the output power of the PV field;

\(P'\) : is the output power of the PV field without regulation;

\(\Delta P\) : is the reduced power of the PV field;

\(f\) : is the measured frequency of the grid;

\(f_r\) : is the value of frequency to start regulation;

\(f_{\text{max}}\) : is the maximum value of frequency to disconnect the PV field;

\(f_{\text{min}}\) : is the minimum value of frequency to disconnect the PV field [16].

![Figure 34: Active power regulation of the PV field [16].](image)
3.4.3. MODEL OF PV STATIC GENERATOR IN POWERFACTORY

The PV field is represented in PowerFactory by the model of static generator when it is implemented in the mode of current source.

![Equivalent circuit of static generator in PowerFactory](image)

Figure 35: Equivalent circuit of static generator in PowerFactory [8].

The static generator is a power source which does not have rotary parts. The real and imaginary parts of the reference value of current are input signals of the static generator model. The active power of the static generator is defined by the real part of its current. Therefore, the value of real part of reference current (id_ref) should be defined by the PV controller.

3.4.4. MODEL OF PV CONTROLLER

The implemented model of controller considers the previously mentioned regulations, and sends the signal of (id_ref) to the model of PV field to determine the output active power.

The composite model frame of the PV field control includes 4 slots. The first slot is the frequency phase measurement (ElmPhi). The second slot includes the time delay, which sends the signal of frequency after a short delay to the controller in the third slot. The controller calculates the demanded value of (id_ref) and sends the signal to the model of PV field in the fourth slot.

The values of $f_r$, $f_{min}$ and $f_{max}$ are determined as parameters of the controller in addition to a parameter called (limit), whose value is multiplied by the (id_ref) to represent a limiting factor of clouds on the PV field. The PV field provides the dispatch value of power when the frequency is close to the nominal value of the grid and limit=1. The dispatch value represents in this case the output power of the PV field according to the solar irradiation.
Note: This implemented model is developed to for the project (Galapagos) [17].

Figure 36: Composite model frame of the PV field control [17].

The PV field of the thesis has the capacity of 3 [MWp], which can be entered in the tab of (basic data) in the model of PV field, while the dispatch value of power can be entered in the tab of (load flow).

Calibration of the parameters of the PV controller:

In the simulations of the thesis, the PV controller is configured according to the parameters Table 8.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>fmin</td>
<td>[HZ]</td>
<td>minimum cut frequency</td>
<td>47</td>
</tr>
<tr>
<td>fr</td>
<td>[HZ]</td>
<td>frequency to start limitation</td>
<td>51</td>
</tr>
<tr>
<td>fmax</td>
<td>[HZ]</td>
<td>frequency to be at 0</td>
<td>52.5</td>
</tr>
<tr>
<td>limit</td>
<td>-</td>
<td>additional factor product of clouds</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 8: Parameters of the PV controller.
3.4.5. SIMULATION OF PRIMARY CONTROL OF BESS AND DIESEL GENERATORS AND PV FIELD IN PARALLEL

The model of PV field is integrated with the grid of a diesel generator and the BESS, and a load step of 10% increase is simulated. The dispatch power of the diesel generator is the nominal power (0.816 [kW]), the dispatch value of the PV field is 2 [MW], and the dispatch value of the BESS is zero. The generator and the BESS have a droop value of 0.02 [pu/pu].

Figure 37: The grid components for the simulation of primary control of the PV field, BESS and 3 diesel generators.

Figure 38: Simulation results of a generator (droop=0.02 [pu/pu]), BESS (droop=0.02 [pu/pu]) and a PV field with a load step of 10% increase.
Figure 38 shows that the PV field supplies the dispatch value of active power, which represents the available power by the solar irradiation. Shortly after the load change, the power of the PV fluctuates, but it restores the initial value after a short while. On the other hand, the output power of the BESS and the diesel generator increases to compensate the load increase until the frequency stabilizes.

**Note:** according to active power regulation, when the frequency of the grid is close to the nominal value, the output power of the PV field is independent from frequency. In this case, the model of the PV field is similar to a negative load, which supplies power regardless of the grid frequency.

**Note:** since the thesis does not focus on the fault analysis or critical frequency deviations, the PV field is represented by a negative load in the following long-term simulation, because it is less complicated to enter the power values of the PV field to a load model in PowerFactory.

### 3.5. MODEL OF THE HYBRID PLANT

After the definition of the main components of the plant, the models are integrated with supplementary models to form the hybrid plant. The analyzed grid is a small stand-alone grid and independent from the primary power grid. The analyzed plant is composed of three diesel generators, a PV field and a BESS, which have the capacity according to the following table:

<table>
<thead>
<tr>
<th>Main components</th>
<th>capacity</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>diesel generators × 3</td>
<td>1.02</td>
<td>[MVA]</td>
</tr>
<tr>
<td>PV field</td>
<td>3</td>
<td>[MWp]</td>
</tr>
<tr>
<td>BESS</td>
<td>23</td>
<td>[MWh]</td>
</tr>
</tbody>
</table>

**Table 9:** Capacity of the main components of the plant.

**Note:** the capacities of the plant components are chosen by referring to some previously implemented hybrid plants, which have the same combinations of power sources [17]. The sizes of the plant components are assumed to be suitable for the aim of the thesis. However, optimum sizing is not analyzed in this thesis.
Figure 39: Single line diagram of the hybrid plant.

Figure 39 shows the components of the grid in the single line diagram of PowerFactory. In addition to the main components of the plant, the grid includes terminals, a main bus bar, transformers, lines and a load, whose models are built-in models in PowerFactory. In order to limit the power losses in the lines, two voltage levels are implemented; high level (HV: 3 \([kV]\)) and low level (LV: 0.4 \([kV]\)), in addition to a low DC voltage level for the terminal of the batteries. The grid consists of four branches connected to the main bus bar. The lines are implemented to represent different locations of components. Each line in the figure represents two parallel lines with high voltage level. The transformers are implemented to connect two voltage levels, since the PV field and the BESS have low voltage level. Each transformer in the figure represents three parallel (1 \([MVA]\)) transformers.
3.6. DEVELOPING A MODEL OF SECONDARY CONTROLLER

3.6.1. PHYSICAL DESCRIPTION OF THE SECONDARY CONTROLLER

When the load in the grid changes, unbalances occur between the active power output of the power sources and the active power consumed by the loads. The primary control, which is in our grid regulated by the governors of diesel generators and the frequency controller of the BESS, adapts the output power of the power sources in order to balance the active power of the grid again. However, this adaptation leads to a steady state frequency drop or increase in the grid according to the droop control of the power sources. The secondary control is the supplementary control, which reacts to the frequency deviation and brings it back again to the nominal value. The secondary control increases or decreases the output power of the attached power sources by changing the set points until the frequency stabilizes at the nominal value. The reaction of the secondary controller is much slower than the reaction of the primary control in order to avoid the interaction with the transient values of frequency deviations shortly after the load changes. Therefore, the secondary control regulates in terms of seconds to minutes. This reaction is much slower than the reaction of the primary control, which regulates in terms of few seconds [5], [9].

![Figure 40: Mechanism of secondary control with drooping power source.](image)

Figure 40 shows three operating points and two droop characteristics of a power source. At point (1), the frequency of the grid is at the nominal value ($f_0$). At point (2), the load increased and the frequency decreased according to droop control. At point (3), the set point of the power source is increased in order to retrieve the frequency.
A simple model of controller with closed loop is made up of the general elements which are shown in the following chart.

![Diagram of closed loop control system](image)

**Figure 41: The basic chart of closed loop control system showing the basic elements [11].**

In the studied plant, the output signal is the frequency which is obtained from the frequency measurement, the set value is 50 [HZ], the controller is the secondary controller and the studied system is composed of the governors of the diesel generators and the power controller of the BESS.

### 3.6.2. DEVELOPING A COMPOSITE MODEL FRAME OF SECONDARY CONTROLLER

To build a model of secondary controller in PowerFactory, we need to build first the frame model, which represents the basic chart of the controller. The composite model frame is the overall structure, which includes all the common models involved in the demanded control, and the signal flow between them. However, the summation point cannot be seen in the frame, but it is included inside the common model of secondary controller instead, because it is only possible in PowerFactory to include signals and slots of common models inside the frame. The frame of the secondary controller includes six slots. The first left slot is the frequency measurement (ElmPhi), which provides the frequency in the reference bus bar (HV/Main_BB) and sends the signal to the secondary controllers. The second left slot is the secondary controller which receives the measured frequency and sends the control signals in order to keep the frequency at the nominal value. The third left slot is the VP-controller of the BESS. And the last three slots are the diesel governor models.

The control signal (dp_sec) is the change value of active power which is added to the initial set point of the controlled models to set a new value of active power set point.
Figure 42: Composite model frame of secondary control.

The models of diesel governors and VP-controller need to be adjusted by adding one input of (dp_sec) to each one, and we sum its value by means of new summation points to the original power set point of each model.

Note: Although the frame model includes all the common models which can contribute to the secondary control, not all slots have to be attached to one of them (i.e. only the attached common models will receive control signals and contribute to the secondary control).
Figure 43: Model of the diesel governor showing the adjustment for the secondary control.

Figure 44: Model of the voltage and power controller of the BESS showing the adjustment for the secondary control.
3.6.3. DEVELOPING A COMMON MODEL OF SECONDARY CONTROLLER

The secondary controller is the common model, which is attached in the slot number two of the composite model frame of the secondary control. The input of the model is the frequency, which is provided by the frequency measurement device. The output of the model is the change value of active power, which is sent to the governors of the diesel generators (dp_diesel), and the power controller of the batteries (dp_BESS). The secondary controller is simply designed from seven slots which are attached by standard macro models.

Figure 45: Common model of the secondary controller.

The slots have the following numbers:

1- Time delay: to represent the longer reaction of the secondary control compared to the primary control.

2- Gain 1/f: to return the value of the frequency from [HZ] to per unit value.
3- Constant signal: the set value of the frequency which is 1 [pu].

4- Primitive controller type PT1: is from the standard macros in the global library of PowerFactory, which has the transfer function of \(1/(K+sT)\).

5- Signal divider: it divides the control signal between the attached common models to determine their contribution to the secondary control.

6- Constant signal: the base value of active power of the diesel generators, which is multiplied by the control signal in order to change it from per unit value to (MW) value.

7- Constant signal: the base value of the power of the BESS, which is multiplied by the control signal in order to change it from per unit value to (MW) value.

### 3.6.4. DISTRIBUTION OF SECONDARY CONTROL ACTIVE POWER

The active power of the secondary control is distributed between the attached diesel generators and the power controller of the BESS according to the corresponding nominal active power of each one of them.

\[
Kp_j = \frac{P_{\text{disp},j}}{\sum_{i=0}^{i=n} P_{\text{disp},i}}
\]

- \(Kp_j\) : is the power sharing factor of the secondary control for the power source (j).
- \(P_{\text{disp},j}\) : is the dispatch power of the power source to be applied in secondary control.
- \(n\) : is the number of the attached power sources in the secondary controller.

\[
P_j = P_{\text{primary},j} + Kp_j \cdot dp_{\text{secondary}}
\]

- \(P_j\) : is the power output of the power source.
- \(P_{\text{primary},j}\) : is the power output of the power source, which is defined by the primary control.
- \(dp_{\text{secondary}}\) : is the total power change which is demanded by the secondary controller.
Notes:

• The sharing factors of the diesel generators and the BESS are defined in the primitive model of the secondary signal divider with DSL language.

• In order to change the sharing factors of a power source, it is possible to change the $P_{\text{disp,j}}$, which is configured as a parameter of the secondary controller.

• The power sources, which are not providing secondary control, restore the initial generation before the load change i.e. according to the original set point [5].

**Calibration of the parameters of the secondary controller:**

In all the simulations of the thesis, the secondary controller is configured according to the parameters in Table 10. However, the number of the diesel generators, which are attached in the secondary controller, can be changed for the different cases of simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Delay time constant</td>
<td>[s]</td>
<td>0.001</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Gain of controller</td>
<td>[pu/pu]</td>
<td>0.0001</td>
</tr>
<tr>
<td>$T_1$</td>
<td>Controller time constant</td>
<td>[s]</td>
<td>2</td>
</tr>
<tr>
<td>$P_{\text{BESS}}$</td>
<td>Dispatch power of BESS</td>
<td>[MVA]</td>
<td>6</td>
</tr>
<tr>
<td>$P_{\text{diesel}}$</td>
<td>Dispatch power of diesels</td>
<td>[MVA]</td>
<td>1</td>
</tr>
<tr>
<td>$F$</td>
<td>Nominal frequency</td>
<td>[HZ]</td>
<td>50</td>
</tr>
<tr>
<td>$N_{\text{diesel}}$</td>
<td>Number of attached diesel generators</td>
<td>[unit]</td>
<td>3</td>
</tr>
<tr>
<td>$N_{\text{BESS}}$</td>
<td>Number of attached diesel generators</td>
<td>[unit]</td>
<td>1</td>
</tr>
<tr>
<td>$y_{\text{min}}$</td>
<td>Minimum limit of frequency measurement</td>
<td>[HZ]</td>
<td>0</td>
</tr>
<tr>
<td>$y_{\text{max}}$</td>
<td>Maximum limit of frequency measurement</td>
<td>[HZ]</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 10: Parameters of the secondary controller.
CHAPTER FOUR:
SIMULATION AND RESULTS
4. SIMULATION AND RESULTS

4.1. PROPOSED CONTROL STRATEGIES

The active power control of the plant is in three levels; the primary, secondary and dispatch control. At any time of operation the three levels of control should be available in the plant. The thesis focuses on the primary and secondary control, which have shorter-term regulation and different function from the dispatch control. Therefore, different possible control strategies according to primary and secondary control are analyzed. The BESS, the diesel generators and the PV are considered the power sources in the plant. However, the PV field is configured to supply all the available energy by the solar irradiation without considering the changes of the load, since the BESS temporarily stores the excess energy, or supplies the residual energy in the grid. Therefore, the primary and secondary control from the PV field is not considered in the control strategies of the plant. On the other hand, the BESS can provide primary and secondary control only if it is not fully charged or discharged. The BESS is considered in the control strategies that it can always provide or share the primary or secondary control of the plant since it is always connected to the grid [3].

The diesel generators are not always connected to the grid, especially during sunny days. If the PV field receives high irradiation during the day so that enough energy is generated, the diesel generators are usually disconnected. For this reason, the diesel generators cannot be configured to provide all the primary or secondary control of the plant. In other words, the diesel generators are considered only able to share the primary or secondary control of the plant.

A large number of different sharing combinations of primary and secondary control can be suggested. However, for the objective of the thesis, four control strategies in relation to primary and secondary control are proposed and analyzed.

• Control strategy (1): the primary control of active power is provided by the diesel generators and the BESS in parallel. All the diesel generators and the BESS have the same droop value (0.02 [pu/pu]); consequently they have the same sharing of primary control according to their
rated power. The secondary control of active power is provided only by the BESS in this control strategy.

- Control strategy (2): the primary control of active power is provided by the diesel generators and the BESS in parallel with the same sharing of primary control (droop: 0.02 [pu/pu]). The secondary control of active power is provided by the diesel generators and the BESS in parallel. The BESS provides two thirds of the secondary control, whereas the connected diesel generators provide one third equally.

- Control strategy (3): the primary control of active power is provided mainly by the BESS (droop: 0.004 [pu/pu]), which means that the diesel generators (droop: 0.1 [pu/pu]) provide a very low primary control compared to the BESS. The secondary control in this strategy is provided only by the BESS.

- Control strategy (4): the primary control of active power is provided mainly by the BESS (droop: 0.004 [pu/pu]), which means that the diesel generators (droop: 0.1 [pu/pu]) provide a very low primary control compared to the BESS. The secondary control of active power is provided by the diesel generators and the BESS in parallel. The BESS provides two thirds of the secondary control, whereas the connected diesel generators provide one third equally.

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Primary control of active power</th>
<th>Secondary control of active power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BESS &amp; diesel generators</td>
<td>BESS</td>
</tr>
<tr>
<td>2</td>
<td>BESS &amp; diesel generators</td>
<td>BESS &amp; diesel generators</td>
</tr>
<tr>
<td>3</td>
<td>mainly BESS</td>
<td>BESS</td>
</tr>
<tr>
<td>4</td>
<td>mainly BESS</td>
<td>BESS &amp; diesel generators</td>
</tr>
</tbody>
</table>

Table 11: The proposed control strategies.
4.2. DYNAMIC SIMULATION

4.2.1. SIMULATION OF SECONDARY CONTROL OF THE PLANT

In order to study the operation of the secondary controller, the simulation results of the plant operation are analyzed with a load step of 10% increase (Figure 39). The dispatch value of the diesel generators is set to the nominal value (0.816 [MW]), whereas the dispatch value of the BESS is zero, since the BESS can temporarily supply or store energy according to frequency control. The simulation includes a load increase in active power as a load step of 10%. The configuration of the three governors is according to Table 1, the configuration of the VP-controller of the BESS is according to Table 6, and the configuration of the secondary controller is according to Table 10.

The simulations represent the four control strategies, which are proposed (i.e. 2×2; two cases according to primary control and two cases according to secondary control).

Note: all the diesel generators in this simulation have the same configuration, so they have the same output power. Therefore, for the short-term simulations, the result diagrams show only the output of one diesel generator.

4.2.1.1. CONTROL STRATEGY (1)

This control strategy represents the operation of the plant when the primary control is provided by the diesel generators and the BESS in parallel, and the secondary control is provided by the BESS.

To apply the control strategy, the diesel generators and the BESS have a droop value of 0.02 [pu/pu]. Also, the BESS is only attached in the secondary control. Therefore, the value of (N_diesel) should be zero.
Figure 46: Dynamic simulation results of a 10% load increase according to control strategy (1).

Figure 46 shows that the frequency drops directly after the load increase, and then it retrieves the nominal value after about 75 seconds. The output power of the diesel generators increases shortly after the load increase according to primary control, but it drops again after a short while according to secondary control. On the other hand, the output power of the BESS increases instantaneously as the load increase according to primary control, and then it increases again to cover all the extra demanded power by the load in order to restore the frequency to the nominal value.

4.2.1.2. CONTROL STRATEGY (2)

This control strategy represents the operation of the plant when the primary control is provided by the diesel generators and the BESS in parallel, and the secondary control is provided by the diesel generator and the BESS in parallel.
To apply the control strategy, the diesel generators and the BESS have the droop value of 0.02 [pu/pu]. The BESS and the diesel generators are attached in the secondary control. The value of \((N_{\text{diesel}})\) should be three, because all diesel generators are attached in the secondary control.

![Graph](image)

**Figure 47: Dynamic simulation results of a 10% load increase according to control strategy (2).**

Figure 47 shows that the frequency drops directly after the load increase, and then it retrieves the nominal value after about 50 seconds. The settlement time is shorter, because more power sources contribute to the secondary control. The output power of the diesel generators increases shortly after the load increase according to primary control, and then it stabilizes at a higher value than the initial output power according to secondary control. On the other hand, the output power of the BESS increases instantaneously as the load increases according to primary control, and then it decreases slightly until it reaches the steady state value according to secondary control.
4.2.1.3. CONTROL STRATEGY (3)

This control strategy represents the operation of the plant when the primary control and secondary control are provided mainly by the BESS.

In order to apply the control strategy, the diesel generators have the droop value of 0.1 [pu/pu]. The BESS have the droop value of 0.004 [pu/pu]. In addition, the BESS is only attached in the secondary control. Therefore, the value of (N_diesel) should be zero.

Figure 48: Dynamic simulation results of a 10% load increase according to control strategy (3).

Figure 48 shows that the frequency drops directly after the load increase, and then it retrieves the nominal value after about 85 seconds. The output power of the diesel generators increases slightly according to primary control because of the relatively high value of droop, and then it stabilizes at the initial value of output power according to secondary control. On the other hand, the output power of the BESS increases instantaneously as the load increases according to primary control, and then it increases slightly until it reaches the steady state value according to secondary control.
4.2.1.4. CONTROL STRATEGY (4)

This control strategy represents the operation of the plant when the primary control is provided mainly by the BESS, while the secondary control is provided by the diesel generator and the BESS in parallel.

To apply the control strategy, the diesel generators have the droop value of 0.1 [pu/pu], whereas The BESS has the droop of 0.004 [pu/pu]. In addition, the diesel generators and the BESS are attached in the secondary control. Therefore, the value of (N_diesel) should be three.

Figure 49: Dynamic simulation results of a 10% load increase according to control strategy (4).

Figure 49 shows that the frequency drops directly after the load increase, and then it retrieves the nominal value after about 95 seconds. The output power of the diesel generators increases slightly according to primary control, because of the relatively high value of droop, and then it increases according to secondary control until the frequency stabilizes. On the other hand, the output power of the BESS increases instantaneously as the load increases according to primary control, and then it decreases slightly until it reaches the steady state at the nominal value.
4.2.2. SIMULATION OF FUEL CONSUMPTION

In order to analyze the fuel consumption of the diesel generators, the model of fuel measurement is implemented, and the simulation is run for the control strategy (2) with a load increase of 10%.

![Graph of fuel consumption](image)

**Figure 50: Dynamic simulation results of fuel consumption of control strategy (2).**

Figure 50 shows that the fuel flow rate increases shortly when the load changes to compensate the increase of generator output power. The specific fuel consumption ($sf_c$) increases obviously at the load step then it drops gradually until it reaches the steady state $sf_c$.

In order to analyze the effect of the control strategy on the fuel consumption, the same simulation is run according to control strategy (3).

![Graph of fuel consumption](image)

**Figure 51: Dynamic simulation results of fuel consumption of control strategy (3).**

Figure 51 shows that the fuel flow rate does not increase considerably, since the output power of the diesel engine is almost constant. Also, the increase of $sf_c$ at the load step is relatively slight.

In general, sharp increases of $sf_c$ leads to less efficient operation when the load changes.
4.3. CASE STUDY (SIMULATION OF ONE EXAMPLE DAY)

4.3.1. ASSUMPTIONS

For comprehensive analysis of the control strategies, a simulation of the plant for one day is run. As sample data for a stand-alone plant, the applied load profile and PV output power profile are synthesized for a (1 [MVA]) plant in (Galapagos) island in Ecuador [17]. The implemented profiles are the synthesized profiles for the 17th of March multiplied by a factor of 3, because the analyzed plant is (3 [MVA]). The capacities of the plant components are shown in Table 9. The simulation is run for each control strategy based on 0.1 [sec] as simulation step size.

In order to minimize the fuel consumption of the plant, diesel generators should be disconnected or connected according to the need of power supply in the grid. On the other hand, since the BESS is the grid forming element, it is always connected to the grid to improve the reliability of power supply. In addition, it is preferable to extract all the possible energy from the PV field, because it provides zero fuel energy. Therefore, the PV field supplies power like a negative load. The scheduling of the generators switching is expressed as dispatch control. The strategy of the dispatch control can play a significant role in the sizing of the plant components and also in the fuel consumption. Many combinations of possible dispatch strategies can be proposed, but not all of them are practical or advisable [18].

The followed dispatch strategy in the thesis has the objective of storing the PV energy in the day to use it during the peak time. Therefore, the diesel generators are disconnected one by one during the high irradiation time, and then they are reconnected after a while to give the opportunity for the exploitation of the charged energy in the BESS.

Four criterions are considered in the comparison of different control strategies; the frequency deviations, fuel consumption, life time of the battery and the performance of the diesel units.

4.3.2. LOAD PROFILE

To enter the values of the load model along the simulated day in PowerFactory, a measurement file, which can import from a text file, is defined. Then, a simple composite model with two blocks, to which the models of the load and measurement file are attached, is built.
Figure 52: Composite model frame of the load.

Note: the measurement file gives a value of load each 2 minutes.

Figure 53: Load profile for the simulated day.

The simulated load profile has a mean value of (1.58 [MW]), a maximum value of (2.22 [MW]) and a minimum value of (1.28 [MW]). Figure 53 shows that load has a high peak between 7 and 9 o’clock at night.

Note: since the thesis does not study the reactive power control, and to avoid the problem of voltage drop, it is assumed that the load consumes only active power.

4.3.3. OUTPUT POWER OF THE PV FIELD

The PV field is simulated as a negative load. Therefore, it has the same representation as the load in PowerFactory, but the measurements have negative values. However, the PV power profile has the resolution of 5 minutes.
Figure 54: PV power profile for the simulated day.

The PV output power profile is synthesized from sunny day measurements given the average daily global irradiation of 6.5 [kWh/m²/day]. Although the measurements were taken in a sunny day, Figure 54 shows that the PV field output power contains high sizes of fluctuation compared to the load fluctuations.

4.3.4. OUTPUT POWER OF THE DIESEL GENERATORS

The first diesel generator is operated from the beginning of the day, then it is disconnected at 6:00 am, and connected again at 10:30 pm. Total time of operation is 7.5 hours. On the other hand, the second diesel generator is operated from the beginning of the day then it is disconnected at 7:30 am, and connected again at 5:00 pm. Total time of operation is 16.5 hours.
Figure 55: Output power of generator (1) for the simulated day.
Figure 56: Output power of generator (2) for the simulated day.

Figure 55 and Figure 56 show that in the control strategy (1), the output power is always close to the nominal power, but there are high short-term fluctuations. In control strategy (2), the output power of the generators contains long and short-term variations according to the load. Therefore, the output power is not always close to the nominal value. In control strategy (3), the output power is more constant at long and short-term level compared to other strategies, and the generators operate very close to the nominal power. In control strategy (4), the output power of the generators has long-term changes according to the trend of the load, but it has less short-term fluctuations compared to control strategy (2).

In general, in control strategy (3), when the fluctuations of the load and the PV field power are covered mainly by the BESS, the output power of the diesel generators is more constant close to the nominal value compared to other control strategies.

Note: the third generator is not needed according to the conditions of the simulated day. However, it can be needed if the solar irradiation is not high enough for a certain period. Therefore, the third generator is considered as a backup generator for the plant in this day.
4.3.5. OUTPUT POWER OF THE BESS

Since the BESS is the forming component, it is connected to the grid along the simulated day. The BESS charges when its power is lower than zero, and discharges when it is higher than zero.

![Graphs showing output power of the BESS for the simulated day.](image)

Figure 57: Output power of the BESS for the simulated day.
Figure 57 shows that the output power of the BESS fluctuates very frequently. However, the fluctuations are sharper during the day, when the PV field supply its fluctuating power. During the operation of the diesel generators, the fluctuations in control strategy (2) are lower than in control strategy (3), because the generators cover the fluctuations partly in control strategy (2).

4.3.6. ENERGY DISTRIBUTION OF THE PLANT

For comprehensive observation of the plant operation, it is important to illustrate the generated energy of each component for the four control strategies. The energy is generated only by the PV field and the diesel generators, whereas the BESS is considered as a temporary source or storage of power. It is important also to illustrate the stored and the supplied energy by the BESS. The figures illustrate also the dispatch strategy in the thesis, which is followed for all control strategies. The figures are drawn with Matlab by accumulating the power of components, which resulted from the simulation of PowerFactory.

Figure 58: Distribution of the generated energy in the simulated day.
Figure 59: Charging and discharging of the BESS in the simulated day.

Figure 58 and Figure 59 show that the excess energy by the PV field during the day is stored in the BESS instead of wasting it, and then it is supplied during the peak load time. The diesel generators are disconnected one by one when the output power of the PV increases, and then the generator (2) is reconnected when the PV power decreases. The stored energy is supplied after that until the generator (1) is connected again. In general, the BESS compensates all the mismatching between the generated energy and the load profile.

For a proper comparison of the four control strategies, the energy produced and consumed by all the components are calculated. In order to compare the control strategies properly, the produced and consumed energy should not vary considerably, because some criterions of comparison are related to the produced energy, such as the fuel consumption. In addition, the generated energy is needed for later calculations.
Table 12: Generated energy by the plant components for the simulated day.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>secondary control: BESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators</td>
<td>21.1178</td>
<td>5.9454</td>
<td>11.8514</td>
<td>38.9146</td>
<td>38.0995</td>
</tr>
<tr>
<td></td>
<td>secondary: BESS &amp; diesel generators</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>secondary: BESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS</td>
<td>21.1176</td>
<td>6.0167</td>
<td>11.8002</td>
<td>38.9345</td>
<td>38.1010</td>
</tr>
<tr>
<td></td>
<td>secondary: BESS &amp; diesel generators</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12 shows that the total consumed and generated energy does not vary considerably according to the control strategies. In addition, the energy sharing of the plant components is approximately the same for all the control strategies. It is apparent that the PV field provides the majority of the generated energy of the simulated day.
4.3.7. ANALYSIS OF FREQUENCY DEVIATIONS

For the comparison of frequency deviations, the frequency of the main bus bar is simulated for the four control strategies. After that, the maximum deviations for each strategy are obtained.

Figure 61: Frequency at the main bus bar for the simulated day.
Figure 61 shows that the frequency has deviations along the simulated day. It is obvious that the deviations are more frequent and with larger sizes during the day, when the PV field supplies power. However, the frequency in control strategies (1) and (2) has larger and more frequent deviations than control strategies (3) and (4).

In order to ensure that the frequency deviations do not exceed unacceptable limits, the maximum frequency deviations are calculated for the four control strategies. The maximum limits of frequency deviations are mentioned in the grid code of each country.

<table>
<thead>
<tr>
<th>no.</th>
<th>Control strategy</th>
<th>Maximum frequency drop [HZ]</th>
<th>Maximum frequency increase [HZ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>primary control: BESS &amp; diesel generators secondary control: BESS</td>
<td>-0.3868</td>
<td>0.5059</td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators secondary: BESS &amp; diesel generators</td>
<td>-0.3872</td>
<td>0.5069</td>
</tr>
<tr>
<td>3</td>
<td>primary control: BESS secondary: BESS</td>
<td>-0.2993</td>
<td>0.2275</td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS secondary: BESS &amp; diesel generators</td>
<td>-0.2999</td>
<td>0.2265</td>
</tr>
</tbody>
</table>

Table 13: Maximum frequency deviations of the control strategies for the simulated day.

In control strategies (1) and (2), the maximum deviations are higher than in control strategies (3) and (4). This is considered as another indication of lower frequency deviations for the control strategy (3) and (4). In order to have clearer estimation for small size deviations that cannot be analyzed from figure (61), the deviations are distributed in a probability density function according to the size of deviations (histogram) in Matlab [19].
Figure 62: Histograms of frequency deviations for the simulated day according to control strategies.

The histogram reflects the characteristics of the deviations. The lower and wider the curve is, the higher the probability of large size deviations. Figure 62 shows that the control strategy (3) and (4) has higher and narrower curves and thus they have lower frequency deviations. However, the curve in control strategy (3) is slightly higher than in control strategy (4). It can be concluded that the control strategy (3) has lower frequency deviations compared to the other control strategies. This can be explained by the fast reaction of the BESS to provide the power control to compensate power fluctuations of the grid.

4.3.8. ESTIMATION OF FUEL CONSUMPTION

In islands, the environment has a particular interest. As an important criterion of comparison between the four control strategies, the fuel consumption is apparently desired to be as low as possible to reduce the fuel cost, and also to reduce CO2 emissions. The fuel consumption of the simulated day is calculated with Matlab for the four control strategies during the operating hours.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>primary control: BESS &amp; diesel generators secondary control: BESS</td>
<td>219.8859</td>
<td>1648.0</td>
<td>0.2810</td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators secondary: BESS &amp; diesel generators</td>
<td>213.8880</td>
<td>1603.0</td>
<td>0.2810</td>
</tr>
<tr>
<td>3</td>
<td>primary control: BESS secondary: BESS</td>
<td>219.8995</td>
<td>1648.0</td>
<td>0.2810</td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS secondary: BESS &amp; diesel generators</td>
<td>217.0824</td>
<td>1626.9</td>
<td>0.2810</td>
</tr>
</tbody>
</table>

Table 14: Fuel consumption of generator (1) for the simulated day.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>primary control: BESS &amp; diesel generators secondary control: BESS</td>
<td>218.3888</td>
<td>3165</td>
<td>0.2810</td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators secondary: BESS &amp; diesel generators</td>
<td>232.8995</td>
<td>3375.8</td>
<td>0.2811</td>
</tr>
<tr>
<td>3</td>
<td>primary control: BESS secondary: BESS</td>
<td>218.3846</td>
<td>3165.4</td>
<td>0.2810</td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS secondary: BESS &amp; diesel generators</td>
<td>224.3532</td>
<td>3251.9</td>
<td>0.2811</td>
</tr>
</tbody>
</table>

Table 15: Fuel consumption of generator (2) for the simulated day.
<table>
<thead>
<tr>
<th>no.</th>
<th>Control strategy</th>
<th>Total fuel consumption by both generators [litre]</th>
<th>Mean specific fuel consumption [litre/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>primary control: BESS &amp; diesel generators secondary control: BESS</td>
<td>4813.5</td>
<td>0.2810</td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators secondary: BESS &amp; diesel generators</td>
<td>4978.9</td>
<td>0.2811</td>
</tr>
<tr>
<td>3</td>
<td>primary control: BESS secondary: BESS</td>
<td>4813.4</td>
<td>0.2810</td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS secondary: BESS &amp; diesel generators</td>
<td>4878.8</td>
<td>0.2811</td>
</tr>
</tbody>
</table>

Table 16: Total fuel consumption for the simulated day.

Figure 63: Comparison of the fuel consumption of the four control strategies for the simulated day.

The results show that the fuel consumption of control strategy (3) has the lowest value, whereas the fuel consumption in control strategy (2) has the highest value, while fuel consumption of control strategy (4) and (1) has the second and third highest value respectively. The fuel consumption of control strategy (3) is lower than strategy (2) by 3.5% approximately.
Although the diesel generators supply approximately the same amount of energy in all the control strategies, the fuel consumption varies considerably. This can be explained not only by the ramping of output power of the diesel generator, but also by the different operation point of the generators along the day in each control strategy. In control strategy (1), the power of the generators has more short-term fluctuations than control strategy (3), nevertheless the fuel consumption of strategy (1) is not considerably higher than strategy (3), since the generators are always operating close to the nominal power in both strategies.

Note: the mean specific fuel consumption does not show a clear difference between different control strategies, because of rounding. Therefore, a clearer estimation is considered from the total consumption of the simulated day.

In conclusion, the control strategy (3) provides lower fuel consumption compared to other control strategies.

4.3.9. EFFECTS OF THE CONTROL STRATEGY ON THE BATTERY LIFETIME

As another criterion of comparing the four control strategies, the effect of the control strategy on the life time of the batteries is analyzed.

4.3.9.1. OVERVIEW ON BATTERY LIFETIME

The lifetime of the battery bank is determined by the lifetime throughput and the battery float life. The lifetime throughput represents the usage of the battery, whereas the float life represents the aging of the battery according to the boundary conditions, such as the ambient temperature. In normal conditions, the float life of the battery is considered to be 20 years. The lifetime of the battery bank life is calculated according to the following equation [20]:

\[
R_{bat} = MIN\left(\frac{N_{bat} \cdot Q_{\text{lifetime}}}{Q_{\text{thrpt}}}, R_{bat,f}\right)
\]

\(R_{bat}\) : is the battery bank lifetime [year];

\(N_{bat}\) : is the number of batteries in the battery bank;
$Q_{lifetime}$: is the lifetime throughput of a single battery [kWh];

$Q_{thrpt}$: is the annual battery throughput [kWh/year];

$R_{bat,f}$: is the battery float life [year].

The annual battery throughput is the amount of energy, which cycles through the battery bank in one year, while the life time throughput can be calculated according to [20]:

$$Q_{lifetime} = F \cdot d \left( \frac{q_{max} V_{nom}}{1000} \right)$$

$F$: is the number of cycles to fail;

$d$: is the depth of discharge [%];

$q_{max}$: is the maximum capacity of the battery [Ah];

$V_{nom}$: is the nominal voltage of the battery [V].

In the datasheet of the battery, the number of cycles to failure is mentioned as a function of the design value of depth of discharge.

![Figure 64: Number of cycles to failure as a function of the depth of discharge (Appendix C)](image)

It can be concluded from the equations that the more annual energy cycled in the battery bank, the shorter the lifetime of the battery can be expected.
4.3.9.2. ENERGY CYCLE OF THE BESS

In order to analyze the effect of the control strategy on the life time of the battery bank, the energy which is cycled in the battery during the simulated day is calculated for each strategy. The energy cycled means the energy charged and discharged in the simulated day. However, if the state of charge at the end of the simulated day is different according to the control strategy, the energy cycled cannot be compared between the strategies, because the charged energy is different from the discharged energy according to the control strategy. For a proper comparison between the strategies, the SOC at the end of the simulation should have the same value for all the strategies. Therefore, the state of charge of the battery should be illustrated.
Figure 65: State of charge of the BESS for the simulated day.

Figure 65 shows that the SOC has approximately the same value in all the control strategies in the beginning and end of simulation. Nevertheless, the SOC reaches higher values in strategy (1) and (3) than in strategies (2) and (4).

For the estimation of the battery lifetime, the energy supplied and stored by the BESS is calculated with Matlab. The annual energy cycled of the battery bank is needed in order to calculate its expected lifetime. Therefore, it is not possible to calculate the lifetime of the battery bank based on one day simulation results. However, the energy cycled for one day for each control strategy can provide an indication for the comparison between the strategies.

<table>
<thead>
<tr>
<th>no.</th>
<th>Control strategy</th>
<th>Energy discharged by BESS [MWh]</th>
<th>Energy charged by BESS [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>primary control: BESS &amp; diesel generators secondary control: BESS</td>
<td>7.8007</td>
<td>-7.9589</td>
</tr>
<tr>
<td>2</td>
<td>primary control: BESS &amp; diesel generators secondary: BESS &amp; diesel generators</td>
<td>7.4491</td>
<td>-7.6410</td>
</tr>
<tr>
<td>3</td>
<td>primary control: BESS secondary: BESS</td>
<td>7.8058</td>
<td>-7.9536</td>
</tr>
<tr>
<td>4</td>
<td>primary control: BESS secondary: BESS &amp; diesel generators</td>
<td>7.5963</td>
<td>-7.8055</td>
</tr>
</tbody>
</table>

Table 17: Energy cycle of the battery for the simulated day.
The results show that the energy cycled in control strategy (2) has the lowest value, whereas strategy (3) has the highest value. Therefore, it can be concluded that the lifetime of control strategy (2) is expected to be the longest compared to the other control strategies.

4.3.10. EFFECTS OF THE CONTROL STRATEGY ON THE PERFORMANCE OF THE DIESEL GENERATORS

As previously analyzed, the control strategy affects the output power of the diesel generators. Control strategy (3) provides more constant output power of the diesel generators closer to the nominal power, whereas control strategy (2) provides higher variations of output power of the diesel generators. The pattern of the diesel generators loading has considerable effects on their performance. Operating the diesel generators at low level of loading is not recommended by the manufacturers, because of the adverse effects, such as increased fuel consumption, high friction and slobbering problems [21], [6]. On the other hand, overloading a diesel generator has several restrictions. As specified by standards, the diesel engines are designed for overloading of 10% for only 1 hour in every 12 hours of operation, while the AC generators are designed to meet 50% overload for not more than 15 seconds [22]. In addition, load ramping of the diesel generators causes transient torques on the rotating shaft. In general, frequent variations in the power of the diesel generators can apparently lead to less favorable operation compared to constant output power close to the nominal value. As a result, the control strategy (3) is expected to have better performance, while the control strategy (2) is expected to have the less favorable performance of diesel generators compared to other strategies.
4.4. ECONOMICAL OVERVIEW

4.4.1. ECONOMICAL DEFINITIONS

• The annualized cost of a component is its annual operating cost in addition to its capital and replacement costs annualized over the project lifetime [20]:

Annualized cost = annualized capital cost + annualized replacement cost + annual O&M cost + annual fuel cost.

• The annualized capital cost is the initial capital cost of each component annualized over the project lifetime. The initial capital cost of a component is the total installed cost of that component at the beginning of the project [20].

\[ C_{acap} = C_{cap} \cdot CRF(i, R_{proj}) \]

\( C_{acap} \): is the annualized capital cost;

\( C_{cap} \): is the initial capital cost;

\( CRF \): is the capital recovery factor;

\( i \): is the real interest rate;

\( R_{proj} \): is the project lifetime.

• The capital recovery factor is a ratio used to calculate the present value of annual installments [20]:

\[ CRF(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1} \]

\( N \): is a number of years.

• The interest rate reflects the value of time of annualized costs. The real interest rate is related to the nominal interest rate and the inflation rate [20].
\[ i = \frac{i' - f}{1 + f} \]

\( i' \) : is the nominal interest rate at which the loan can be obtained;

\( f \) : is the annual inflation rate.

- The annualized replacement cost of a component is the annualized cost of all the replacements occurring throughout the lifetime of the project, minus the salvage value [20].

\[ C_{arep} = C_{rep} \cdot f_{rep} \cdot SFF(i, R_{comp}) - S \cdot SFF(i, R_{proj}) \]

\( C_{arep} \) : is the annualized replacement cost;

\( C_{rep} \) : is the capital cost of the replaced components;

\( S \) : is the salvage at the end of the project lifetime;

\( R_{comp} \) : is the lifetime of the component;

\( SFF \) : is the sinking fund factor, which is calculated by [20]:

\[ SFF(i, N) = \frac{i}{(1 + i)^N - 1} \]

\( f_{rep} \) : is a factor to compensate the difference between the component lifetime and the project lifetime, which is calculated by [20]:

\[ f_{rep} = CRF(i, R_{proj}) / CRF(i, R_{rep}) \]

\( R_{rep} \) : is the replacement cost duration, which is calculated by [20]:

\[ R_{rep} = R_{comp} \cdot INT\left( R_{proj} / R_{comp} \right) \]

\( R_{comp} \) : is the lifetime of the component;

\( INT \) : is the integer function which returns the integer portion of a real value.
• The O&M cost of a component is the operation and maintenance cost which is necessary to maintain the component with proper operation along its lifetime. The total O&M cost of the plant is the sum of the O&M costs of the plant components.

• The levelized cost of energy (COE) is the average cost per kWh of useful electrical energy produced by the plant [20].

\[
COE = \frac{\text{total costs}}{\text{total generated energy}}
\]

4.4.2. ECONOMICAL CALCULATIONS OF THE PLANT

The aim of this section is to show the effect of different control strategies on the cost of the generated energy units. The criterions of comparison should be considered in the economical evaluation of the control strategies. However, the effect of the control strategies on the lifetime of the battery, the maintenance cost and the frequency deviations cannot be economically considered depending only on the simulation of one day. Therefore, only the effect of the control strategies on the fuel consumption is considered in the cost evaluation.

Since the available data covers only one simulated day, the economical calculations are subjected to several assumptions. Nevertheless, the difference of the cost between the studied control strategies can be considered since the assumptions are applied on all the strategies. The initial capital cost is approximately calculated by considering reference costs of the plant components per power unit. The supplementary components of the plant such as lines and bus bars are considered as integrated parts with the main components [17].

<table>
<thead>
<tr>
<th>Components of the plant</th>
<th>Reference capital cost</th>
<th>Reference operation and maintenance costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel generators</td>
<td>1.3 [MUSD/MW]</td>
<td>0.105 [USD/hour/kW]</td>
</tr>
<tr>
<td>PV field including inverters</td>
<td>4.4 [MUSD/MW]</td>
<td>52 [USD/year/kW]</td>
</tr>
<tr>
<td>Battery bank</td>
<td>680 [USD/kWh]</td>
<td>2.40 [USD/year/kWh]</td>
</tr>
<tr>
<td>Battery inverters</td>
<td>680 [USD/kW]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 18: Reference initial capital cost of the system components [17].
It is assumed that the control strategy does not affect the capital cost of the plant because they do not require extra components. The lifetime of the project is assumed to be 25 years [23]. The real interest rate is assumed to be 3.3% [24]. The salvage value of the project is 32% of the initial cost [25]. The diesel cost per litre is assumed with 1.2 USD/litre [26]. The lifetime of the batteries is assumed to be 8 years [27].

The load and the solar irradiation can have considerable variations along the year. Therefore, the fuel consumption of a complete year cannot be calculated, since the simulations in the thesis cover only one day. As a simplified method to calculate the energy cost of the simulated day, the annualized costs, which are independent from the fuel consumption, are calculated, and then divided by the number of days per year.

<table>
<thead>
<tr>
<th></th>
<th>Diesel generators</th>
<th>PV plant including inverters</th>
<th>Battery inverter</th>
<th>Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial capital cost</strong></td>
<td>$3,182,400.00</td>
<td>$13,200,000.00</td>
<td>$2,040,000.00</td>
<td>$15,640,000.00</td>
</tr>
<tr>
<td><strong>Annualized capital cost</strong></td>
<td>$189,612.67</td>
<td>$786,477.91</td>
<td>$121,546.59</td>
<td>$931,857.16</td>
</tr>
<tr>
<td><strong>Annualized replacement cost</strong></td>
<td>$56,802.22</td>
<td>$235,604.98</td>
<td>$36,411.68</td>
<td>$1,561,131.43</td>
</tr>
<tr>
<td><strong>Annual O&amp;M cost</strong></td>
<td>$684,883.08</td>
<td>$156,000.00</td>
<td>$0.00</td>
<td>$55,200.00</td>
</tr>
<tr>
<td><strong>Total annualized cost of the plant</strong></td>
<td>$931,297.97</td>
<td>$1,178,082.89</td>
<td>$157,958.26</td>
<td>$2,548,188.59</td>
</tr>
<tr>
<td><strong>Total annualized costs</strong></td>
<td></td>
<td></td>
<td></td>
<td>$4,815,527.71</td>
</tr>
</tbody>
</table>

**Table 19: Annualized costs of the plant which are independent from the fuel consumption.**

Table 19 shows that the batteries have the highest cost of the plant components. This can be explained by the high capital cost and the relative short lifetime compared to other plant components.

The daily costs are calculated with the fuel cost according to each control strategy.
<table>
<thead>
<tr>
<th></th>
<th>Control strategy 1</th>
<th>Control strategy 2</th>
<th>Control strategy 3</th>
<th>Control strategy 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost [$/day]</td>
<td>5,560.26</td>
<td>5,560.26</td>
<td>5,560.26</td>
<td>5,560.26</td>
</tr>
<tr>
<td>Replacement cost [$/day]</td>
<td>5,177.95</td>
<td>5,177.95</td>
<td>5,177.95</td>
<td>5,177.95</td>
</tr>
<tr>
<td>O&amp;M cost [$/day]</td>
<td>2,455.02</td>
<td>2,455.02</td>
<td>2,455.02</td>
<td>2,455.02</td>
</tr>
<tr>
<td>Fuel cost [$/day]</td>
<td>5,776.20</td>
<td>5,974.68</td>
<td>5,776.08</td>
<td>5,854.56</td>
</tr>
<tr>
<td>Total cost [$/day]</td>
<td>18,969.43</td>
<td>19,167.91</td>
<td>18,969.31</td>
<td>19,047.79</td>
</tr>
<tr>
<td>Levelized cost of energy [$/kWh]</td>
<td>0.488</td>
<td>0.493</td>
<td>0.488</td>
<td>0.489</td>
</tr>
</tbody>
</table>

Table 20: Costs of the plant for the simulated day.

Figure 67: Costs for the simulated day according to the control strategies.
Figure 68: Levelized cost of energy in the simulated day according to the control strategies.

Table 20 shows that control strategy (3) can provide the least levelized cost of energy, whereas control strategy (2) provides the highest levelized cost of energy, while control strategy (4) and (1) provide the second and third highest cost in the simulated day respectively. The saving in the fuel cost in control strategy (3) is approximately 3.5% compared to control strategy (2), consequently the saving in the levelized cost of energy in control strategy (3) is 1% compared to control strategy (2).
CHAPTER FIVE:
CONCLUSIONS
5. CONCLUSIONS

In this thesis, the dynamic operation of a hybrid PV-diesel generator-battery plant in off grid power supply is simulated in PowerFactory. The primary and secondary control of active power is considered to compensate the active power fluctuations, which result from the variations of the load and PV field power. Four control strategies are proposed to represent different contribution to the primary and secondary control between the battery energy storage system (BESS) and the diesel generators.

1- Control strategy (1): the primary control is provided by the diesel generators and the BESS in parallel, and the secondary control is provided only by the BESS.

2- Control strategy (2): the primary and secondary control is provided by the diesel generators and the BESS in parallel.

3- Control strategy (3): the primary and secondary control is provided mainly by the BESS.

4- Control strategy (4): the primary control is provided mainly by the BESS, while the secondary control is provided by the diesel generators and the BESS in parallel.

The control strategies are compared according to four criterions; the frequency deviations, fuel consumption, the expected lifetime of the batteries and the performance of the diesel generators.

The results show that each control strategy leads to a different level of variations in the output power of the diesel generators and the BESS. Control strategy (3) leads to more constant output power close to the nominal value of the diesel generators, whereas control strategy (2) leads to a higher level of variations in the output power of the diesel generators, while control strategy (4) and (1) lead to the second and third higher levels of the variations in the loading of the diesel generators respectively.

• In general, when the primary and secondary control covers the power fluctuations from the BESS, the output power of the diesel generators becomes more constant and close to the nominal value.
• The frequency deviations are lower when the BESS mainly provides the primary and secondary control of active power to cover the power fluctuations.

• The fuel consumption is lower when the output power of the diesel generators is constant and close to the nominal value, which means that the power fluctuations are compensated by the BESS. As a result, CO2 emission is lower in this control strategy. In this case, the fuel consumption is 3.5% lower than in the case, in which power fluctuations are covered by the BESS and the diesel generators in parallel.

• The lifetime of the batteries is expected to be lower when the BESS mainly covers the power fluctuations, whereas it is expected to be higher when the fluctuations are covered by the BESS and the diesel generators in parallel.

• The performance of the diesel generators is better when the output power of the diesel generators is constant and close to the nominal value, which means that the BESS mainly covers the power fluctuations of the grid.

• An economical overview is performed by considering the difference in the fuel consumption for each control strategy. The results show that a lower cost of energy is achieved when the power fluctuations are mainly covered by the BESS. The cost of energy for the corresponding control strategy is approximately 1% less compared to the control strategy, when the power fluctuations are covered by the BESS and the diesel generators in parallel. However, the cost saving can be higher if the fuel price increases.

In conclusion, the analyses in this thesis demonstrate that the control strategy, in which the primary and secondary control of active power is mainly provided by the BESS, leads to preferable operation of the plant and lower cost of energy compared to the other analyzed control strategies.
CHAPTER SIX:
RECOMMENDATIONS FOR FUTURE WORK
6. RECOMMENDATIONS FOR FUTURE WORK

6.1. ONE YEAR SIMULATION

The model of the hybrid PV-diesel generator-battery plant, which is built in PowerFactory, can be used as a base for further analysis with dispatch control. A model of dispatch control must be integrated in order to be able to run a one year simulation if the required input data is available.

A one year simulation is useful to study the effects of different dispatch strategies on the operation and cost of the plant. Moreover, the simulation results of one year can be used for more accurate analysis of the fuel consumption of the plant and the lifetime of the battery bank. In addition, it can provide a better economical evaluation compared to one day simulation. Based on one year simulation results, an economical comparison between the control strategies according to the different fuel consumption and different expected lifetime of the batteries can be performed.

6.2. INTEGRATING THE MODEL OF BESS WITH THE EFFECT OF BATTERY AGING

Battery banks are susceptible to performance degradation according to the aging effect. The capacity and the DC voltage of the battery decrease by the time, which can negatively affect the performance of the BESS [14]. However, in this thesis, it is assumed that the capacity and the voltage are not affected by the age; because the simulation is only for one day. For a longer simulation, integrating the model of the BESS with the effect of aging can provide more accurate results, which can be used for better analysis of the lifetime and optimum sizing of battery banks.

6.3. INTEGRATING THE MODEL OF DIESEL GENERATOR WITH THE MAINTENANCE ESTIMATION

As an improvement for the performed analysis in this thesis, the required maintenance of the diesel generators should be analyzed. The maintenance is dependent on the operation conditions including the loading factor of the diesel generators. Integrating the model of diesel generator
with maintenance estimation can provide important results, which can also be used for a more detailed cost analysis of the plant operation and costs.

6.4. CASE STUDY IN SYRIA

As an important implementation of renewable energy technology in the MENA region, the hybrid PV-diesel generator-battery plant in stand-alone operation can be proposed for Arwad. Arwad is a Syrian island that greatly depends on energy supply from the Syrian main land. However, an implementation of the hybrid plant can improve the performance of energy supply in the island and also improve the socio-economic conditions of Arwad people. The Island has a population of 10,000 inhabitants with an area of 200,000 [m²]. The island is located in the Mediterranean Sea, 3 [km] to the west of Tartus city in the Syrian mainland [28]. As an attractive natural and historical site, implementing renewable energy technology in the island can be a desired option that helps to preserve the environment. In addition, a PV field is visually more acceptable compared to wind turbines. Furthermore, the diesel generators can be fueled by biodiesel as an additional option of utilizing renewable energy.

![Figure 69: Location of Arwad [28].](image)

As a recommendation for future work, the implementation of the analyzed hybrid plant can be studied including the sizing, energy yield and economical evaluation of the plant in Arwad.

In fact, a more detailed study case of the implementation of the plant in Syria was planned, but unfortunately the conditions were not suitable for field trips.
REFERENCES


http://targetstudy.com/exams/bee/


http://data.worldbank.org/indicator/FR.INR.RINR


### APPENDIX A: DATASHEET OF THE GENERATOR

#### THREE PHASE SYNCHRONOUS GENERATOR
**MJH 400 LB4**

<table>
<thead>
<tr>
<th>CONTINUOUS DUTY</th>
<th>4 poles</th>
<th>50 Hz - 1500 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBIENT TEMPERATURE</td>
<td>40°C F</td>
<td>WINDING DATA</td>
</tr>
<tr>
<td>INSULATION CLASS</td>
<td>0,8</td>
<td>Number of leads</td>
</tr>
<tr>
<td>POWER FACTOR</td>
<td></td>
<td>Winding pitch</td>
</tr>
<tr>
<td>TEMPERATURE RISE</td>
<td>105/40 c.l.F</td>
<td>80/40 c.l.B</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>Star V</td>
<td>3000</td>
</tr>
<tr>
<td>RATING</td>
<td>1020</td>
<td>890</td>
</tr>
<tr>
<td>kW</td>
<td>816</td>
<td>712</td>
</tr>
<tr>
<td>EFFICIENCY [%] @ 0.8 p.f.</td>
<td>4/4</td>
<td>94.9</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>94.9</td>
</tr>
<tr>
<td></td>
<td>2/4</td>
<td>94.5</td>
</tr>
<tr>
<td>EFFICIENCY [%] @ 1 p.f.</td>
<td>4/4</td>
<td>96.0</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>96.0</td>
</tr>
<tr>
<td></td>
<td>2/4</td>
<td>95.7</td>
</tr>
<tr>
<td>SHORT CIRCUIT RATIO</td>
<td>SCR</td>
<td>0.56</td>
</tr>
<tr>
<td>REACTANCES [%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct axis synchronous</td>
<td>Xd</td>
<td>225</td>
</tr>
<tr>
<td>Quadature axis synchronous</td>
<td>Xq</td>
<td>122</td>
</tr>
<tr>
<td>Direct axis transient</td>
<td>Xd</td>
<td>20.0</td>
</tr>
<tr>
<td>Direct axis subtransient</td>
<td>X'd</td>
<td>9.0</td>
</tr>
<tr>
<td>Quadature axis subtransient</td>
<td>X'q</td>
<td>10.0</td>
</tr>
<tr>
<td>Negative sequence</td>
<td>X2</td>
<td>9.0</td>
</tr>
<tr>
<td>Zero sequence</td>
<td>X₀</td>
<td>2.4</td>
</tr>
<tr>
<td>TIME CONSTANTS [s]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open circuit</td>
<td>T'do</td>
<td>2.43</td>
</tr>
<tr>
<td>Transient</td>
<td>T'd</td>
<td>0.19</td>
</tr>
<tr>
<td>Subtransient</td>
<td>T'd</td>
<td>0.016</td>
</tr>
<tr>
<td>Armature</td>
<td>T_a</td>
<td>0.025</td>
</tr>
</tbody>
</table>

### MECHANICAL CHARACTERISTICS

| D-end bearing/Lubrication | 6324 C3 / With grease nipple |
| N-end bearing/Lubrication | 6318 Z C3 / Preflubricated |
| Overspeed [r.p.m.] | 2250 |
| Inertia (J) [kgm²] | Refer to B34 construction |
| Weight [kg] | Refer to B34 construction |
| Method of cooling | IC01 |
| Cooling air required [m³/s] | 1.30 |
| Degree of protection | IP23 |
| Types of construction available | BZ (SAE) - IM B34 - IM B20 |
| Direction of rotation (Standard) | CW |

### OTHER DATA

| Overloads | 10% for 1 hour every 12 hours |
| 3-phase short circuit sustained current | ≥ 300 % (3 ln) with VARICOMP device |
| Voltage regulation accuracy | ± 1% in steady state condition |
| Radio interference | EN 55011 - Class B Group 1 |
| Wave form THF | < 5% |
| Total harmonic content | < 3% - At no load |

### STANDARDS

| IEC 60034-1, CEI 2-3, BS 4999-5000; VDE 0530, NF 51-100,111; OVE M-10, NEMA MG 1,22. |
# APPENDIX B: DATASHEET OF DIESEL ENGINE

## STANDBY 800 e kW 1000 kVA

60 Hz 1800 rpm 480 Volts

## TECHNICAL DATA

<table>
<thead>
<tr>
<th>Open Generator Set - - 1800 rpm/60 Hz/480 Volts</th>
<th>DM7686</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA Certified for Stationary Emergency Application (EPA Tier 2 emissions levels)</td>
<td></td>
</tr>
<tr>
<td>Generator Set Package Performance</td>
<td></td>
</tr>
<tr>
<td>Genset Power rating @ 0.8 pf</td>
<td>1000 kVA</td>
</tr>
<tr>
<td>Genset Power rating with fan</td>
<td>800 e kW</td>
</tr>
<tr>
<td>Coolant to aftercooler temp max</td>
<td></td>
</tr>
<tr>
<td>Coolant to aftercooler temp max</td>
<td>49 °C 120 °F</td>
</tr>
<tr>
<td>Fuel Consumption</td>
<td></td>
</tr>
<tr>
<td>100% load with fan</td>
<td>216.9 L/hr 57.3 Gal/hr</td>
</tr>
<tr>
<td>75% load with fan</td>
<td>171.7 L/hr 45.4 Gal/hr</td>
</tr>
<tr>
<td>50% load with fan</td>
<td>122.3 L/hr 32.3 Gal/hr</td>
</tr>
<tr>
<td>Cooling System</td>
<td></td>
</tr>
<tr>
<td>Air flow restriction (system)</td>
<td>0.12 kPa 0.48 in. water</td>
</tr>
<tr>
<td>Air flow (max @ rated speed for radiator arrangement)</td>
<td>1137 m³/min 40153 cfm</td>
</tr>
<tr>
<td>Engine Coolant capacity with radiator/exp. tank</td>
<td>160.0 L 42.3 gal</td>
</tr>
<tr>
<td>Engine coolant capacity</td>
<td>55.0 L 14.5 gal</td>
</tr>
<tr>
<td>Radiator coolant capacity</td>
<td>105.0 L 27.7 gal</td>
</tr>
<tr>
<td>Inlet Air</td>
<td></td>
</tr>
<tr>
<td>Combustion air inlet flow rate</td>
<td>62.8 m³/min 2217.8 cfm</td>
</tr>
<tr>
<td>Exhaust System</td>
<td></td>
</tr>
<tr>
<td>Exhaust stack gas temperature</td>
<td>511.4 °C 952.5 °F</td>
</tr>
<tr>
<td>Exhaust gas flow rate</td>
<td>170.3 m³/min 6014.1 cfm</td>
</tr>
<tr>
<td>Exhaust flange size (internal diameter)</td>
<td>203 mm 8 in</td>
</tr>
<tr>
<td>Exhaust system backpressure (maximum allowable)</td>
<td>10.0 kPa 40.2 in. water</td>
</tr>
<tr>
<td>Heat Rejection</td>
<td></td>
</tr>
<tr>
<td>Heat rejection to coolant (total)</td>
<td>330 kW 18767 Btu/min</td>
</tr>
<tr>
<td>Heat rejection to exhaust (total)</td>
<td>796 kW 45269 Btu/min</td>
</tr>
<tr>
<td>Heat rejection to aftercooler</td>
<td>162 kW 9213 Btu/min</td>
</tr>
<tr>
<td>Heat rejection to atmosphere from engine</td>
<td>110 kW 6256 Btu/min</td>
</tr>
<tr>
<td>Heat rejection to atmosphere from generator</td>
<td>36.8 kW 2092.8 Btu/min</td>
</tr>
<tr>
<td>Alternator</td>
<td></td>
</tr>
<tr>
<td>Motor starting capability @ 30% voltage dip</td>
<td>2131 e kVA</td>
</tr>
<tr>
<td>Frame</td>
<td>597</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>130 °C 234 °F</td>
</tr>
<tr>
<td>Lube System</td>
<td></td>
</tr>
<tr>
<td>Sump refill with filter</td>
<td>68.0 L 18.0 gal</td>
</tr>
<tr>
<td>Emissions (Nominal)</td>
<td></td>
</tr>
<tr>
<td>NOx g/hp-hr</td>
<td>5.18 g/hp-hr</td>
</tr>
<tr>
<td>CO g/hp-hr</td>
<td>0.23 g/hp-hr</td>
</tr>
<tr>
<td>HC g/hp-hr</td>
<td>0.03 g/hp-hr</td>
</tr>
<tr>
<td>PM g/hp-hr</td>
<td>0.24 g/hp-hr</td>
</tr>
</tbody>
</table>

1 For ambient and altitude capabilities consult your Cat dealer. Air flow restriction (system) is added to existing restriction from factory.
2 Generator temperature rise is based on a 40°C ambient per NEMA MG-1-32. UL 2200 Listed packages may have oversized generators with a different temperature rise and motor starting characteristics.
3 Emissions data measurement procedures are consistent with those described in EPA CFR 40 Part 89, Subpart D & E and ISO8178-1 for measuring HC, CO, PM, NOx. Data shown is based on steady state operating conditions of 77°F, 28.42 in HG and number 2 diesel fuel with 35° API and LHV of 19,380 btu/lb. The nominal emissions data shown is subject to instrumentation, measurement, facility and engine to engine variations. Emissions data is based on 100% load and thus cannot be used to compare to EPA regulations which use values based on a weighted cycle.
APPENDIX C: DATASHEET OF BATTERY

Technical Specification of BAE Secura PVS solar

Terminals are designed as female poles with brass inlay M10 for flexible insulated copper cables with cross-section 25, 35, 50, 70, 95 or 120 mm² or insulated solid copper connectors with cross-section 90, 150 or 300 mm².

4. Design
Positive electrode: tubular-plate with a woven polyester gastight and solid grids in a corrosion-resistant PbSbSnSe-low antimony alloy
Negative electrode: grid-plate in a low antimony alloy with long life expander material
Separation: microporous separator
Electrolyte: sulphuric acid with a density of 1.24 kg/l at 20 °C
Container: high impact, transparent SAN (Styrol-Acryl-Nitrile), UL-94 rating: HB
Lid: high impact, SAN in dark grey colour, UL-94 rating: HB
Plugs: labyrinth plugs for arresting aerosol, optional ceramic plugs or ceramic funnel plugs according to DIN 40740
Pole-bushing: 100 % gas- and electrolyte-tight, sliding, plastic-coated “Panzerpel”
Kind of protection: IP 25 regarding DIN 40050, touch protected according to VBG 4

5. Installation
BAE Secura PVS solar batteries are designed for indoor applications. For outdoor applications please contact BAE.

6. Maintenance
Every 6 months: check battery voltage as well as temperature
Every 12 months: check connections, record battery cell voltage as well as temperature
Every 3 years: average water-refilling interval (depending on utilization and ambient temperature)

7. Operational data
Depth of discharge (DOD): max. 80 % (U = 1.91 V/cell for discharge times >10 h, 1.74 V/cell for 1 h)
Charge current: deep discharges of more than 80 % DOD have to be avoided
Charge voltage at cyclic operation: unlimited, the minimal charge current has to be Imin
Floating voltage/non cyclic voltage: 2.23 V/cell
Adjustment of charge voltage: no adjustment necessary if battery temperature is between 10 °C and 30 °C in the monthly average, otherwise ΔU/ΔT = -0.003 V/cell per K
Recharge to 100 %: within a period of 1 up to 4 weeks
IEC 61427 cycles: 3150 (A+B)
Battery temperature: -20 °C to 55 °C, recommended temperature range 10 °C to 30 °C
Self-discharge: approx. 3 % per month at 20 °C

8. Number of cycles as function of DOD (Depth of discharge)

9. Transport
Batteries are not subject to ADR (road transport), if the conditions of special rule 598 (chapter 3.3) are observed.

10. Standards
Test standard: IEC 60896-11, IEC 61427
Safety standard, ventilation: EN 50077-2

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Fax +49 30 33541949
E-mail: info@bae-berlin.de
www.bae-berlin.de
الملخص

تعتبر المحطات الكهربائية الهجينية المكونة من مصادر الطاقات المتجددة مثل الخلايا الشمسية بالإضافة إلى مولدات الديزل ونظام تخزين القدرة الكهربائية بالبطاريات في نظام شبكة مزدوجة من أفضل الخيارات لتزويد المناطق البعيدة بالقدرة الكهربائية. إلا أنه من أجل تنظيم التردد في الشبكة فإن مولدات الديزل والبطاريات تكون معرضة لتغييرات في التحميل لتعويض التغيرات المختلفة في طاقة نظام الخلايا الشمسية والإحمال الكهربائي. تؤدي هذه التغييرات إلى نتائج سلبية على أداء مولدات الديزل من حيث زيادة استهلاك الوقود والصيانة وغيرها.

في رسالة الماجستير سوف يتم تحليل عدة طرق تحمك من أجل تحصين أداء المحطة الهجينية وبالتالي تقليل كلفة التشغيل. لذلك تم اقتراح أربعة طرق تحمك بالنسبة للتحكم الأولي والثاني للاستطاعة الحقيقية. كل طريقة تحمك تؤدي إلى تحميل مختلف لمولدات الديزل ونظام البطاريات. بعد ذلك يتم القيام ببنودة ديناميكية لأداء المحطة لكل طريقة تحمك على حدة ثم يتم مقارنة تأثير طريقة التحكم على أداء المحطة بحسب أربعة معايير هي انحرافات التردد، استهلاك الوقود، عمر البطاريات، وأيضاً أداء مولدات الديزل. وفي النهاية يتم حساب كلفة واحدة القدرة للمحطة لكل طريقة تحمك مع الأخذ بعين الاعتبار اختلاف استهلاك الوقود في كل طريقة تحمك.

إن نتائج النمذجة ببنت أن طريقة التحمك التي تؤمن تعويض تغيرات الطاقة في الشبكة من نظام البطاريات تؤدي إلى تحميل ثابت لمولدات الديزل، وأقل انحرافات لتردد الشبكة، وأقل استهلاك وقود، وأداء أفضل لمولدات الديزل، وكفالة أقل لواحدة القدرة، ولكن عمر أقل لنظام البطاريات. بينما طريقة التحكم التي تؤمن تغييرات الطاقة من نظام البطاريات ومولدات الديزل على التوالي تؤدي إلى تغييرات في تحميل مولدات الديزل، وأقل انحرافات أكبر لتردد الشبكة، واستهلاك أكبر للوقود، وأداء غير أفضل لمولدات الديزل، وكفالة أعلى لواحدة القدرة، ولكن عمر أطول لنظام البطاريات.
النماذجة الدينياميكية لمحطة هجين من خلايا شمسية ومولدات ديزل وبطاريات في حالة شبكة كهربائية معزولة

إعداد

باسم الإدليبي

رسالة مقدمة إلى كلية الهندسة، جامعة القاهرة

و كلية هندسة الكهرباء و علم الحاسوب، جامعة كاسل

كجزء من متطلبات الحصول على درجة الماجستير في الطاقة المتجددة وكفاءة الطاقة

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الجيزة، مصر

جامعة القاهرة

أذار، 2012
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Declaration:

I declare that this master thesis is my own genuine work and has not been submitted in any form for another degree or diploma at any university or other institute of tertiary education. Information derived from the published and unpublished work of others has been acknowledged in the text and a list of references is given in the bibliography.

March, 2012

Kassel, Germany

Basem Idlbi

Signature: ............................................