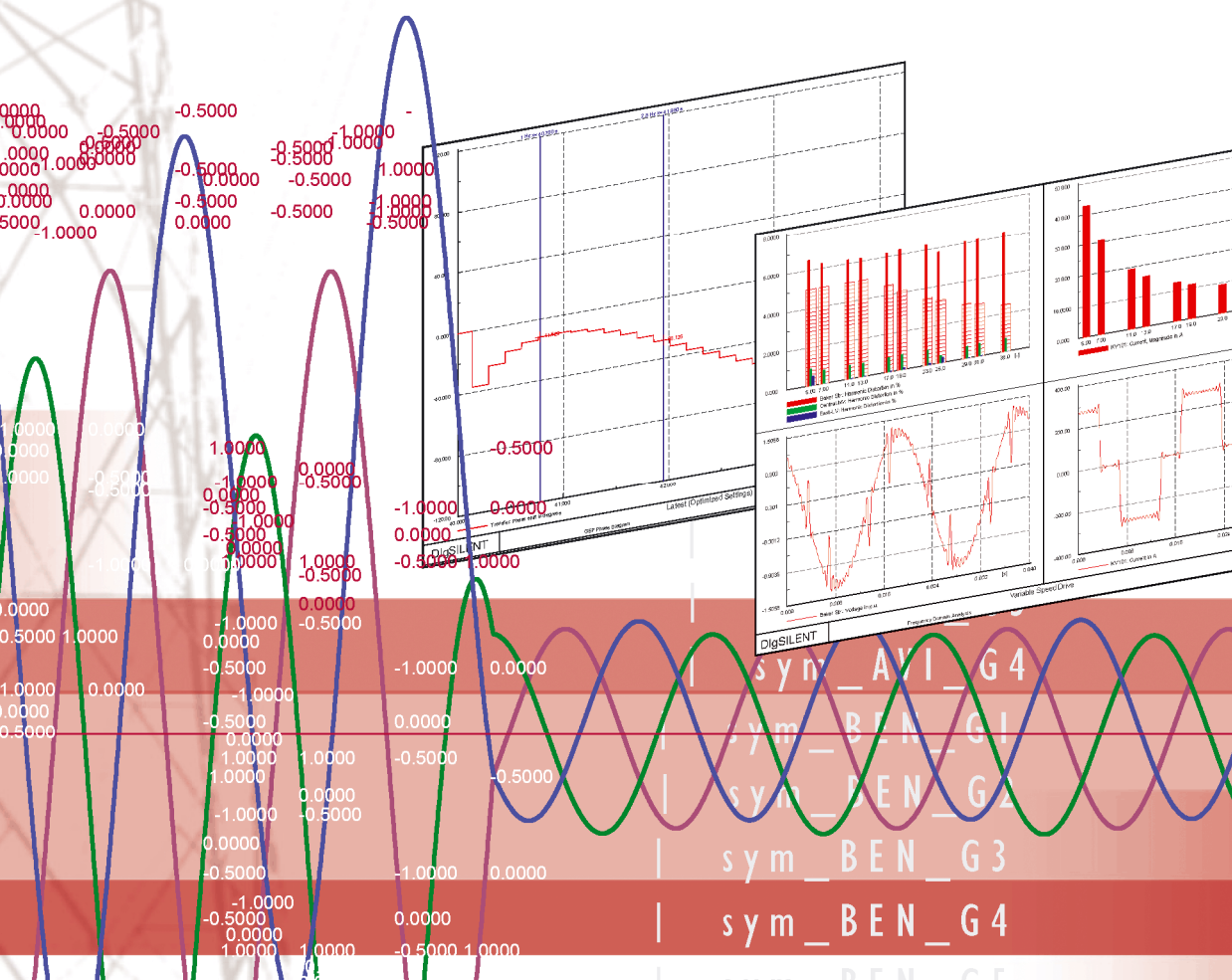


DigSILENT *PowerFactory* Application Example

Battery Energy Storing Systems BESS



$T_p = 0.9$
41300 ALD---
ARG_3.3-G
41811 AVI---G
41812 AVI---G
41813 AVI---G
41814 AVI---G
42011 BEN16
42017 BEN16--
42011 BEN16--
42012 BEN16--
42013 BEN16--



DigSILENT GmbH

Heinrich-Hertz-Str. 9
72810 - Gomaringen
Germany

T: +49 7072 9168 00
F: +49 7072 9168 88

<http://www.digsilent.de>
info@digsilent.de

Copyright ©2010, DigSILENT GmbH. Copyright of this document belongs to DigSILENT GmbH. No part of this document may be reproduced, copied, or transmitted in any form, by any means electronic or mechanical, without the prior written permission of DigSILENT GmbH.

Contents

| | |
|--|-----------|
| 1 Introduction | 3 |
| 2 BESS Simulation Model | 3 |
| 2.1 Battery Model | 3 |
| 2.2 Voltage Sourced Converter (VSC) | 7 |
| 2.2.1 Short Circuit Calculation | 8 |
| 2.3 The BESS Controller | 8 |
| 2.4 Testing the BESS | 14 |
| 3 Network Model | 15 |
| 4 Application Case 1: Frequency Regulation | 18 |
| 4.1 Replacement of Primary Control Energy (Load Change) | 18 |
| 4.2 Replacement of Primary Control Energy (Generator Outage) | 22 |
| 5 Application Case 2: FRT Simulation | 25 |
| References | 28 |

1 Introduction

Large Battery Energy Storage Systems (BESS) are being increasingly used in Flexible AC Transmission Systems (FACTS) applications as a way to improve the voltage, frequency, oscillatory and/or transient stability of the system and hence enhance the reliability of power supply. These applications include different FACT controllers, where the storage devices are interfaced with the power system through either shunt- or series-connected voltage sourced converters (VSC).

This document describes the assessment of a BESS to replace the spinning reserve/primary reserve in a test network. The document gives the reader guidance on how to perform the analysis in the simulation tool *PowerFactory* (PDF). This BESS application becomes significantly important in small or island power system, with rather low spinning reserve, where load perturbations have a considerable effect on the network frequency.

In the first part of this application guide describes the relevant characteristics of the test network and discusses all modelling and project organisational issues that must be taken into account when setting up the model in PDF. Secondly, all required dynamic models, including the battery and the shunt VSC controller models, are presented and verified. Finally, different cases are simulated and results discussed.

For a better usability are the names of the study cases of the project as well as the important steps in *PowerFactory* given. This parts are marked in italic. So the reader could use the document in parallel with the *PowerFactory* project of the BESS.

2 BESS Simulation Model

A battery energy storing system (BESS) consists of two parts. Firstly a storing part that could store/restore energy in an electrochemical process. Secondly a rectifier/inverter that could transform the DC-voltage from the storing part to the AC-voltage needed for the grid and vice versa. The rectifier/inverter is normally based on a voltage sourced converter (VSC) with a pulse width modulation (PWM). This element is well known and available in *PowerFactory*. The storing part in this case a rechargeable battery is an element that depends on the actual application. The problem with batteries is the huge diversity of the technologies and also the variety inside one technology. So there is no easy, accurate model, valid for all batteries [4][3][2][5].

2.1 Battery Model

There are two main challenges with battery models. The first problem is to get a model that is not too complex but accurate enough. The second problem is to get the parameters from manufacturers or own measurements needed for the model. Only a model with appropriate parameters could deliver good results.

Common batteries in the industry are often lead-acid batteries. But there are also a lot of other types like nickelcadmium (NiCd), nickel-metal hybrid (NiMH) and several lithium-ion types. Each type has its own assets and drawbacks.

To design a good model for a battery is a science on itself. Different approaches could be found in [3], [2] and [5]. A battery model should depict the terminal voltage and the internal resistance which are a function of several intern-related variables such as the Battery State of Charge (SOC), the age and temperature of the battery [5]. The State of Charge corresponds to the current loading state of the battery. The battery is fully loaded if the SOC is one and it is zero if

the battery is empty.

A simple electric equivalent for a battery together with a more complex equivalent with parasitic path is shown in Figure 2.1. It depends on the application case which model will be used. There is an important equation for the capacity of all lead-acid batteries, called "Peukert's law" (1). It expresses the capacity of a battery in terms of the rate at which it is discharged. As the rate increases, the battery's available capacity decreases.

$$C_p = I^k t \quad (1)$$

C_p is the capacity according to Peukert, at a one-ampere discharge rate, expressed in Ah.

I is the discharge current, expressed in A.

k is the Peukert constant, dimensionless.

t is the time of discharge, expressed in h.

For a lead-acid battery, the value of k is typically between 1.1 and 1.3. The problem with Peukert's law is, that at a discharge current of zero, the available capacity becomes infinity.

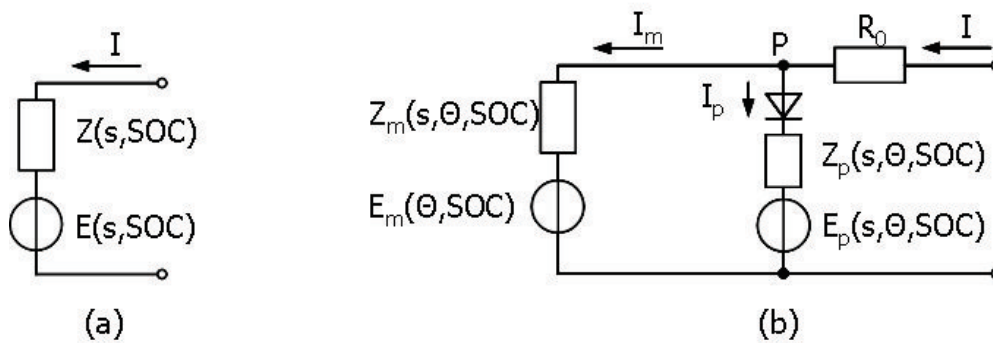


Figure 2.1: Battery Electric Equivalent, (a) simple, (b) with parasitic reaction [5]

The discharge voltage of a battery is also dependent on the SOC as exemplarily shown in the picture below. It is obvious, that the battery voltage is nonlinearly dependent on the SOC, especially for $0 < \text{SOC} < 0.2$.

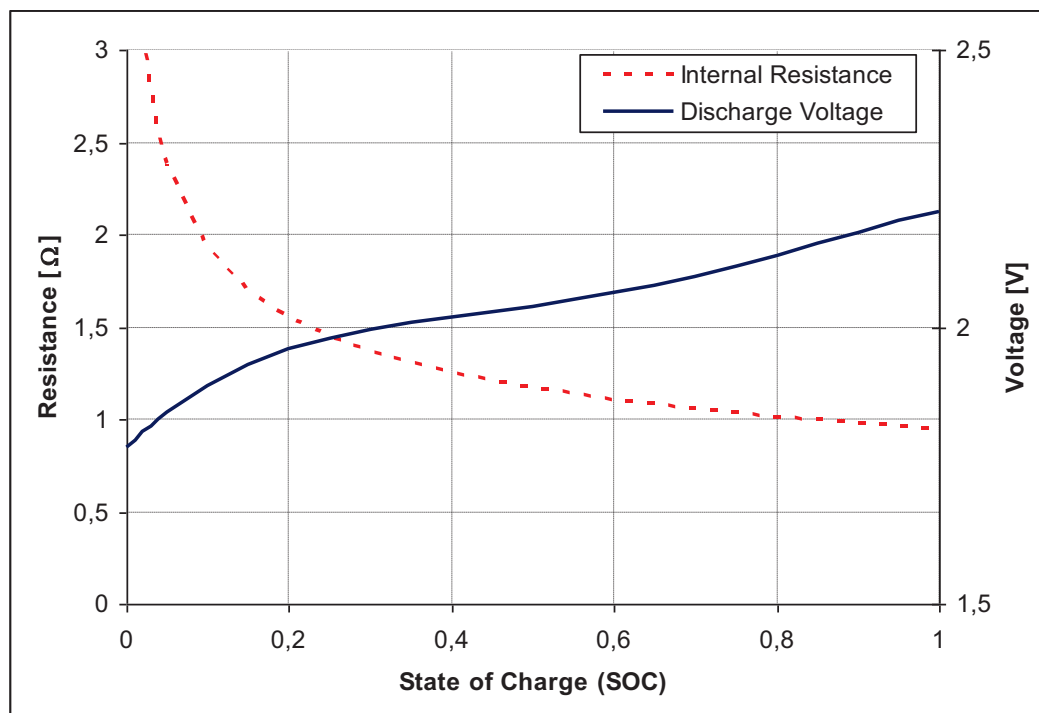


Figure 2.2: Typical Discharge Profile of a Lead-Acid Battery [1]

Also the internal resistance is dependent on the SOC (Figure 2.2). Again the nonlinearity is obvious, especially for low values of the SOC.

There are no general empirical equations available to describe the behaviour of arbitrary batteries. But if there is a detailed datasheet for one specific battery it is possible to use that data in a *PowerFactory* DSL model. The data could be stored in a one- or two dimensional array and then used in a DSL model. Such a battery model would be more accurate for one specific battery. But it is not easy to obtain the needed manufacturer data.

In the following a simplified battery model for a showcase BESS is presented. Some assumptions are made to get a simple, but functional model. At first, it is assumed, that the battery is only discharged down to 20%. In that case the voltage could be assumed as linearly dependent on the SOC. Additionally the internal resistance is assumed as constant because it has to be anyway very small due to the high current application. The battery capacity is assumed as constant, this is valid if the discharge current is known in advance. So the expected capacity could be calculated and inserted in the data of the model. If the battery is discharged at other rates than assumed before the capacity has to be recalculated and changed in the battery model parameters.

With the assumptions above the battery model will be similar to the equivalent simple model in Figure 2.1 with a constant inner resistance $Z(s, SOC) = Z$ and a voltage source with a voltage dependent on the SOC. This is detailed enough for an application case but for a detailed study is also a detailed battery model needed. The equation for the model is given in 2. The SOC is calculated with an integrator, counting the current of the battery.

$$U_{DC} = U_{max} \cdot SOC + U_{min} \cdot (1 - SOC) - I \cdot Z_i \quad (2)$$

The implementation of the battery model is done in DSL (Figure 2.3). 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 is may be needed for a charge controller.

| Variable | Unit | Description |
|---------------|------|---|
| u_min | V | Cell voltage of discharged cell. |
| u_max | V | Cell voltage of fully loaded cell. |
| CellCapacity | Ah | Capacity of one cell for the used discharge current (see Peukert's law) |
| CellsParallel | Int | Amount of parallel connected cells (increases the total capacity). |
| CellsInRow | Int | Amount of serial connected cells (increases the output voltage). |
| RiCell | Ohm | Internal resistance per cell (average value). |
| Unom | kV | Voltage rating of the connected DC-busbar. |
| SOC0 | Int | State of Charge at the beginning of the Simulation. |

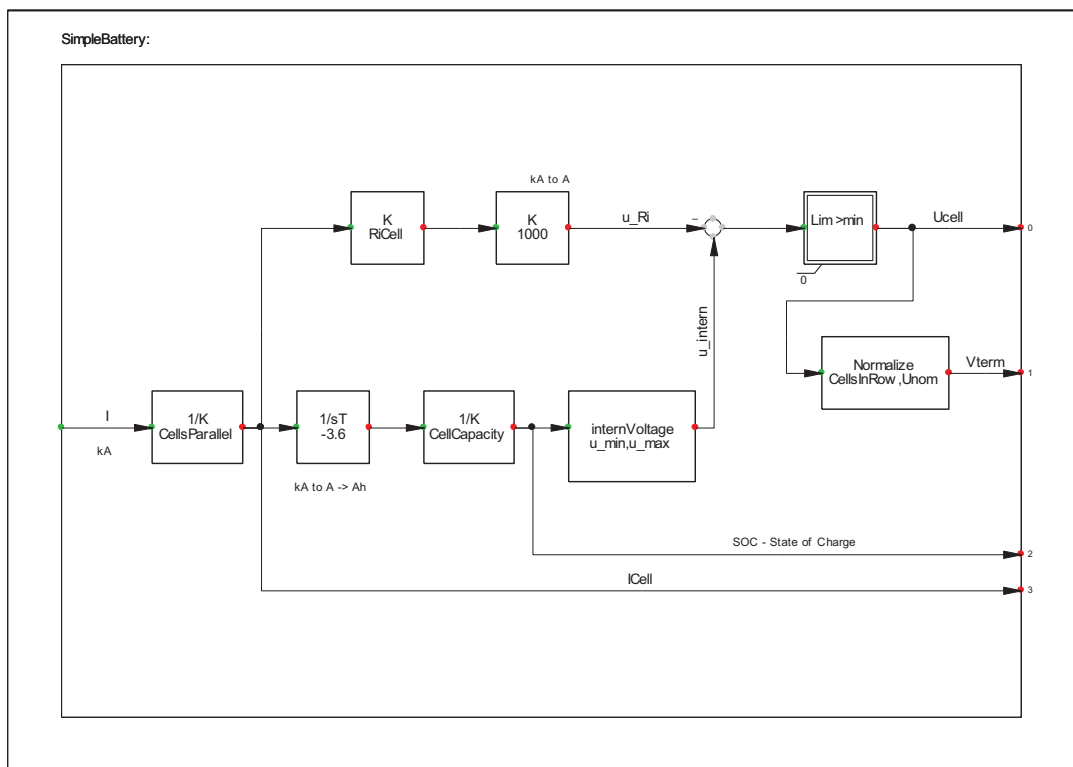


Figure 2.3: Simplified Battery Model in DSL (*.BlkDef)

The integrator (1/sT) that counts the current in- and output of the battery needs an initial condition (SOC0). This value is part of the model parameters. During the initialisation process it is assumed, that the battery is not being charged or discharged. So the active power exchange of the BESS is zero for the load flow.

The battery appears in *PowerFactory* in the single line diagram as a DC-voltage source. To apply the voltage output of the battery model (Figure 2.3) to the DC-voltage source is a DSL-frame needed (Figure 2.4).

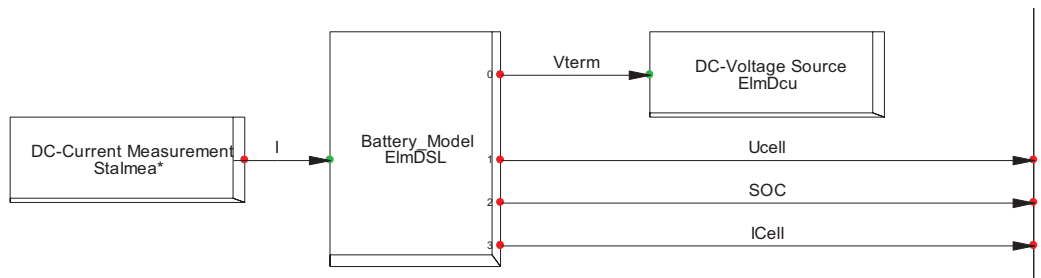


Figure 2.4: Frame for the Battery Model in DSL (*.BlkDef)

2.2 Voltage Sourced Converter (VSC)

The VSC converts the DC-voltage from the battery to an AC-voltage through fast switching of IGBT-valves.

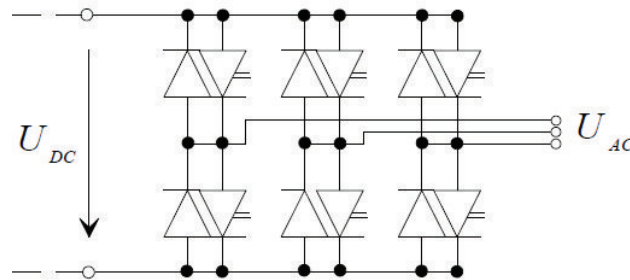


Figure 2.5: Equivalent Circuit of a PWM Converter

The switching signal, also called amplification factor (P_m), comes from the control system of the VSC. This could also be expressed for a fundamental frequency model as:

$$U_{ACr} = K_0 P_m U_{DC} \quad (3)$$

$$U_{ACi} = K_0 P_m U_{DC} \quad (4)$$

U_{ACr} and U_{ACi} is the real, respectively imaginary part of the AC-voltage. P_m is the already mentioned amplification factor and U_{DC} is the DC-voltage of the battery. K_0 is a constant factor, depending on the used PWM-method. For sinusoidal modulation:

$$K_0 = \frac{\sqrt{3}}{2\sqrt{3}} \quad (5)$$

For $|P_m| \leq 1$ the equations above are valid. If P_m becomes bigger than one there are problems with harmonics. So it has to be secured, that the DC-voltage is always over a certain level:

$$U_{DC} \geq \frac{2\sqrt{2}}{\sqrt{3}} |U_{AC}| \quad (6)$$

This could also be showed in Figure 2.6.

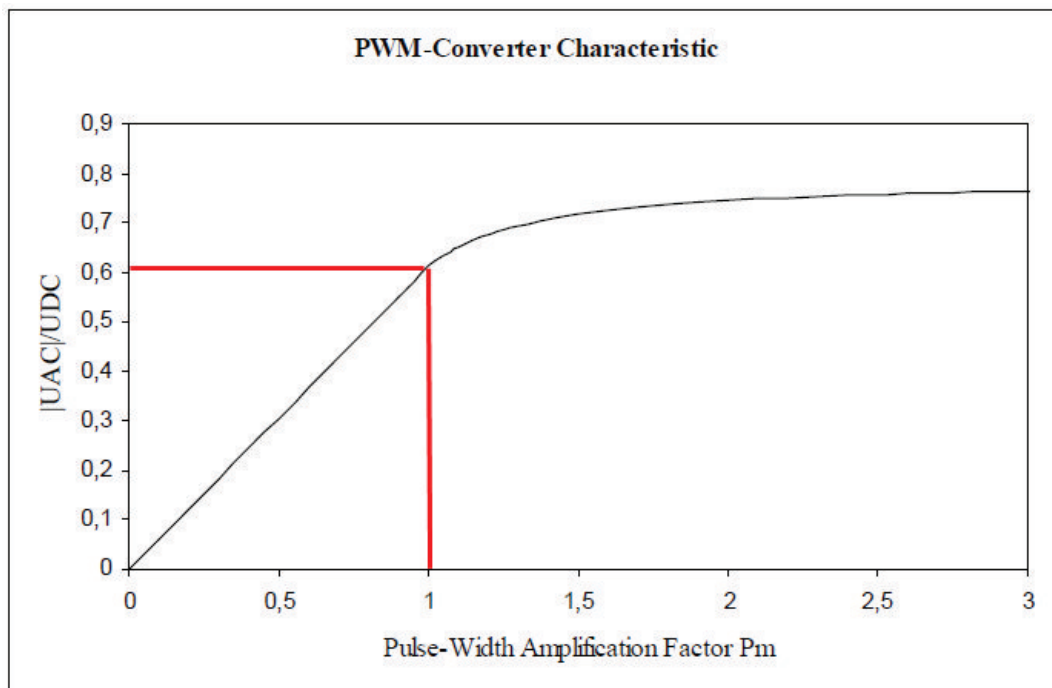


Figure 2.6: Saturation of a VSC with Sinusoidal PWM

The *PowerFactory* PWM-converter model has different possible input combinations. For that case the "id_ref" and "iq_ref" input is used. This is the current phasor of the PWM-converter transformed in a dq-reference frame. The advantage of the transformation is that "id_ref" equates to the active power output of the converter and "iq_ref" equates to the reactive power of the PWM-converter. So it is easy to implement a controller for the BESS. The PWM-model uses an internal current controller to generate the actual signal for the modulation factor.

2.2.1 Short Circuit Calculation

Short circuit calculation according to IEC60909 / VDE0102 is not possible with a BESS because devices with power electronics like the PWM-converter are not considered by the norm. But *PowerFactory* offers also the possibility to calculate a short circuit according to the so called complete method. The complete method takes also the load flow into account. Furthermore it is possible to configure the PWM-converter model for the complete short circuit method. The two options are constant current or constant voltage. For an IGBT-based converter would be "constant I". the right choice because the valves of the converter are only designed for a certain maximum current. To obtain the maximum current with the complete short circuit method the PWM-converter has to be configured to full active power on the load flow page. Better results could be achieved with a RMS simulation this is described in chapter 5 (only symmetrical cases).

2.3 The BESS Controller

Before a controller could be implemented it has to be clear what the task of the controller is. In the case of the BESS with an IGBT-based converter there are two current parameters to control,

one in the d-axis and one in the q-axis. This equates to the real and reactive power. With the real power output it is possible to control the frequency of a grid with synchronous generators. With the reactive power could the AC-voltage be controlled. The reactive power output of the BESS is not bound to the battery capacity, so the AC-voltage could be controlled continuously. But the apparent power of the PWM-converter is limited and so the reactive power (7).

$$S = \sqrt{P^2 + Q^2} \quad (7)$$

There are more boundary conditions that have to be considered:

- The BESS could only consume active power if the battery is not fully loaded (SOC < 1).
- The BESS could only supply active power if the battery is not discharged (SOC > 0).
- The battery should be recharged if the SOC is below a certain level. So that the BESS has always the ability to control the active power in both ways.
- The total output of active and reactive power should together not be bigger than the apparent rated power, according to (7). Hence a priority for the active or reactive power is needed.

All the conditions could be fulfilled from a charge controller. For the showcase it was assumed, that the SOC is available as a signal. In a real application the SOC has to be calculated from the battery current and voltage.

When all tasks and conditions for the controller are known the design in DSL could be started. For a better overview it is recommended to divide the whole controller in smaller parts:

- Frequency controller (Frequency Control)
- Active/reactive power controller (PQ-Control)
- Charging controller (Charge Control)

Together with the needed measurement devices we get the structure showed in Figure 2.8. This structure is called a frame in *PowerFactory*. A frame and also a DSL model (like the battery model showed in Figure 2.3) are only the definition (*.BlkDef), like a type of a line or a transformer. The entity of a frame is a composite model (*.ElmComp). The entity of a DSL model is a common model (*.ElmDsl).

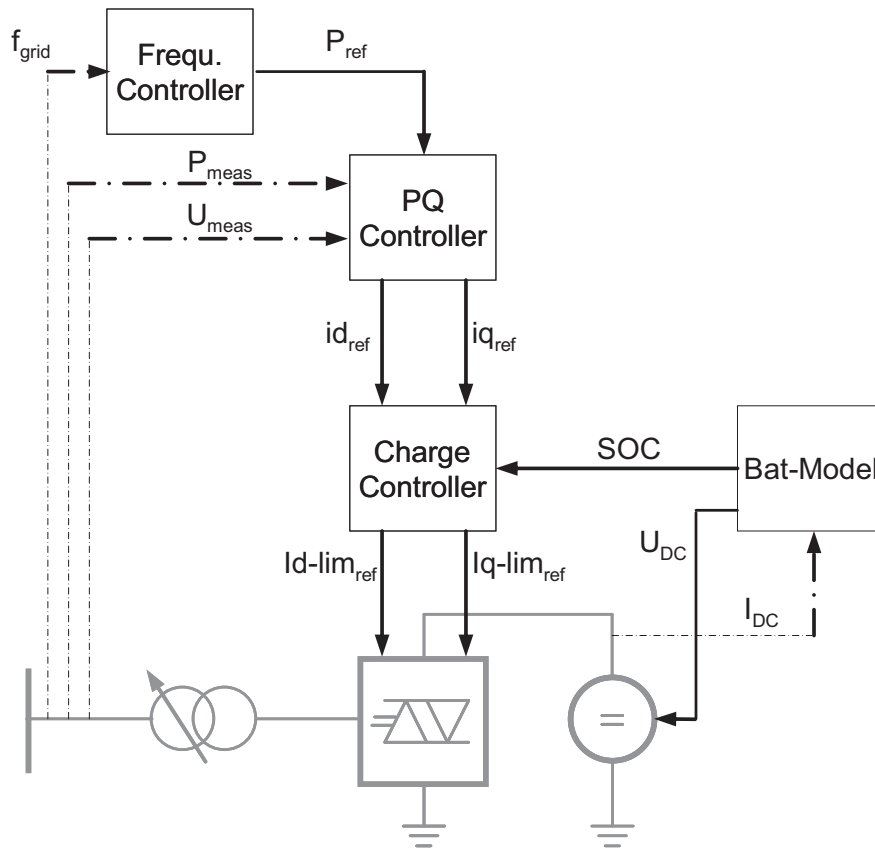


Figure 2.7: Structure of the BESS

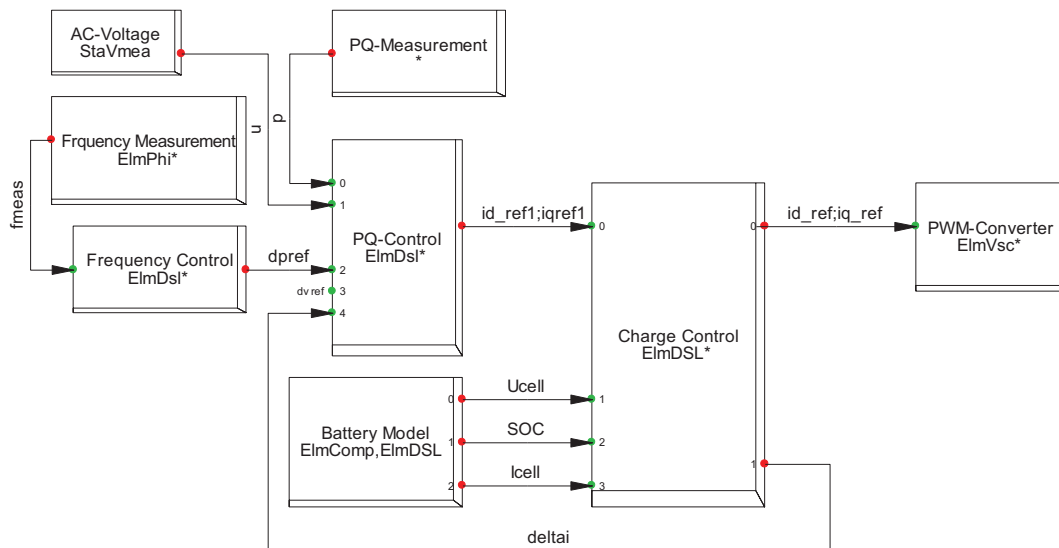


Figure 2.8: Frame for the BESS-Controller (*.BlkDef)

The frequency controller is a simple proportional controller with a small dead band. In a real

power system it is important, that there is only one integrator that controls the frequency. Otherwise there could be problems with oscillations. The model of the frequency controller is showed below. The droop defines how much active power is activated in a case of a frequency deviation. Granted that $K = 0.04$ then the full active power of the BESS is activated if the frequency deviation is equal or greater than 2 Hz (in a 50 Hz system). All values are per unit values. The droop should be coordinated to fulfil grid code requirements in a certain application case.

The command variable is f_0 , during the initialisation process this value will be fixed to frq (normally 1) with the command $inc(f_0) = frq$. The block "offset" with the output "p_0" is used to compensate "dpref" if that value is not equal to zero after the load flow (because "p_order_frequ" is always zero after the initialisation).

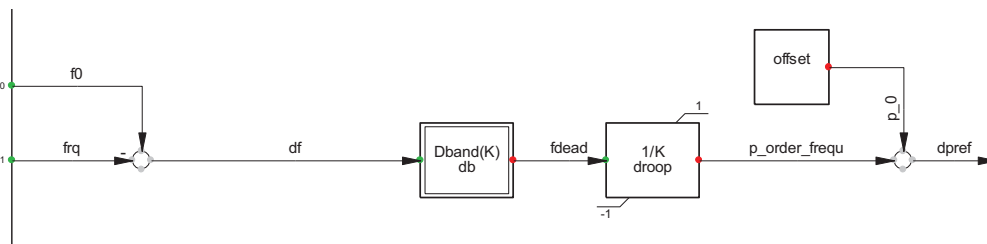


Figure 2.9: Model of the Frequency Controller (*.BlkDef)

The controller for the active and reactive power is a little bit more complex. It is showed in Figure 2.10. The control deviation is filtered with a PT1 element. After that the signals are used as a input to a PI-controller. In the active path is the signal "delta_i" added. In Figure 2.8 could be seen, that "delta_i" comes from the charge controller. The voltage (or Q) controller has a very slow I-controller for set point tracing and a slope with a dead band for proportional voltage support.

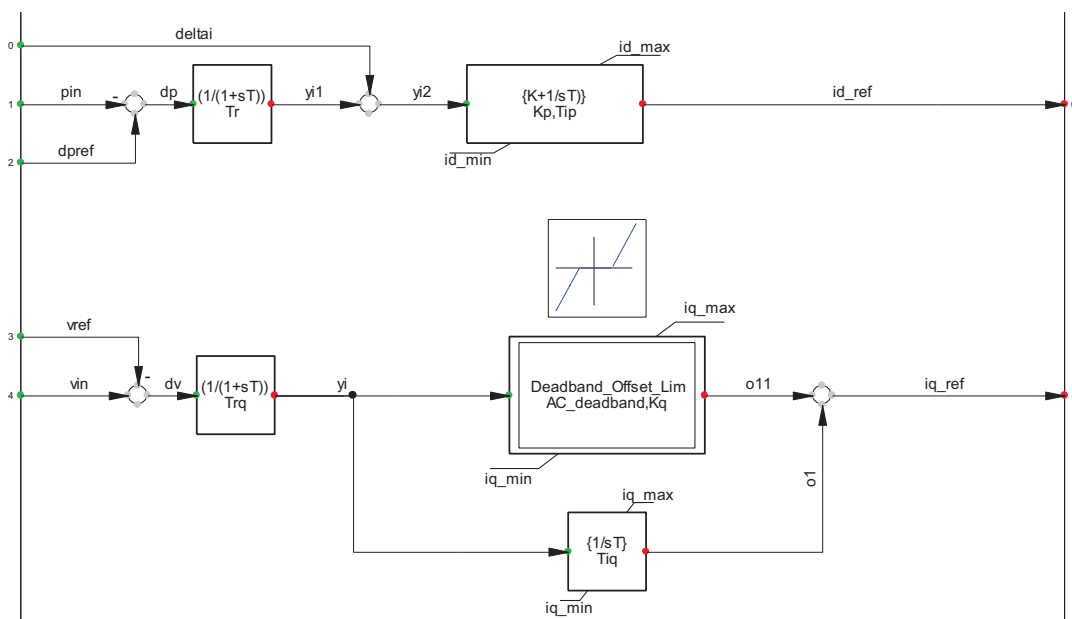


Figure 2.10: Model of the PQ-Controller (*.BlkDef)

The charge controller consists of two parts (Figure 2.11). One charging logic to achieve the

already described boundary conditions and one block that limits the absolute value of the current order according to (7). The active current (d-axis) has always the higher priority than the reactive current (q-axis).

There are only four parameters needed. The charging current (ChargingCur), the minimal SOC (minSOC), the maximum SOC (maxSOC) and the maximal absolute current (maxAbsCur). The signal "deltaI" is the difference of the reference d-current from the PQ-controller and the modified d-current from the charging logic. The feedback of that signal to the PQ-controller prevents a windup of the PI-controller.

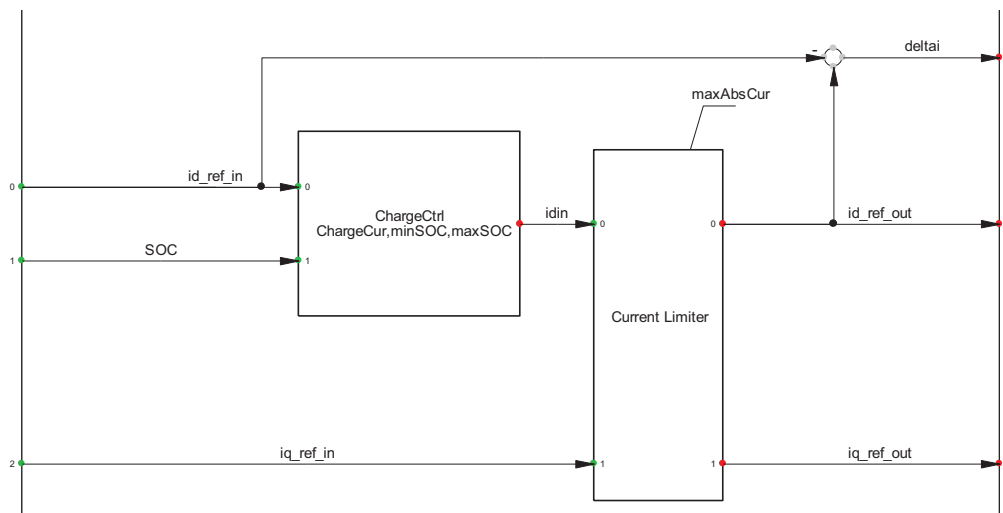


Figure 2.11: Model of the Charge Controller (*.BlkDef)

To get a working model of the controller in *PowerFactory* it is important to use the right names for the signals in the frame definition. Only signals with the same names in the frame and in the model, inserted in the frame are connected. Furthermore it is important to understand how the initialisation process works. The first step of a simulation is the initialisation. *PowerFactory* uses for that a load flow. If the load flow converges the results are used inside the DSL models to set all integrator outputs. A starting point of a simulation should always be a balanced state. So all derivatives have to be zero, i.e. all inputs of integrators have to be zero too. The inputs, known from the load flow results are in the composite model of the controller (Figure 2.8):

- id_ref/iq_ref - (the currents in the dq-frame in p.u.) known from the PWM-converter
- fmeas - (the frequency in p.u.) known from a PLL measurement device
- u - (the absolute AC-voltage in p.u.) known from a voltage measurement device
- p - (the active power in p.u.) known from a power measurement device

The slot "Battery Model" is filled with the composite model of the battery (Figure 2.4). From there is after the initialisation load flow also the current known.

After designing the frames and the models (i.e. the types) the composite and common models could be created. There are two composite models, one for the battery (Figure 2.12) and one for the BESS controller (Figure 2.13). The slots are filled with the appropriate entities of the DSL models. The measurement devices have to be created and connected properly. A voltage

measurement device has to be connected only to the proper bus. But for a current or a power measurement device it is also important to select the proper cubicle on the bus. Otherwise the prefix of the measured signal could be wrong and so the whole control strategy.

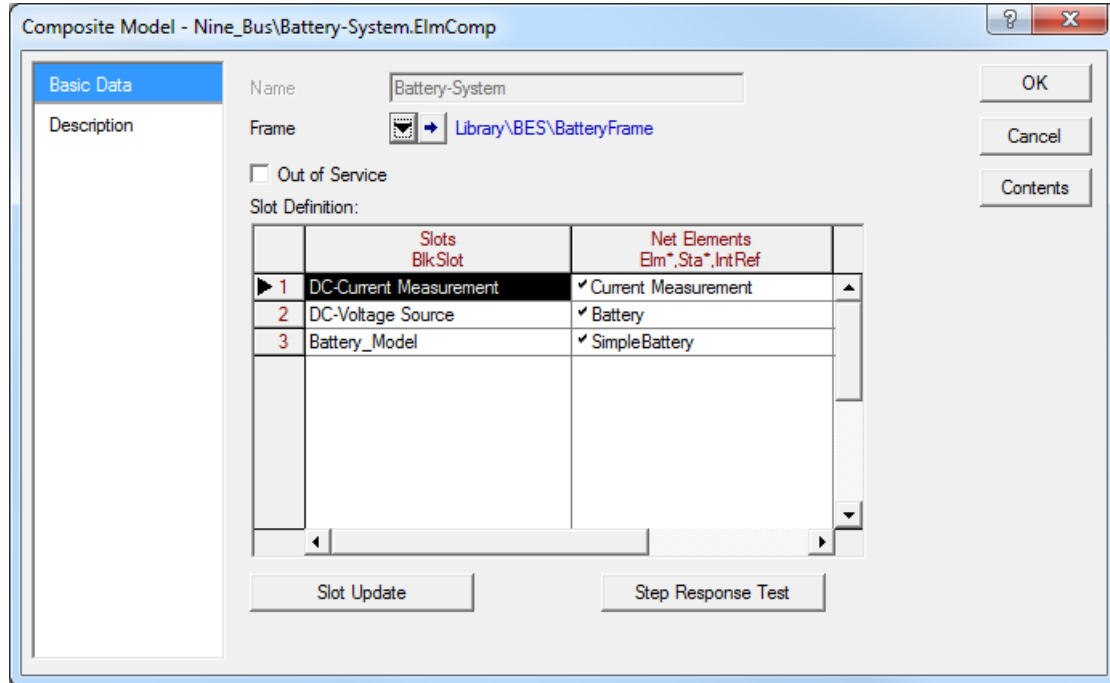


Figure 2.12: Composite Model of the Battery (*.ElmComp)

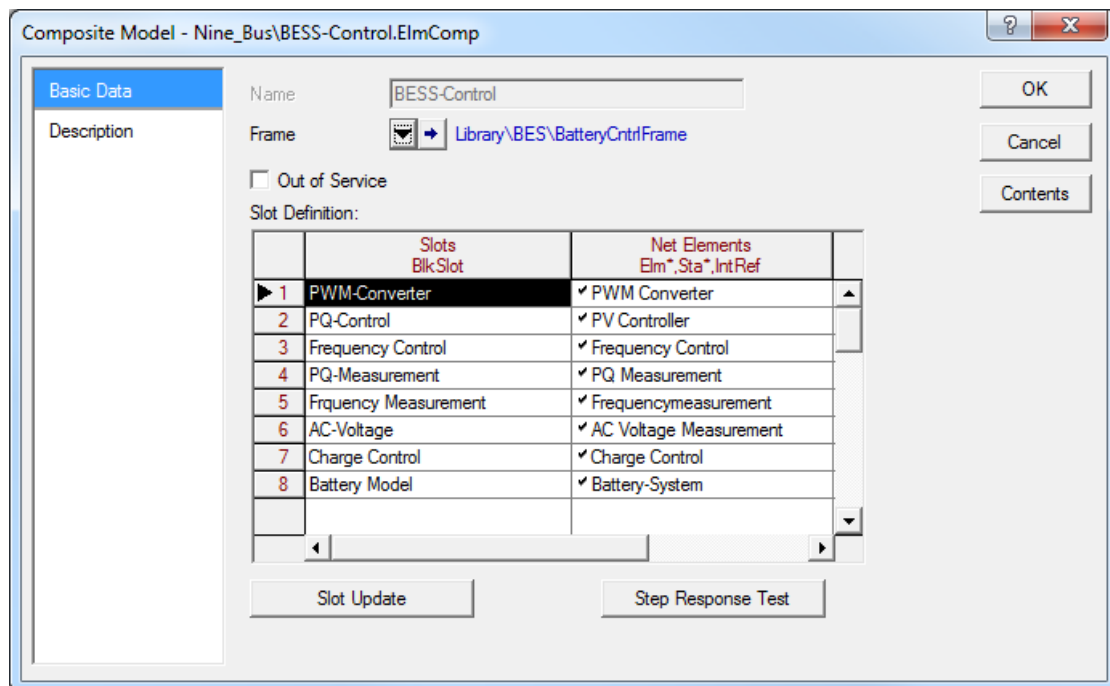


Figure 2.13: Composite Model of the BESS Controller (*.ElmComp)

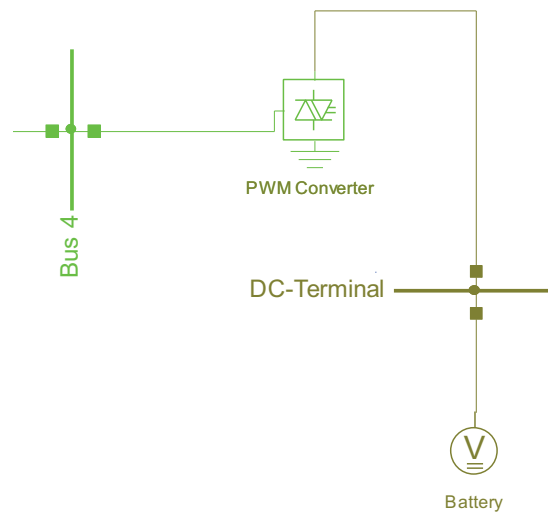


Figure 2.14: The BESS in the Single Line Diagram

The model for the BESS is now complete; only the parameters and the configuration of the elements in the single line diagram are missing. All elements in the single line diagram have different tabs for the basic data, the load flow etc. For the DC-voltage source only the Basic Data has to be configured. Only the value of the nominal voltage (U_{nom}) is of interest. In the showcase is the value 0.8 kV. The data for the battery model should be chosen so that equation (6) is fulfilled for all charging states. Otherwise the PWM converter saturates and the control of the whole BESS will not work properly.

The PWM-converter has also to be configured. On the basic data tab the AC- and DC-voltage (U_{nom}/U_{ndomdc}) and the rated power (S_{nom}) have to be inserted. The data on the load flow page is important for the initialisation load flow. One control condition should be $P = 0$ as already mentioned (this is the condition for the d-axis). The other condition could be a certain value for the reactive power or an AC-voltage on a selected node (q-axis). In case of the PWM-converter the data on the RMS-Simulation tab is important too. There should be the "Use Integrated Current Controller" activated. The gain is 1 for both axis; the integrator time constants are both 1 ms, a very fast inner control loop for the current.

The parameters of the frequency, PQ and charge controller depends of the requirements of the application case. The battery parameters depend on the selected battery and on the used model for that battery.



It is important to consider the limitations of the battery and the PWM-converter during operation. For that the single controllers are equipped with limiters. For realistic simulation results these limits should be set right. Some batteries could be discharged with a higher current than they could be charged. For that case the PQ-controller needs other limits for the positive d-current than for the negative d-current.

In some cases it may be also high active negative control power needed. In that case a copper inside the DC circuit could consume that power. But normally a BESS is needed to prevent a frequency under-run. Then a copper is not needed.

2.4 Testing the BESS

Study Case: Testing Case

Before the model could be used in a bigger simulation grid it should be tested in a small testing environment. That testing grid should be simple so that the right functionality of the BESS could be verified. The grid consists of three loads, one synchronous machine and one BESS. "Load 1" with 110MW active and 10MVar reactive power and "Load 2" with 30MW active and 10MVar reactive power are connected to the terminal. After initialisation of a RMS simulation (root mean square based values) the synchronous machine supplies 140MW active power to the grid. The BESS supplies no active power. After 120 s the load "Load Step" is connected to the grid. This is equal to a power plant outage with 25MW active power. Hence the turbine governor is configured as very slow the BESS supplies the missing power. After 540 s the "Load 2" is reduced to zero with a slope within 60 s, this could be another power plant that is activated. The BESS starts loading after that.

The first step of a dynamical simulation is the initialisation in *PowerFactory*. For that the "Calculate Initial Conditions" button  is used. If all elements are initialized (no errors in the output window) then the simulation could be started with the "Start Simulation" button . The simulation results could then be found in the virtual instrument panel named "Testresults" in the lower left area of the *PowerFactory* window.

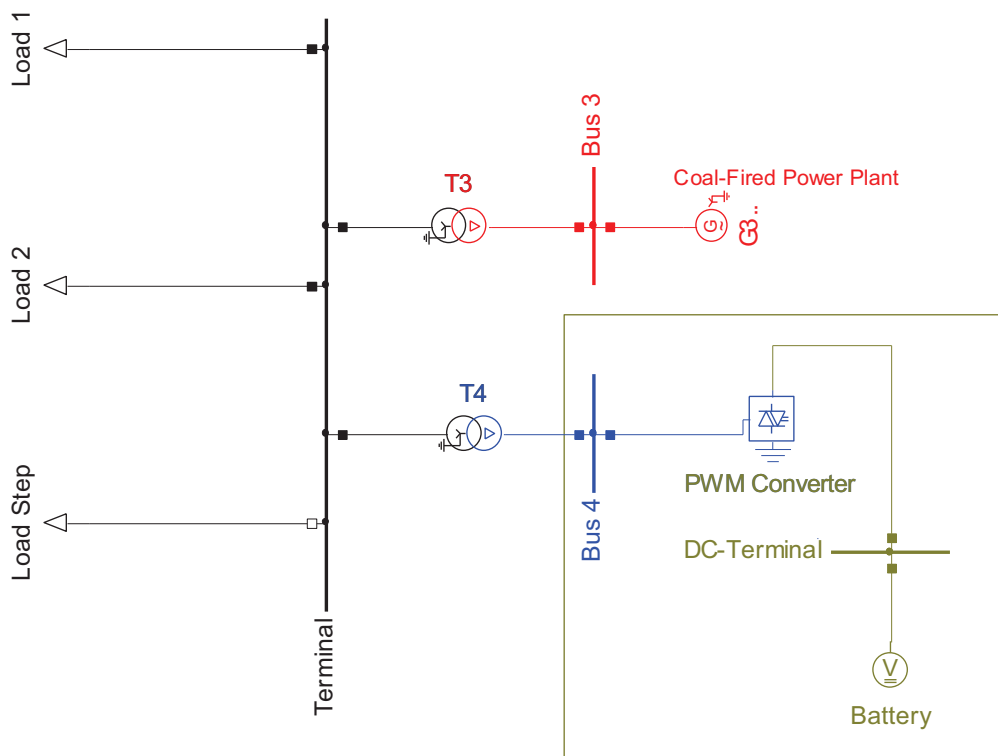



Figure 2.15: Small Testing Grid for the BESS

3 Network Model

The investigated network consists of three power plants; one coal-fired power plant, one fast gas turbine and one medium fast hydropower plant (Figure 3.1). The three plants are connected on the 230 kV level via a closed ring with overhead lines. The loads are aggregated to three loads (Load A to C), also on the 230 kV level.

With *PowerFactory* it is easy to get a full report of all installed active/reactive power, the installed capacity and the spinning reserve in the model (Output Calculation Analysis  - Grid Summary).

The maximum load is assumed to be 345 MW, for that all three power plants are needed. The minimum load case is 2/3 of the maximum load. During the low load period the power of the gas turbine is reduced, because the gas turbine is normally the most expensive plant. For different load scenarios Operation Scenarios are used in *PowerFactory*.

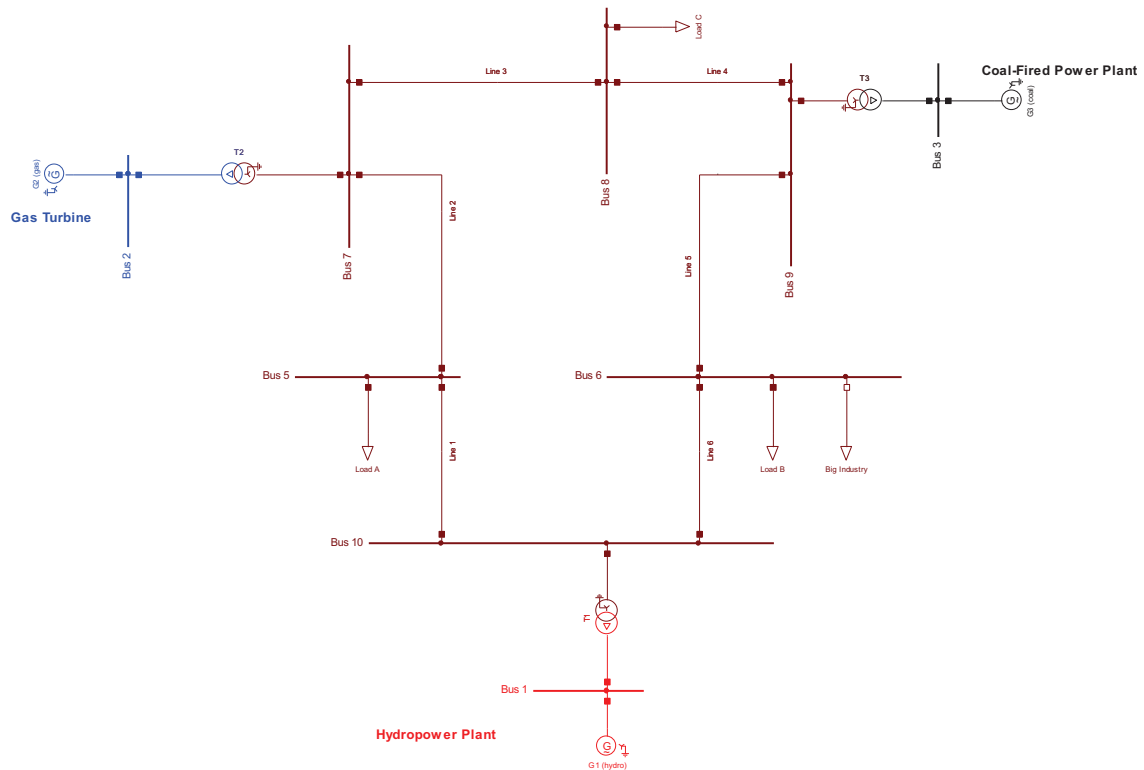



Figure 3.1: Single Line Diagram

For a steady state load flow analysis () are no further dynamic models of the power plants needed. Only the generator types of the power plants and the information on the load flow page has to be configured. In that information is also the capability limit curve for reactive power included. It is important to have one reference machine in the grid. The generator from the hydropower plant is the reference in the sample grid. The other generators are configured as PV-nodes, they control their active power output and the local voltage.

If the load flow is calculated with the option "Active Power Control according Secondary Control" then it is possible to configure the participation of the plant on the compensation of a load change with the variable "Primary Frequency Bias" (Kpf). An outage of a generator is for example a very big load change in the network. With the configuration of Kpf it is possible to define a maximum frequency deviation. If an outage of the gas turbine (60 MW) should be compensated from the coal power plant and hydropower plant within a frequency deviation of 1,5 Hz, then the Kpf-factor has to be 20 MW/Hz (=60 MW / 2 / 1,5 Hz).

The transformers have automatic tap changers to control the voltage on the high voltage side. To make sure, that the tap changers work automatically and that the generators are inside their reactive power limits the options "Automatic Tap Adjust of Transformers" and "Consider Reactive

Power Limits” have to be activated in the load flow calculation dialogue.

It is important, that the original grid is configured right. Otherwise it is later together with the BESS more complicate to find errors or problems. So the first step should be a Data Verification (🔍). If there are no errors or warnings, then as a next step a load flow with the original setup is recommended. If the option ”Show Verification Report” on the ”Output” tab of the load flow command is checked, then there are only overloaded (more than 80% loading) elements printed in the output window. It is also important, that there are no warnings in the output window after the load flow.

For a planned expansion of the grid, like in this case with a BESS it is recommended to use the variations in *PowerFactory*. So the original grid could be easily restored and fast switching between different expansion stages is possible.

To simulate different cases (generator outage, short circuits etc.) in the time domain, different study cases are used. So each case could be treated separately with a different set of simulation events, result plots, active operation scenarios and variations. It is generally recommended to work with study cases, operation scenarios and variations. Operation scenarios are used to simulate different operating points with the same grid setup. So the original setup is not changed since all parameters are stored in the appropriate scenario. To manage changes in the grid setup are variations used. With variations could be different expansion stages of the original grid managed without a change on the original grid. In *PowerFactory* the variations are connected to a certain (user defined) date and time. Each study case has its own time also set by the user. With the study case time could be different expansion stages of one variation handled.

Up to that point only a static load flow was considered. For a RMS-simulation in the time domain are however further detailed models of the power plants needed. The models are implemented in DSL (DlG SILENT Simulation Language). For the different power plants are pre defined and standardized models used. The average voltage controller (vcoIEEE1), the turbine governor (pcuIEEE1) and the synchronous machine (G3) are connected in a composite model (Figure 3.2). A power system stabilizer (PSS) is not used in this case; therefore the pss-slot is empty.

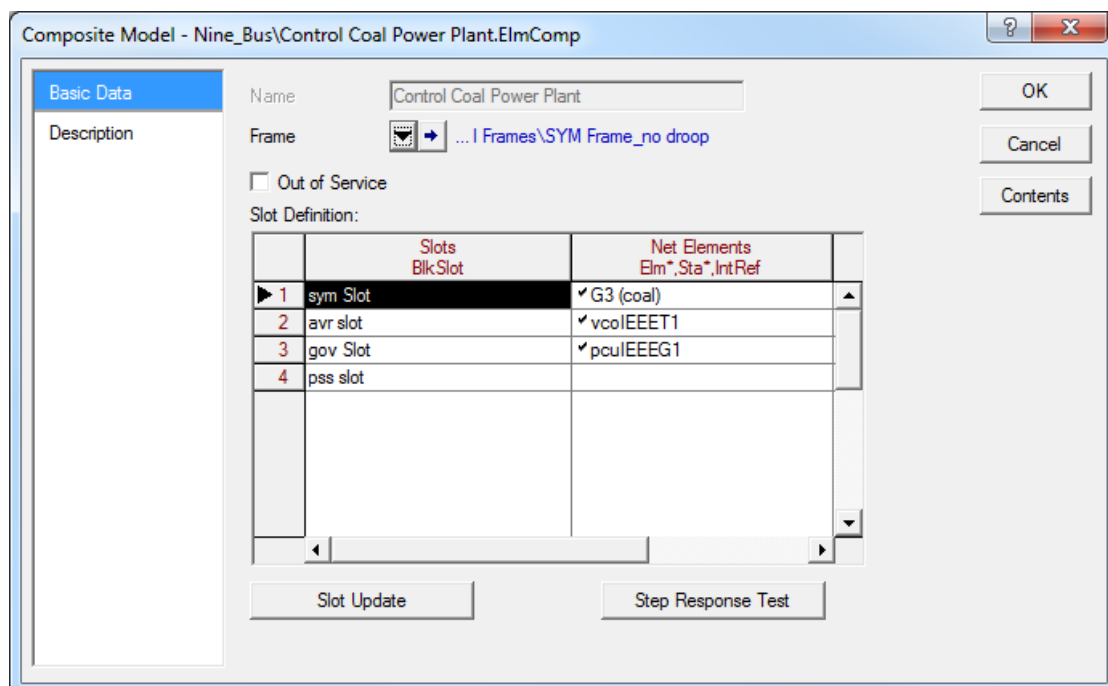


Figure 3.2: Composite Model - Power Plant Control (*.ElmComp)

The turbine governor controls the speed of the turbine and so, via the synchronous machine the electric frequency. In case of a fast load change, for example the outage of a power plant, the frequency rapidly drops due to the lack of active power in the grid. To prevent a slowdown of the whole system the turbine governor has to activate more power. This is called primary frequency control or also spinning reserve, activation has to be instantaneous. This means in reality that a coal-fired power plant has all the time a loss of energy due to the permanent choking on the turbine valve. So it would be more economic if another device could deliver the primary control energy until the coal power plant has increased the active power. This is called secondary frequency control; activation has to occur within 15 minutes after the frequency deviation. To fill that gap a battery energy storing system (BESS) could be a solution.

4 Application Case 1: Frequency Regulation

Application case 1 consists of two parts. The first part is a simulated load change for that are two study cases used in the *PowerFactory* project; one with and one without a BESS. The second part is a simulated generator outage of the fast gas turbine. For that are also two study cases used.

4.1 Replacement of Primary Control Energy (Load Change)

Study Case: Industry Load without BESS; Industry Load with BESS

Primary control energy is needed in a grid to control the frequency within a very small gap between an upper and a lower frequency limit. In the UCTE-grid this margin is only 200 mHz in the positive and negative direction. The worst expected case in the UCTE is the double outage of a nuclear power plant. This would lead to an active power gap of 3 GW. The 3 GW have to be activated within 30 seconds and the power has to be continued for at least 15 minutes. But there are a lot of power plants who do that primary control, so the control power of each plant is not so big. The demand from the UCTE is that each grid operator has to deliver 2% of his actual produced active power as primary control power. This primary control power could also come from a BESS.

If a BESS is used for primary control, then it should be known how much active power is needed. With the known active power for the worst case and the time (as mentioned 15 min in the UCTE) is it possible to calculate the needed capacity of the battery. Normally one single battery cell has a DC-voltage between 1.2 and 3.4 V dependent on the battery technology. The capacity per cell varies from a few mAh up to several 100 Ah. So a battery of a BESS is always a combination of parallel and serial connected single cells. The more batteries are connected in parallel, the higher is the total capacity, the total inner resistance will be lower. The current per cell will also be lower. But there are also serial connected cells needed to get a higher total DC-voltage. With the DC-voltage is also the internal resistance increased.

As described in (6) the DC-voltage shouldn't under-run a certain level. So there should be enough cells in series to ensure this. The AC-voltage level depends on the case and so does the DC-voltage level.

If the BESS is used for primary control, then the battery technology should support constant loading/unloading cycles without a (fast) degeneration in terms of a so called memory effect. The control power is activated if the frequency deviation is more than 10 mHz or 0.0002 pu in a 50 Hz system. So the dead band showed in Figure 2.9 has to be very small. The variable "droop" has to be 0.004, i.e. activation of the full active power (of the PWM converter) within 200 mHz frequency deviation.

For the following investigation is the already described grid used. The PWM-converter has a rated power of 30 MVA. This corresponds with the already mentioned frequency control bias to a frequency bias of $30 \text{ MW}/0.2 \text{ Hz} = 150 \text{ MW/Hz}$. To test the BESS a sudden load change of 30 MW active power is simulated (simple connection of a additional load).

During the simulation without the BESS (study case: "Industry load without BESS") all governor controllers are tuned with standard values. It is obvious, that a load change of nearly 10% of the total grid load causes a big frequency under-run (red curves in Figure 4.2 and Figure 4.3). The gas turbine is important for the grid because it could increase the active power output much faster than the hydropower plant or the coal power plant. A under frequency of nearly 49 Hz would lead in the UCTE grid to severe action.

In the second simulation (study case: "Industry load with BESS") the BESS replaces the primary control power of the coal-fired power plant. The turbine governor control of the coal-fired power plant is modified for that. The controller gain is reduced from the standard value ($K = 25$) to $K = 1$. The participation of G3 on the primary control is now reduced to nearly zero. With the fast BESS the frequency under-run is stopped and stabilized within a range of 200 mHz. 7 Minutes after the load step the active power of the coal-fired power plant is increased due to a dispatch command. The power is ramped up from 148 MW to 170 MW in five minutes. This equates to a gradient of only 2.6%/min. With the BESS all power plants are unburdened from fast load changes.

The dispatch command is set via a parameter event in *PowerFactory*. To obtain a slope with a certain gradient and no step the model of the governor was expanded with a gradient limiter block (Figure 4.1).

With *PowerFactory* it is possible to display results from different simulations within one plot. For that are different result files used. In Figure 4.2 and Figure 4.3 the results are from two different study cases. But it is also possible to use several result files within one study case. The advantage of one study case/variation per result file is that the results and the used parameters for the simulation match together.

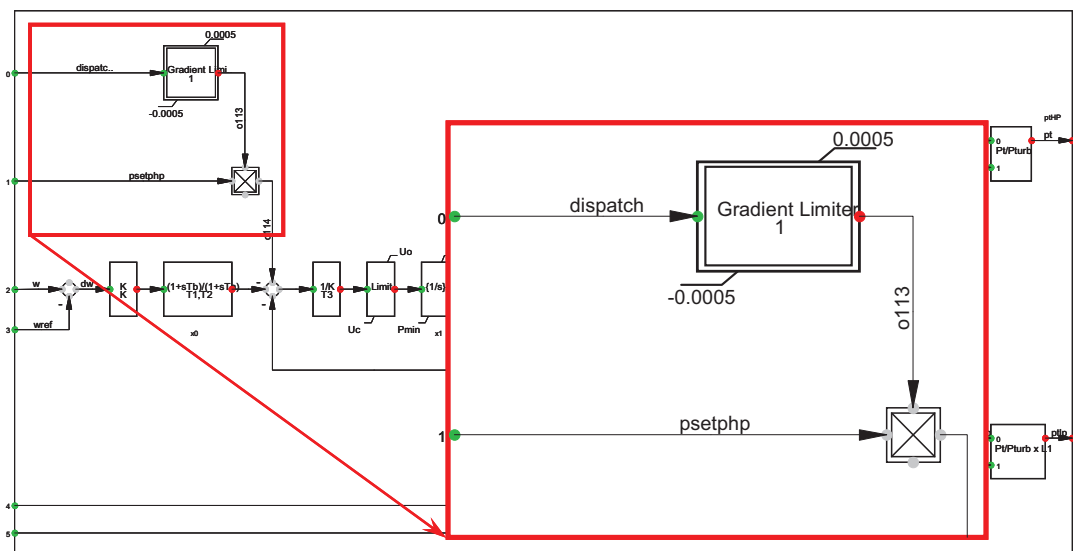


Figure 4.1: Edited Governor Controller for Dispatch Command (via event)

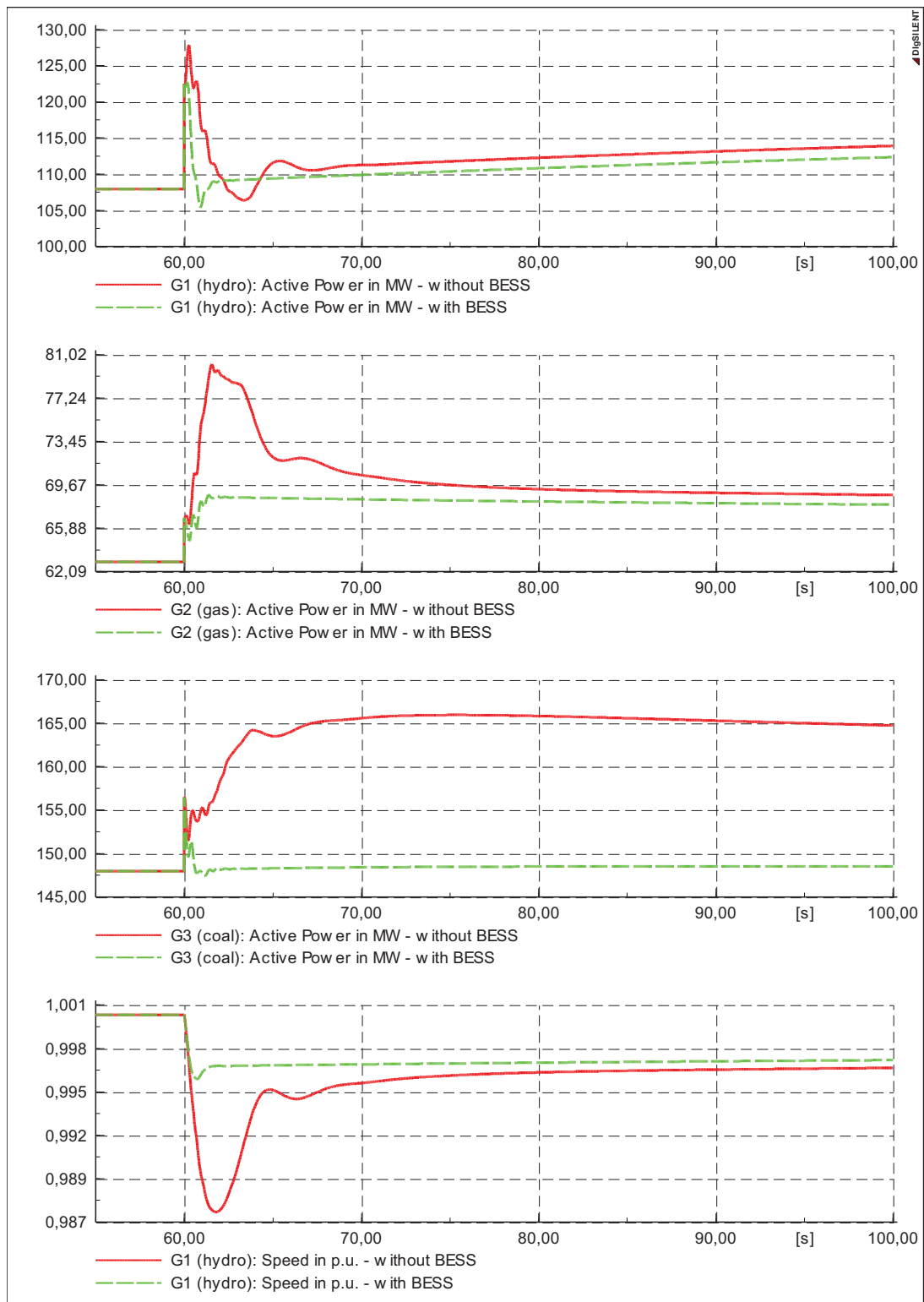


Figure 4.2: Simulation Results of a 30 MW Load Step (detail)

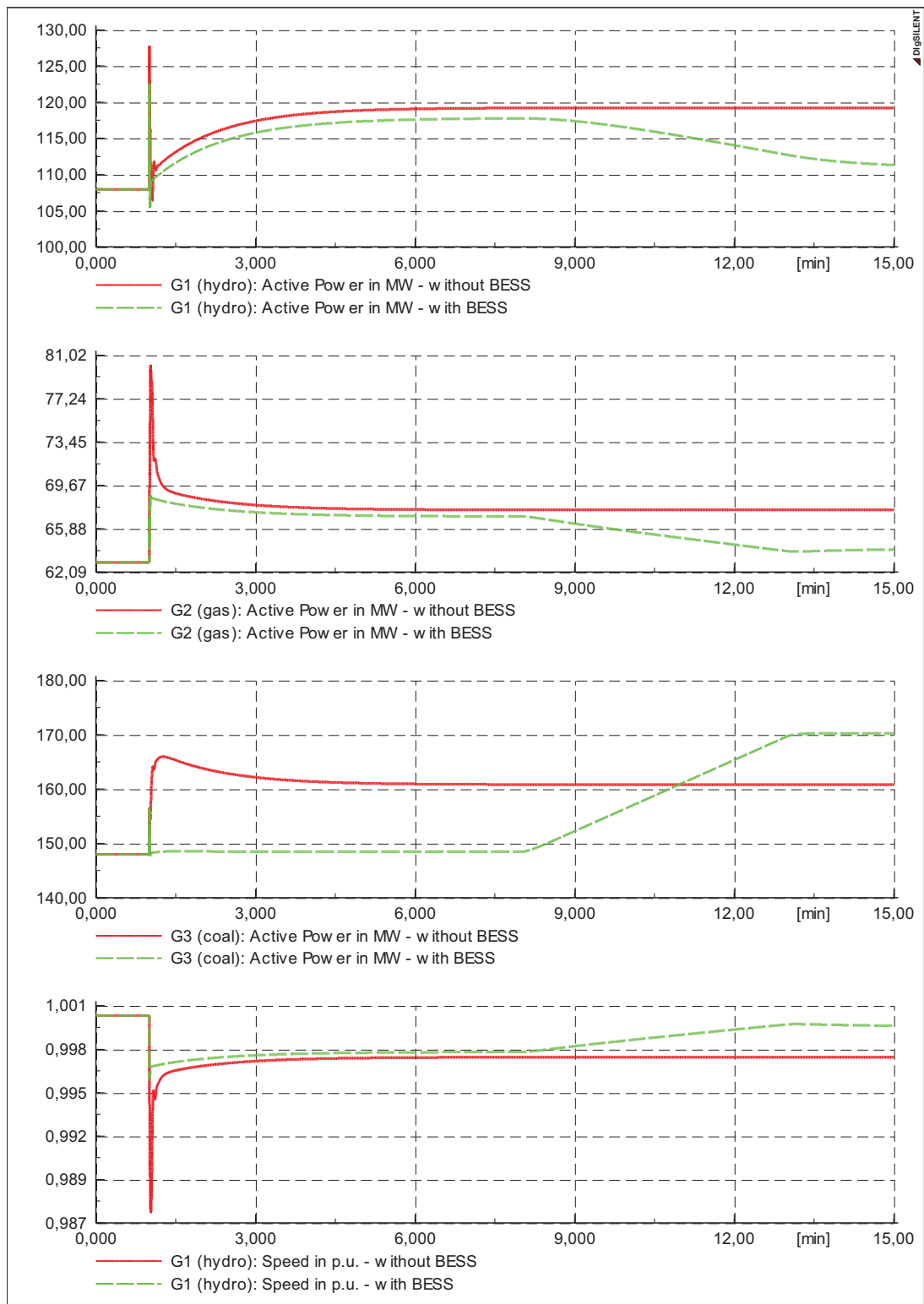


Figure 4.3: Simulation Results of a 30 MW Load Step (full)

4.2 Replacement of Primary Control Energy (Generator Outage)

Study Case: Gas Outage without BESS; Gas Outage with BESS

The worst case for a generator outage in the small showcase grid is the outage of the gas turbine. The gas turbine is the fastest power plant in the grid. Without that fast controllable plant would it be much harder to control the frequency after a disturbance. To study the outage with more realistic results a low load scenario is assumed with only 80% of the original loads. For that is an operation scenario used in *PowerFactory*. With an operation scenario is it possible to change and store operational data for different cases, like a low load and a high load case without the need for an additional variation.

The outage of the power plant with the gas turbine is simply simulated by opening the switch on the HV-side of the main transformer. The following frequency under-run is without the BESS more distinct than in the load change chase. This comes from the lack of a fast controllable power plant (Picture x red curves).

Again the BESS is used to improve the behaviour of the grid performance and to replace the primary control power of the coal-fired power plant. The BESS could control the active power output much faster than a power plant because there are no mechanical inertia and delays. Therefore the frequency deviation is smaller.

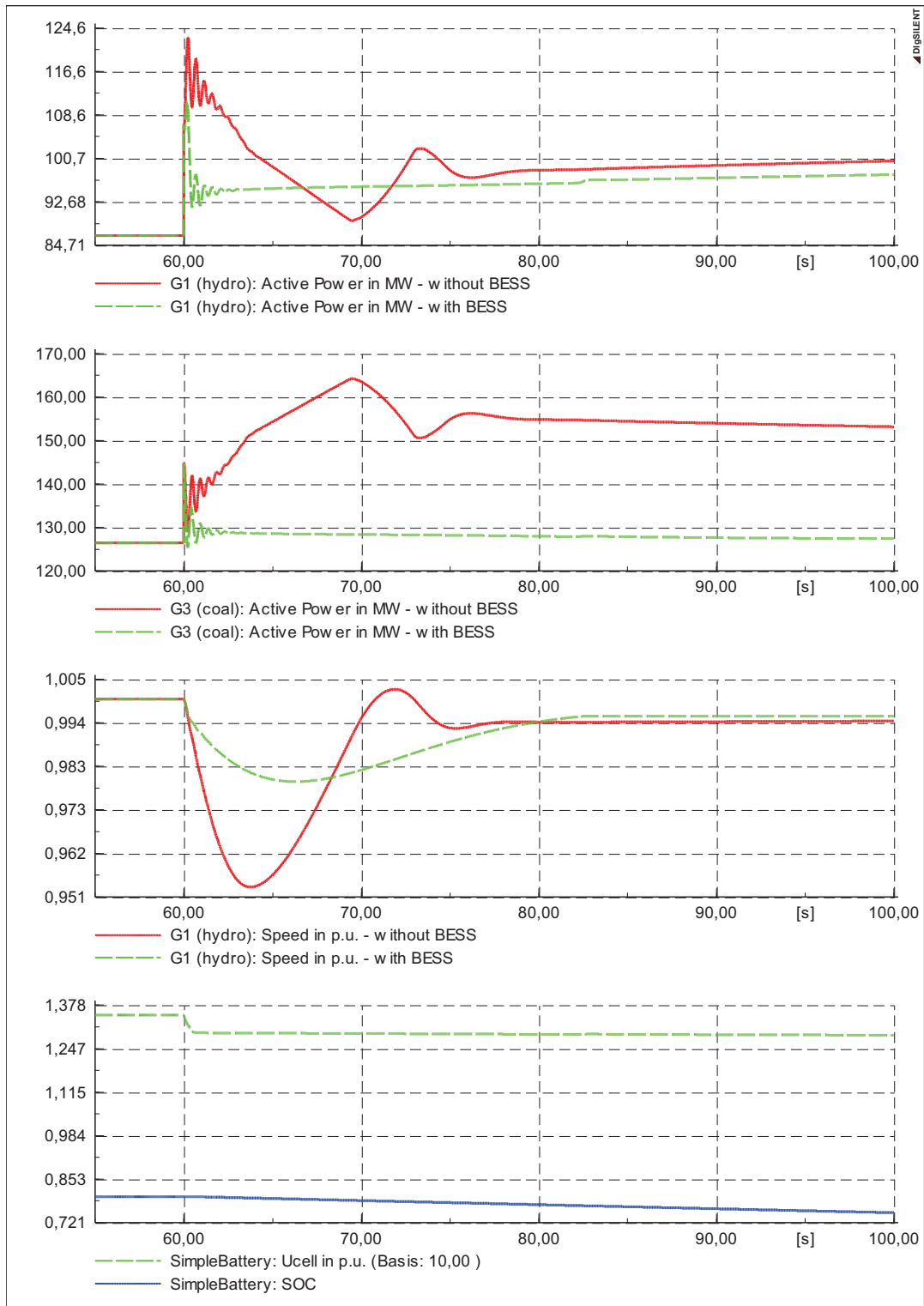


Figure 4.4: Simulation Results of Gas Turbine Outage (detail)

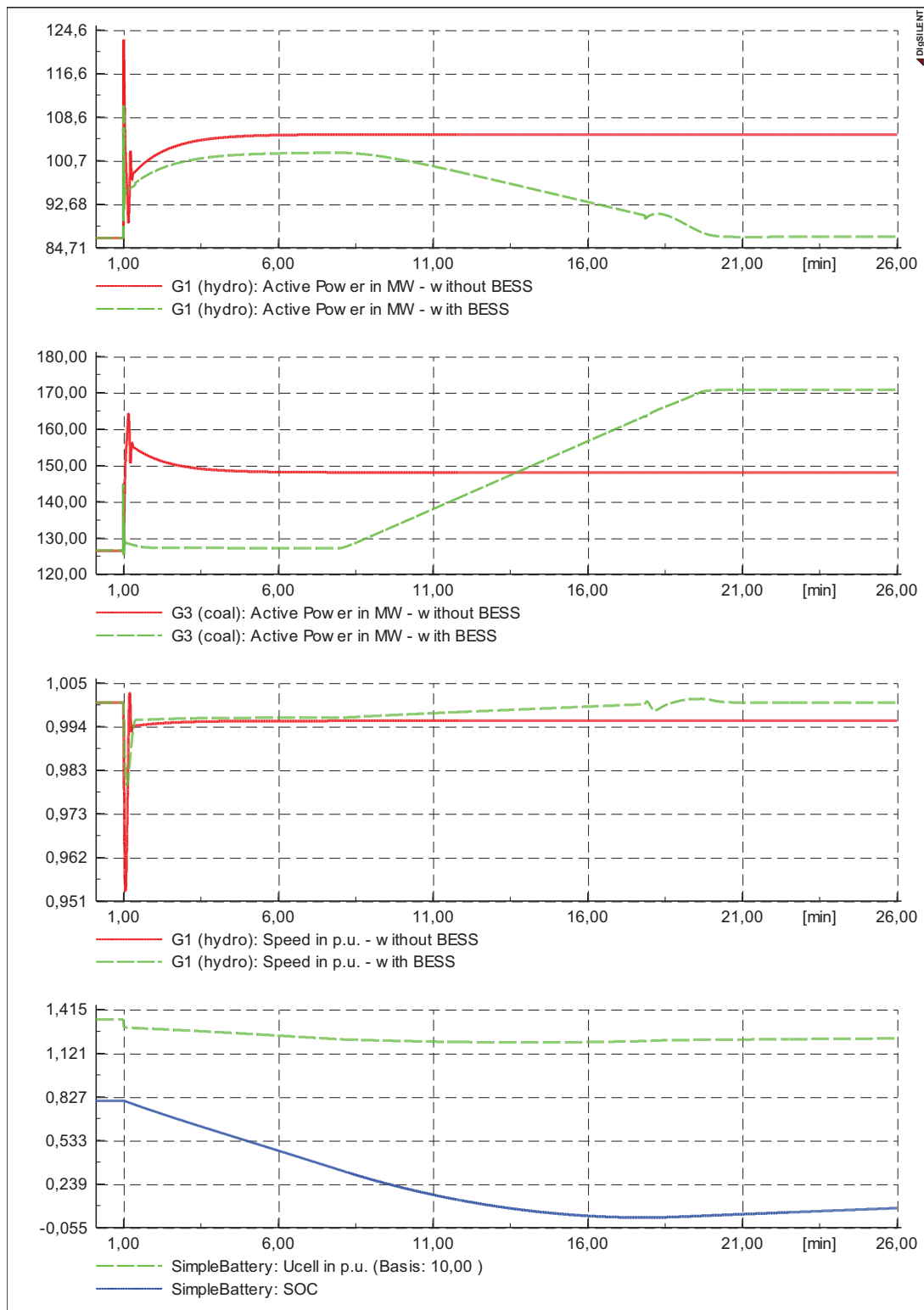


Figure 4.5: Simulation Results of Gas Turbine Outage (full)

5 Application Case 2: FRT Simulation

Study Case: FRT without BESS; FRT with BESS

Together with the different renewable energy sources, such as wind turbines and photovoltaic, the ride through of voltage dips becomes more and more an important topic. So it is also important to have a BESS model that could be used in a fault ride through (FTR) study. Since the FRT is a very fast but also short action the model could be simplified in some parts. It is very unlikely that the SOC of the battery changes significantly within one or two seconds. Also the battery DC-voltage could be assumed as constant during that time. The important branch of the BESS model is then the PV/PQ- and the current controller. To obtain that the whole battery-system frame is out of service in the used study cases. So the SOC in the charge controller is fixed to a constant value (0.8 pu). The DC-voltage is also constant fixed to 1 pu. To improve the behaviour of the BESS the charge controller is expanded with a fault modus. If the AC-voltage deviates more than 0.1 pu from its nominal value the charge controller is switched to reactive power preference.

The example grid is supplemented by a 8 MW asynchronous motor. The BESS is to the motor bus connected for that simulation as shown in Figure 5.2. During a voltage dip an asynchronous motor delivers reactive power to the grid. But after the voltage dip an asynchronous motor needs a lot of reactive power to re-magnetize the rotor, then during the re-magnetization the voltage on the motor bus is low. Using the BESS connected to the Motor Bus the voltage recovers faster due to the effect of the BESS reactive power control.

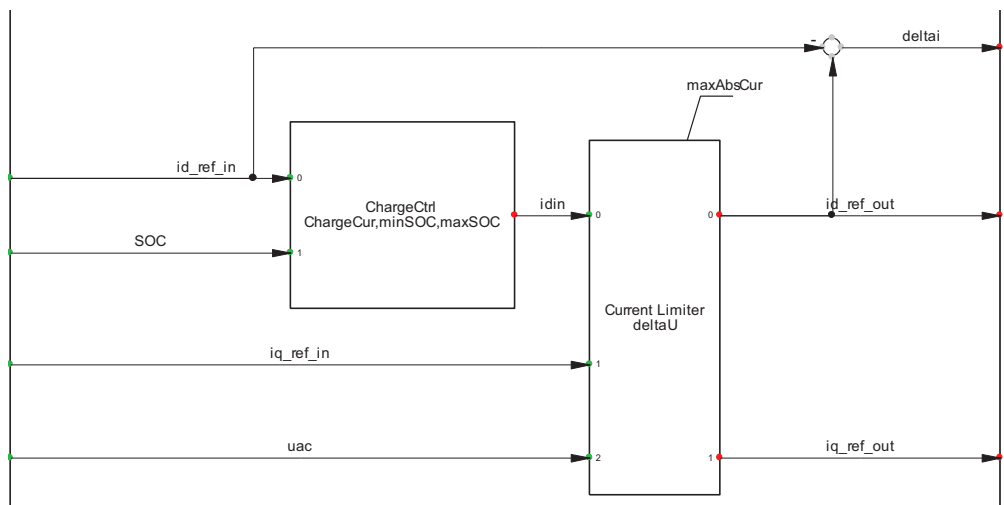


Figure 5.1: Charge Controller with switchable Current Limiter (ElmDsl)

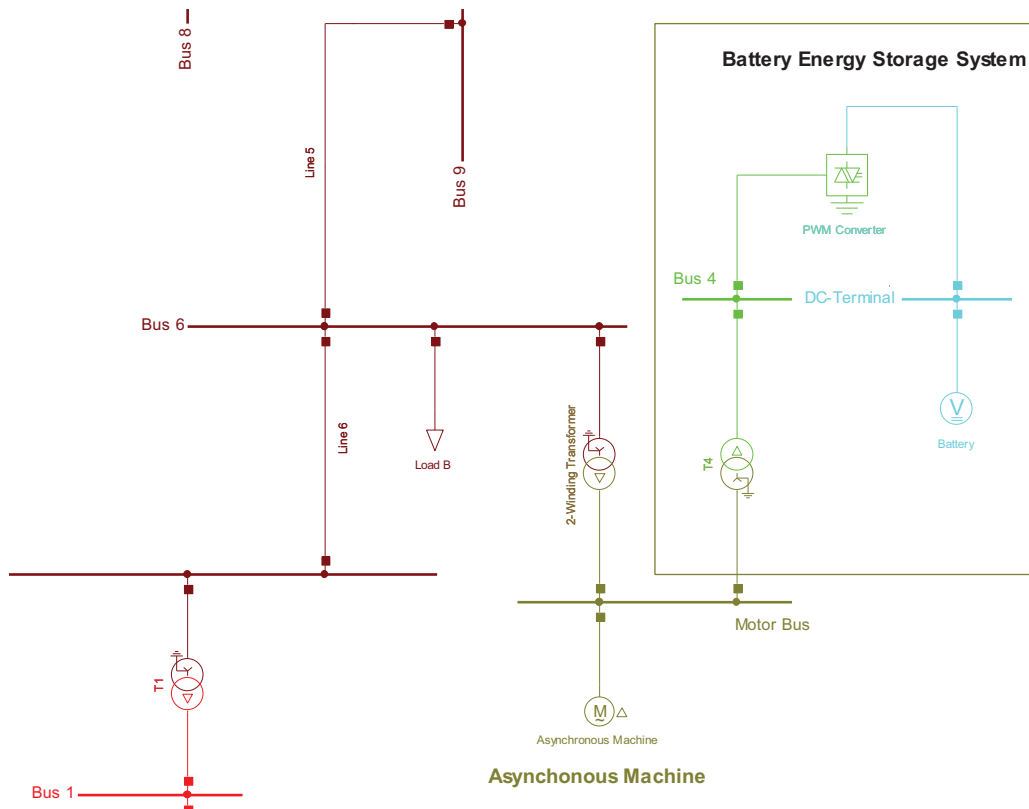


Figure 5.2: Changed Grid Structure for FRT-Study

In the results (Figure 5.3) is it obvious, that the recovery of the system with the BESS is faster than the recovery of the system without the BESS.

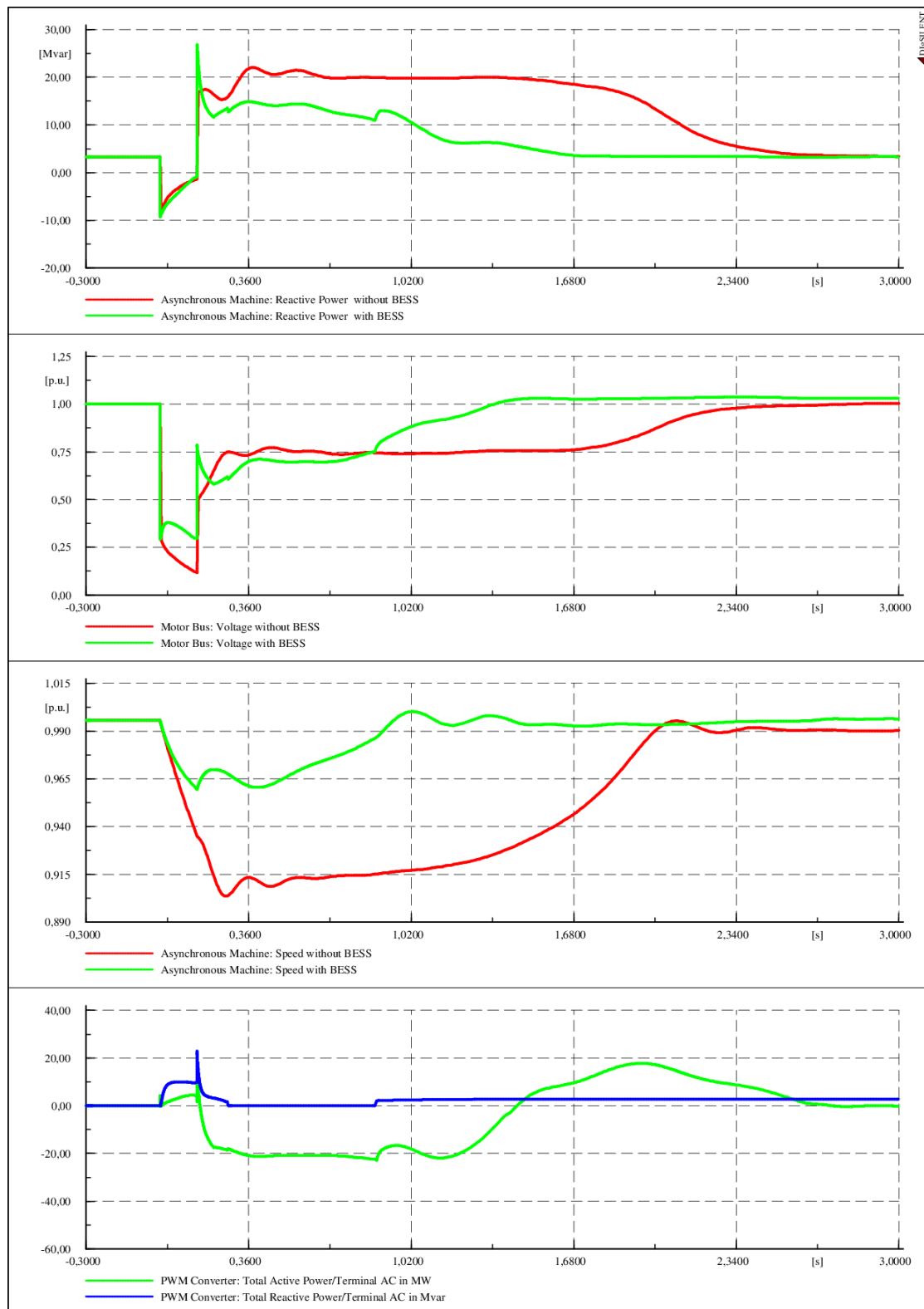


Figure 5.3: Simulation Results of a Short Circuit on Bus 6

References

- [1] Rechargeable Batteries Applications Handbook. Technical report, Technical Marketing Staff of Gates Energy Products Inc. Butterworth-Heinemann, 1992.
- [2] S. Barsali and M. Ceraolo. Dynamical Models of Lead-Acid Batteries: Implementation Issues. *IEEE Transactions on Energy Conversion*, 17(1), March 2002.
- [3] M. Ceraolo. New Dynamical Models of Lead-Acid Batteries. *IEEE Transactions on Power Systems*, 15(4), November 2000.
- [4] D. Kottick, M. Blau, and D. Edelstein. Battery Energy Storage for Frequency Regulation in an Island Power System. *IEEE Transactions on Energy Conversion*, 8(3), September 1993.
- [5] N. K. Medora and A. Kusko. *Dynamic Battery Modeling of Lead-Acid Batteries using Manufacturer's Data*. Twenty-Seventh International Telecommunications Conference, INTELEC '05., 2005.