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Analysis of electric networks in island operation with a large penetration of wind power

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Abstract — The percentages of wind power penetration in some areas of the electric distribution system are reaching rather high levels. Due to the intermittent nature of wind power, the voltage and frequency quality could be seriously compromised especially in case of island operation of such an area of the grid. In this paper the impact of wind power in island distribution systems has been analysed with respect to voltage and frequency. Possible measures for controlling both voltage and frequency are suggested and have been analysed. The suggested measures are static voltage controller (SVC), dump loads, kinetic energy storage systems, and load shedding. It is shown that the measures effectively can bring voltage and frequency quality within the normal operation range.

Index Terms — Dump load, Flicker, Island operation, Kinetic energy storage system, Load shedding, SVC, Wind power.

1. INTRODUCTION

For many years the power consumption has relied on the production of centralized power plants interconnected through transmission lines and thereby accomplishing a rather stable power system. Nowadays this philosophy is changing due to the increase of the embedded generation of small combined heat and power (CHP) plants and wind farms. This configuration leads to some drawbacks but also to advantages. Considering the fact that the electric power has to flow through distribution lines instead of transmission lines, the losses will be increased in many cases. In addition, in the case of wind turbines, the nature of the energy source and the use of power electronics in the generation process can affect the power quality. Nevertheless, wherever the embedded generation capability is able to fulfil the consumption, in cases of e.g. disturbances in the grid or imminent blackout, the network could be split in autonomous grid cells working independent from each other as shown in Figure 1.

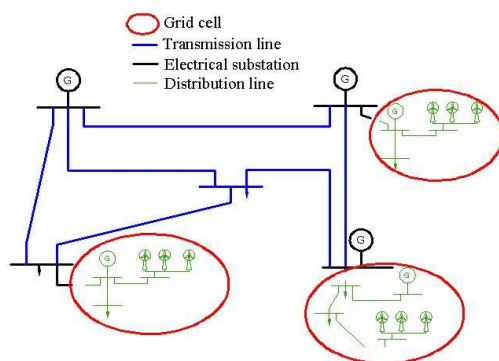


Figure 1. Split network.

The arising problem is the possible instability in terms of voltage and frequency due to the weakness of such a small electric network operated in island. Regarding the frequency, the problems are caused mainly because of the rather low inertia (H) of the system. As it is shown in the network electromechanical equation (1) a mismatch between produced power (P_{mech}) and consumed power (P_{elec}) generates variations in the angular frequency ω of the generators and thereby the frequency of the system. These variations are dumped by the inertia of the system, and since the inertia, in this case, is much smaller than in non isolated operation, the frequency will be more affected.

$$\omega \frac{\partial \omega}{\partial t} = \frac{P_{mech} - P_{elec}}{2H} \quad (1)$$

In the case of the voltage, the reactive power variations of the demand and wind generation have a more significant impact on the total reactive power balance of the system compared with interconnected operation. Considering that the excitation systems of the synchronous generators are not fast enough to compensate such variations, the voltage will be affected.

Considering the objections of the isolated operation, this paper presents the results of a study on the dynamic behaviour of a typical Danish electric distribution network in island operation. The study has been realized by use of the power systems simulation program *PowerFactory* by *DigSilent* based on a quite simple grid. The considered power system includes a variable demand, a CHP plant and a wind farm with variable production.

The wind power is going to be considered as wind turbines of the *Danish concept* type and without any power control capability, i.e. they are fixed speed wind turbines and do not have active stall or pitching systems for controlling the power output. Under these conditions, the power output of the wind turbine will depend mainly on the wind speed; hence the wind power production is an uncontrollable energy source which, as in the case of the variable demand, might generate disturbances in the grid.

The fluctuating wind power and its penetration percentage present a key issue in a grid cell. In order to outbalance the frequency disturbances from the wind power in a grid cell, the use of dump loads, kinetic energy storage systems and load shedding is considered, and in the case of the voltage, the application of a SVC is considered.

2. STUDIED MODEL

The analyzed model is representative of a grid cell. It consists of three nodes interconnected through a distribution line in the level of 60 kV. In one node there is a gas engine based CHP plant, in another node there is a wind farm which rated power will be modified to study different cases, and in the third node variable consumption is located.

In order to get a good approximation to the real network behaviour in the studied conditions, the grid components models must be as accurate as possible and real data has to be used whenever possible.

The CHP have four groups of 3.5 MW each and is modelled considering real data provided by the Danish transmission system operator *Energinet.dk*. The model includes a voltage controller, a power controller (speed controller), a primary mover unit model and the electric generator. The models for both the voltage controller and the primary mover unit are realised with the actual values of the CHP model. However, since in normal operation this plant is not requested to control the frequency, the speed controller which was basically a proportional controller was replaced by a PID controller which should be able to perform a good frequency control since it has no steady state error.

The wind farm considered consists of 8 wind turbines with a rated power of 500 kW each. Since there was not enough data available to realise an aggregated model for the wind farm, the 8 wind turbines have been modelled separately. The model of the wind turbines is done with data from a 500 kW Nordtank wind turbine [4]. This model uses the mechanical power as input along the simulation time, and considers the soft coupling of the low speed shaft and the electric generator, both with the actual values for the parameters. The data used as input for the wind turbine models is a key issue. It would not be a real case if all the wind turbines had the same input, because the smoothing effect, which takes place in the power output of the wind farm with respect to a single wind turbine, would be neglected [4]. To overcome this problem, 8 measurement files of the Nordtank wind turbine were taken in which the average wind speed and turbulent value were similar to simulate the real behaviour in a wind farm.

The consumption values used to simulate the dynamic behaviour of the load are based on measured values from *DONG Energy*, one of the Danish distribution companies in four of its 10 kV feeders. The average active and reactive consumption is 7 MW and 4 Mvar, respectively. The measurement of active and reactive power was with one second resolution which permits to simulate faithfully the load profile. In the node where the load is located, the corrective measures proposed to help with the frequency and voltage control will be placed.

In the simulations the impact of wind power in both, frequency and voltage is analysed. The impact of wind power in the grid cell depends on one hand on the wind behaviour, as previously mentioned, and on the other hand on the penetration percentage of wind power in the network. Hence, the influence of five different penetration percentages of wind power between 0% (if there is no wind turbine connected) and 52% (if all the wind turbines are connected) of the total mean demand in the network is going to be discussed.

To analyze the frequency and voltage it is necessary to set up the quality standards taken into account. According to the Nordic grid code [1] the maximum frequency deviations in normal operation must not exceed ± 0.1 Hz. The frequency data from the simulation results will be presented into histogram pictures and tables. By using these tools it is easier to evaluate the frequency quality.

Concerning voltage, the limit considered in this study is set by the maximum short term flicker power (P_{st}) which has to be below one according to IEC [3]. In this case, an algorithm is applied to the voltage rms values obtained in the simulations to compute the P_{st} . This algorithm is developed according to [2].

3. CORRECTIVE MEASURES PROPOSED

Due to the reasons explained previously, this paper proposes measures to deal with frequency and voltage instability. These are, in the case of the frequency dump loads, load shedding and systems of kinetic energy storage. On the other hand, the use of an SVC will be discussed for the voltage control. Hereafter are presented thoroughly these proposals and in the appendix are shown the developed models used in the simulations.

3.1. Dump Load

A dump load is basically a type of load which consumption can be controlled quite fast to perform frequency control. Dump load is widely used in hybrid wind-diesel systems because the diesel engine is not capable to perform a good frequency control. In the early days the energy of the dump load was wasted in a resistors bank, but now it can be used to charge batteries or heating up water. Normally, the dump loads are specifically designed for working as such, which is an important drawback in this case because most of the time they would not be necessary as the network would not normally be in island operation.

A possible solution for this problem would be to use some normal consumers as dump loads. The requested power could be modified without causing big problems. Some of those peculiar consumers could be:

- Desalination plants. The change on requested power in this kind of industry would be realised by controlling pumps and would only affect the water flow.
- Heaters. In big installations in which electric energy is used for heating up e.g. fluids.
- Pumping stations. This is a similar case to the desalination plant..
- Ice making factories. The power consumption changes would affect to the time needed to make the ice.

If the power of these loads is momentarily changed, either increased (if it is possible) or decreased, the troubles caused would be hardly noticeable whenever the averaged power consumption stays constant. A so called dynamic grid interface could manage these loads to meet the requirements of frequency control. In this study, a dump load of 600 kW is considered. It is assumed that the dump load has a normal operational power of 400 kW and an up-and-down regulating capability of ± 200 kW.

3.2. Kinetic energy storage system (KESS).

A kinetic energy storage system is a device which stores energy in kinetic form in a flywheel. This device can either release or absorb energy according to the requirements. It is considered to be a useful device in the studied case because it could help to the balance between demand and supply due to its fast response capability.

For storing energy another device such as batteries could be used, however they would not be so suitable due to the operating conditions needed. Since the frequency may flicker very fast, the energy storage system has to be charged and discharged as well very fast. This cyclic loads upon batteries, would lead in the real life to a decrease in their lifetime. Nevertheless, a flywheel can stand much better these cyclic loads without a big impact on its durability.

The model made in *PowerFactory* does not consider the interface between the system and the grid, i.e. the power converter is not taken into account. This consideration can be assumed in this dissertation because the scope is only analyzing the frequency control capability of this system and not how the power controller works. The data for the model was obtained from the characteristics of a real KESS [13], which in this case is able to store 18 MWs with a maximum power of 300 kW.

3.3. Load Shedding

Load shedding consists of load which in cases of under frequencies, is disconnected to reach a new balance between production and consumption. All major electric power systems have certain amount of load able to be shed under extreme low frequencies. These loads are typically complete distribution feeders including all connected customers. This load shedding philosophy has a major impact on consumers and it is not supposed to help to the frequency control in small deviations.

In recent years another sort of load shedding philosophy [9] has been proposed. It consists of making automatic load shedding and is formed by a large number of small loads instead of few large loads. These small loads would belong to the household and residential consumption in such a manner that their partial disconnection from the grid would not affect the consumers comfort. Examples of this sort of loads are:

- Refrigeration. For short periods of time it is disconnected from the compressor, meanwhile the lights are on.
- Clothes dryers. The heating element is interrupted and the rotating drum is not stopped.
- Water heating. The thermostat is set back temporarily.
- Cookers. The heating devices of the cookers can be intermittently disconnected hardly affecting the cooking time.
- Other heat sources, as i.e. those used for keeping the coffee warm once it is made, could also be temporarily disconnected.

In the simulation program, this has been modelled as a load which connects or disconnects itself according to the requirements of the frequency. Since the frequency is permitted to be in the range between 49.9 Hz and 50.1 Hz, the load shedding is activated when the frequency goes under 49.9 Hz and it is not reconnected until the frequency is totally recovered to 50 Hz. As the size of the load shedding

has a major impact on the frequency, results with several quantities of load shedding will be presented.

3.4. Static Var Compensator (SVC)

Since the only reactive power source in the network is the CHP generators which excitation systems are not fast enough to perform a rapid control of the voltage, a system with capability to deal with the sudden reactive power variations is needed. That is provided by an SVC; it consists of a three-phase capacitor directly connected to the network in parallel with a three-phase reactor connected through thyristors. This configuration leads to a fixed reactive power injection caused by the capacitor bank and a controllable reactive power consumption by the reactor. The reactive power control is performed by setting the appropriate firing angle for the thyristors which is the reason for its fast control.

PowerFactory itself contains a model for this device, so it was only needed to setup its governor. The work philosophy of the SVC, in this case, consists of keeping the rms value of the voltage in the consumers node constant to avoid the flicker problems.

4. NETWORK OPERATION WITHOUT CORRECTIVE MEASURES

The frequency histogram is depicted in Figure 2. Each colour corresponds to a wind power penetration percentage in the network which varies from 0% to 52% in 13 % steps of the total average power consumption of 7 MW.

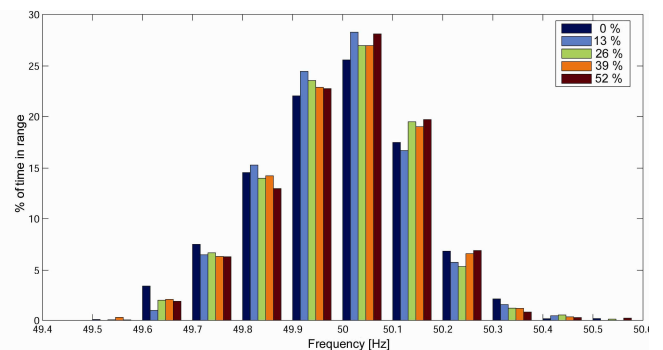


Figure 2. Frequency histogram for different wind power percentages.

Table 1. Impact on frequency and voltage with several percentages of wind power penetration

% of wind power	% time inside limits	P _{st}
0	47	3.73
13	53	2.91
26	51	3.01
39	50	3.1
52	51	3.28

Reminding the normal operation limits of 50 ± 0.1 Hz, it is possible to notice in Figure 2 that the frequency goes out of its normal operation limits under all wind power penetration levels. The frequency deviations are quite remarkable and for rather big percentages of time. In almost all the cases, the frequency is out of limits for approximately the half of the simulation period as it is shown in Table 1. Carrying out a deeper look into the results for the different wind power

percentages, the case with no wind power in the network leads to the worst frequency results. The reason for this can be explained by (1) which links the balance between produced and consumed power with the system frequency. When a mismatch between produced and consumed power takes place, the system frequency is affected. Since the system inertia (H) is dividing the power mismatch, the bigger the inertia is, the smaller is the influence in the frequency. Due to their really big rotors, wind turbines have a big inertia meaning an important part of the total inertia in isolated systems as is the case. Nevertheless, there is not a linear link between the inertia increase caused by wind turbines and the frequency improvement. In fact, increasing the wind power percentage level makes the frequency worse. The reason why this happen is because on one hand, wind turbines increase the inertia of the system which helps the frequency, but on the other hand, due to the variable nature of the wind and to the types of wind turbines used, the wind fluctuations are transformed into power fluctuations and generating power imbalances. In short, in terms of frequency, the wind power in the grid cell has a positive effect due to the inertia increase but also a negative one due to the power perturbations it generates.

To study the voltage quality a flicker analysis, which results are shown in Table 1, is performed. Considering that the limit for short term flicker power (P_{st}) is set to 1 by the IEC standard [3], the results are rather poor in all the cases. These flicker levels would result in being annoying for the consumers.

5. NETWORK OPERATION WITH CORRECTIVE MEASURES

Next the simulation results will be presented and analysed considering the different measures proposed. Since those taken to improve the frequency can hardly improve the voltage, the SVC system will be used in all cases studied.

5.1. Dump load and SVC

The use of the dump load together with the SVC should improve respectively the frequency and the voltage in the network. In addition to the frequency and the voltage study, it will be discussed how the dump load will be operated along the simulation to get an idea of how the end use of the load would be affected.

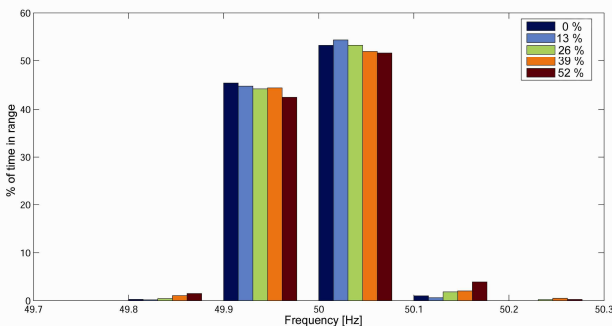


Figure 3. Frequency histogram with the use of the dump load and the SVC.

The results of the frequency are shown in Figure 3. The improvement with regard to the case of no corrective measures is very large. The frequency still goes out of the limits, but just for very small percentages of time. It seems that the deviations are bigger when the wind power

penetration is increased, this is more clearly shown in Table 2. In all the different wind power penetration percentages the frequency is within the permitted range more than the 90% of the time, reaching values as high as 99% in the case of 13% of wind power penetration in the grid. The reason for this great improvement is that the fast and relatively small power changes are dumped by the dump load, meanwhile the CHP only has to deal with the long term power changes which are usually quite slow and not causing big problems. Since the consumption range of the dump load is between 200-600 kW, the total amount of power able to be dumped is 400kW which means less than the 6% of the average consumption in the simulated situation. This is a very good advantage, because with a few percentage of power dumping capability the improvement in the frequency is very high. In Table 2 the mean values of the power consumption of the dump load are shown, P_{dl} . These values increase slightly with the percentage of wind power penetration in the grid cell.

In Table 2 the values of the short term flicker power (P_{st}) are shown. For all cases the flicker levels are below the limit set by the standard at $P_{st} = 1$, but with the maximum wind power penetration considered (52%) the value is quite close to the limit. Under these conditions, the addition of more wind power to the grid would probably lead to annoying flicker levels.

Table 2. Impact on frequency and voltage with the use of the dump load and the SVC.

% of wind power	% time inside limits	P_{st}	P_{dl} [MW]
0	98.7	0.53	0.41
13	99.2	0.62	0.43
26	97.5	0.69	0.44
39	96.5	0.77	0.45
52	94.2	0.91	0.47

5.2. Kinetic energy storage system and SVC

The kinetic energy storage system can supply or consume either active power or reactive power. The active power is absorbed or released by a flywheel according to the requirements set to control the frequency. The reactive power can be controlled by the power electronics which connect the flywheel with the grid, however, in these simulations, that task is performed by an SVC.

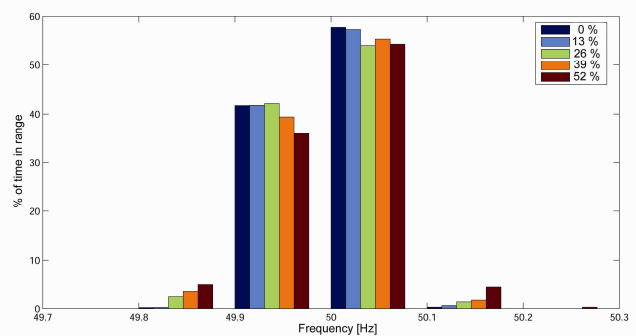


Figure 4. Frequency histogram with the use of the KESS and the SVC.

In Figure 4 the frequency histogram for different wind power percentages penetration is illustrated. It seems that the frequency is quite well controlled, and stays within the limits

most of the time. The deviations in the case of no wind power in the grid are almost completely eliminated. In the histogram it is also possible to notice that the higher the percentage of wind power in the network is, the higher are the deviations from the permitted range. However, comparing this result with the case of no corrective measures taken, the over and under frequencies are much attenuated. The values of the percentage of time, in which the frequency is within the permitted range, and the short term flicker power values are presented in the Table 3. Here it is possible to note that in all the cases of wind power penetration studied, the kinetic energy storage system is able to keep the frequency within the range of 49.9-50.1 Hz for more than 90% of the time. It is even reaching values as high as 99% for the cases of no wind power in the network and 13% of wind power penetration.

Table 3. Impact on frequency and voltage with the use of the KESS and the SVC.

% of wind power	% time inside limits	P _{st}
0	99.4	0.47
13	99.2	0.55
26	96.2	0.65
39	94.7	0.74
52	90.7	0.87

In terms of voltage, the improvement is very remarkable. All the values of short term flicker power are below one, which is the maximum permitted level. It can as well be noticed that the values in this case are smaller than the values with the dump load. The reason for this could be related to the different response from the KESS and the dump load. While the KESS simply modify its active power exchange with the grid, the dump load changes both, active and reactive power. These reactive power changes are another source of voltage disturbances which the SVC system has to deal with.

5.3. Load shedding and SVC

Since the load shedding only has been set up to be able to help with the under frequency problems, it is more interesting to examine the percentage of time where the frequency drops below 49.9Hz. The possible impact in the consumers comfort due to the load shedding is discussed as well by mean of computing the percentage of time that the load is connected.

Table 4. Underfrequency percentages with different amounts of load shedding.

% of wind power	0 kW	50 kW	100 kW	150 kW
0	25.5	17.2	11.4	4.1
13	22.9	16.2	9.8	3.4
26	22.2	16.8	12	6
39	21.9	17.2	11.7	6.4
52	20.8	17.4	13.3	8.5

In the Table 4 the values of percentage of time in which the frequency is below 49.9Hz are shown. Cases of 0kW, 50kW, 100kW, 150kW of load shedding are shown. The average power consumption is 7MW, so the cases of load

shedding correspond to 0%, 0.71%, 1.4% and 2.1% of the total consumption. Those percentages are quite small in comparison with the very noticeable improvement they generate in terms of under frequencies. The improvement is illustrated by comparing the column for 0% load shedding with the following, in which the load shedding is applied. As it could be expected, the higher the load shedding amount is, the smaller is the percentage of time with under frequencies. With 150kW of load shedding capability the under-frequencies are highly reduced leading the frequency to go below the limit for small percentages of time.

Table 5. Percentages of time that the load is connected.

% of wind power	50 kW	100 kW	150 kW
0	71	76	77
13	72	75	78
26	72	75	77
39	72	75	77
52	73	75	76

To check the impact in the consumers comfort it is necessary to look at the percentage of time along the simulation in which the load is connected. In Table 5 such percentages are shown. The percentage of time each load shedding capability is connected does not change much by rows. It can be approximated that with 50kW the load is consuming 72% of the time, with 100kW it is consuming 75% of the time, and with 150kW it is consuming 77% of the time. In all the cases, there would be some impact on the customers. The consequence of this could for some loads concern the time needed for carrying out their task (e.g. water heaters), or slightly affect their duty cycles (refrigerators, space heating or freezers)

Table 6. Impact on frequency and voltage (% time inside frequency limits and P_{st}, respectively) with the use of different amounts of load shedding and the SVC.

% of wind power	50 kW		100 kW		150 kW	
0	64	0.65	73	0.68	83	0.70
13	65	0.67	42	0.70	83	0.73
26	62	0.75	71	0.77	79	0.79
39	62	0.83	72	0.87	79	0.86
52	57	0.89	67	0.93	74	0.95

In Table 6 it is possible to take a general view of the improvements in frequency and voltage in the conditions discussed in this section. In terms of frequency, the improvement is not as noticeable as with the dump load or the KESS. This is, as mentioned before, due to the fact that the load shedding is only able to overcome problems with under frequencies and not able to react to over frequencies. Regarding voltage, the SVC manages to keep the voltage quite stable and all the flicker power values are below the limit of one.

6. CONCLUSION

The operation of a grid cell (average load: 7 MW) separated from the interconnected power system has been analysed under several different scenarios of wind power percentage

penetration from 0% to 52%. The grid cell is representative for a Danish distribution system with respect to characteristics for local CHP, wind turbines and consumption. Without introduction of any specific measures simulation results unveiled that the variable load is able to cause considerable deviations in frequency (49.5-50.5 Hz) and very wide variations in the voltage; leading to annoying flicker levels ($P_{st}=3.73$). The normal consumption variations in active and reactive power cannot be compensated fast enough by the local CHP. With 13% of wind power in the network a slightly improvement in the frequency quality takes place. The reason for this is the system inertia increase with the addition of wind turbines. The higher the inertia of the system is, the smaller the frequency deviations are.

For improving the frequency control the use of a dump load and a kinetic energy storage system has been examined. Testing these devices gave very satisfactory results and the frequency deviations were highly reduced. With 400 kW of dumping load capability the frequency is kept within limits more than 94% of time, and with a 300 kW KESS more than 90%. This kind of devices are very helpful for controlling short term frequency deviations, but the long term deviations have to be controlled by other means.

The effect of different amounts of automatic load shedding has also been considered. This operation is useful for cases of under frequencies, and the results were quite good. The under frequencies were reduced, and the frequency improvement increased with increasing amount of load shed. The possible impact on the customers was also analyzed by calculating the percentage of time the loads would be connected.

For improving the poor voltage quality, the use of a Static Var Reactor (SVC) has been considered. This device is able to control the voltage in the consumers' node eliminating the flicker problems due to its capability of controlling the reactive power very fast.

7. DISCUSSION

Even though it might seem like the use of these devices are not feasible to apply in the actual grid, due to the need of a large amount of such devices spread along the whole network, the application could be feasible if the following considerations are taken into account:

- There are a lot of loads spread in the electric grid which potentially can be used as dump loads. For becoming a dump load a Dynamic Grid Interface (DGI) is needed, which would control the power according to requirements for frequency. The DGI could also be used in a cost-effective operating philosophy in non isolated operation. In that operation mode, the dump load would be controlled for example to avoid the penalty fares of large power peaks in the consumption of a large factory. This could encourage the use of these devices.
- The kinetic energy storage systems could have two different purposes, on one hand they could perform the task exposed here, but nowadays they are already being used as Uninterrupted Power Supply (UPS). These two possible applications of the KESS could make their use in the electric grid suitable.
- The SVC is a quite expensive system and large scale use would probably not be affordable. However, the

task realised by this system could be done by other devices. For example, the power converters of the KESS or DGI could perform the task of a SVC in a small scale. In fact, in the datasheet for the used KESS model, its capability for voltage support by reactive power control is explained.

APPENDIX

Dump load model in PowerFactory

In Figure 5 the blocks diagram of the model is depicted and the values used for the parameters are shown in Table 7.

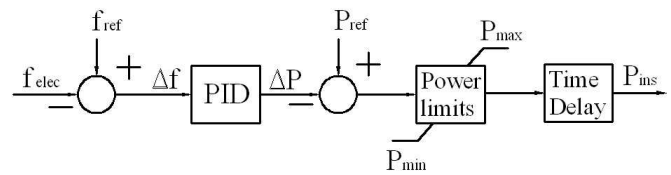


Figure 5. Blocks diagram of the dump load model built in PowerFactory.

Table 7. Parameter values of the dump load model.

Definition	Parameter	Value
Frequency reference	f_{ref}	1 [pu]
PID Gain	K	80
PID integral constant	T_i	0.005
PID differential constant	$[\alpha, T_D]$	[0.5, 2]
Power reference	P_{ref}	0.4 [MW]
Maximum power	P_{max}	0.6 [MW]
Minimum power	P_{min}	0.2 [MW]
Time delay constant	T_r	1.5 [s]

KEES model in PowerFactory

The model used for the kinetic energy storage system is depicted in Figure 6. That figure does not show the PID controller which transform the frequency deviation in the signal a_r , but in the Table 8 the values of its parameters are shown.

