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**Study on maximum permissible intermittent electricity
generators in an electricity supply network based on
grid stability power quality criteria**

Master Thesis

by

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Sterling Heights (Michigan, USA), 2012

Michael Knopp

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Abstract

This study analyzes potential integration of renewable energy like wind and solar power in the isolated power system of the Caribbean Island St. Vincent (St. Vincent and the Grenadines). St. Vincent’s power generation system is based on diesel and hydro generators; a wind park of about 3.6 MW is planned, and other RE generation is desired. Deterministic criteria that constrain the penetration of variable renewable (VRE) generation are analyzed from a technical point of view.

Based on the analysis, the following questions have been analyzed:

- What are the main constraints that limit the penetration of variable renewable sources in small island power generation systems?
- What is the maximum deterministic VRE penetration for St. Vincent’s electricity generation system according these constraints?
- Which technical measures are necessary to increase the VRE penetration?
- Is the power system stability and reliability assured?

The assessment of the VRE penetration scenarios is performed with an Excel based simulation tool. In the simulation the power flow of different renewable integration scenarios can be calculated according to the current setup and operation approach of the Transmission system operator (TSO) of St. Vincent power system, VINLEC. It is shown that the system adequacy is critically dependent on the wind and solar penetration margin. Different scenarios regarding solar and wind power installation are studied. Via stability simulation, using the software NEPLAN, the reaction of wind speed, active and reactive load variations is analyzed to verify the system stability under the penetration constraints.

Finally the study summarizes the results and makes concrete recommendations for short, mid and long term modifications of the power system to accommodate a higher share of VRE sources. Also, estimations of the technical maximum share of renewable energy are made according to the several improvement scenarios.

Abbreviations

AVR	Automatic Voltage Regulator
CARICOM	Caribbean Community
CARILEC	Caribbean Electric Utility Service Corporation
CREDP	Caribbean Renewable Energy Development Programme
CDS	Generator with fully rated converter
DFIG	Double Fed Induction Generator
EPSS	Electrical Power Supply Systems
GIZ	Deutsche Gesellschaft fuer Internationale Zusammenarbeit (German Agency for International Cooperation, formerly GTZ, InWend and DED)
GTZ	Gesellschaft fuer Technische Zusammenarbeit (German Agency for Technical Cooperation)
GWh	Gigawatt-hour
HFO	Heavy Fuel Oil
IG	Induction Generator
kW	Kilowatt
kWh	Kilowatt-hour
LPG	Liquefied Petroleum Gas
MW	Megawatts
Pen	Instantaneous penetration
PV	Photovoltaic
UCTE	Union for the Coordination of Transmission of Electricity
SVG	St. Vincent and the Grenadines
STVIN	St. Vincent Power System
VRE	Variable Renewable Energy
VINLEC	St. Vincent Electricity Services Limited
TSO	Transmission System Operator
SpR	Spinning reserve
STATCOM	Static Synchronous Compensator
SynG	Synchronous Generator
TSC	Thyristor Switched Capacitors

1. Introduction

1.1. *Motivation and scope*

The Electrical Power Supply Systems (EPSS) worldwide are facing the challenges of rising prices for primary energy sources and the climate change as a negative effect of greenhouse gas emission. One of the major strategies to moderate these problems is the integration of renewable energy sources into the EPSS. Power generation technology based on renewable sources contributes to the protection of natural resources, to climate change mitigation and reduces dependencies on imported fossil resources.

Especially the energy sectors of small island developing states (SIDS) are threatened by the price increase of the primary energy sources. These countries are mainly depending on expensive fuel imports. The main energy source, diesel or heavy fuel, needs to be shipped over wide ranges and to steadily increasing prices. As a result, most Caribbean countries have high electricity tariffs of up to 0.50 US\$ per kWh. Because of the high electricity tariffs in these countries many renewable energy generation types are economically competitive and offer a good chance for these countries to reduce their dependency on fossil fuels.

Because of the variability of many renewable energy sources it is challenging to integrate them into the EPSS, and hence their measure of penetration is usually limited. Variability means that most Renewable Energy generation types are available on an intermittent basis, e.g. Wind Power is available when the wind blows, Photovoltaic (PV) when the sun is shining. Beside the variability on the demand side that is common to each EPSS, systems with Renewable Energy generation also face variability on the supply side. Compared to EPSS without VRE generation types, the generators of EPSS with VRE have to be more flexible to respond to that generator variability. In a worst case scenario, the generators have to compensate a fast increase on the demand side combined with quick decrease on the supply side. Without technical adjustments or operational changes the EPSS can only absorb a limited amount of intermittent generation without getting stability problems. Governing factors for the systems stability are the generator types, spinning reserve, ramping characteristics and the storage capacity.

This study analyses the EPSS of St. Vincent, the major island of St. Vincent and the Grenadines (SVG), as one example for an isolated power system. The purpose is to investigate the impact of VRE on the reliability performance of isolated power systems. After introducing the study’s subject and the examined island St. Vincent in Chapter 1, Chapter 2 will give a general overview about the impact of VRE in EPSS and describe the terms of system stability of power systems. The EPSS of St. Vincent will be introduced in Chapter 3. Chapter 4 shows the modeling methodology that has been developed for simulating the reliability performance of the power system. The constraints are described and the maximum possible VRE penetration is calculated. Technical changes and operational strategies which increase the potential amount of VRE are shown in Chapter 5, broken down into short, mid and long term measures. Chapter 6 shows a dynamic validation of the limitations that have been presented in Chapter 4 based on the Software NEPLAN. In Chapter 7 the main recommendations to achieve a maximum amount of VRE in the power system are summarized.

The key goals of the study can be summarized as:

- The constraints for VRE penetration in the EPSS of St. Vincent are elaborated.
- The maximum permissible VRE rate is calculated based on the penetration constraints.
- Technical or operational changes to increase the VRE penetration limits are defined.
- The power stability is validated for the existing VRE penetration limits.

1.2. St. Vincent and the Grenadines

St. Vincent and the Grenadines (SVG) is situated between Saint Lucia and Grenada in the Windward Islands chain of the Lesser Antilles, an island arc between Caribbean Sea and Atlantic Sea [1]. The islands of Saint Vincent and the Grenadines include the main island of Saint Vincent and seven smaller inhabited islands with about 30 uninhabited islets stretching south from Saint Vincent to Grenada. Together, the islands occupy a total landmass of 388 km².



Figure 1.1.: St. Vincent and the Grenadines within the Caribbean Sea [Source: Wikipedia]

The territory was disputed between France and the United Kingdom in the 18th century, before being ceded to the British in 1783. It gained independence on 27th October 1979. Approximately 120,000 people live on the islands. Kingstown is the chief town with a population of 19,300 people. The rest of the population is dispersed along the coastal strip, which includes the other five main towns of Layou, Barrouallie, Chateaubleair, Georgetown, and Calliaqua, and the Marriaqua Valley.

Saint Vincent, the main island of SVG, is a volcanic island. It is 30 km long and 18 km wide and is located 160 km west of Barbados. It is dominated by the active volcano called La Soufriere. The island is mountainous and well-forested. The island is tropical humid, with an average of between 18 and 31 °C, depending on altitude. The annual temperature variation is very low pending around 26 °C.

2. Issue – VRE in isolated power systems

2.1. General aspects and modeling

An EPSS is defined as a network of one or more generation units, loads and power transmission lines including the associated equipment connected to it [2]. Isolated EPSS differ from Interconnected EPSS according their size and the lack of possibility of power transfer due different TSO. An example for a highly Interconnected EPSS is the European Network of Transmission System Operators for Electricity (ENTSO- E) in Europe. The ENTSO-E contains 42 TSOs from 34 countries, which now share an interconnected transmission grid in the European Union. The interconnection of several generation areas allows energy flows between the TSOs. Because of the connection between several generation and distribution systems the amount of required backup systems for outages is relatively low. That results in low energy cost and high power quality.

Isolated EPSS are not interconnected to other EPSS. They are mostly located on islands or in remote areas and are operated by only one TSO. Generally the installed generation capacity and the total demand are much lower than of Interconnected EPSS. In comparison to the interconnected EPSS, isolated EPSS face specific problems that are related to their planning and operation. Their customers face generally higher costs and poorer quality of supply than the customers of large interconnected EPSS [3].

The assessment of maximum VRE penetration in the St. Vincent EPSS requires appropriate modeling of its features that affect its operation. These features are deduced from a reliability assessment study of a small Greek island [4], and are described as follows:

I) The generation system mainly consists of thermal generating units like steam turbines, internal combustion engines, combined cycle engines and combustion turbines. Additionally the generation system may also contain hydro power plants including appropriate generating units and applicable reservoirs.

II) Internal combustion engines like Diesel Power Plants or steam turbines mainly supply the system's base-load demand. Due to the high production cost of combustion turbines, they normally supply the daily peak load demand or the load demand that cannot be supplied by the other system units. This might occur in outage conditions or while VRE variation.

III) In every time period like day or night, an appropriate number of thermal generating units is called on to operate in order to supply the relevant load demand. The operating policies are according to a priority order (“merit order”) that is determined by their production cost. The operation of these units has major limitations due to the spinning reserve capacity that must be available. This spinning reserve capacity is usually determined by using an appropriate security criterion and it can be equal to either a certain percentage of the system load demand, the capacity of the largest unit in operation or the maximum outages of VRE power. For this reason, the power output of one or more conventional generating units is smaller than their rated power.

IV) Hydro power plants that are located on the same river, including reservoirs, can also exist in the EPSS. Potential storage capacity of reservoirs is determined by the topographical sites or the construction facilities. The power generating characteristic is a result of the water management and reservoir operation of each unit and can be used in order to calculate the power output and the water volume used by the hydro power plants during a certain period of time.

V) Certain operating and water management policies can be implemented in EPSS with hydro power plants. These policies have a significant impact on the reliability performance of systems that have limitations in the energy produced from hydro power plants.

VI) Isolated EPSS with a high VRE penetration might face voltage and frequency deviations and dynamic unstable situations. These situations might occur during fast wind speed variations and sudden loss of wind power generation. This loss can be compensated with additional production from the remaining generating units that provide either spinning reserve or sufficient ramping speed and capacity flexibility to compensate the wind power generation fluctuations. This determines the wind penetration margin that is expressed as a fraction of the wind power generation to the system power demand. This penetration margin can be increased by considering several strategies like improved operation modes of hydro power plants or storage facilities.

2.2. Stability and control

Power system stability can be defined as the ability of an EPSS, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables controlled so that practically the entire system remains intact. The equilibrium of the EPSS is directly dependent to the frequency of the system. The Power system stability is classified in the three main groups Rotor angle, frequency and voltage stability [2].

The purpose of frequency control is to keep the balance between demand and supply of electricity. Therefore the system requires sufficient and regulating reserves. System regulation is distinguished in primary, secondary and tertiary control and their respective reserves.

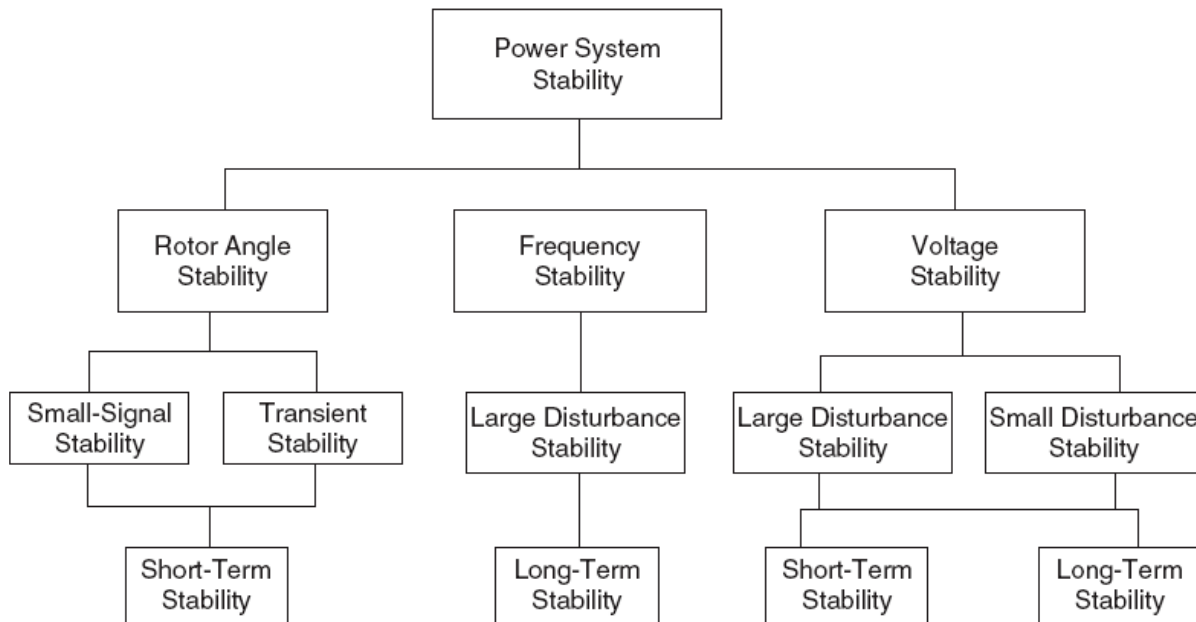


Figure 2.1.: Classification of power system stability [2]

Primary control is local automatic control which provides reserve power in response to any frequency change. The primary control is related to the primary reserves that will be supplied by generation within the first 15 minutes after a disturbance and is synchronized to the power systems frequency.

Secondary control is centralised automatic control which delivers reserve power in order to bring back the frequency and the interchange programs to their target values. The time frame of this control is between 30 seconds and 15 minutes after deviation.

Tertiary control is done by manual change in the dispatching and unit commitment in order to restore the secondary control reserve. In order to manage eventual congestions, and to bring back the frequency and the interchange programs to their target if the secondary control reserve is not sufficient, tertiary control gets activated [2].

In theory, a generating unit could participate in all three levels of control. In large Interconnected EPSS, a generating unit might provide only one, two or none of these reserve services. In Isolated EPSS the conventional generation units have to provide all three services most of the time because the amount and the diversity of different generating units is lower. In the EPSS of St. Vincent the services are provided by Diesel generator sets. These units are the only power supply in the Isolated EPSS that have full grid forming abilities. That means they are able to control the grid frequency through supply of additional active power sourced from Spinning Reserve, and voltage through reactive power supply by Automatic Voltage Regulators (AVR). Figure 2.2 shows the principal setup of the control devices for voltage and frequency control of a Diesel generator set.

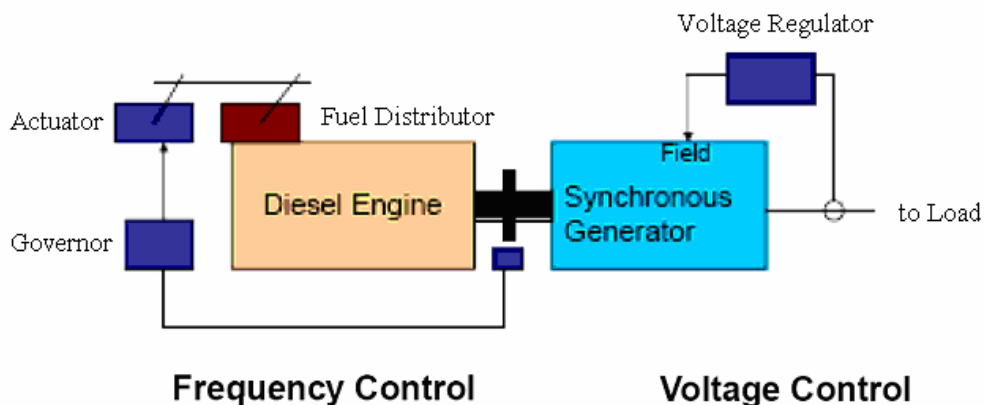


Figure 2.2.: Control Devices of Diesel generator set [11]

VRE sources have limited or no grid forming abilities. Depending on their concepts they are able to participate on voltage control respectively reactive power supply or active power control (active power reduction). Another stability related service that can be provided by VRE units is the so-called “fault-ride-through” capability. This ensures that the power plants will stay connected during and after faults in the power system. At a certain VRE penetration levels the influence on power system control and stability has to be taken into account.

2.2.1. Spinning Reserve

The term Spinning Reserve defines a specific form of control reserve in EPSS. It can be defined as the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power. The term Spinning Reserve is not related to the time frame of the reserve and can be used to describe generating as well as demand capacity. A consumer can provide Spinning Reserve, if it agrees to be disconnected or to reduce its load upon request by the TSO. Pump loads are typical examples for the provision of Spinning Reserve on the demand side. Negative Spinning Reserve is essential for the stability of the power system to be able to reduce the active power production in case of a high frequency [5].

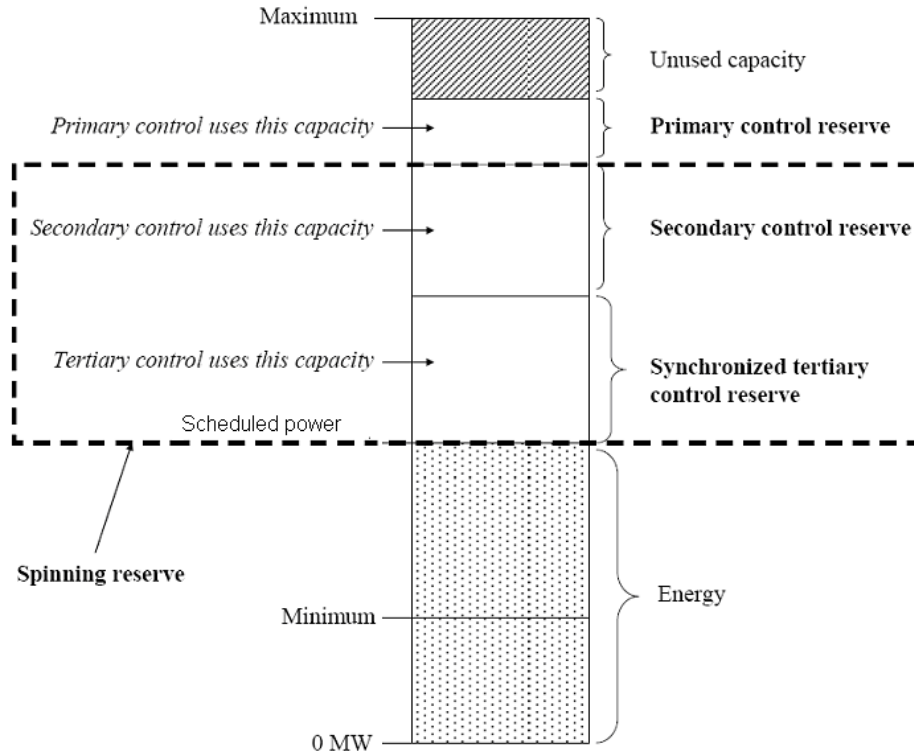


Figure 2.3.: Reserves and generator capacity (Source TU Manchester)

2.2.2. Security, reliability and power quality

Regarding the stability of EPSS two additional terms describe the robustness of the system: security and reliability. Security of an EPSS refers to the degree of risk in its ability to survive approaching disturbances without interruption on the demand side. It relates to the robustness of the system to disturbances and, therefore, depends on the system operating condition as well as the probability of disturbances. Reliability of an EPSS refers to the probability of its satisfying operation over a long period of time. It shows the ability to supply adequate electric service on an almost continuous basis, with few interruptions over an extended period of time [2].

The power quality refers to the deviation of the power characteristics from their specifications. Maintaining power quality assures that the power is supplied appropriate enough for needs like wave form, amplitude and harmony [2]. Maintaining power quality is a typical problem that occurs at low levels of VRE penetration. The main power quality variable is the voltage in the distribution

system. Voltage quality problems include the slow and steady variations in voltage amplitudes. These amplitudes must be limited due to protect the consumer’s electrical equipment. Potential failures that might occur due to voltage variations are thermal overload or flicker [18].

2.3. Variability of VRE

Renewable generation units rely on primary power source like wind, sun, rain or tides. Unlike traditional sources like thermal generating units that provide a controllable, steady stream of power, some renewable sources are variable and intermittent. The output from VRE plants fluctuates according to the available resource [14].

Variability is not a phenomenon that is only caused by renewable sources. In EPSS demand is fluctuating up and down during daily and seasonal periods. The resulting imbalances have to be managed, mainly by dispatchable power generators. Variable renewable electricity in the system is an additional challenge because the variability lies on the supply side and the generation of VRE provides uncertainty. These fluctuations cause that other parts of the system will have to change their output or consumption more rapidly and more frequently than already required. The ability of the system to react quick enough to accommodate such extensive and rapid changes has to be assured. Residual load ramping caused by supply variation is more extreme than demand variation alone.

Figure 2.4 shows an example of this issue. The upper line shows the shape of the everyday demand fluctuations over the course of the week. The electricity demand follows a regular pattern during weekdays and the weekend. The lower line shows demand after accounting for wind and solar output, called the residual or net load. The residual load tracking highlights the higher variability caused by a high share of VRE (according the Western Interconnection, USA). Indeed, the diagram shows three periods in which the residual load drops below zero. At these times, VRE output of wind power (green area) and Solar power (yellow area) must be curtailed, stored or exported. Otherwise the VRE power would be higher than the total demand.

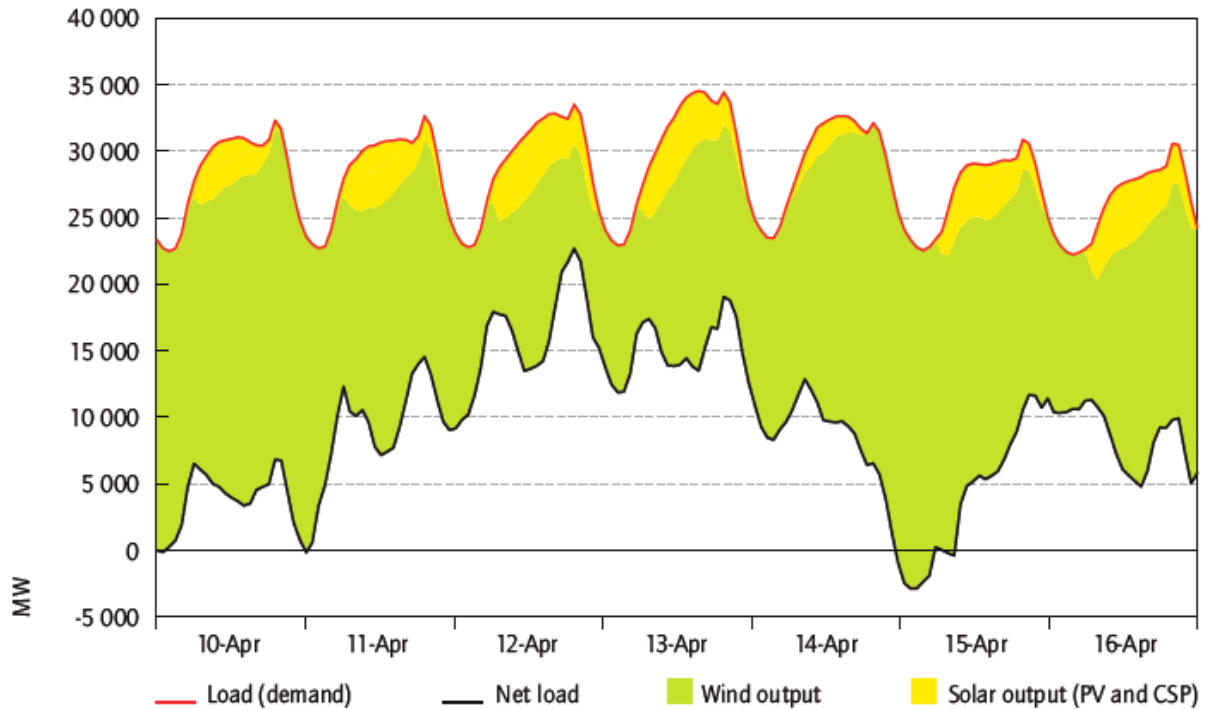


Figure 2.4.: Example of variability in demand and in Residual/ Net Load during one week [14]

The minimum and maximum of the residual load as well the extent of the residual load ramps, and their rate and frequency constrain the penetration of VRE in existing EPSS. The variability of the residual load caused by VRE sources can get in conflict with existing EPSS operation policies like dispatch orders and power output requirements. Integrating a substantial fraction of VRE sources into the energy mix typically requires extensive backup generation or energy storage capacity to remove the variable and intermittent nature of such sources. The flexible operation of EPSS due to the increasing extent and fluctuation of residual load has major impact on the power system stability and power quality.

Another aspect regarding the variability of VRE sources is the timeframe of variation. In a timeframe of days the availability of VRE power according the production forecast is an important matter for the TSO to manage the power supply backup. This aspect concerns the long term operation in a time frame of days. Variations like wind speed fluctuation is a matter of seconds to minutes. Thus, VRE control for fluctuating RE conditions and the dynamics of their controllers need a response time of some milliseconds to seconds.

2.4. Enabler for VRE

To Enable VRE to enter into EPSS, the system needs an additional margin of flexibility to respond the variability. The key for increasing flexibility in EPSS is the amount and the availability of spinning reserve. The amount that is required to assure the system performance and reliability is defined as spinning reserve demand. The spinning reserve demand of the system is a specific amount of generation capacity that needs to be synchronized to the system. The amount is determined by different spinning reserve criteria that consider generation outages in the EPSS caused by VRE and conventional units. Figure 2.5 shows a scheme for the division of supply for Energy and spinning reserve of several generation units and two different demand scenarios.

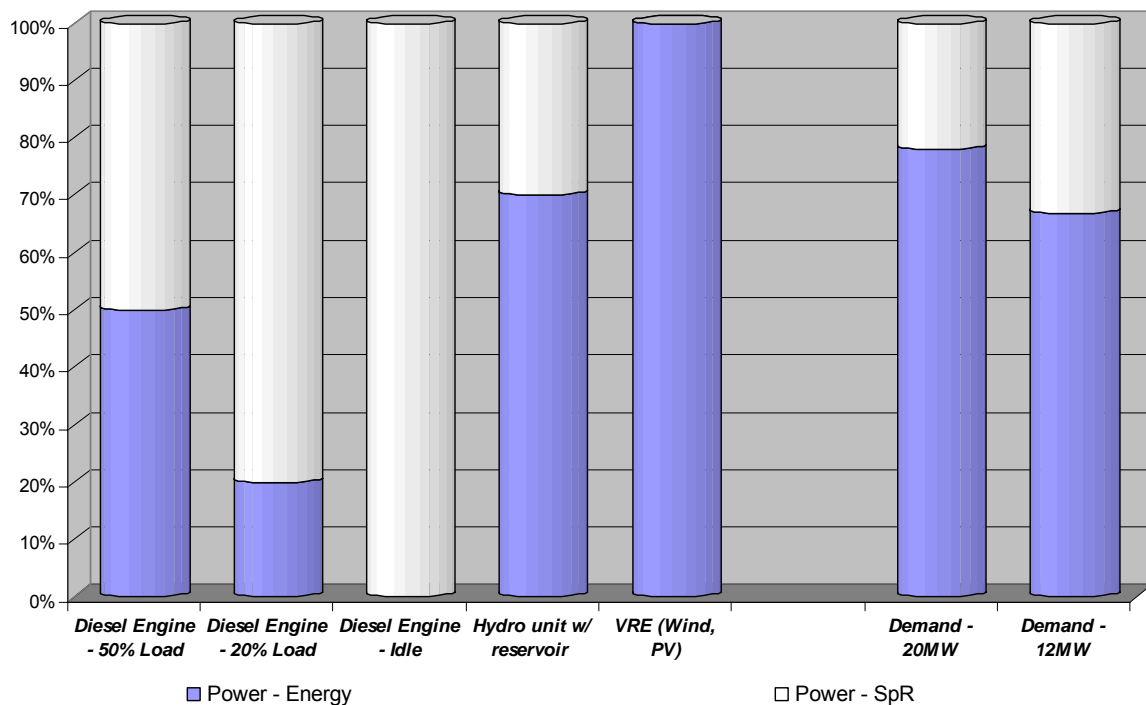


Figure 2.5.: Fragmentation between Power for Energy supply and Spinning reserve supply

The TSO has to assure that in every operating situation, during peak demand as well as during low demand, the amount of spinning reserve demand is satisfied. Therefore sufficient spinning reserve capacity has to be dispatched. These can be thermal generation units that operate below their rated capacity or hydro generation units connected to a reservoir that operate below their maximum

output. It is also possible that generation units supply only spinning reserve, like idling diesel units. Due to their variable power sources VRE units can not provide spinning reserve. Figure 2.5 also shows an example of several generation units and their spinning reserve supply.

Flexibility on the demand side might be available and can decrease the spinning reserve demand. Methods of demand side management include the control of electricity consumers or diverse tariff structure to give incentives for electricity use in off-peak hours. The use of storage can also be seen as demand side control. The overall demand of the system can be managed if additional storage facilities are dispatched to increase or reduce the system demand as required. The increase of demand reduces the amount of required instantaneous spinning reserve.

The system’s available spinning reserve capacity can be increased through combination of individual EPSS, particularly in large supply areas. Combinations of EPSS with different flexibility characteristics offer the potential to increase the available spinning reserve of each individual system through overlay of different variability characteristics. In particular where the combination of connected EPSS stretch over various time zones, a balancing effect of demand and electricity generation, e.g. photovoltaic, can be found.

3. Model - St. Vincent’s EPSS

3.1. Energy sector

Small island countries in the Caribbean differ in several aspects, but there are some common traits which can be identified for the energy situation. The first and most obvious is the high dependency on imported fossil fuels. On the Caribbean islands, more than 90 % of electricity production depends on fossil fuels and in average less than 5 % of electricity is supplied by renewable sources. In addition, most Caribbean territories feature a monopoly for the utilities, which is typical for small markets of less than 150 MW installed power. This, the use of diesel as fuel and the high distribution cost contribute to the high electricity tariffs of up to US\$ 0.50/kWh (at an oil price of 100 US\$ per barrel) that can be found in many Caribbean countries [6]. Some utilities have long term supply contracts with guaranteed rates of return on investment, which do not incentivise investment in RE.

In the 1970s and 1980s the most of the utilities of these countries were privatized. Energy forecasting and formulation of energy policy both were left in the hands of the utilities. Due to these facts most of the countries have no incentives to use renewable sources or to foster energy efficiency. In many Caribbean countries electricity supply acts guarantee a rate of return on investment of, for example, 15 % for electric utilities. In most cases the utilities pass on the fluctuating cost for electricity by means of fuel charge, fuel surcharge or similar surcharges.

SVG, as one example for a small Caribbean island state, is dependent on imported petroleum products for its electricity generation. The energy mix (i.e. electricity generation, transport and other energy uses) of SVG is based with more than 96% on petroleum and about 3% on hydro power. All islands except St. Vincent depend entirely on diesel generation for their electricity supply. On the main island St Vincent, 80% of the electricity is produced by diesel generators and the remaining 20% by small hydro generation units.

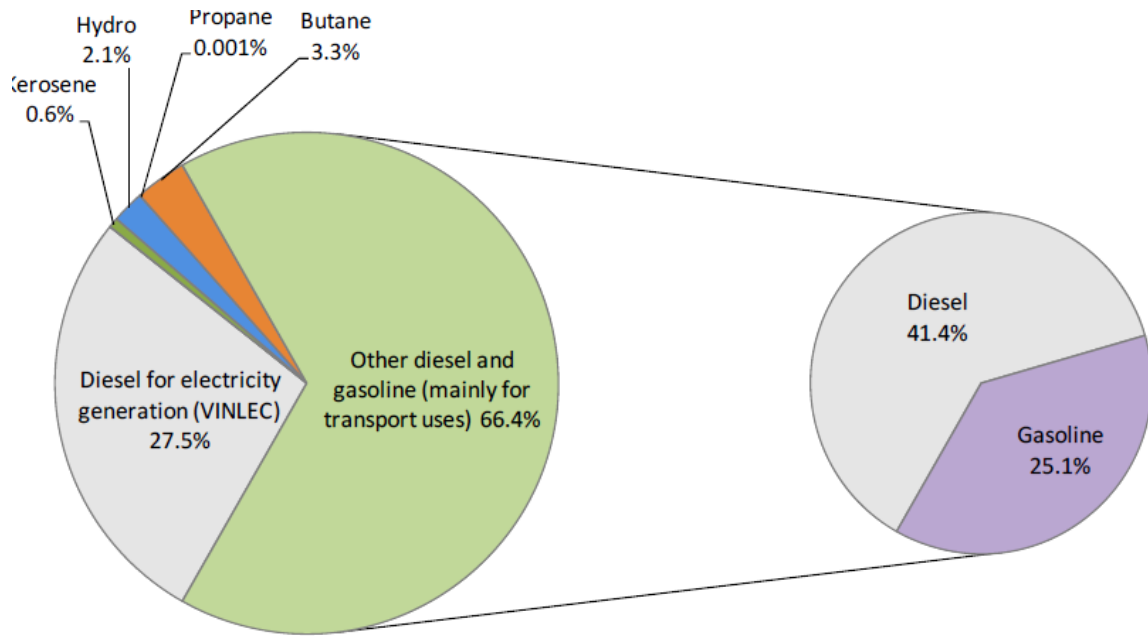


Figure 3.1.: Energy mix of SVG by energy source in 2008 (Source: VINLEC, 2009)

St. Vincent Electricity Services Limited (VINLEC) is the Transmission System Operator (TSO) and sole provider of electricity of SVG. It is a state owned company incorporated in 1961. Since then VINLEC is running the system on the main island of St. Vincent, and the Grenadine islands of Bequia, Canouan, Union Island and Mayreau. VINLEC operates diesel and small hydro power stations on St. Vincent, the main island. The islands Bequia, Union Island, Canouan and Mayreau are completely reliant on diesel powered EPSS. The rest of the Grenadine islands are supplied by privately owned EPSS on the basis of diesel power plants. VINLEC is situated in the capitol of SVG, Kingstown, and delivers electricity to 37,619 customers in 2008. It has over 280 employees in 9 locations. VINLEC offers several electricity tariffs depending on the different customer groups like domestic, commercial, industrial and street light. In 2011 the tariffs were varying for the several customers from 42.50 to 56 EC cents/kWh excluding the additional fuel surcharge [7].

VINLEC is the largest sole consumer of imported petroleum products, using 33.83% of total oil imports in 2008. The same year, 49% of total diesel imports were used to generate electricity.

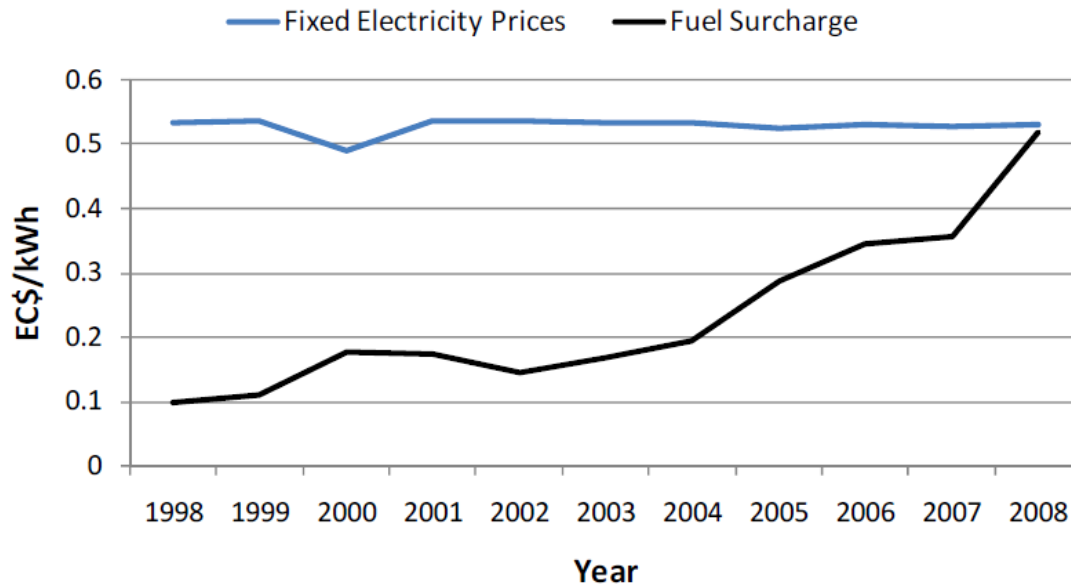


Figure 3.2.: Fuel Surcharge of SVG according VINLEC 2008

VINLEC transmits and distributes the electricity using 33kV transmission lines, 11kV primary distribution lines and 400V secondary distribution lines. The distribution network is spanning over 350 miles of lines.

3.2. Demand and consumption

Figure 3.3 shows the breakdown of the energy consumer groups of SVG. Residential and commercial sector are the largest consumer groups of electricity on the islands. The industrial consumption and consumption for street lighting is marginal. The total consumption went from 74.6 GWh in 1998, to 122.9 GWh in 2008.

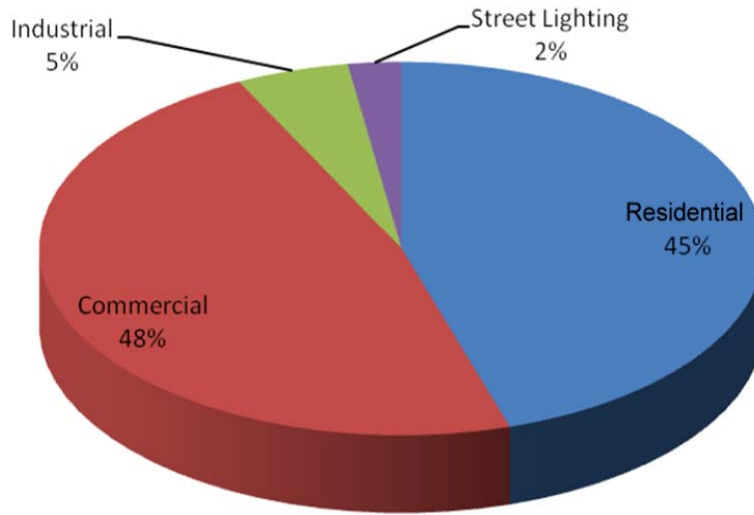


Figure 3.3.: Basic Properties of the SVG EPSS [7]

Frequency	50 Hz	+3%,-3%
Voltage - low tension	230V/400V	+4%,-8%
Voltage - high tension	11kV	-
Voltage - transmission	33kV	-
Electrical Short Power - Max Single-Phase	3kVA	-
Electrical Short Power - Max Three-Phase	5kVA	-

Figure 3.4.: Electricity consumption in SVG in 2008 (Source: VINLEC, 2009)

The demand of St. Vincent is shown in Figure 3.5, in a weekly, and Figure 3.6., in a yearly timeframe. In 2010 the weekly demand ranged between 20 MW during daytime and 12 MW during nighttime. Typical day load curves for St. Vincent shows a ramp up at 6:00 am and a ramp down at 5:00 pm. A high demand occurs during 10:00 am to 4:00 pm. A smaller peak occurs from 7:00 pm to 8:00 pm on weekdays, whilst weekend peak demand takes place from 6:00 pm to 10:00 pm. The yearly demand fluctuation is about 10% between the lowest demand in January and the highest in August.

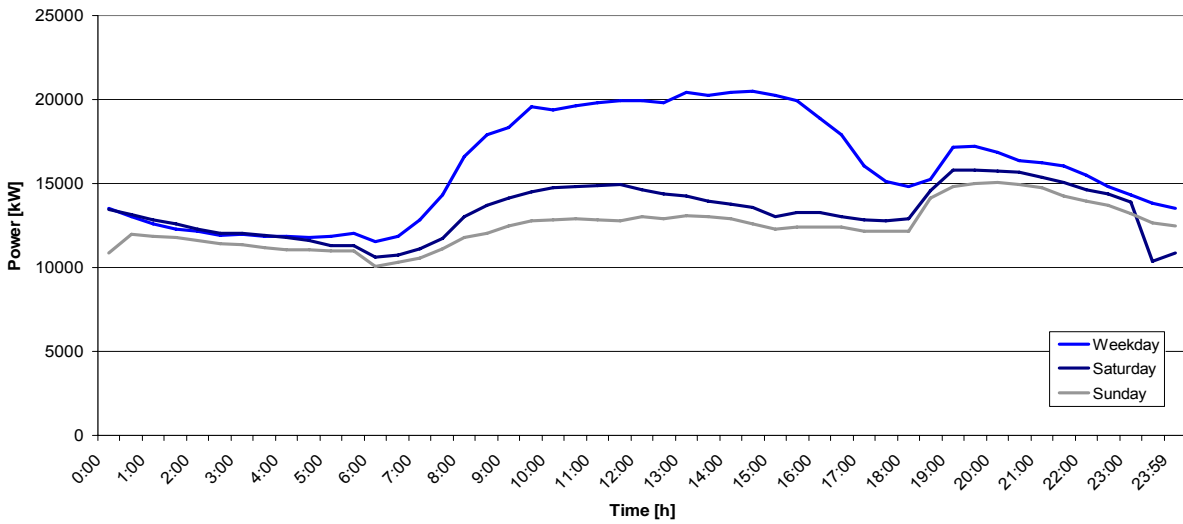


Figure 3.5.: Load curves for typical weekday and weekend [Source: Load data, VINLEC, 2011]

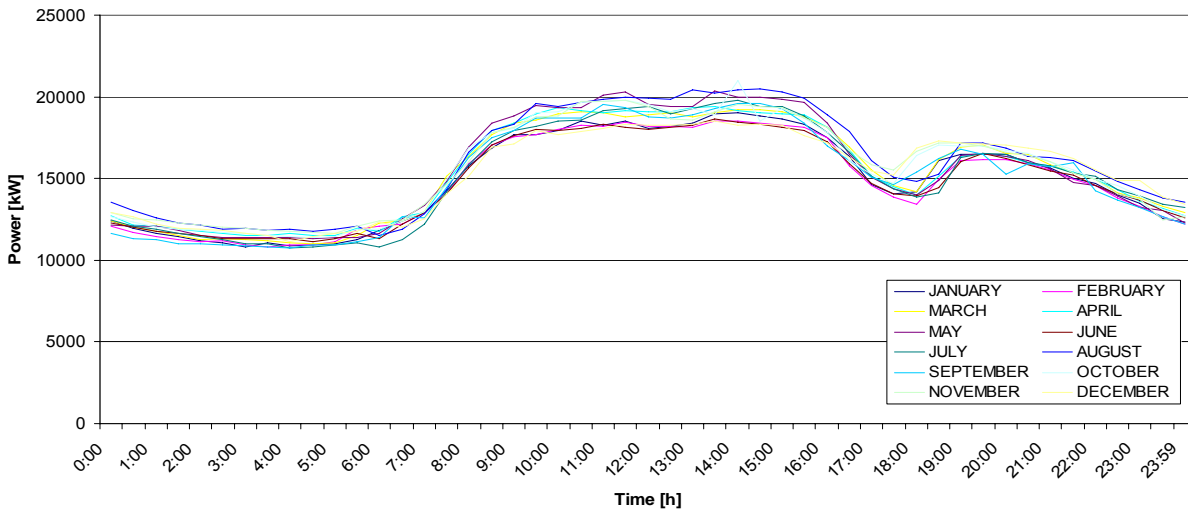


Figure 3.6.: Load curves for typical weekday during the year 2011 [Source: Load data, VINLEC, 2011]

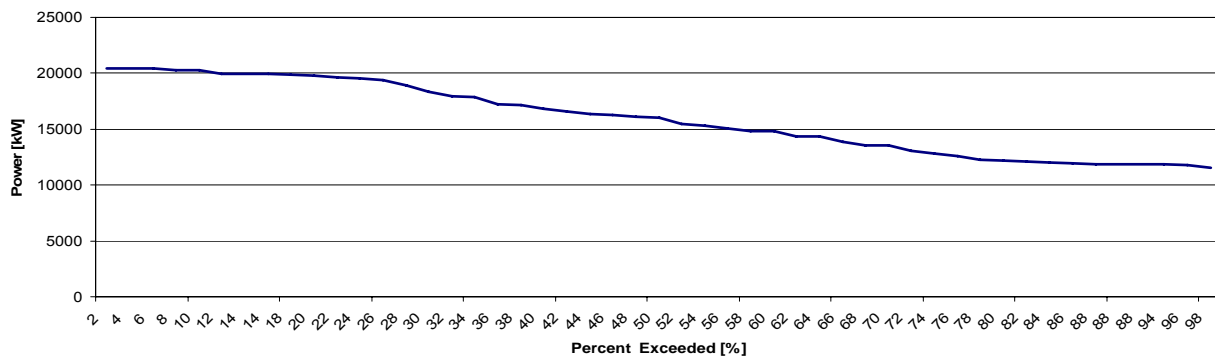


Figure 3.7.: Load duration curve for typical weekday during the year 2011 [Source: Load data, VINLEC, 2011]

Between 1998 and 2007 electricity demand yearly has grown on an average of 5.4% in the domestic sector, 7.7% in the commercial sector, 1.1% in the industrial sector and 4% in street lighting. Meanwhile, peak demand has grown 5% per year. Figure 3.8 shows the expected demand forecast till 2024.

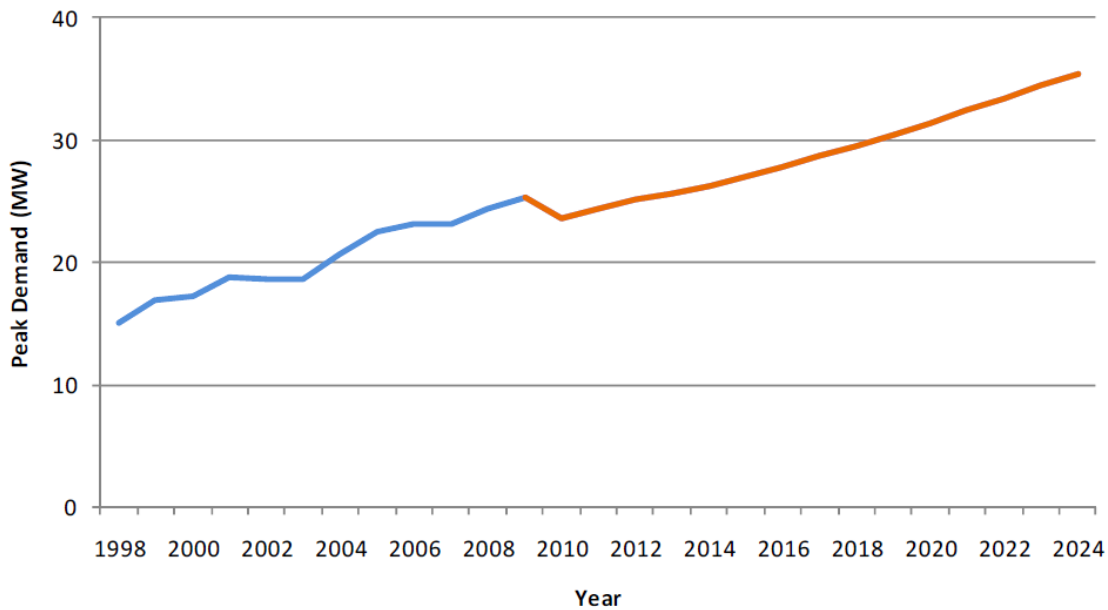


Figure 3.8: Peak demand scenarios for SVG till 2024 [Source: SVG-Energy action plan]

3.3. Power generation

3.3.1. Diesel power plants

The power generation of the St. Vincent EPSS consists of two diesel- and three hydro power plants. Since hydro power is not available at full scale year round and some diesel power plants work only as backup systems, the firm capacity reached 32MW in 2009. The main capacity is based on the two diesel power plants Cane Hall and Lowmans Bay with an amount of 83% of installed capacity (of the total installed capacity in 2008).

Name	Station	Type	Turbine/ Generator	Rated Power [kW]
LB/G1	Lowmans Bay P/S	Diesel	MAN 9L 32/40	4300
LB/G2	Lowmans Bay P/S		MAN 9L 32/40	4300
LB/G3	Lowmans Bay P/S		MAN 9L 32/40	4300
LB/G4	Lowmans Bay P/S		MAN 9L 32/40	4300
CH/G10	Cane Hall P/S	Diesel	CATERPILLAR 3516	1280
CH/G12	Cane Hall P/S		CATERPILLAR EUI 3516B	1280
CH/G2	Cane Hall P/S		ALLEN 12VBCS 12 EX 750 D4	1262
CH/G4	Cane Hall P/S		Stork- Werkspoor TM410	3243
CH/G5	Cane Hall P/S		Stork- Werkspoor TM410	3250
CH/G7	Cane Hall P/S		CATERPILLAR 3516	1470
CH/G9	Cane Hall P/S		CATERPILLAR 3616	3780
CH/G11	Cane Hall P/S		Wartsila Vasa 12V32LN	4200

Figure 3.9.: Rated power of diesel engines [Source: VINLEC]

Cane Hall Power Station was officially commissioned in 1976 and consists of 8 diesel engines of different manufacturers and ages. The oldest engine, the ALLEN 12VBCS, has been manufactured in 1973, the newest, the Caterpillar EUI 3516 in 2001. The plant consists of base load and peaker units and has an overall rated output of 19.8MW.

Lowmans Bay Power Station, the most recent addition to the VINLEC Power Plants, was commissioned in November 2006 by MAN diesel turbo as a Full Turnkey Power plant project with a plant output of 17.2MW. The plant has been designed as a base load power plant. It consists of four identical MAN 9L 32/40 engines.

The operation mode of the diesel power plant varies during the year according rain and dry season caused by the different amount of precipitation and hence the different rated hydro power capacity. Figure 3.11 shows the intended dispatch order of VINLEC according the two seasons. On standard weekday in a dry season four to five of the 3,780kW to 4,300kW units run on a daily base of 80%

to 90% rated capacity. During rain season between three and four of these units plus additional 3MW units (CH/G4, G5) are dispatched. If additional power is needed at any time the peaker units in Cane Hall Power plant (CH/G7, G10 and G12) get dispatched.

VINLEC tries to operate all base load units between 75% to 90% rated capacity. However, when the hydro generators operate at full load and demand is low, VINLEC operates the diesel units at lower load. The minimum operation limit for the diesel units causing a shutdown is 50% of their rated power.

The spinning reserve is shared by all units that are connected and online. The spinning reserve demand is determined by the outage of the largest generator and is covered through under-frequency protection.

Due to the use of fossil fuel for diesel power plants, the generation costs are highly dependent on the oil price. The costs as a function of the oil price per barrel have been established for Lowmans Bay power plant, varying from 6US\$ cents per kWh for a world market crude oil price of 30US\$/bbl and 13.5US\$ cents per kWh for an oil price of 100US\$/bbl.



Figure 3.10.: Lowmans Bay power station with MAN 9L 32/40 engine [Source: MAN Diesel and Turbo]

Dispatch Order	Installed Capacity [kW]	Dry season	Rain season
LB/G1	4300	1	1
LB/G2	4300	2	2
LB/G3	4300	3	3
LB/G4	4300	-	-
CH/G2	1262	-	-
CH/G4	3243	6	5
CH/G5	3250	-	-
CH/G7	1470	7	6
CH/G9	3780	5	4
CH/G10	1280	8	7
CH/G12	1280	9	8
CH/G11	4200	4	-

Figure 3.11.: Dispatch order for Lowmans Bay and Cane Hall power plant (peaker engines -grey)

[Source: VINLEC]

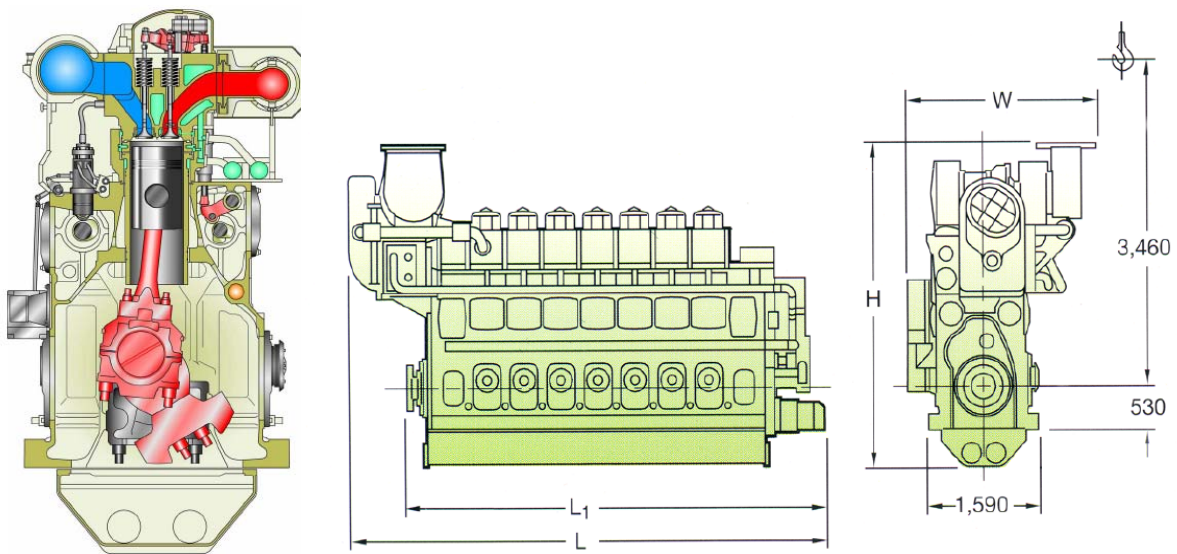


Figure 3.12.: Lowmans Bay engine cross section MAN 9L 32/40 [Source: MAN]

3.3.2. Hydro power plants

Hydro power has a total installed capacity of 5.6MW, of which about 5.2MW are available. Hydro power provides around 20% of VINLEC gross electricity production (17% in 2008, Source: VINLEC).

Name	Station	Type	Turbine/ Generator	Rated Power [kW]
RM/G1	Richmond P/S	Hydro	Gilkes Turgo (Impulse)	550
RM/G2	Richmond P/S		Gilkes Turgo (Impulse)	550
CB/G1	C3 S/S (Cumberland)	Hydro	Neypric Francis Turbine (Horizontal)	465
CB/G2	C3 S/S (Cumberland)		Neypric Francis Turbine (Horizontal)	465
SV/G1	C2 S/S (Spring Village)		Neypric Francis Turbine (Horizontal)	640
SV/G2	C2 S/S (Spring Village)		Neypric Francis Turbine (Horizontal)	640
GR/G1	C1 S/S (Grove)		Neypric Francis Turbine (Horizontal)	1464
SR/G1	South Rivers P/S	Hydro	Gilkes Turgo (Impulse)	275
SR/G2	South Rivers P/S		Gilkes Turgo (Impulse)	275
SR/G3	South Rivers P/S		Gilkes Turgo (Impulse)	320

Figure 3.13.: Rated power of hydro turbines [Source: VINLEC]

Due to varying precipitation over the year, the constant available capacity, also called firm capacity, is way lower than the rated capacity. The firm capacity recently is about 2 MW. The precipitation varies over the year with highest amounts of rainfall in the rain season (June till December) and the lowest in dry season (January till May). The hydro power facilities at South Rivers (3 turbines with a total rated capacity of 0.9MW) and Richmond (2 turbines with a total of 1.1MW rated capacity) were built in the late 1950's and early 1960's, respectively. The plant at Cumberland was built between 1987 and 1988 (5 turbines with a total of 3.7MW). All hydro power plants are run-of-river type power plants with no significant storage capacity.

The hydro power facilities at South Rivers get fed by Colonaire river, Richmond by Richmond river and Cumberland by Cumbeland river. Due to local separation of the rivers the water supply areas are separated. The hydro power plants Cumberland, Spring Village and Groove are all located and fed by Cumberland river. Groove power station is connected to an 11,000m³ water reservoir which allows limited dispatch operation. The hydro output of Groove power station determines the throughput for the Spring Village turbines at first and Cumberland turbines at second. Due to the cascade of this hydro chain, the overall output is determined by the dispatch of the Groove power station. The hydro power plants can operate throughout the year when the water quantities of the relevant reservoirs are available. Dry season operation allows four to five hours of full load until the reservoir is emptied. The rain season with nearly double precipitations allows about eight to twelve hours of full load. The South River hydro power plant also has an integrated reservoir not used by the TSO.

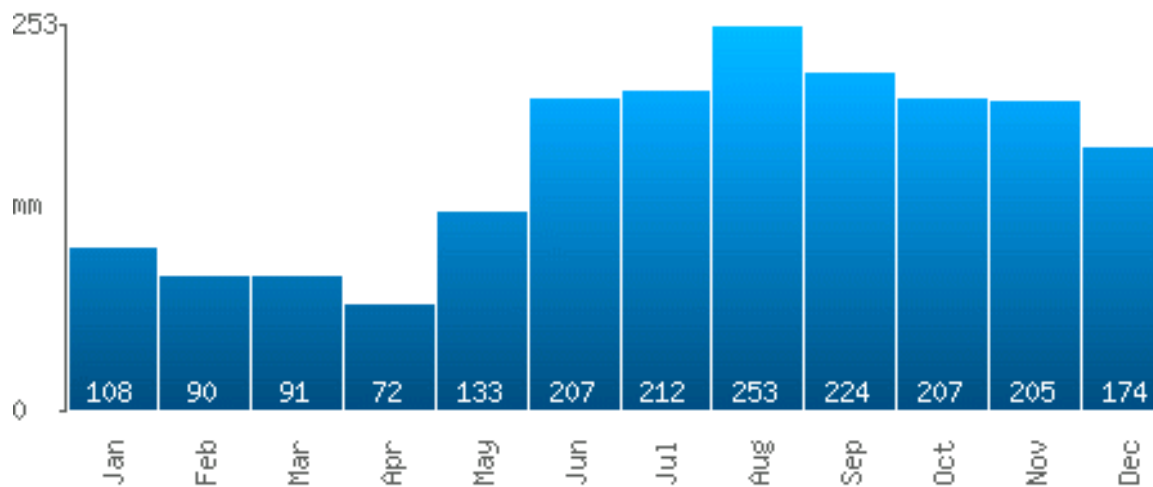


Figure 3.14: Average precipitation by month [Source: UNDP Climate Change Country Profile – SVG]



Figure 3.15: Hydro Reservoirs Groove (left) and South Rivers (right) [Source: GIZ]

3.4. Renewable power generation

3.4.1. Wind diesel systems

The basic concept of wind diesel hybrid power systems combines wind turbines with diesel generators to obtain a maximum contribution by the intermittent wind resource while providing continuous high quality electric power. Objectives of wind diesel systems are reducing fossil fuel consumption and diesel run time. Consequently, the benefits are reduced system operating costs and lower environmental impacts [8].

Reasons for the use of wind diesel systems can be found in several advantages of the common technologies. A large base of installed diesel power plants and a lot of diesel operating experience exist. Also fuel and service infrastructures already exist and capital costs are relatively low compared to other dispatchable generator types. Wind turbines provide several advantages as well. Wind is a completely clean and domestic energy source. Wind power is mature technology with the lowest cost of all renewable technologies (except of large hydro power plants). Especially small island coastal regions have mostly excellent wind resources around the year.

A critical design factor for wind diesel systems is the relation between demand and wind power supply, defined as penetration. Wind diesel systems can be divided into three types, the low, medium and high penetration systems. The term penetration is differentiated in instantaneous and average penetration. Instantaneous penetration is used to understand control requirements and reactive power needs for voltage and frequency regulation. Average penetration generally is calculated on monthly or annual basis and determines the total energy savings, loading on the diesel engines as well as spinning reserve losses and efficiencies. Both penetration terms are defined as follows:

$$\text{Instantaneous penetration [\%]} = \text{Power Output [kW]} / \text{Primary Electrical Load [kW]}$$

$$\text{Average penetration [\%]} = \text{Energy Produced [kWh]} / \text{Primary Energy Demand [kWh]}$$

PENETRATION CLASS	OPERATING CHARACTERISTICS	PENETRATION	
		PEAK INSTANTANEOUS	ANNUAL AVERAGE
LOW	<ul style="list-style-type: none"> • Diesel runs full time • Wind power reduces net load on diesel • All wind energy goes to primary load • No supervisory control system 	< 50%	< 20%
MEDIUM	<ul style="list-style-type: none"> • Diesel runs full time • At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading • Alternatively, wind turbines are curtailed during high winds and low loads • Requires relatively simple control system 	50 – 100%	20 – 50%
HIGH	<ul style="list-style-type: none"> • Diesels may be shut down during high wind availability • Auxiliary components required to regulate voltage and frequency • Requires sophisticated control system 	100 - 400%	50 – 150%

Figure 3.16.: Classification of wind diesel systems by penetration class [Source: NREL]

The several penetration scenarios have different qualities and show following characteristics [8]:

	Estimated capital costs	Diesel modification	Estimated fuel savings	Secondary load	Integration effort	Automated supply
Low penetration:	\$1,000-1,500/kW wind capacity, excluding diesel plant	No modification necessary	20%	Not necessary	Easy	No automated supply
Medium penetration	\$1,500-2,500/kW wind capacity, excluding diesel plant	Requires relatively simple supervisory control	40%	Usually must install/integrate secondary loads	Medium	Automated diesel operation desirable
High penetration:	\$2,500-4,000/kW wind capacity, excluding diesel plant	Significant diesel control modifications may be necessary	70%	Must install/integrate secondary loads	High	Requires sophisticated supervisory control system

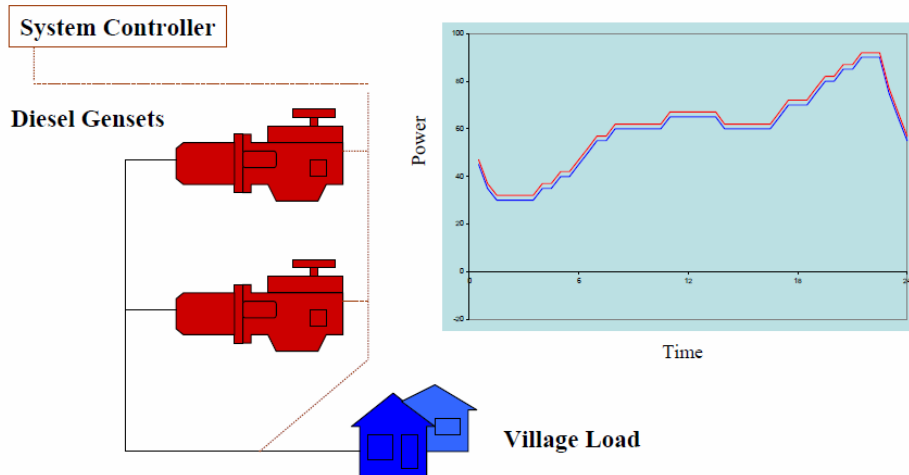


Figure 3.17.: Diesel Only wind-diesel system [8]

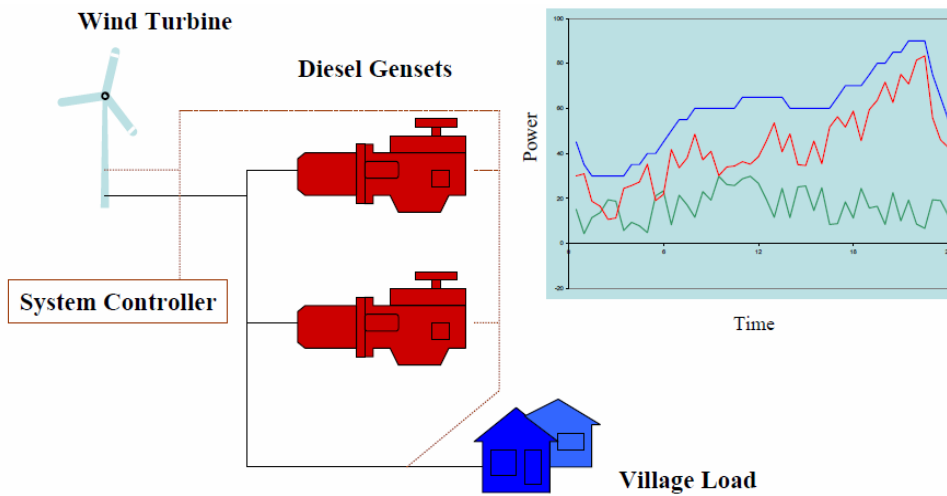


Figure 3.18x.: Low penetration wind-diesel system [8]

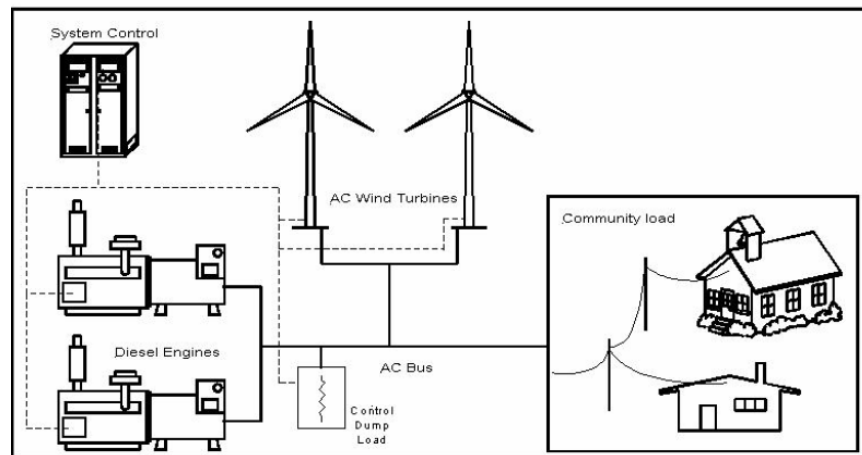


Figure 3.19.: Medium Penetration wind-diesel system [8]

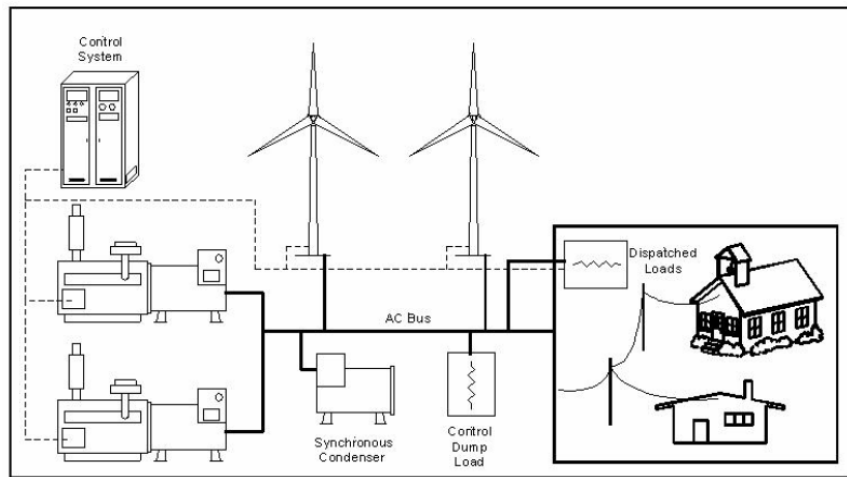


Figure 3.20.: High Penetration w/o storage wind-diesel system [8]

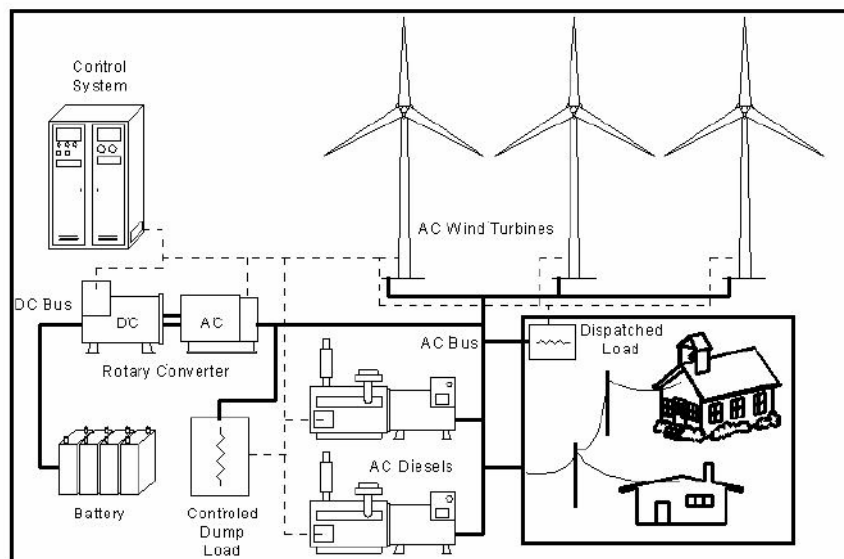


Figure 3.21.: High Penetration w/ storage wind-diesel system [8]

3.4.2. Renewable energy sources

SVG has substantial renewable energy sources that can provide electrical power. The conceivable sources in St. Vincent are based on wind, geothermal, hydro and solar. While these resources offer the potential to supply a large share of future energy needs, only hydro and solar (small PV and water heating systems) energy are being tapped [9].

Hydro power, besides a negligible contribution from PV, is the only renewable source that currently provides electrical power for the EPSS of St. Vincent. Beside the existing resources further potential exists for additional hydro power exploitation. This potentials can be harvested through rehabilitation and expansion of existing plants and development of new sites. A feasibility study of 2009 was carried out for the rehabilitation of the Richmond and South Rivers plants. It focused additionally on the development of a second plant along the Colonaire River, downstream of the existing South Rivers plant. The estimated unused hydro power potential for the rivers of Wallibou and Buccament is in the range of 5 MW to 10 MW. The future of hydro power production mainly depends on the long term availability of sufficient water resources. The river flows on the island, as the sources for renewable hydro power, are threatened by deforestation, variation of annual precipitations caused by climate change and competing uses, like fresh water supply and irrigation.

Another potential source for renewable energy on the island is wind power. Preliminary findings show that there is a technical potential for wind power in the range of several MW on St. Vincent. Wind measurements have indicated wind speeds of 7 to 8 m/s on eastward facing ridges. More precise wind measurements have been made by CREDP/GTZ and VINLEC at Brighton and at Ribishi Point.

A medium solar radiation of 5.0kWh/m² throughout the island with only little seasonal variation shows the good potential for solar power on St. Vincent. A growing number of applications exists where photovoltaic panels can be used at competitive costs. Those options may increase significantly with the continuing decline in price of solar photovoltaic systems.

The volcanic root of the island St. Vincent provides geothermal potential. This offers the capability to supply all of the base load electricity demand on St. Vincent through geothermal power. Through interconnections, to other neighbouring islands like the Grenadine islands, geothermal power could be shared all over the region. The actual potential is not yet confirmed by proven drillings.

In 2009 an assessment study of the electricity generation potential of different biomass residues for biogas production was concluded. Some feedstock, such as banana trunks, can be used for the production of biogas. It has been examined to what extent the organic content of

agricultural and municipal waste can be utilized for the purpose of biogas production. The study estimates that the realistic potential for electricity generation from biogas in St. Vincent is within 3 to 4 MW, and outlines a project concept for the initial development of a biogas plant [9].

3.4.3. Ribishi point wind-park

The major renewable energy project in St. Vincent is a wind park at the peninsula Ribishi Point. According to the current planning the wind park will have a rated power between 2.5MW and 4MW and will go online approximately by the end of 2013 (Source VINLEC, January2012). The proposed wind park Ribishi Point offers excellent wind resources, which would allow net capacity factors close to 40 % [10].



Figure 3.22.: Site of Ribishi Point and main wind direction



Figure 3.23.: Ribishi Point wind park as seen from the main wind direction (Photo Montage) [10]

Since 1985 several assessment and market studies had been done to evaluate the potential for wind power in St. Vincent. According to a four year measurement at Ribishi point at 30 m above ground an annual average wind of 8.43 m/s was established. At 70 m hub height, close to 9 m/s can be expected. Calculating the annual average energy output for two reference turbines resulted in 2.82MWh and 3.13MWh for the Enercon E44 and the UNISON U50. That results in calculated capacity factors of 35.7% respectively 47.6 %. Based on these results the estimated energy costs are between 6 to 8US\$ cents per kWh. That is competitive to corresponding generation costs in VINLEC’s major diesel power plant at Lowmans Bay (if oil price is above 50 US\$ per barrel). In 2008 VINLEC requested tenders of private investors for the installation and operation of a 6 to 8MW wind park at Ribishi Point. Two different turbine types have been offered, the 1 MW VERGNET GEVHP, and the NORWIN 47 –ASR-750 kW. The NORWIN turbine uses the active stall control principle and direct grid coupling. With that generator concept, stability and power quality problems can be expected. The wind turbine VERGNET GEV MP is a wind class III machine with a rotor which can be lowered in case of hurricanes [10].

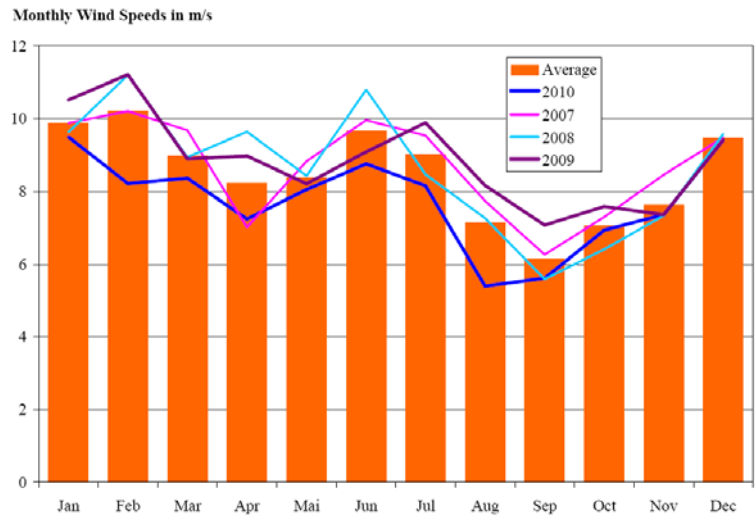


Figure 3.24.: Ribishi Point monthly average wind speeds in m/s 2007-2010 [10]

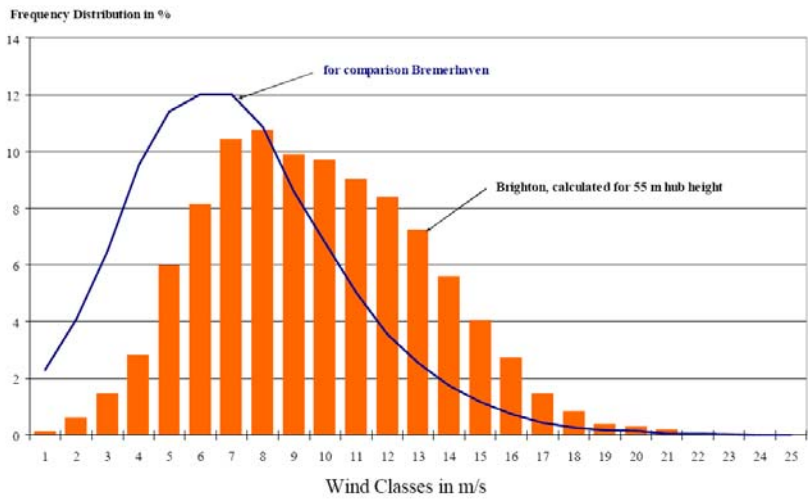


Figure 3.25: Brighton yearly frequency distribution at 10m above ground [10]

4. Simulation – VRE integration approach

4.1. Operating model

The integration of VRE units will change the operation strategy of the existing EPSS of St. Vincent. According to the variable sources and the installed VRE capacity, the VRE power differs and forces the operation mode of the conventional generator compound to change.

To analyze the impact of VRE generation within the St. Vincent EPSS on the operation mode and the energy flow, an spreadsheet (MS Excel) based methodology was developed. This model also allows reliability and stability assessment of the system considering different VRE scenarios. The methodology includes the operating aspects of the renewable sources wind power units, PV systems, geothermal power plants and hydroelectric power plants. Especially the impact on the spinning reserve demand is considered in the methodology. Furthermore the method delivers the residual load of the system and a roadmap for the flexible combustion unit.

4.1.1. Operating features

Power Generating units						
Base Load			Variable		Flexible	
Diesel Engines	Hydro Power	(Geothermal Power)	Wind Power units	PV Power units	Hydro Power (dispatchable)	Diesel Engines (dispatchable)

Figure 4.1.: Separation of power generating units in the Excel model

The operating features of St. Vincent’s EPSS are taken into account. The model reflects the operating modes of the EPSS according to the description by VINLEC’s staff. These aspects and features are the following:

- The generation units are divided into the categories base load, variable and flexible according to their ability to dispatch. Compared to the flexible units, base load and variable units are not dispatchable.
- The system’s diesel engines are divided into two groups according to their technical characteristics to supply base load or residual load. The base load units are the four units of Lowmans bay (LB/G1-G4) and the Cane Hall units CH/G4, CH/G5, CH/G9 and CH/G11. The flexible units that supply the residual load are the Cane Hall peaker units CH/G2, CH/G7, CH/G10 and CH/G12.
- Geothermal generation can optionally be considered in the model as well. It is included in the base load category. The units can operate between 50% and 100% rated capacity.
- The hydro power plants are also divided into two groups according to their water supply characteristics, the base load and flexible load units. The hydro power base load plants are the run-off river plants South River and Richmond. They can operate throughout the year according to the water supply. Deduced from the precipitation data the seasonal plant factor of the hydro base load units is determined as 80% in the rain season, compared to 40% in the dry season. The flexible units are the ones that are dispatchable and connected to a water reservoir. That allows the flexible operation when the water quantities of the relevant reservoirs are available. Generation unit Groove (CR/G1) is the only dispatchable hydro unit in the generation compound. The reservoir capacity of 11,000m³ allows four to five hours of full capacity output in the dry season and eight to twelve hours in the rain season. Because of the connection to a reservoir the Cumberland hydro compound allows a reduced output operation which can provide additional spinning reserve. Hence the Cumberland units are a cascade, the other units on the river change their output according to the adjustment of the CR/G1 unit but with a time delay.
- The modeling of the existing environmental constraints for hydro power plants considers that the water quantities of each reservoir are kept within pre specified levels for each month of the year. According to the precipitation levels of St. Vincent the water resources of the dry season are estimated as 50% of the resources in the rain season.

- It is assumed that the wind power units are installed at one geographical site in one wind park. The wind park consists of a certain number of identical generating units and is connected to the appropriate system busbar at Cane Hall power station. Basis of the calculated output of the wind park is the wind data of Ribishi point. The wind power output is calculated according to the characteristic of the wind turbine NORWIN 47 – ASR-750 kW which is one likely option for the planned wind park in Ribishi point. The characteristic can be found in figure 4.4. The wind speed scenarios are based on the wind measurements at Ribishi point in the years 2010 and 2011 and are categorized into the Beaufort scale according to the average speeds over one day period. Figure 4.2 shows the corresponding Beaufort category and the day on which this average wind speed occurred at Ribishi point. The wind speed scenarios in figure 4.2. are used in the simulation model.
- The installed PV power consists of a certain amount of generating area. All generated PV energy is calculated according to an insolation curve for a sunny day. The insolation curve is determined according to the solar data of Bequia airport (Source: SMA, Sunnyportal, www.sunnyportal.de), for a PV production yield of 5.33 kWh per m² and day. The total output is calculated with an estimated efficiency of 12% for the PV generators and the insolation curve of figure 4.3.

HURRICAN (Tomas) Average Wind Speed 118-133km/h Occurred: 30.10.2010	HIGH WIND Average Wind Speed 50-61km/h Occurred: 12.01.2011	STRONG BREEZE Average Wind Speed 39-49km/h Occurred: 13.01.2011	FRESH BREEZE Average Wind Speed 29-38 km/h Occurred: 06.01.2011	MOD-FRESH BREEZE Average Wind Speed 25-33km/h Occurred: 18.08.2011	MODERATE BREEZE Average Wind Speed 20-28km/h Occurred: 03.01.2011	LIGHT-GENTLE BREEZE Average Wind Speed 9-14 km/h Occurred: 02.09.2011	LIGHT AIR Average Wind Speed 1-5km/h Occurred: 11.09.2011	CALM Average Wind Speed 1km/h Occurred: 26.09.2011
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Figure 4.2: Wind speed categories according to their occurrence

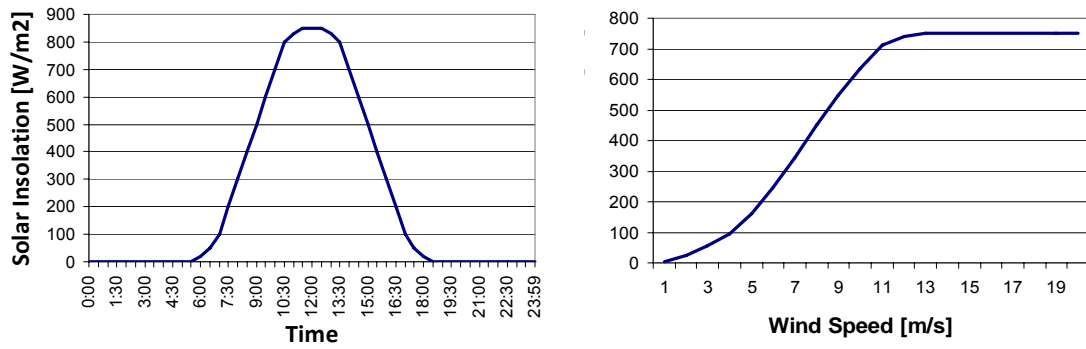


Figure 4.3: Solar insolation curve (left)

Figure 4.4: Wind power curve according to NORWIN 47-ASR-750 kW (right)

Diesel engines				Hydro power					
Lowmans Bay		Cane Hall		Cumberland River		Richmond		South River	
LB/G1	4300	CH/G2	1262	CB/G1	465	RM/G1	550	SR/G1	230
LB/G2	4300	CH/G4	3243	CB/G2	465	RM/G2	550	SR/G2	230
LB/G3	4300	CH/G5	3250	SVG1	640			SR/G3	250
LB/G4	4300	CH/G7	1470	SV/G2	640				
		CH/G9	3780	GR/G1	1464				
		CH/G10	1280						
		CH/G12	1280						
		CH/G11	4200						
						Index:			
						Dispatchable		Hydro - Base Load	
						Diesel - Base Load		Hydro - Reservoir	

Figure 4.5: Classification of power generating units in St. Vincent’s EPSS

4.1.2. Energy flow

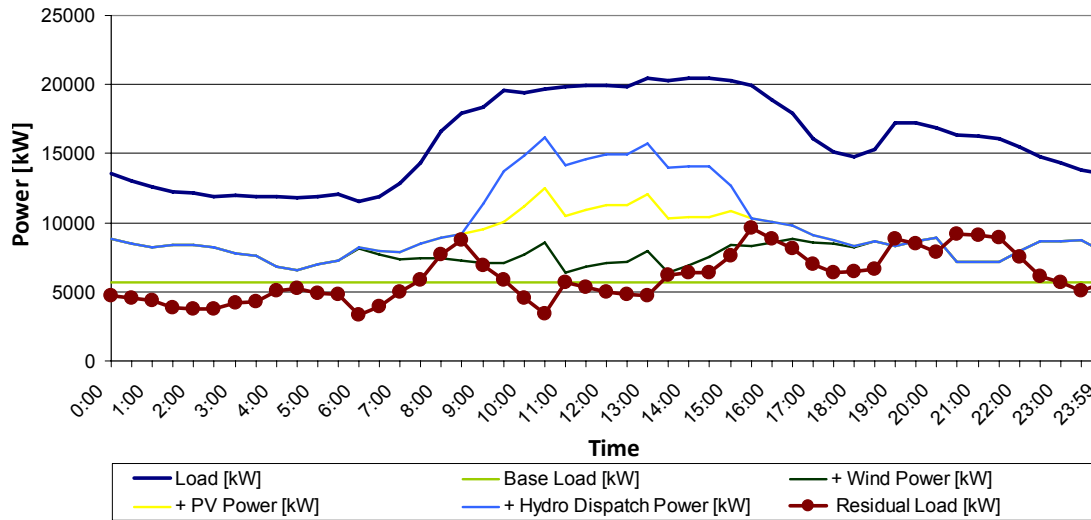


Figure 4.6.: Model of the energy flow

The operation mode of the EPSS is set up according to the following appropriate algorithm and incorporated in the above methodology:

- The system’s demand is implemented in 30 minute time steps. The simulation uses weekday demand. Basis of a typical dry season demand curve is the demand curve of the 20 January 2011. The rain season demand is represented by the demand curve of the 18 August 2011 (Figure 4.6. dark blue line)
- The generating units that are assigned to supply the base load (combustion, hydro or geothermal), are called on to operate at an output level between 50% to 100% while the minimum output level is 50%. According to the current operation mode of VINLEC the base load units operate between 80% and 90% (Figure 4.6. line light green).
- The power output of each wind power unit is calculated using the wind speed data of the site of Ribishi point for a strong breeze (according data of the 13 January 2011) and the total amount of power being produced by the wind park is determined based on the amount of installed turbines and the characteristic of the turbine NORWIN 47-ASR-750

kW. The wind data of a strong breeze is chosen because it shows a worst case scenario regarding the spinning reserve demand (Figure 4.6. line dark green).

- The power output of the PV generating units is calculated using the solar insolation curve of figure 4.3 and an efficiency factor of is set as 12%. (Figure 4.6 line yellow).
- Additional power is supplied by the dispatchable hydro generating unit. Their power output is calculated according to their technical characteristics and the level of the water in the reservoirs. The characteristics used can be found in figure 4.7 for the dry and figure 4.8 for the rain season (Figure 4.6. line light blue).

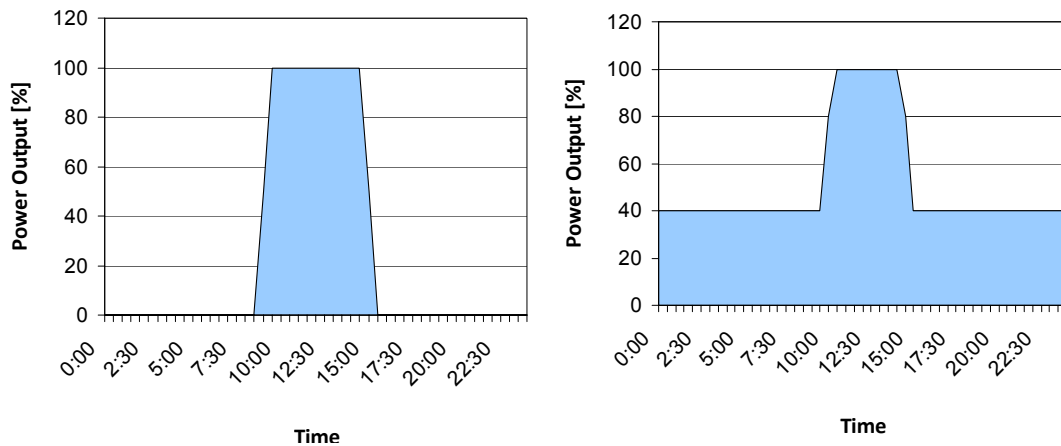


Figure 4.7.: Example for dispatch hydro output for dry season (left)

Figure 4.8.: Example for dispatch hydro output for rain season (right)

- If additional power is still required for supplying the load demand, the thermal generating units (diesel engines) are called on to operate according to their priority order.
- The additional generation still required for supplying the load demand, is called the residual load which is supplied by dispatchable diesel engines of the Cane Hall power plant. According to the instantaneous demand for residual load the appropriate generating combination can be chosen. The minimal loading of this units is 50% as well.

4.2. Penetration constraints for VRE

Operation of variable, non dispatchable generation units in isolated EPSS is characterized by restrictions related to the absorption capability of the system. It is caused by technical constraints limiting the VRE penetration in relation to the conventional penetration. The following chapter describes the four mayor constraints that have been considered in this study. The resulting constraints are time varying and depend on the system’s load level. The maximum allowable VRE penetration is given by the strictest constraint.

To visualize the penetration constraints a diagramm like figure 4.9. will be used. The diagramm shows grey lines representing the minimal loading of several Cane Hall generator combinations (see chapter 4.2.1). A bold red line represents the VRE penetration constraint for each specific case. If the Residual load is known, the maximum penetration for VRE can be read in the diagramm. If, for example, the residual load is 4000 kW and the residual load generation is provided through Cane Hall generator set G10/G12, the maximum possible VRE generation is limited to 2720 kW (see figure 4.9.)

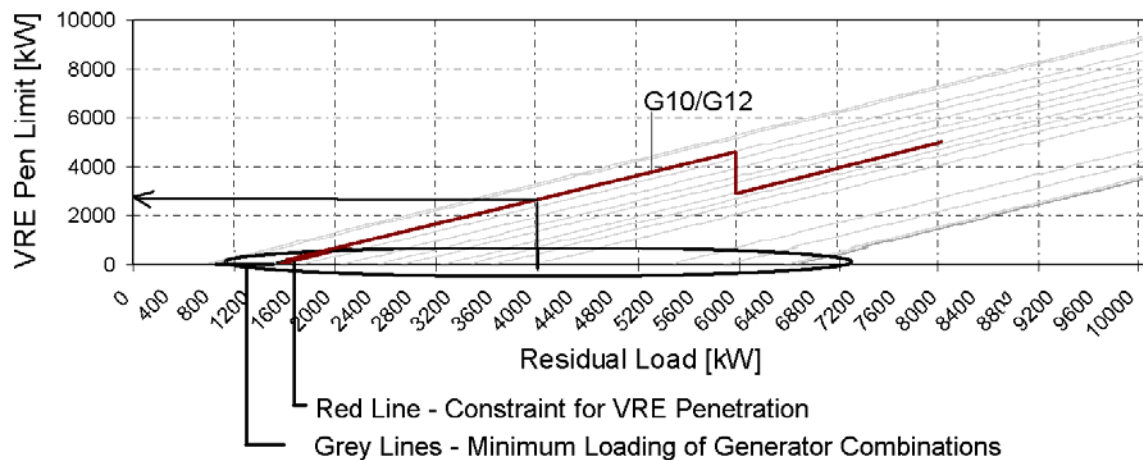


Figure 4.9: Example for use of penetration constraint diagramm

4.2.1. Diesel loading

Diesel engines are described by their operating constraints; their maximum and minimum output power. The constraints ensure that none of the operating diesel generators is loaded below or above predefined output levels which can be defined by either the technical capability or a TSO restriction. TSO limitations are related to emission regulations, engine failure risk and danger of premature ageing of the diesel generators. Additionally the operation at light load conditions is causing insufficient combustions and higher emissions of Sulfur Oxides and nitrous gases as well as higher fuel consumptions. The fuel consumption of a diesel engines increases by about 23% for operation at 25% loading in comparison to the rated load (Source: Fuel consumption for CAT D3512 Diesel engine) [19].

According to the recent operating policy of VINLEC the minimum diesel output for all existing units is 50%. The VRE penetration constraint which ensures the minimal loading of the diesel units can be calculated as:

$$P_{VRE, Limit} \leq P_{Load} - \sum P_{Diesel, min}$$

where:

$P_{VRE, Limit}$ VRE penetration limit [kW]

P_{Load} Load demand [kW]

$P_{Diesel, min}$ Minimum output of the diesel generator combinations [kW]

$P_{Diesel, rated}$ Rated capacity of the diesel generator combinations [kW]

Generator Combination	$P_{Diesel, rated}$	$P_{Diesel, min}$
G10	1,280 kW	640 kW
G7	1,470 kW	735 kW
G10/G12	2,560 kW	1,280 kW
G4	3,243 kW	1,621.5 kW
G7/G10/G12	4,030 kW	2,015 kW
G4/G7	4,713 kW	2,357 kW
G7/G9	5,250 kW	2,625 kW
G4/G7/G10	5,993 kW	2,997 kW

G7/G9/G10	6,530 kW	3,265 kW
G4/G7/G10/G12	7,223 kW	3,612 kW
G7/G9/G10/G12	7,810 kW	3,905 kW
G4/G5/G7/G9/G10/G12	10,523 kW	5,262 kW
G4/G7/G9/G10/G12	11,053 kW	5,527 kW
G4/G5/G9/G10	11,553 kW	5,777 kW
G4/G5/G9/G10/G12	12,833 kW	6,417 kW
G4/G5/G7/G9/G10	13,023 kW	6,512 kW
G4/G5/G7/G9/G10/G12	14,303 kW	7,152 kW

Figure 4.10: Generator set combinations at Cane Hall power plant

The different generator combinations at Cane Hall power plant (listed in figure 4.10.) create different penetration lines (shown in figure 4.11.). According to the amount of expected residual load and the dispatch order the generator combination will be chosen. The higher the amount of installed rated capacity the lower the VRE power which can be permitted. If, for example, the TSO chooses the generator combination G10/G12 and the instantaneous residual load is 4000kW, the maximum possible VRE penetration would be 2720kW when no spinning reserve is considered (4000kW minus the minimum loading of the diesel combination of 1280kW).

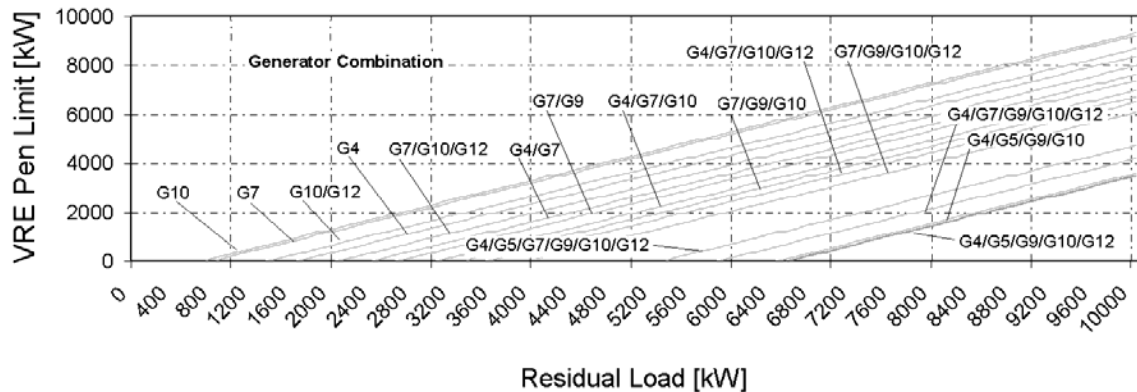


Figure 4.11.: VRE penetration limit straits for different generator combinations

The maximum power output of the diesel engines is determined due to their installed capacity. Although some diesel engines allow the operation in overload conditions up to 130% of their installed capacity the maximum power should not exceed 100%. Operating in overload conditions is only permitted for short amounts of time. Otherwise damages are likely and the tear and wear increases rapidly. In high load conditions additional generators will be dispatched.

4.2.2. Spinning reserve requirements

Providing secure and reliable power during all load conditions can only be assured if the spinning reserve demand is satisfied. Four criteria define the minimal spinning reserve demand.

The first, defined as criteria A, is set to 10% of the load, criteria B depends on the largest generation unit in the system. According to the dispatch order the largest units are the diesel generators in the Lowman’s bay power plant. These units have a rated power of 4,300kW. These criteria shall assure that an emergency shutdown of the largest generation unit can be absorbed by the operating generation units. Looking at the existing EPSS criteria B describes the worst case spinning reserve criteria. For a power demand of 20MW the spinning reserve demand due to criteria B is 21.5% of the overall demand. That shows that criteria B is always higher and criteria A can be ignored for further consideration.

Spinning reserve criteria	Criteria A	10% Load
	Criteria B	Largest unit
	Criteria C	Wind slack
	Criteria D	Solar slack

Figure 4.12.: Spinning reserve criteria

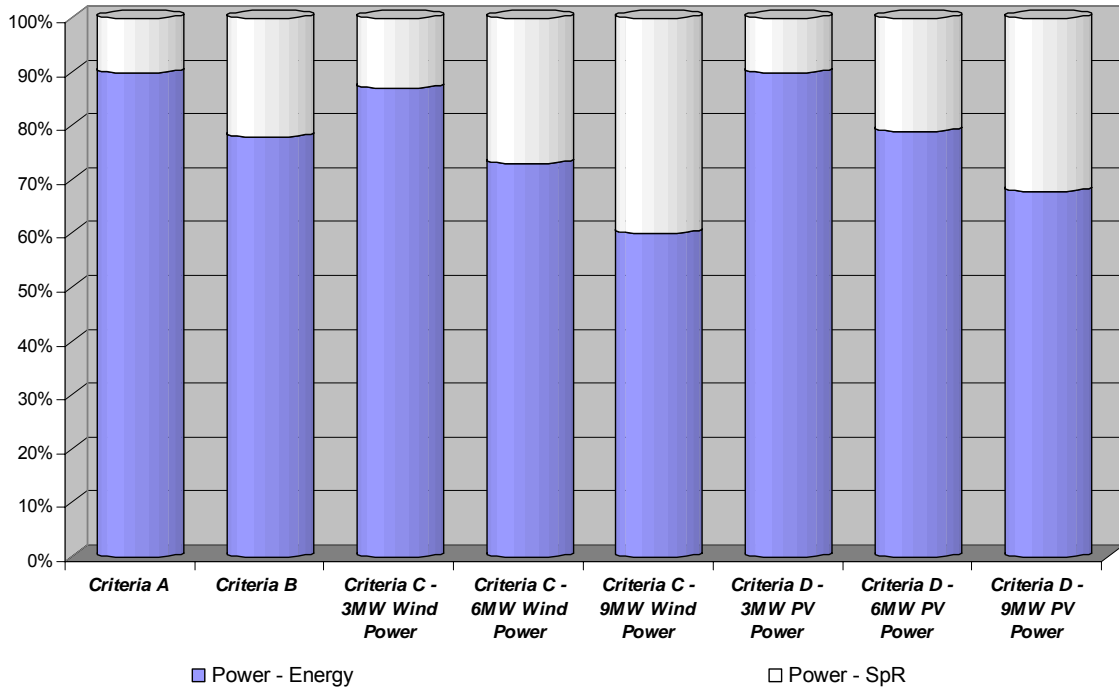


Figure 4.13.: Spinning reserve demand according to the different criteria A-D

Due to VRE in the system two additional criteria are necessary. Criteria C depends on the maximum wind slack that might occur due to wind speed variation in a 10 minute time frame. The data base of the assessment is the wind measurement of Ribishi point of January 2011. January is the month of the highest average wind speed and the highest variation in wind speed. The worst case wind drop occurred on January 23rd at 1 pm. According to the wind speed slack the maximum spinning reserve requirement is determined as 89% of the rated wind power.

In criteria D the maximum estimated loss of PV power caused by dimming of solar insolation is considered. The data of the solar power plant at Bequia airport of 2011 is basis for the spinning reserve assessment (Source: SMA, Sunny Portal). According to the maximum solar slack the spinning reserve requirement is determined as 70% of the rated PV power in a time frame of 10 minutes.

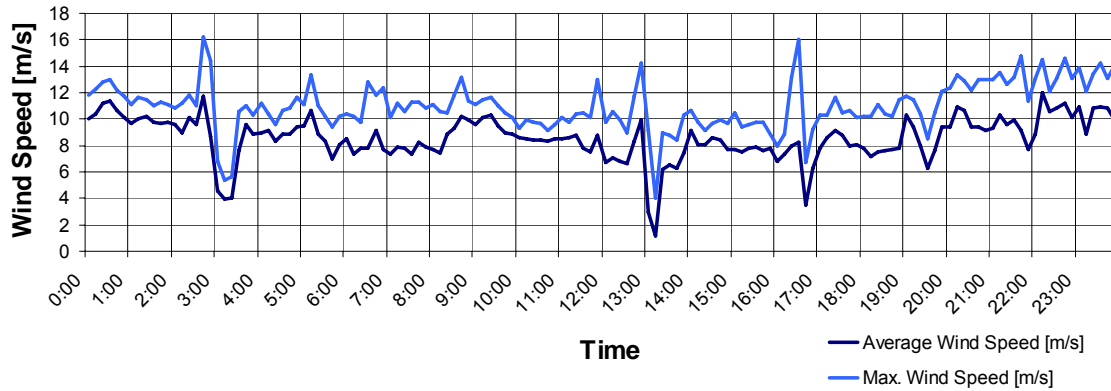


Figure 4.14.: Average daily wind variation within October 2010 and October 2011

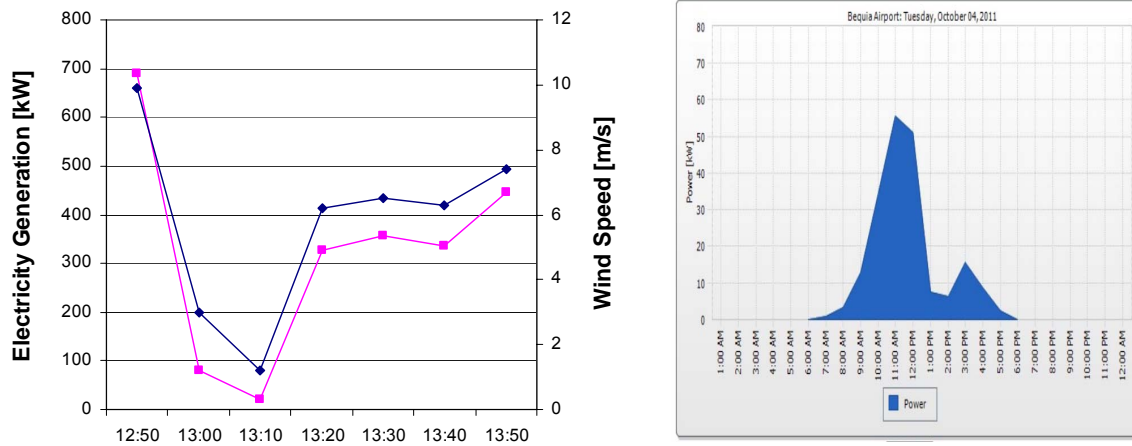


Figure 4.15.: Maximum wind slack on 23 January 2011 (left)

Figure 4.16.: PV slack on 10 April 2011 (right)

The instantaneous required spinning reserve can be calculated as:

$$P_{SpR \min} \geq \text{Maximum of (criteria A, criteria B, criteria C, criteria D)}$$

where:

$$P_{SpR \min} \quad \text{Minimum of required spinning reserve}$$

The four spinning reserve criteria calculate a different spinning reserve demand according to the specific instantaneous generation of wind, PV or conventional power. The criteria for a wind and a PV loss is based on the worst case generation loss analysed over a one year time range. Because of the low occurrence it is unlikely that the criteria B, C or D superimpose at any time. Hence, the minimum required spinning reserve can be simplified determined as the maximum of one of the criteria A ,B ,C or D.

In the EPSS of St. Vincent the diesel engines provide the spinning reserve in an equal share. Also the dispatchable hydro plant at Cumberland can provide spinning reserve as soon as the plant is not running at full capacity. According to the dispatch order of St. Vincent the power plant of Lowman’s bay is providing the base load, Cane Hall mostly the residual load. Due to this adjustment Cane Hall generators provide the major amount of spinning reserve. Lowman’s bay generators mostly are running at a high efficient level of 80 to 90% capacity.

To satisfy the system’s spinning reserve demand sufficient spinning reserve supply units have to be dispatched. Because of their minimum load restriction these units have to supply at least 50% of their rated capacity which means that at the most 50% of spinning reserve can be supplied. The supply of additional capacity is reducing the residual load, which is the portion of the load on which the allowed VRE penetration depends. Therefore a reduction of the residual load caused by the spinning reserve demand combined with the minimum diesel loading constraint is reducing the maximum allowed VRE penetration. The spinning reserve requirement moves the penetration limit line parallel to the right, as shown in the penetration diagram of figure 4.17. It shows two limitation lines for a minimum spinning reserve of 2,000kW and 4,000kW according to a minimal diesel output of 50%. At a residual load of 4,000kW and a spinning reserve demand of 4,000kW the maximum VRE penetration is 0kW . Is the spinning reserve demand 2,000kW maximum allowed VRE penetration increases to 2,000kW.

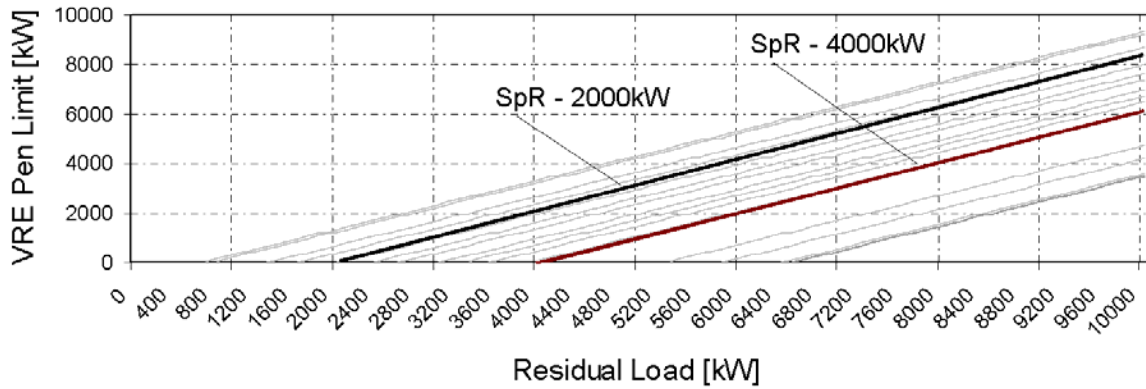


Figure 4.17: VRE penetration limit (red line) at a required spinning reserve of 4,000kW

4.2.3. Dynamic limitation

The dynamic constraint limits the penetration to a predefined maximum of the VRE operating capacity. This constraint is related to the dynamic response considerations of the EPSS and shall assure that at least a predefined amount of generators with control abilities is online to avoid power quality issues. Since the spinning reserve requirement considers that enough frequency control reserve is online, the dynamic limitation is focusing on the voltage control ability of the system.

The maximum amount of VRE sources according to the dynamic stability constraint is calculated as follows:

$$P_{VRE, Limit} \leq p_{max} * (\sum P_{Diesel, rated} + \sum P_{Hydro, rated})$$

where:

- $P_{VRE, Limit}$ VRE generation
- p_{max} Dynamic stability limit
- $P_{Diesel, rated}$ Diesel generator rated capacity
- $P_{Hydro, rated}$ Hydro generator rated capacity

The dynamic constraint considers the limitations given through the power quality impact of VRE sources. Power quality gets regulated and controlled by the grid forming generation units. In the EPSS of St. Vincent the frequency is controlled by the diesel engines and the dispatchable hydro generator GR/G1. The voltage is regulated by all generation units, even the base load hydro units through automatic voltage regulators (AVR).

In recent studies of wind diesel systems the minimum penetration of diesel engines varies in a wide range. Minimum diesel penetrations of 30% [11], 40% [12] and up to 70% [13] can be found. Experiences on existing island grids with wind power have shown that 30% to 50% minimum diesel penetration should not be undershoot to assure dynamic stability [12]. The penetration limit of VRE units according to dynamic limitations is depending on the number, type and geographic dispersion of the units, as well as on their regulator characteristics. The general system setup like grid strength and the interconnection within the grid has an impact as well. Dynamic stability and power quality therefore is dependent on the specific EPSS setup. General approaches for dynamic limitations can not be made according to the existing studies.

Due to the fact that the hydro generation units in St. Vincent’s EPSS also participate in voltage control the penetration constraint does not only depend on the minimum diesel penetration, like in wind diesel systems, but on the total amount of voltage controlling units. Because dynamic limitations are highly dependent on the specific system, the limit is analyzed in Chapter 6 based on a simulation of St. Vincent’s EPSS. For further assessment the maximum dynamic limit can be chosen as 50% VRE penetration. Exceeding this limit may lead to instability because of perturbations in voltage and frequency.

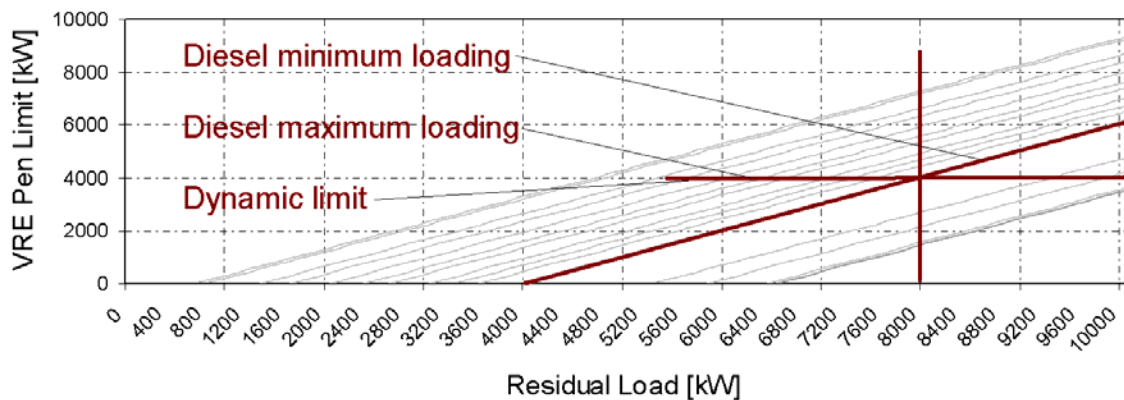


Figure 4.18.: Example of a VRE penetration limits (red lines) for a 7,000kW diesel generator set

4.2.4. Diesel ramping characteristic

Since spinning reserve and dynamic limitation are constraints that occur in a short or transient time frame of milliseconds up to a few minutes, the diesel ramping characteristic occurs in a time frame of around 15 minutes. The diesel ramping characteristic describes the ability of secondary control to bring back the frequency to their target values.

The increase of variable generation sources in the system causes a more flexible operation mode of the dispatchable units. Because of the additional variation on the supply side the total variation of supply and demand needs to be covered. This variation can be found in the residual load, which is the difference between base load plus variable generation minus load demand. The generation units balancing the residual load are the diesel engines of Cane Hall power plant. The supply of active power by the controlled and dispatchable generators is limited through their ramping characteristic. It has to be assured that the diesel engines can follow a certain load change, increased or decreased.

According to the operating model of St. Vincent the diesel engines of Cane Hall compensate the residual load. Short time changes in the residual load get compensated by the peaker units CH/G7, CH/G10 and CH/G12. These units have been taken into account to determine the ramping capability of the EPSS. Due to a lack of data the ramping characteristic is assumed as 50% rated capacity in 10 minutes for a loading ramp up. The estimation is based on data of Waertsilae diesel engines, these units can provide 100% rated capacity in 10 minutes (see figure 4.19). The curtailment to 50% includes uncertainties due to the data lack and the age of the Cane Hall units. For a loading ramp down the speed is assumed as 100% in 10 minutes. This is a very conservative approach as well. Practically, the diesel engines react immediately on the reduced fuel injection and reduce the power output.

<i>Power increase within 10 minutes by peaker units</i>	<i>202 kW/min</i>
<i>Power decrease within 10 minutes by peaker units</i>	<i>-403 kW/min</i>

The following step determines if the ramping characteristic of the peaker units is sufficient to balance the maximal residual load changes. Therefore wind data of the 23 January 2011 are

taken into account because this day shows the highest daily wind speed variety within one year (October 2010 till October 2011 wind data of Ribishi Point, VINLEC). The typical demand curve for the rain season (18 August 2011) is used. The load increases and decreases are calculated in 15 minute residual load steps. It is found that with a wind installation of more than 13MW the maximum residual load increase is higher than the ramping ability of the peaker units. That means, to compensate the generation loss of 13MW wind power, which would have been occurred on January 23rd 2011, the ramping ability of the three Cane Hall peaker units CH/G7, CH/G10 and CH/G12 would be completely used. Further wind installation would fail this criteria. Because the constraints of minimal diesel loading for spinning reserve and the demand constraint occur much earlier, the VRE penetration is limited far below this ramping criteria.

The diesel output easily can be increased by adding additional units for the balance of residual load. Furthermore, the ramping speeds are approached very conservatively. Compared to other thermal generation units, diesel engines can change their output within minutes. Therefore they are well suited to be combined with VRE generation sources. The technical reason for the quick respond ability is the diesel governor setup. Diesel engines have a short mechanical path between the governor actuator and the fuel delivery system to the combustion chamber which results in a system that responds very quickly to load change requests from the governor. According to this assessment the ramping constraint will not limit the VRE penetration in the current setup.

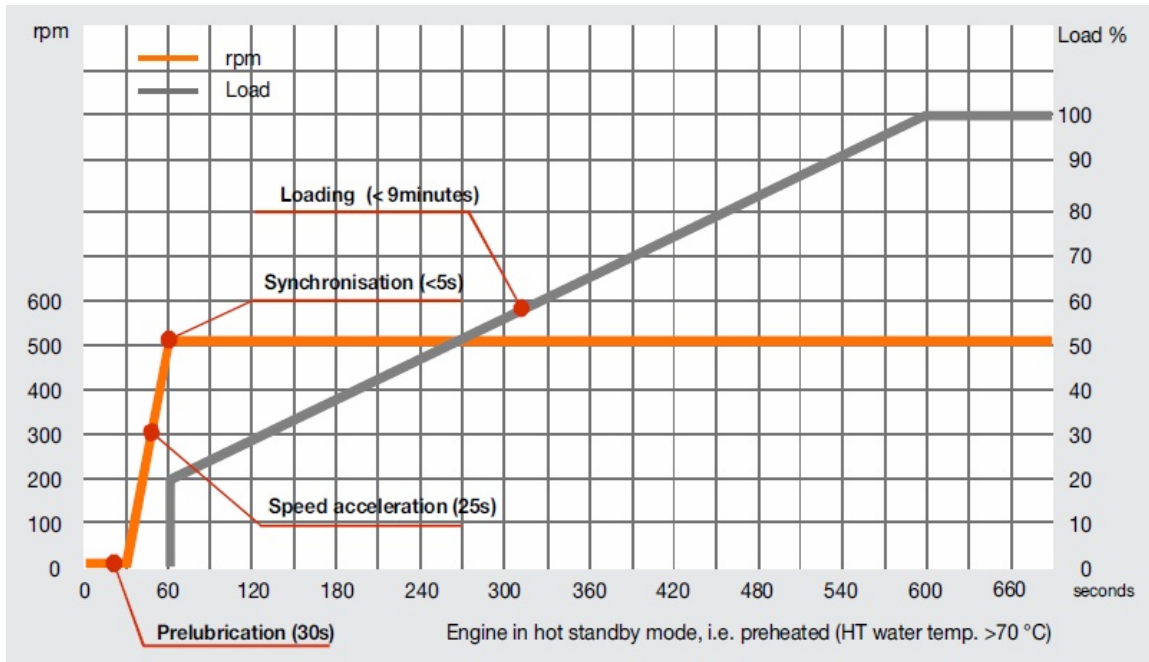


Figure 4.19: Ramp up curve for Waertsilae diesel engine [Source: Waertsilae]

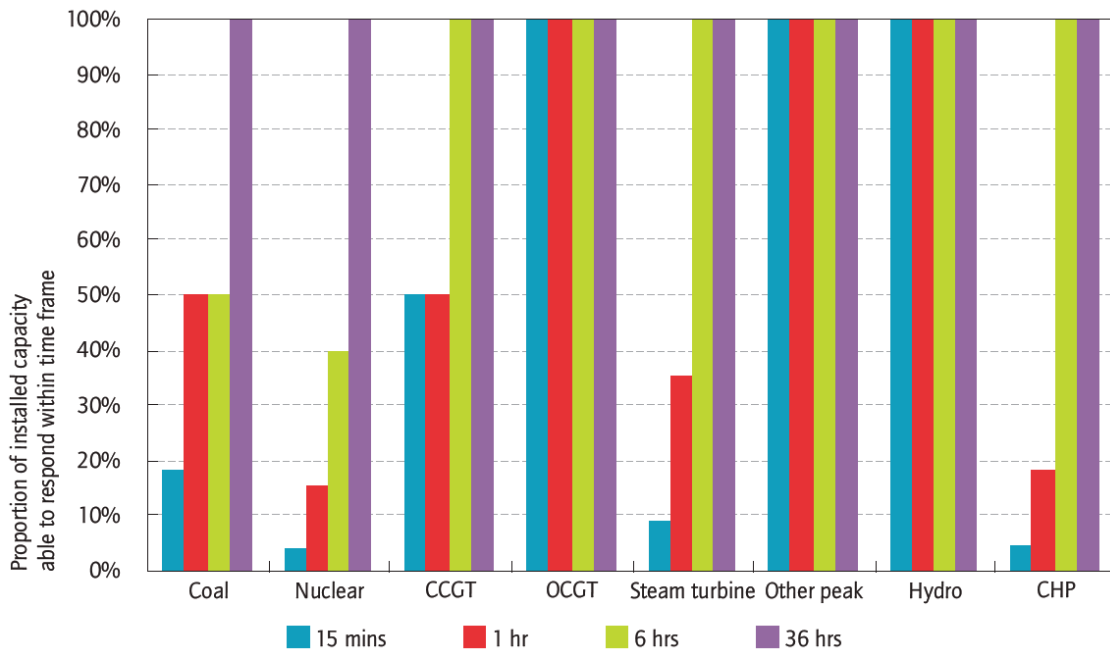


Figure 4.20.: Technical ramping capabilities of power plants (CCGT – Combined Cycle Gas Turbine, OCGT - Open Cycle Gas Turbine, Other peak – LPG/ HFO/Diesel, CHP – Combined Heat and Power) [14]

4.2.5. Demand constraint

Due to the fact that electrical energy in EPSS can not be stored directly it is necessary that at all times the generated power is equal to the total load demand. Deviations between demand and supply will cause accelerations or deceleration of the rotating generator sets connected to the EPSS. This acceleration can cause stability problems if the deviation does not get balanced sufficiently by the primary control units. In an EPSS without storage capabilities the demand constrains the power generation. If more power is produced than demanded the generation has to be curtailed or load has to be dumped. In that case, controlled dump loads which are fast acting devices, that help to balance the generation and demand, are used. VRE generation units also can employ load regulators to control imported power generation at light load conditions in order to keep the supply within the demand constraint. One example for load regulating VRE devices are modern PV inverters. They are able to control their power output according to the grid frequency to avoid over frequencies and device shutdowns [15].

St. Vincent’s EPSS does not have any dump loads or storage devices. Furthermore the spinning reserve mostly is supplied by the diesel engines of Cane Hall that also provide the residual load. According to their minimum loading constraint, a minimum residual load is required to operate the engines above their loading constraint. This causes in turn that the residual load can never be negative if the Cane Hall units have to supply additional spinning reserve. In that case, the Cane Hall units can neither provide energy nor spinning reserve and the spinning reserve demand would not be generated. Therefore, the demand is not constraining the VRE penetration in the recent setup of the system.

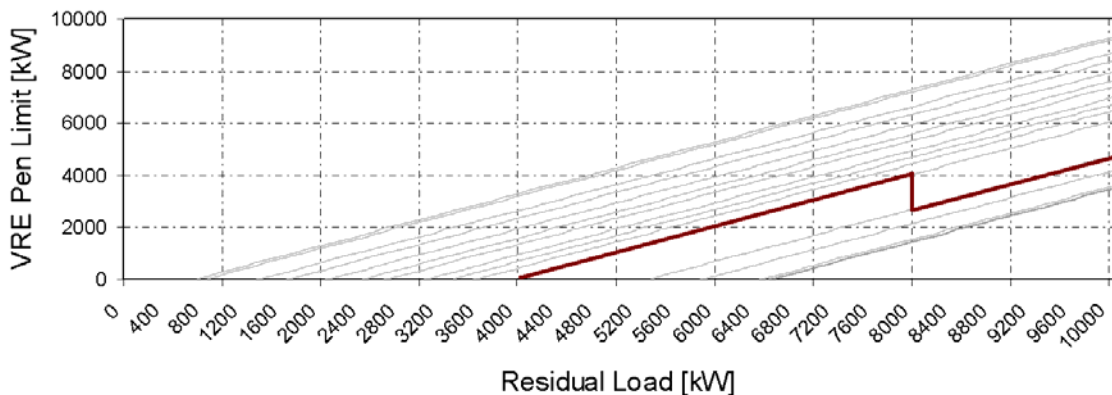


Figure 4.21.: VRE penetration limit (blue lines) for minimal spinning reserve of 4,000kW on Cane Hall generator combinations

4.3. Integration scenarios

4.3.1. Required spinning reserve

Due to the implementation of VRE generation units, additional spinning reserve might be required to address the outage or drop of these VRE units. In Chapter 4.2.2 four requirements determining the spinning reserve demand of the system have been defined. The VRE penetration levels increasing the spinning reserve demand in relation to the conventional setup is crucial for the TSO because the additionally required spinning reserve caused by VRE sources has a negative cost impact on the EPSS.

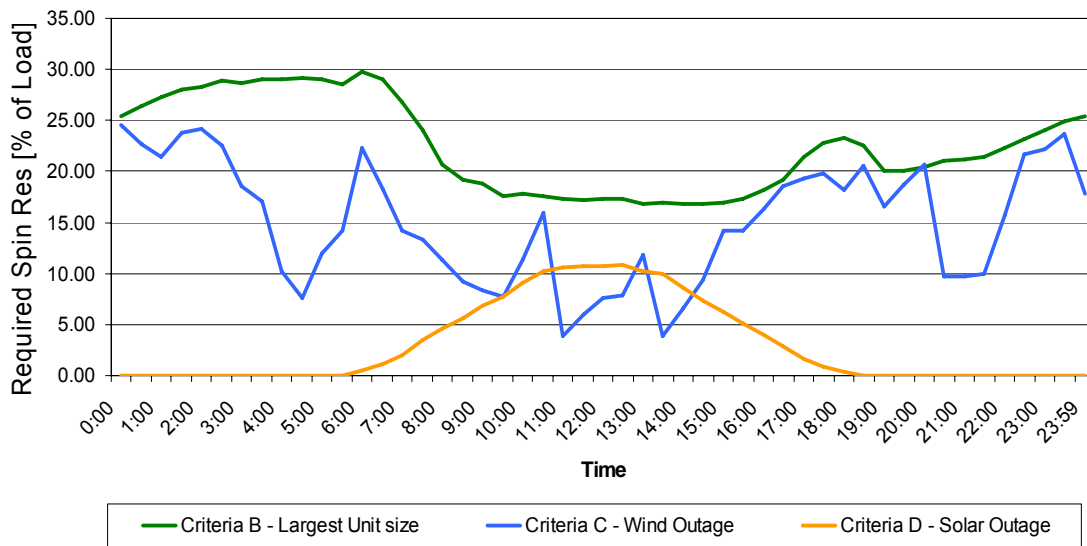


Figure 4.22: Example for spinning reserve impact of criteria B, C and D during one day with a moderate-fresh breeze wind

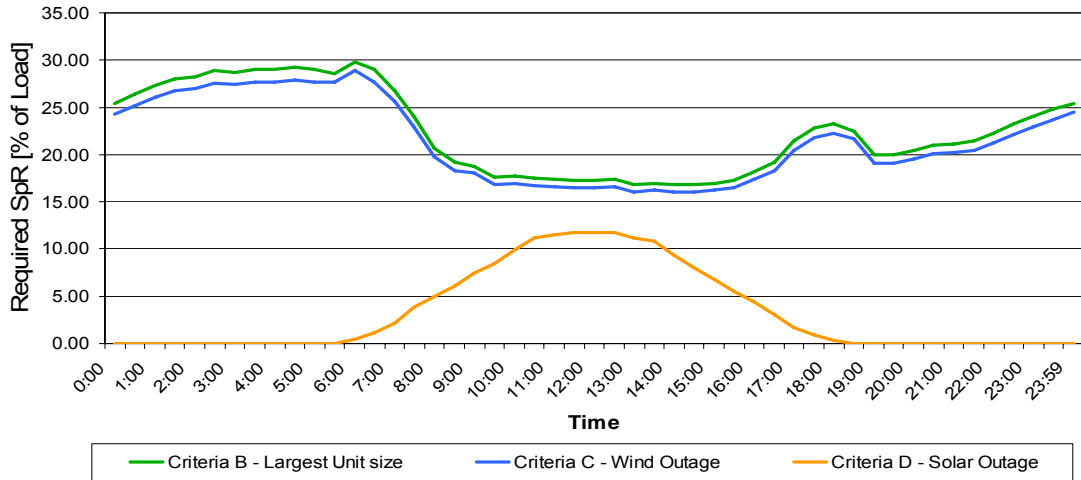


Figure 4.23: Example for spinning reserve impact of criteria B, C and D during one day with a strong breeze wind

Figure 4.22 shows an example of the required spinning reserve due to the main criteria B, C and D. The amount of required spinning reserve is determined either as the outage of the largest diesel unit (criteria B), the outage of wind power of 89% (criteria C) or the outage of 70% of the PV power (criteria D). The maximum of the four criteria determines the spinning reserve demand. The required reserve is shown for a moderate-fresh breeze in figure 4.22 and a strong breeze in figure 4.23.

The penetration of wind and PV power causing a higher amount of required spinning reserve in relation to criteria B are calculated as shown in figure 4.24. The required spinning reserve by criteria B is calculated according to several output capacity levels of the LB/G1 unit. The following example explains the calculation in figure 4.24: a diesel output of 90% of LB/G1 rated capacity causes a spinning reserve demand of 3870kW according to criteria B; the same spinning reserve demand of 3870kW occurs at a wind penetration of 4348kW according to criteria B or at a PV penetration of 5529kW according to criteria D.

Diesel output level	90%	80%	70%	50%	25%
Criteria B [kW]	3870	3220	3010	2150	1075
Criteria C [kW]	4348	3865	3382	2416	1208
Criteria D [kW]	5529	4914	4300	3071	1536

Figure 4.24: Instantaneous penetration of wind and PV power that cause equal spinning reserve demand like criteria B

4.3.2. Wind power implementation

The only VRE project of VINLEC is the wind park of Ribishi point. The installation capacity has not been determined yet but is assumed to be between 2.5MW and 4.0MW. As shown in chapter 4, several constraints limiting the amount of VRE penetration in an existing island EPSS exist. Without additional measures penetration amounts that are higher than the existing constraint can not be fed in the system and have to be curtailed or dumped if dumping facilities are available.

According to the current setup of the St. Vincent’s EPSS the main constraint for the wind penetration is the minimal loading constraint of the diesel units. The setup does not allow operating the diesel engines below 50% of their capacity. Without the ability of dumping or storing wind power, the amount of installed wind capacity is limited due to the diesel loading constraint.

To find the maximum amount of wind penetration that is allowed in the current system the following setup has been considered for the Excel based methodology:

- Diesel - base load: one generator (LB/G1) at 80% output
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according rain season (figure 4.25)
- Wind speed: strong breeze, data of 13.01.2011

According to this setup the maximum wind installation can be determined as:

<i>Wind power installation</i>	<i>3690 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>32 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>23.2 %</i>

Together with the hydro generation it allows a maximum average renewable penetration of 48.57 % within this day. Because the maximum wind power output is considered here, the average annual renewable penetration will be way lower.

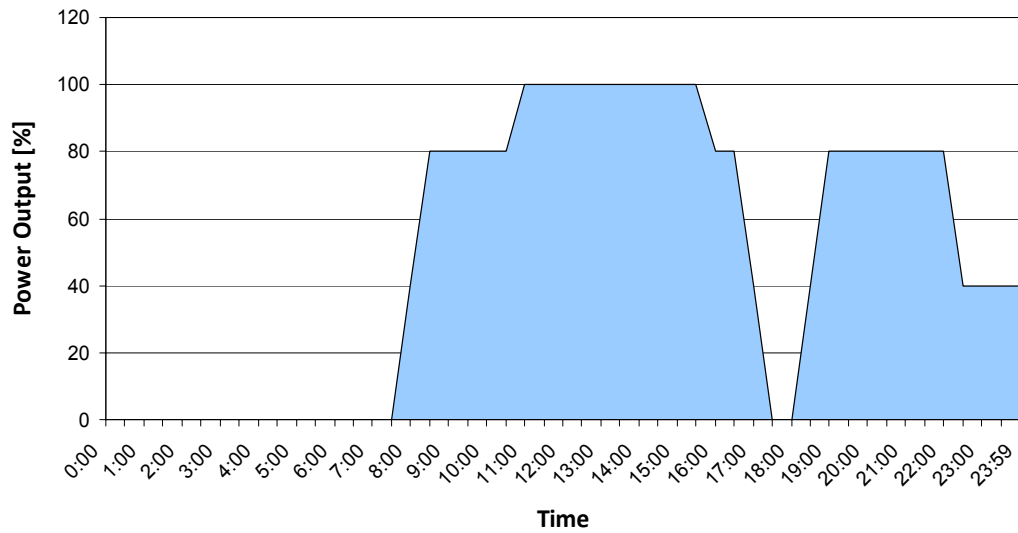


Figure 4.25: Dispatch hydro output for wind implementation analysis

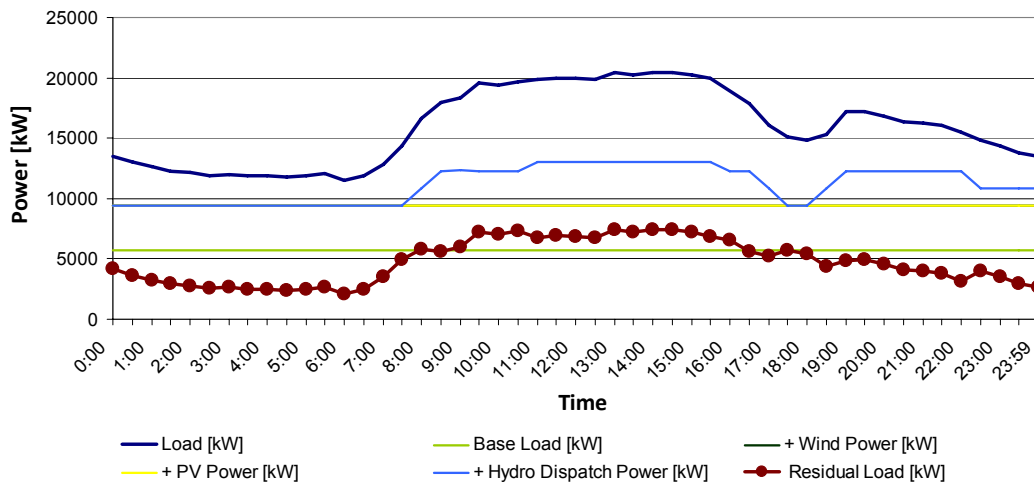


Figure 4.26: Power distribution for wind implementation analysis

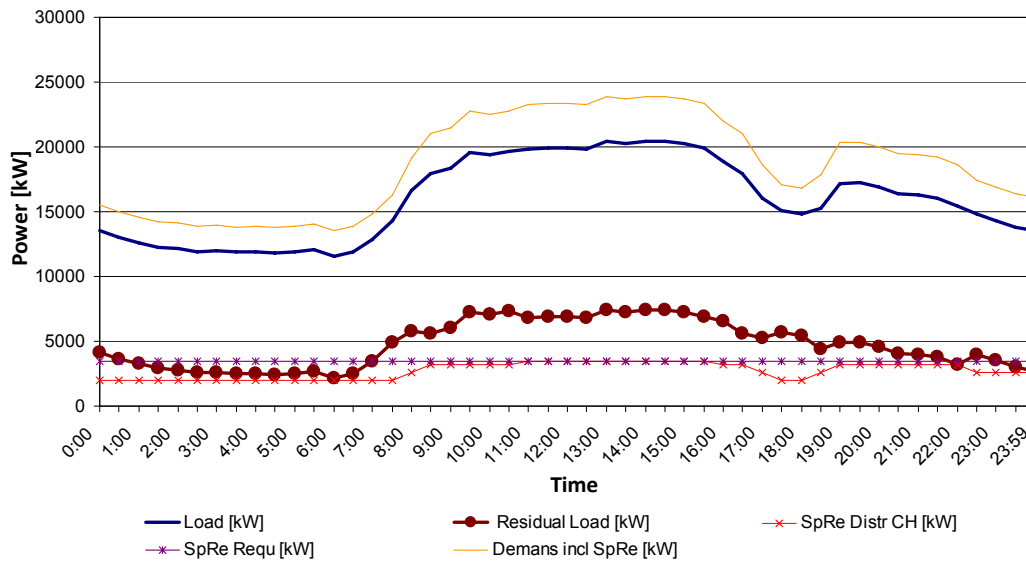


Figure 4.27: Spinning reserve distribution by Cane Hall (Sp Re Distr CH) for wind implementation analysis

4.3.3. PV power implementation

With a medium solar radiation of 5.0kWh per day and m² the fundamentals for PV power on St. Vincent are surpassing good. However, only a few grid-connected PV units are installed. The major ones are on governmental and public buildings like a 10kW unit at Cane Hall power plant and several units are on public buildings in Kingston with around 50kW. According to VINLEC the most PV investments will be domestic driven.

PV power is considered to be a VRE source in the Excel based methodology. The PV generation is added to the wind power implementation scenario of chapter 4.3.2. The following installation scenario is feasible due to the current setup and the diesel load constraint:

<i>PV installation</i>	<i>3930 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>17 %</i>
<i>Occurrence of maximum penetration:</i>	<i>12 am</i>
<i>Average penetration (for one day):</i>	<i>5.81 %</i>

The additional renewable penetration increases the total renewable penetration to 54.38 %. The analysis shows that although the increase of wind generation is limited in this situation, additional VRE like PV power can be fed into the grid. The advantage of PV power is that the maximum solar radiation and the highest demand correlate during the weekdays. The maximum residual load occurs around noon and provides a gap for additional VRE penetration.

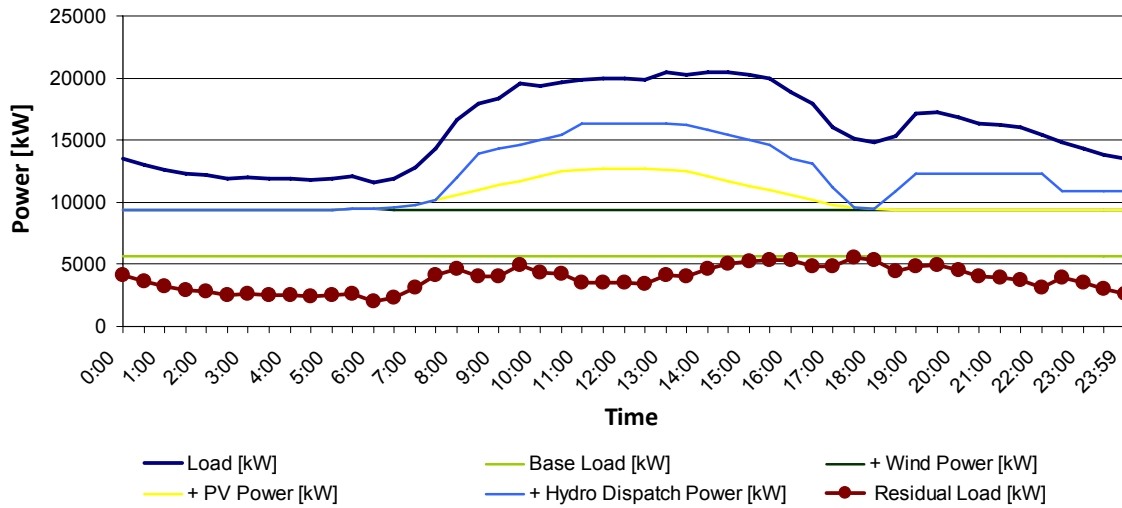


Figure 4.28: Power distribution for PV implementation analysis

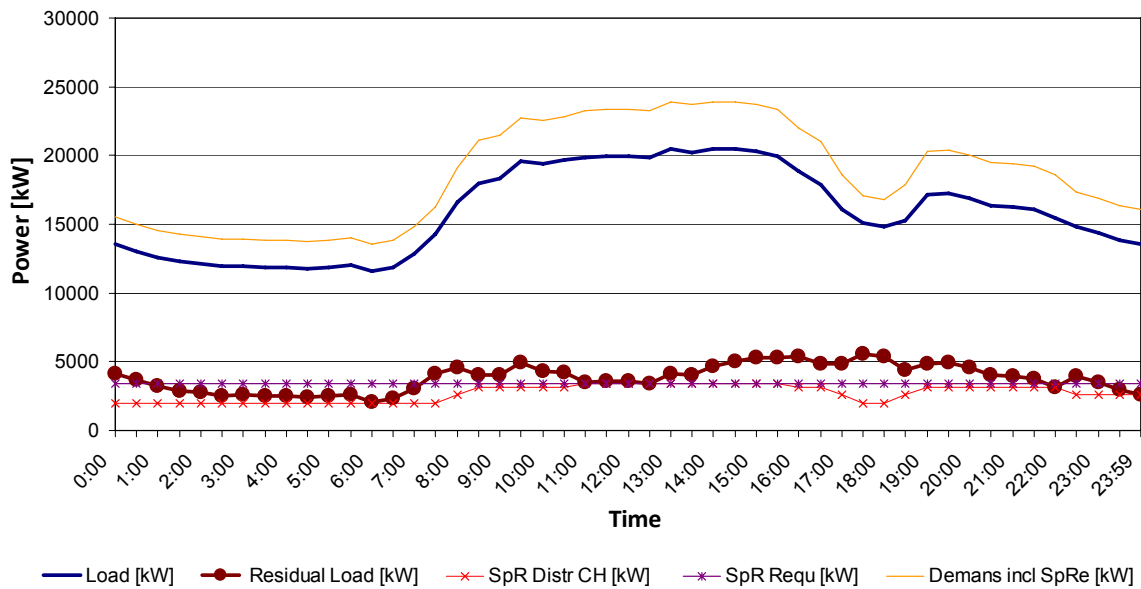


Figure 4.29: Spinning reserve distribution by Cane Hall (Sp Re Distr CH) for PV implementation analysis

5. Assessment - VRE penetration increase

In Chapter 4 the main VRE penetration constraints of St. Vincent’s EPSS were analyzed and the current penetration levels shown. According to these constraints, strategies or technical measures to increase the penetration limit can be developed. The objective is to find strategies and technical measures that eliminate the current constraint or increase the current limitation.

The main constraint in the current St. Vincent’s EPSS that defines the penetration limit for VRE is the minimum diesel loading of 50% combined with relatively high spinning reserve needs of around 4,000kW. On the one hand, the diesel engines have to supply a relatively high amount of spinning reserve caused by the large generation unit at Lowman’s Bay, on the other hand their minimum loading is constrained to 50%. That shrinks the gap for VRE sources to supply their piece of demand.

Based on this setup allowing only a limited VRE penetration, measures increasing the amount of VRE penetration have been developed. The approach to find the measures is shown in figure 5.2. According to the definition for wind diesel hybrid systems the four penetration scenarios are distinguished as low penetration to very high penetration. The measures to achieve the different penetration levels are proposed in chapter 5.1. to 5.3. They are divided into timeframes in which they can be implemented most likely. The long term vision of the approach is a 100% VRE penetration. The study is only focusing on the technical enablers that are required to achieve the several penetration scenarios, keeping in mind that the economical and political constraints can also limit such high penetration levels.

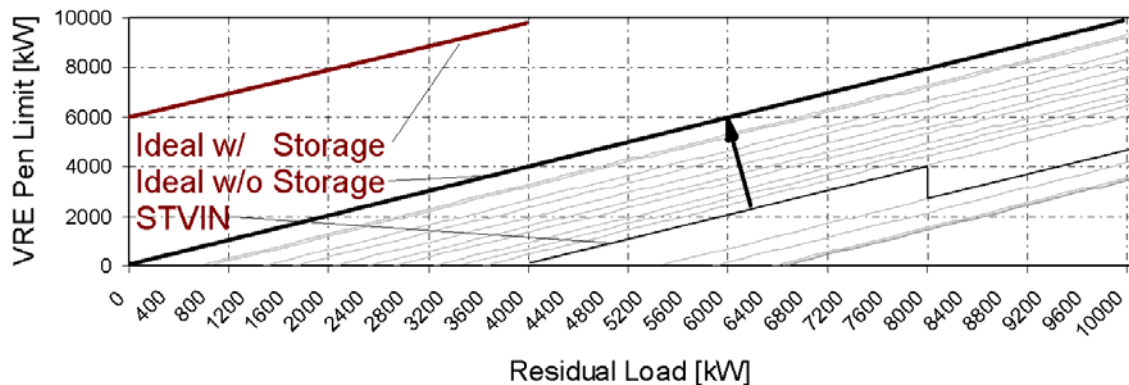


Figure 5.1.: Example of ideal penetration limit with storage facilities (black line – STVIN penetration limit, black bold line – Ideal penetration limit without storage facilities, red line – Ideal penetration limit with storage)

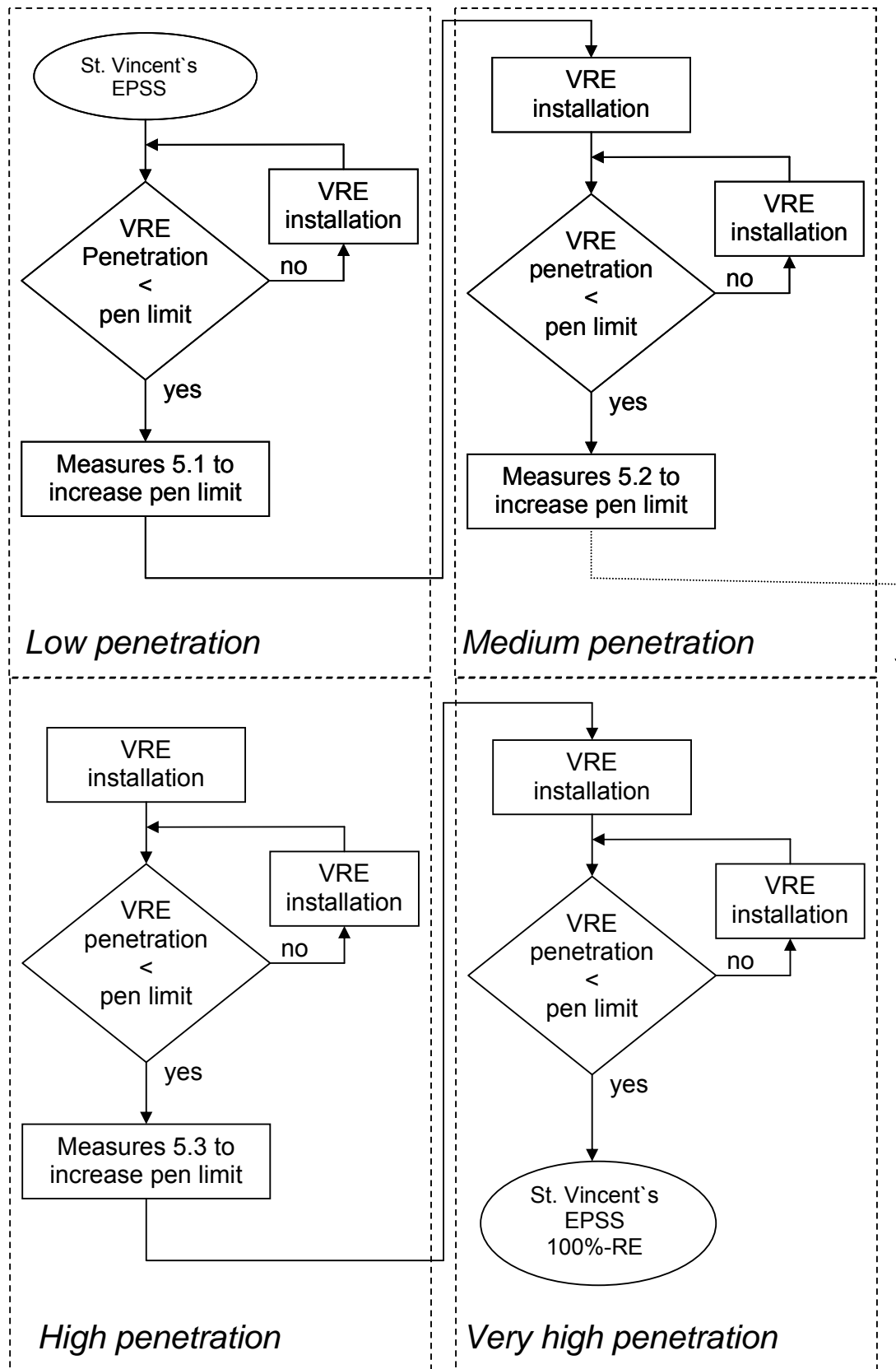


Figure 5.2.: VRE penetration increase approach

5.1. Short term measures

The short term measures require the least amount of technical effort to implement them into the existing system. Mostly these measures change the operation strategy of the TSO or specifications for the VRE units. The goal of the short term measures is to achieve a low penetration setup as seen as in chapter 3.4.1.

5.1.1. Load dumping

In the current St. Vincent’s EPSS, the TSO manages the power generation to meet the overall demand. The TSO has no ability to manage the demand itself. Due to the variability of VRE sources it has to be assured that the overall VRE power generation does not exceed the penetration limit. Without the ability of demand side management or active control, the amount of installed VRE capacity is constrained due to the maximum VRE output and the minimal VRE penetration limit. Since full load conditions are rare and the capacity factor of wind and solar units are relatively low the average instantaneous penetration allows higher VRE installations.

To allow higher VRE installation rates, controlled dump loads are one option. They are fast acting devices that help to balance the generation and load due to "burn off" excess energy production.

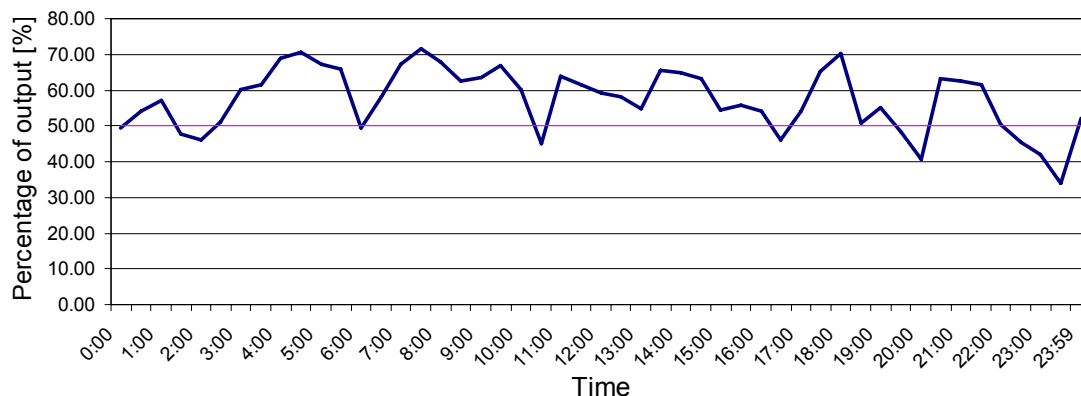


Figure 5.3.: Loading level of dispatchable diesel units (blue line) and loading constraint (pink line)

5.1.2. Active VRE power control

Power control of VRE units is a less obvious solution to imbalance between supply and demand. Unlike a conventional generating plant down regulated VRE power is lost forever. According to the current approach, the VRE power will not get down-regulated or dumped while it exceeds the penetration limit. This causes a limitation in the VRE implementation, means that only as many VRE can be installed as the penetration limit allows. To allow higher VRE installation it has to be assured that VRE power exceeding the penetration limit can get curtailed. This requires active control in the VRE units which control the power output or switches that enable the TSO to curtail or turn off the units. Some European grid codes require large wind farms and new large wind turbines to have active power control. The wind farm controllers are used by the TSO to maintain stability in critical situations, while power producers owning both, wind farms and conventional power plants, take advantage of the rapid controllability of wind farms to balance the much more sluggish response of conventional power plants [18].

5.1.3. Base load reduction

A measure that can easily be realized is the reduction of base load in the EPSS. Thereby, the operation range of the base load units could be decreased from 80% - 90% to 60% - 80% rated capacity. The base load units provide power constantly over the day.

To analyze the impact of a base load reduction on the VRE penetration the following setup has been reviewed in the Excel based model with a reduction of diesel base load from 80% to 60%.

- Diesel - base load: one generator (LB/G1) at 60% output
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according to rain season (figure 4.25)
- Wind speed: strong breeze, data of 13.01.2011
- PV installation 3930 kW

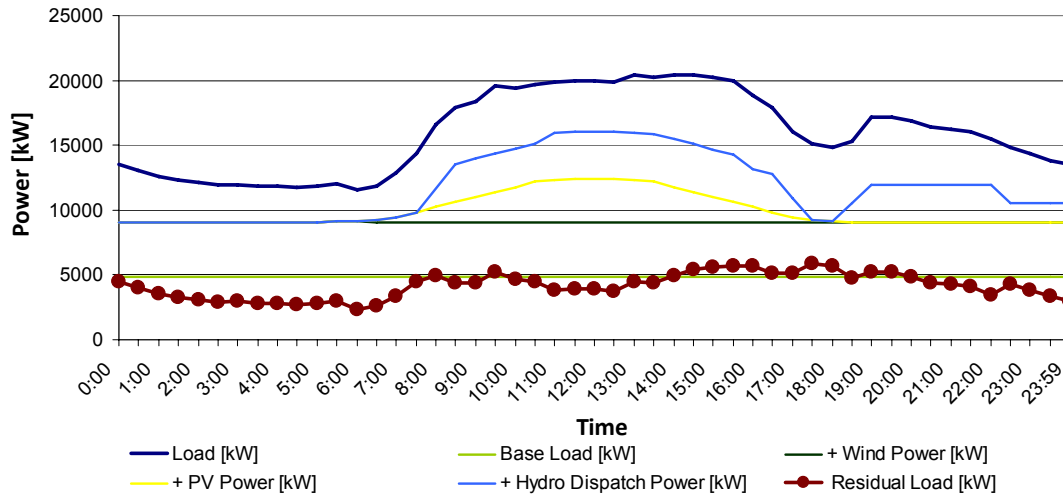


Figure 5.4.: Power distribution for base load reduction scenario

According to this setup the maximum wind installation can be determined as:

<i>Wind power installation</i>	<i>4222 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>37 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>26.55 %</i>

This allows together with the hydro generation a maximum average renewable penetration of 57.73 % within this day. Due to the maximum wind power output that has been considered the average annual renewable penetration will be way lower.

Compared to the scenario with a diesel base load unit at 80% output the wind installation can be 14% higher.

Due to base load reduction, the power that needs to be provided by the dispatchable and VRE sources is higher. That allows higher penetration levels of these sources. An additional advantage is that the required spinning reserve for the largest generation unit (criteria B) is reduced. The largest unit in the system is the diesel base load unit LB/G1. Disadvantages of lower operation levels of diesel base load units are higher consumption as well as wear and

tear. The fuel consumption characteristics of the diesel engines are given at different load values in figure 5.5.

Load % / kW	Engine Power bkW	Fuel Rate Litres / hour	Fuel Efficiency kWh / litre
100 / 925.0	983.2	233.0	3.97
90 / 832.5	886.0	209.2	3.98
80 / 740.0	789.8	186.6	3.97
75 / 693.8	742.0	175.9	3.94
70 / 647.5	694.2	165.2	3.92
60 / 555.0	599.0	144.0	3.85
50 / 462.5	504.4	123.0	3.76
40 / 370.0	413.1	102.8	3.60
30 / 277.5	319.6	82.3	3.37
25 / 231.3	272.0	71.9	3.22
20 / 185.0	223.7	61.4	3.01

Figure 5.5.: Fuel consumption for CAT D3512 diesel engine (Caterpillar Engine D3512, TMI Reference No.: DM 1869-02 PGS Prime, Caterpillar) [Source: Caterpillar]

5.1.4. Reservoir hydro operation

To analyze the impact of a reservoir hydro operation on the VRE penetration, the following setup has been reviewed in the Excel based model with two different operation modes of the hydro dispatch units based on the existing hydro capacities:

- Diesel - base load: one generator (LB/G1) at 80% output
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according to rain season (figure 5.6)
- Wind speed: strong breeze, data of 13.01.2011
- PV installation 3930 kW

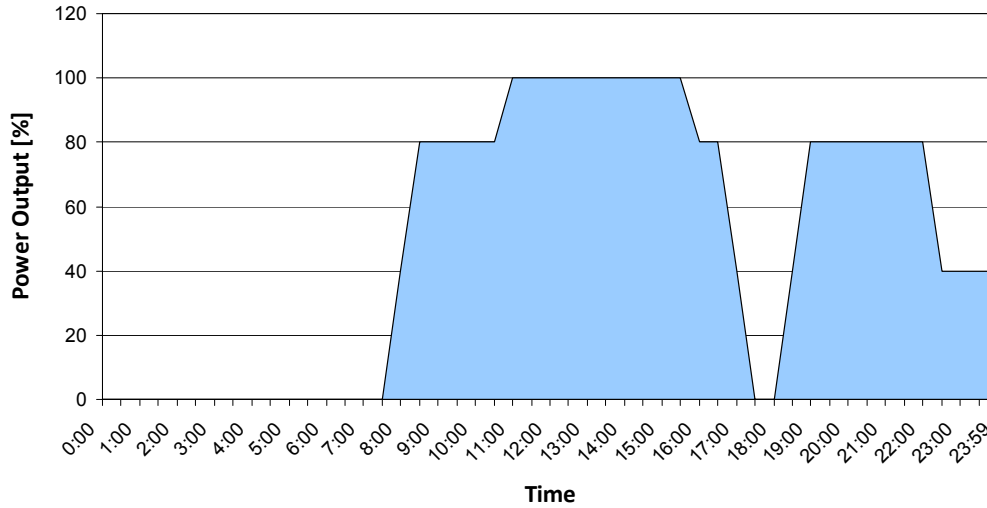


Figure 5.6.: Reservoir hydro operation A (flexible)

According to the hydro – dispatch operation of figure 5.6 the maximum permissible wind installation according to the deterministic penetration limit, can be determined as:

<i>Wind power installation</i>	<i>3682 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>32 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>23.15 %</i>

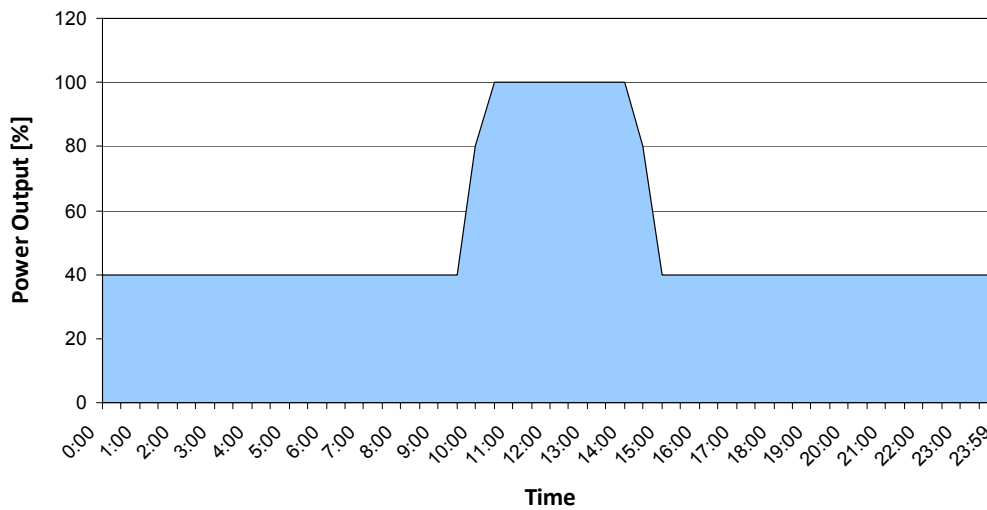


Figure 5.7.: Reservoir hydro operation B (conventional)

According to this hydro dispatch operation of figure 5.7 the maximum permissible wind installation can be determined as:

<i>Wind power installation</i>	<i>1725 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>15 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>10.85 %</i>

The analysis shows two different hydro dispatch operation modes. Operation mode A is optimized for a maximum VRE penetration. Operation mode B represents a conservative reservoir management. The result shows that the more flexible operation of the dispatchable hydro units, which follows the VRE generation and demand, allows much higher VRE penetration. The main reason is that with operation mode A the dispatchable hydro output in low demand conditions is reduced to zero. That keeps the residual load high enough for the dispatchable diesel units to provide sufficient spinning reserve and the required residual load. Another advantage of the operation mode A is that the dispatchable hydro units provide more spinning reserve in low load situations. That allows operating the dispatchable units at higher output levels and a higher buffer to the minimal output constraint. The results show that a more flexible hydro power operation increases the VRE penetration and can reduce required spinning reserve.

Essential for a more flexible hydro reservoir operation is a weather forecast system so that the produced VRE power can be calculated in advance and the dispatchable hydro power can be reduced. In an EPSS with VRE sources the power output of the dispatchable hydro units should not be managed due to the demand change but to the VRE forecast.

5.2. Mid term measures

The mid term measures require higher investments and technical efforts. The goal of the mid term measures is to achieve a medium penetration setup as seen as in chapter 3.4.1.

5.2.1. Low speed diesel

The main penetration constraint in the current St. Vincent’s EPSS is the minimum loading of the diesel units. Especially the loading level of the dispatchable diesel units supplying the residual load is constraining the VRE penetration. On the one hand the dispatchable diesel units have to supply residual load, on the other hand to provide sufficient spinning reserve. That causes the dispatchable diesel units to supply a minimum amount of residual load so that they can operate above their minimum loading.

To analyze the impact of a low load operation on the VRE penetration the following setup has been reviewed in the Excel based model with a reduction of minimum load of the Cane Hall units that provide the residual load from 50% to 30%:

- Diesel - base load: one generator (LB/G1) at 60% output
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according to rain season (figure 5.6)
- Wind speed: strong breeze, data of 13.01.2011
- PV installation 3930 kW

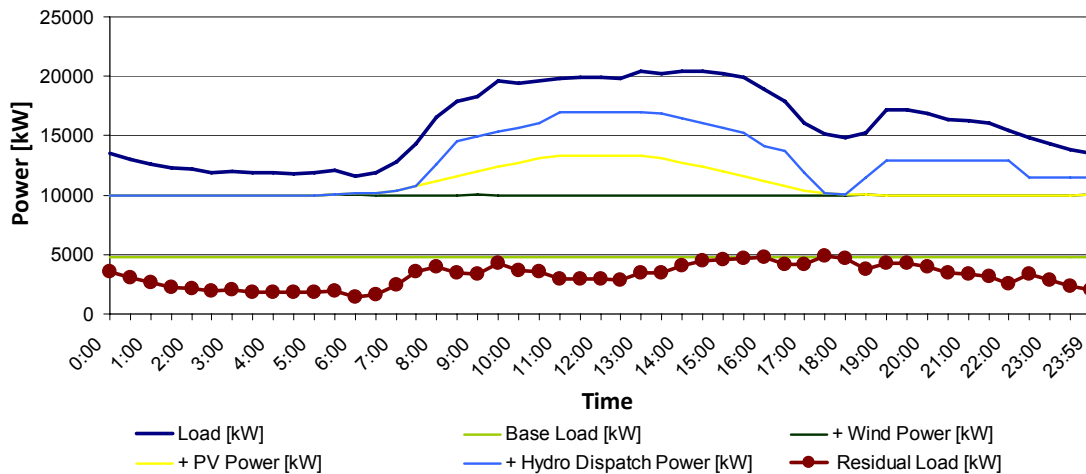


Figure 5.8: Power distribution for a low speed diesel scenario

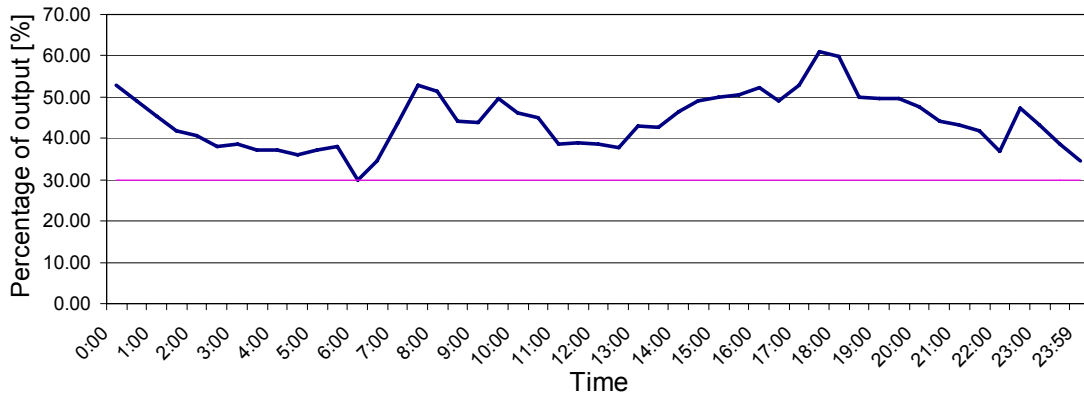


Figure 5.9: Loading level of dispatchable diesel units (blue line) and loading constraint (pink line)

According to this setup the maximum permissible wind installation can be determined as:

<i>Wind power installation</i>	<i>5182 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>46 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>32.58 %</i>

Together with the hydro generation, this scenario allows a maximum average renewable penetration of 63.77 % at that day. Due to the maximum wind power output that has been considered the average annual renewable penetration will be way lower because of the lower average wind generation over one year.

The operation of lower loadings on diesel generators has disadvantages like higher fuel consumption. Figure 5.5 illustrates that the diesel fuel consumption increases by about 23% for an operation at 25% loading in comparison to a full load operation. This might be an important factor in determination of the minimum loading constraint. Another factor is that operation under light load conditions significantly increases the risk of engine failures. Additionally it can cause premature ageing of the diesel generator. Operation at light load also reduces the capability of the generator to follow load changes, keeping in mind that the response time is highly dependent on the type of controls and the load characteristic [11]. Figure 5.10 shows that after a light load operation of less than 20%, the engine (MAN L+V32/40) has to run for a

specific time on a high load level of at least 70% depending on the load level to burn unburned particals and reduce the risk of engine failues. This is called “relieving operation”.

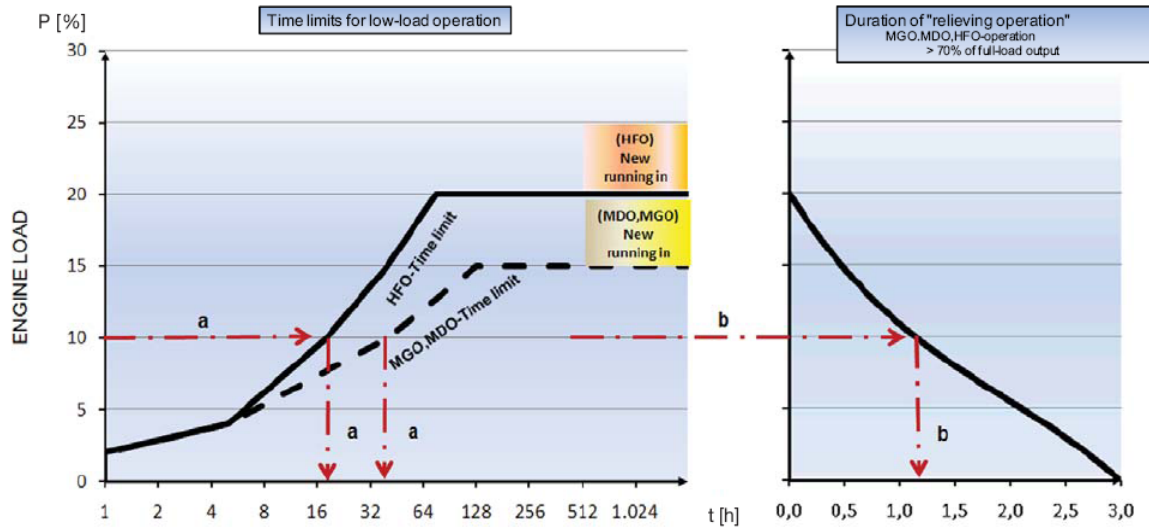


Figure 5.10.: Time limits for low load operation (on the left) and duration of “relieving operation” that need to be done after a low load event (on the right) [Source: MAN L+V32/40 – Project Guide]

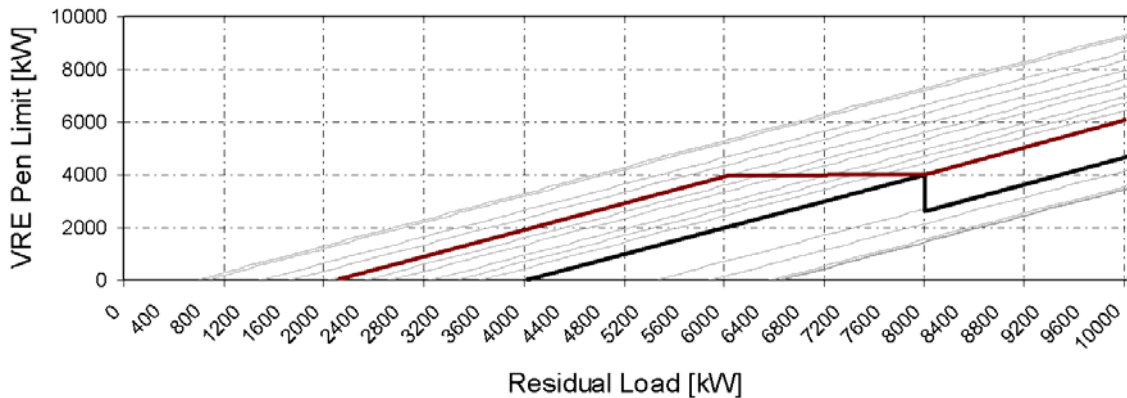


Figure 5.11: VRE penetration limit (red line) for low diesel loading (25% loading) (black line – STVIN penetration limit w/o low diesel loading operation)

5.2.2. Synchronous condenser

Higher VRE penetration levels require that the diesel units will be switched off. That requires high technical efforts since VRE units alone have only limited grid forming abilities, meaning in general they cannot control the grid frequency and voltage and are not able to supply

reactive power to the EPSS¹. All these abilities are required for the functioning of the isolated EPSS. A VRE hybrid system, like e.g. a wind-diesel system requires at least an additional electrical machine for supplying reactive and short circuit power. Normally, a synchronous generator with a nominal power larger than the grid’s peak single load is used to provide grid forming properties. For this generator, a special electronic device allows the variation of the power factor. Beside the term “synchronous condenser” there are several terms being used for this synchronous generator in the literature, such as “rotating phase shifter” or “master synchronous machine”.

To analyze the impact of a synchronous condenser on the VRE penetration the following setup has been reviewed in the Excel based model:

- Diesel - base load: one generator (LB/G1) at 60% output
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according to rain season (figure 5. 6.)
- Wind speed: strong breeze, data of 13.01.2011
- PV installation 3930 kW

According to this setup the maximum wind installation can be determined as:

<i>Wind power installation</i>	<i>5700 kW</i>
<i>Maximum instantaneous penetration:</i>	<i>50 %</i>
<i>Occurrence of maximum penetration:</i>	<i>6.00 am</i>
<i>Average penetration (for one day):</i>	<i>35.84 %</i>

This allows together with the hydro generation a maximum average renewable penetration of 67.05 % within that day. Due to the maximum wind power output that has been considered the average annual renewable penetration will be way lower because of the lower average wind generation over one year.

¹ The wind and PV industry both have recognized this need and offer solutions to provide these grid forming ability, however for additional cost. Some modern PV and wind inverters are able to reduce the real power output to provide spinning reserve for frequency control and change reactive power for voltage control.

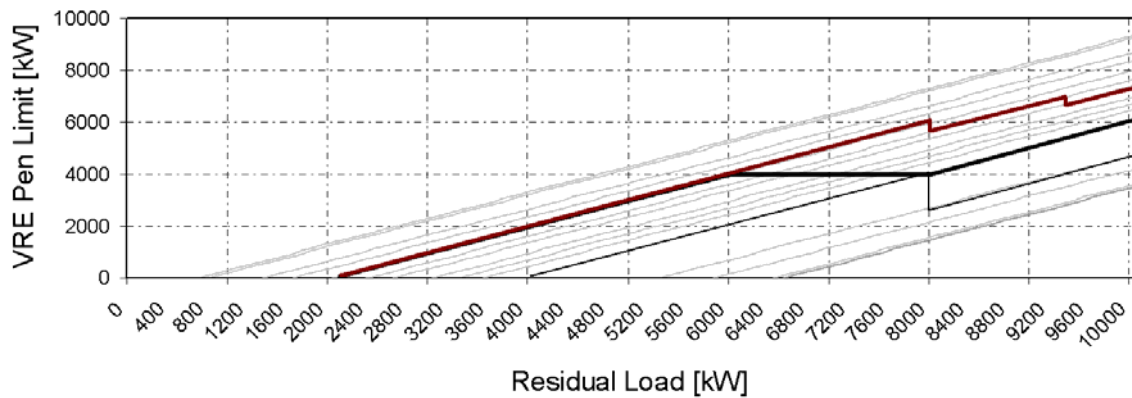


Figure 5.12.: VRE Penetration limit (red line) including synchronous condenser (Black line – STVIN penetration limit, black bold line - Low diesel loading operation penetration limit)

5.2.3. Diesel idle operation

Idling diesel units could provide spinning reserve and reduce its demand that needs to be supplied by the dispatchable units at Cane Hall power station. Idling of a generator set requires an over running coupling that allows a synchronized operation. It is also possible to connect the synchronous condenser directly to one of the diesel generators. According to information of the diesel manufacturer MAN the average fuel consumption during idling is around 20% to 30% of the full loading consumption.

To analyze the impact of an idle operation of a diesel unit on the VRE penetration the following setup has been reviewed in the Excel based model:

- Diesel - base load: one generator (LB/G1) idling
- Hydro - base load: all generators at 80% output
- Hydro - dispatch: according to rain season (Figure 5. 6.)
- Wind speed: strong breeze, data of 13.01.2011
- PV installation 3930 kW

According to this setup the maximum wind installation can be determined as:

<i>Wind power installation</i>	8336 kW
<i>Maximum instantaneous penetration:</i>	73 %
<i>Occurrence of maximum penetration:</i>	6.00 am
<i>Average penetration (for one day):</i>	52.41 %

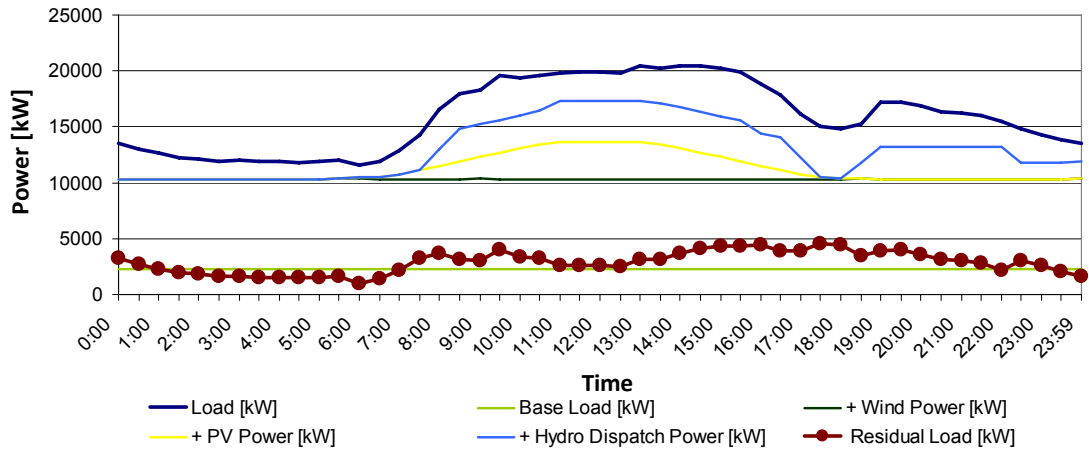


Figure 5.13: Power distribution for a diesel idle scenario

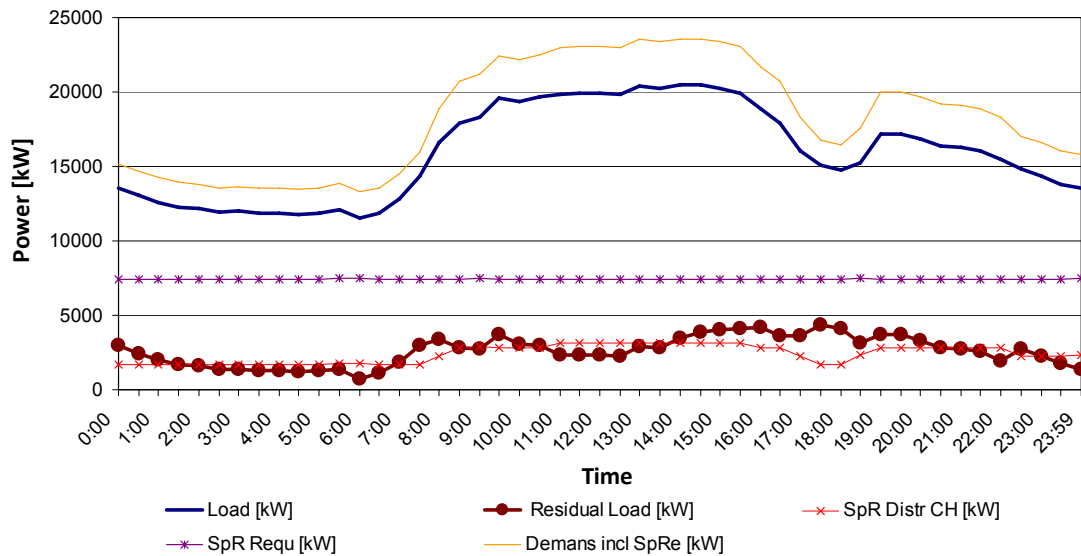


Figure 5.14: Spinning reserve distribution for a diesel idle scenario

This allows together with the hydro generation a maximum average renewable penetration of 83.62 % within this day. Due to the maximum wind power output that has been considered the average annual renewable penetration will be way lower because of the lower average wind generation over one year.

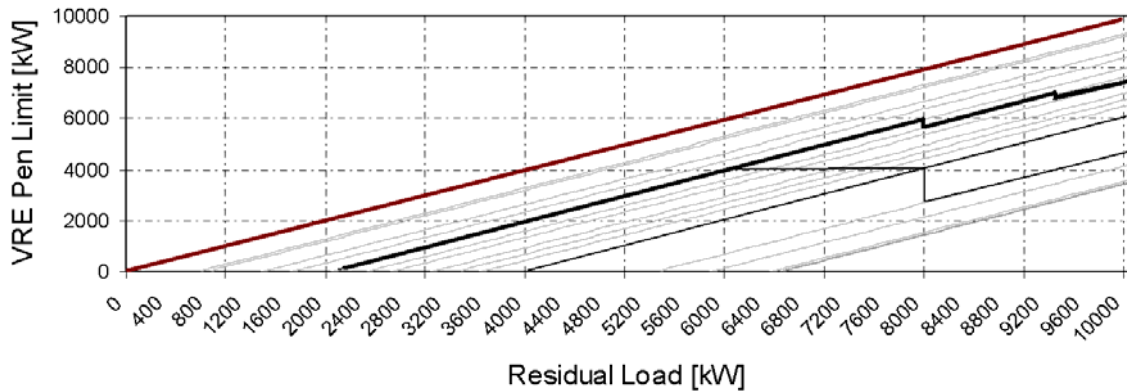


Figure 5.15.: VRE penetration limit (red line) for spinning reserve supply by idling units (black line - low diesel loading operation penetration limit, black bold line – penetration limit including synchronous condenser)

5.3. Long term measures

The long term measures require the highest investment costs and technical efforts. The goal of the long term measures is to achieve high - up to very high VRE penetrations as seen in chapter 3.4.1. The vision is to achieve renewable penetration of 100%, keeping in mind that this is technically feasible but economically probably not.

5.3.1. Energy storage

If the St. Vincent’s EPSS would only consist of diesel generators, a synchronous condenser and VRE sources, the diesel units could be switched off completely when VRE generation would exceed the demand. Indeed, changing wind speeds, solar insulations or load conditions would cause frequent starts and stops of the diesel generator. This would increase the specific fuel consumption as well as the wear and tear of the diesel engines. As a result an energy storage system needs to be integrated into EPSS to reduce the frequency of diesel starts and stops. An

energy storage also reduces the fluctuations of the grid’s frequency and voltage while running in diesel off mode. Therefore the storage converter has to supply the frequency control while the synchronous condenser supplies reactive power and controls the system voltage [10]. Energy storage in the St. Vincent’s EPSS would eliminate the dependence of VRE penetration on the system’s demand. The maximum VRE penetration would only depend on the maximum storage ability of the system. As the example in figure 5.16 shows, a storage facility with 4,000kW capacity would add additional 4,000kW to the VRE penetration limit.

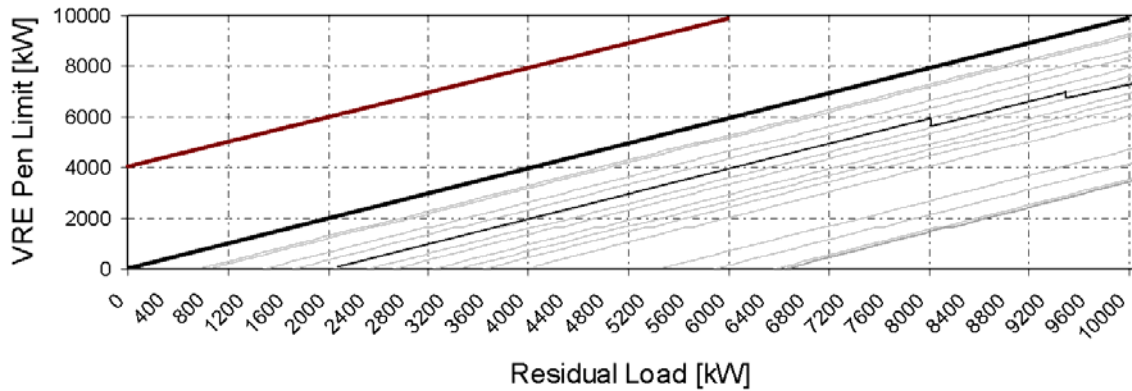


Figure 5.16.: VRE penetration limit (red line, schematic) with energy storage ability

Energy storage facilities are divided into the three groups mechanical, electrical and electro-chemical storages. Figure 5.17 shows several energy storages and their capacities. According to VINLEC the most likely options for St. Vincent’s EPSS are pumped hydro and battery storage facilities.

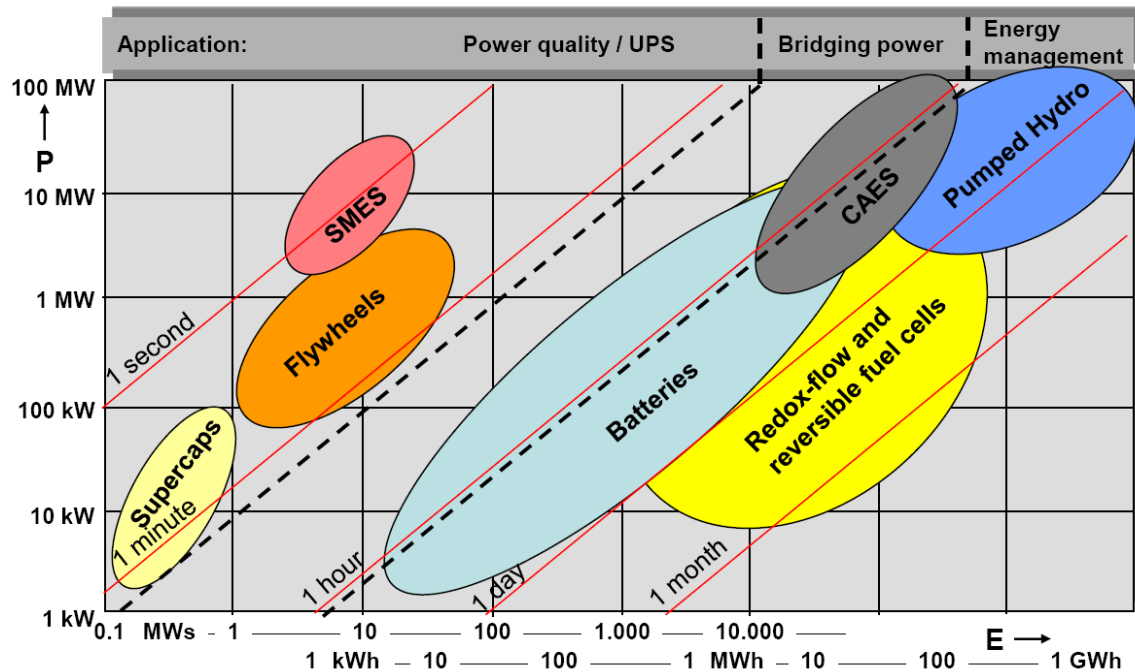


Figure 5.17.: Energy storage and power capacities of different storage technologies over the estimated storage time (SMES – Superconducting magnetic energy storage , CAES – Compressed air energy storage) [16]

One option for the St. Vincent’s EPSS could be to add pumping facilities to existing hydro chains of Groove or South rivers. They provide a hydro reservoir that could allow operating them as a pumping storage. Water would be pumped to an elevated reservoir when the VRE units generate a power surplus. Beside this option additional pump storage power plants operating with sea water are imaginable if adequate sites exist. Another option is the use of large batteries as electricity storage to compensate for supply fluctuations. Modern sodium sulfur batteries are available with a rated power of 3 MW [16].

5.3.2. Flywheel storage

In addition to the battery storage the use of flywheel storages also brings technical advantages. Wind diesel systems using only batteries as an energy storage show short battery life times. The reason for this short battery lifetime is rapidly changing charge and discharge due to the fluctuation of the load cycle. Modern wind diesel systems use flywheels for removing short term fluctuations and batteries for medium term energy storage and achieve much better battery life times.

The flywheel energy storages are working by accelerating a rotor (flywheel) to high rotational speeds. The rotor maintains the energy as rotational energy. The rotational speed of the flywheel is reduced when energy is extracted. Adding energy vice versa results in an increase of the rotational speed of the flywheel. Advanced systems run enclosed in a vacuum using rotors made of high strength carbon structures and magnetic bearings. They achieve rotational speeds of 20,000rpm to over 50,000rpm, power storage between 200kW to 1,500kW and energy storage capacities of 0.5 kWh to 25kWh. Storages response times of 15 seconds to 15 minutes can be achieved [16].

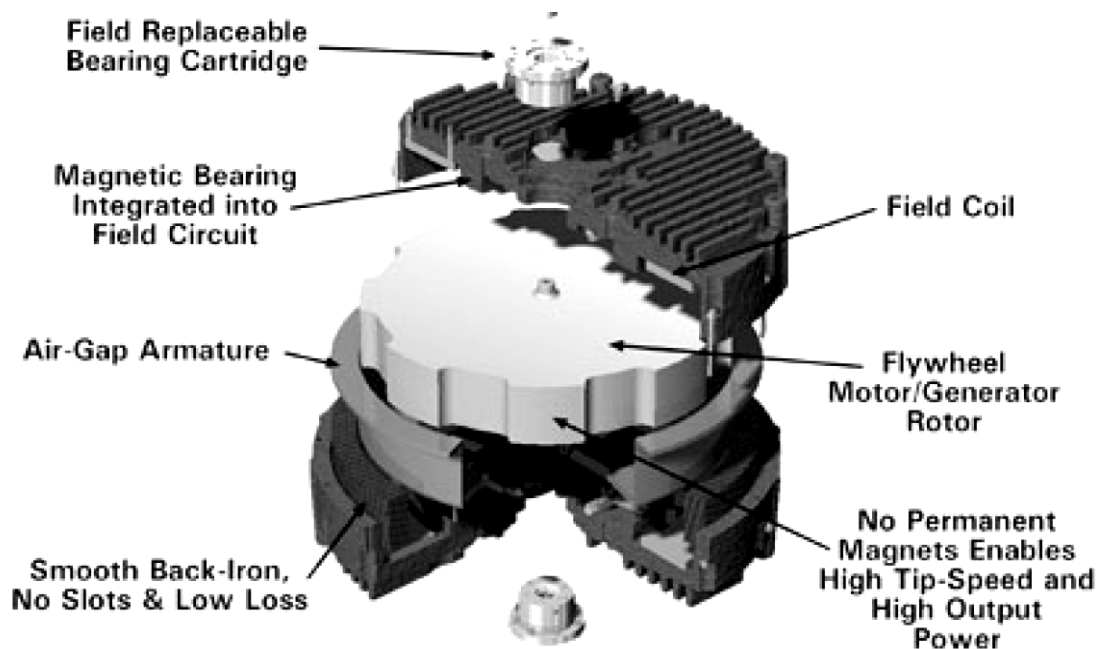


Figure 5.18.: Flywheel motor-generator [16]

6. Validation - Dynamic validation

The available power of VRE units is variable due to the fluctuation of their natural sources. Power quality and reliability are some of the major concerns with regard to the power fluctuation. The dynamic and transient response to the fluctuation is individual for every EPSS. It is determined due to capacities and inductivities of all participating components like generators, loads, transformers and connections. The load follow-up ability of the generators mainly depends on their inertia and the control speed of the governors. To find dynamic limitations, the EPSS has to be simulated according to its specific setup. The simulation software used in this study is NEPLAN from BCP. The simulation model is set up according to the schematic diagram of the main transmission and distribution system of VINLEC of 2011 (figure 6.1). The parameters of the system components are based on VINLEC data or on literature if no data was available.

Beside the power quality and reliability concerns the fault-ride-through capability is another issue regarding the integration of high VRE amounts. In case of grid faults voltage support capability of VRE units and their influence to transient stability becomes critical [2]. The purpose of fault-ride-through is to ensure that VRE units are able to stay connected to the grid during a grid fault. They should not trip out when a short circuit on the grid causes under voltages, over currents, over speeds, or any other conditions going beyond their protection limits. If VRE units like wind turbines are not able to ride through the fault, they will trip. The consequence is a sudden loss of generation which needs to be replaced by fast reserves from other generators. Similar capabilities are also required to ensure continuing the system's operation after a sudden loss of conventional generation (criteria B). In both cases it has to be taken into account that VRE units without sufficient fault-ride-through capabilities could trip simultaneously with the largest generating unit due to the same grid fault. The fault-ride-through behavior of the VRE units is not considered in the dynamic simulation.

6.1. Simulation model

The simulation system is based on the St. Vincent's EPSS according to the schematic diagram (No. 12) of the main transmission and distribution system (VINLEC, September 2011). This schematic and the data of the EPSS facilities are the basis of the simulation model. In addition to the current schematic of diesel and hydro power plants, a wind park is added to the

simulation setup. In figure 6.1 the schematic of the transmission and distribution system is shown. Figure 6.2 shows the simulation model that has been deduced from this base.

As a simplification, the simulation contains only the 33kV and 11kV transmission system excluding the distribution system with their switches and relays. Their energy flow can be represented through the main feeders. In the current system twelve feeders are located on four busbars, Cane Hall, Kingstown, South River and Lowmans Bay. For the dynamic simulation the direction of the energy flow through the single feeders can be ignored because the simulation considers only the generation and the consumption busbars but not the single feeders on each busbar. Hence, the twelve feeders have been eliminated and replaced through four feeders combining the loads of all single feeders.

The setup of diesel and hydro generators is described by data obtained from VINLEC. All generators are synchronous machines. The diesel generator sets are represented in the NEPLAN simulation through a turbine model controlled by a turbine governor and a AVR. That allows active prime control and voltage control of the diesel units. The hydro generator sets are represented through the synchronous machine and an AVR for voltage control. Since the hydro power plants of South River and Richmond are run-of-river types, their power output is not actively controlled. Also the units of the Cumberland hydro compound are not controlled in the simulation model because the power output is not controlled actively but statically by the TSO. The governors of the diesel units are represented through the NEPLAN governor model TGOV1. The wind turbines are represented through the NEPLAN model for double fed induction generator (DFIG). All AVR are represented through the simple exciter model.

“Maximum penetration of variable renewable power in an isolated power system”

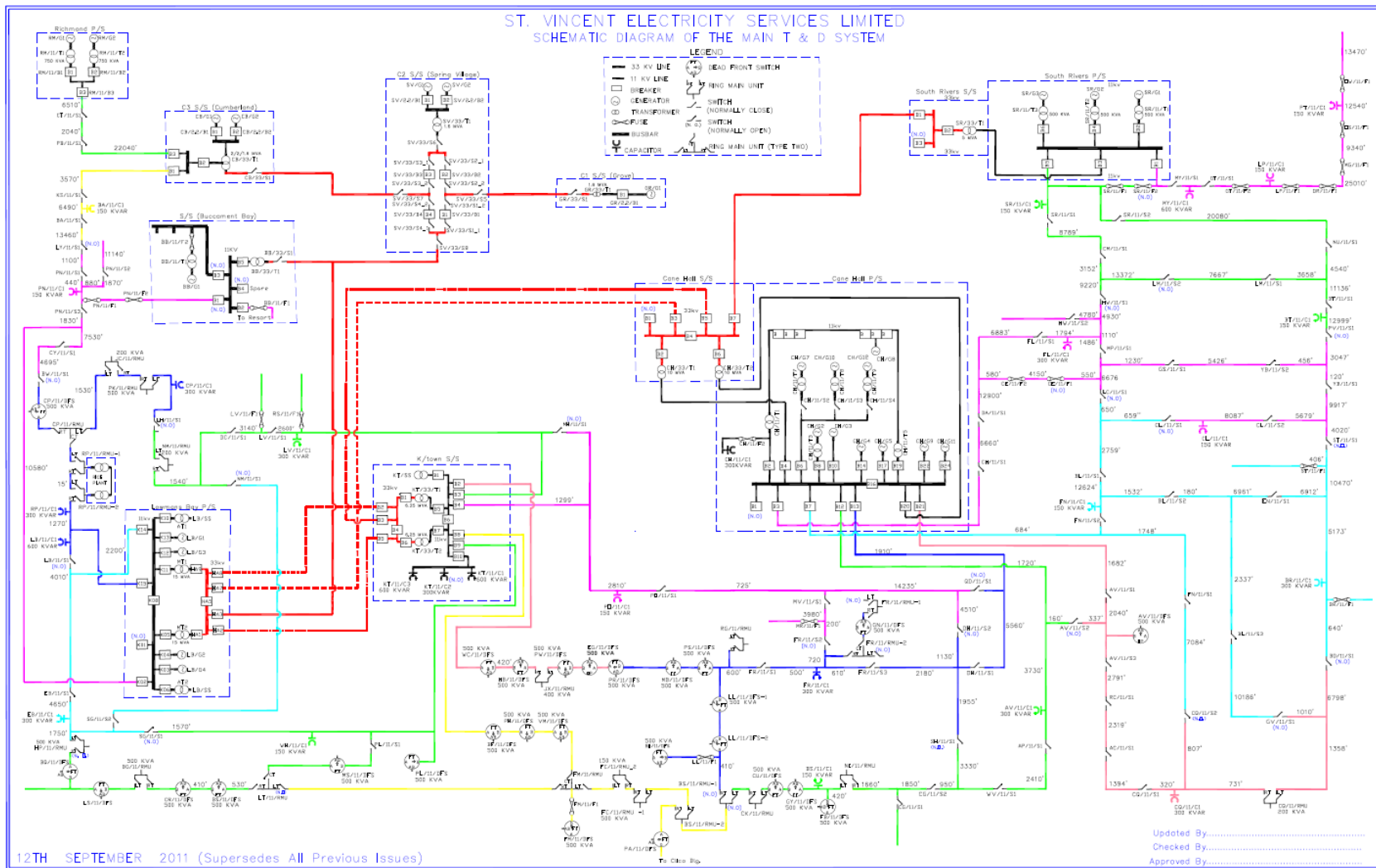


Figure 6.1.: Schematic of St. Vincent’s transmission and distribution system (large format see annex) [Source: VINLEC]

“Maximum penetration of variable renewable power in an isolated power system”

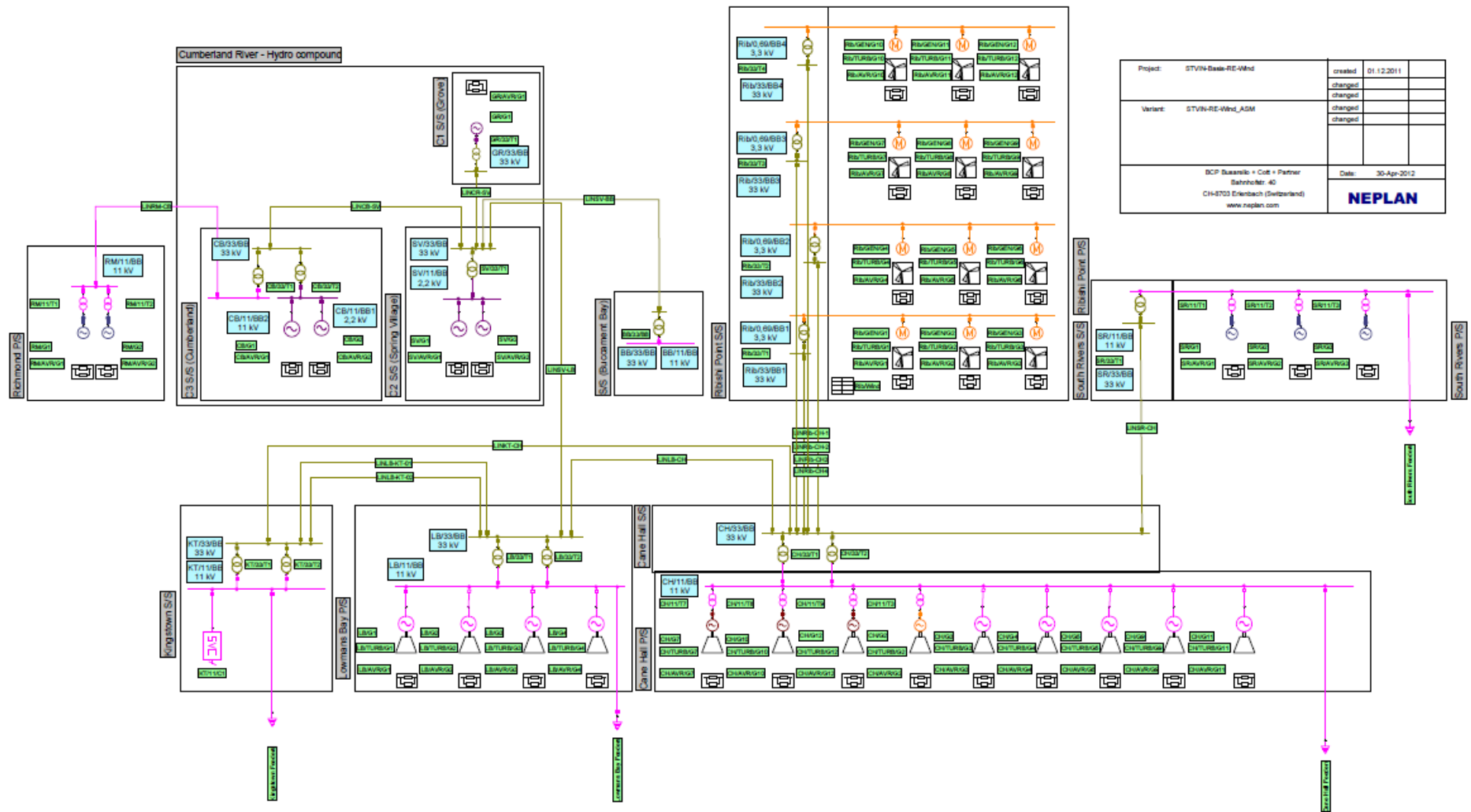


Figure 6.2.: St. Vincent’s EPSS simulation model in NEPLAN (large format see annex)

6.2. Simulation scenarios

The aim of the simulation is to validate the stability of St. Vincent’s EPSS under the dynamic limitation (according to chapter 4.2.3.). If the system remains stable under the impact of several transient disturbances like wind speed, reactive and active load variations, the limitation of chapter 4.2.3 is validated. Therefore two scenarios with different dynamic limitations have been analyzed. The first setup represents a 50% penetration of diesel and hydro units and 50% of the wind power units. In the second approach the wind power units provide 70% of the load, diesel and hydro units provide 30%. Figure 6.3 shows the setup of the generators in both scenarios. The validation of the stability is proven when the system remains stable after the disturbance. The simulation gives an impression of St. Vincent’s EPSS dynamic behavior without reflecting it exactly. Missing data of the existing generation units, especially the voltage and frequency constraints and the estimated simplified future VRE units are causing this uncertainties in the simulation.

Load per feeder:

Kings Town	4.5 MW, power factor 88.3%
Cane Hall	9 MW, power factor 95%
South Rivers	2.7 MW, power factor 99.6%
Lowmans Bay	1.8MW, power factor 84.8 %

Power generation:

Scenario A:	50%	wind power	9 MW
	50%	diesel + hydro power	9 MW
Scenario B:	70%	wind power	12.6 MW
	30%	diesel + hydro power	5.4 MW

Name	Scenario A	Scenario B	P Gen	Q Gen	Ur	LF-Typ	H
-			MW	Mvar	kV	-	s
Hydro							
CB/G1	ON	ON	0.4	0	2.2	PV	0.006
CB/G2	ON	OFF	0.4	0	2.2	PV	0.006
RM/G1	ON	ON	0.5	0	0.4	PV	0.16
RM/G2	ON	ON	0.5	0	0.4	PV	0.16
GR/G1	ON	OFF	1.45	0	2.2	PV	0.041
SV/G1	ON	OFF	0.535	0	2.2	PV	0.014
SV/G2	ON	OFF	0.535	0	2.2	PV	0.014
SR/G1	ON	OFF	0.23	0	0.4	PV	0.008
SR/G2	ON	OFF	0.23	0	0.4	PV	0.008
SR/G3	ON	OFF	0.23	0	0.4	PV	0.008
Diesel							
LB/G1	ON	ON	4	0	11	PV	0.102
LB/G2	OFF	OFF	0	0	11	PV	0.102
LB/G3	OFF	OFF	0	0	11	PV	0.102
LB/G4	OFF	OFF	0	0	11	PV	0.102
CH/G7	OFF	OFF	0	0	0.415	PV	0.043
CH/G10	OFF	OFF	0	0	0.415	PV	0.043
CH/G12	OFF	OFF	0	0	0.415	PV	0.043
CH/G2	ON	ON	-	-	3.3	SL	0.036
CH/G3	OFF	OFF	0	0	3.3	PV	0.096
CH/G4	OFF	OFF	0	0	11	PV	0.089
CH/G5	OFF	OFF	0	0	11	PV	0.089
CH/G9	OFF	OFF	0	0	11	PV	0.104
CH/G11	OFF	OFF	0	0	11	PV	0.116
Wind							
Rib/GEN/G1	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G2	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G3	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G4	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G5	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G6	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G7	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G8	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G9	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G10	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G11	ON	ON	0.75/1.05	0	0.69	MLoad	0.5
Rib/GEN/G12	ON	ON	0.75/1.05	0	0.69	MLoad	0.5

Figure 6.3.: Simulation setup of the NEPLAN model

6.2.1. Wind speed variation

The transient response of St. Vincent’s EPSS has been investigated for a 15% wind speed change, as shown in figure 6.4 to 6.7. After one second, wind velocity is suddenly changed 15% respectively -15%. As the wind speed increases, the contribution from wind power plants increases and drops, respectively. Both scenarios remain stable after 100 seconds of simulation. The voltage and frequency drops, and the reactive power consumption is higher in the 70% wind penetration scenario. This is due to the reactive power demand of the double fed induction generator (DFIG), which varies with the load. Diesel and hydro generators have to supply the reactive power to these generators in addition to the active and reactive power of the system. In scenario B the amount of diesel and hydro units is smaller which results in a higher deviation of reactive demand.

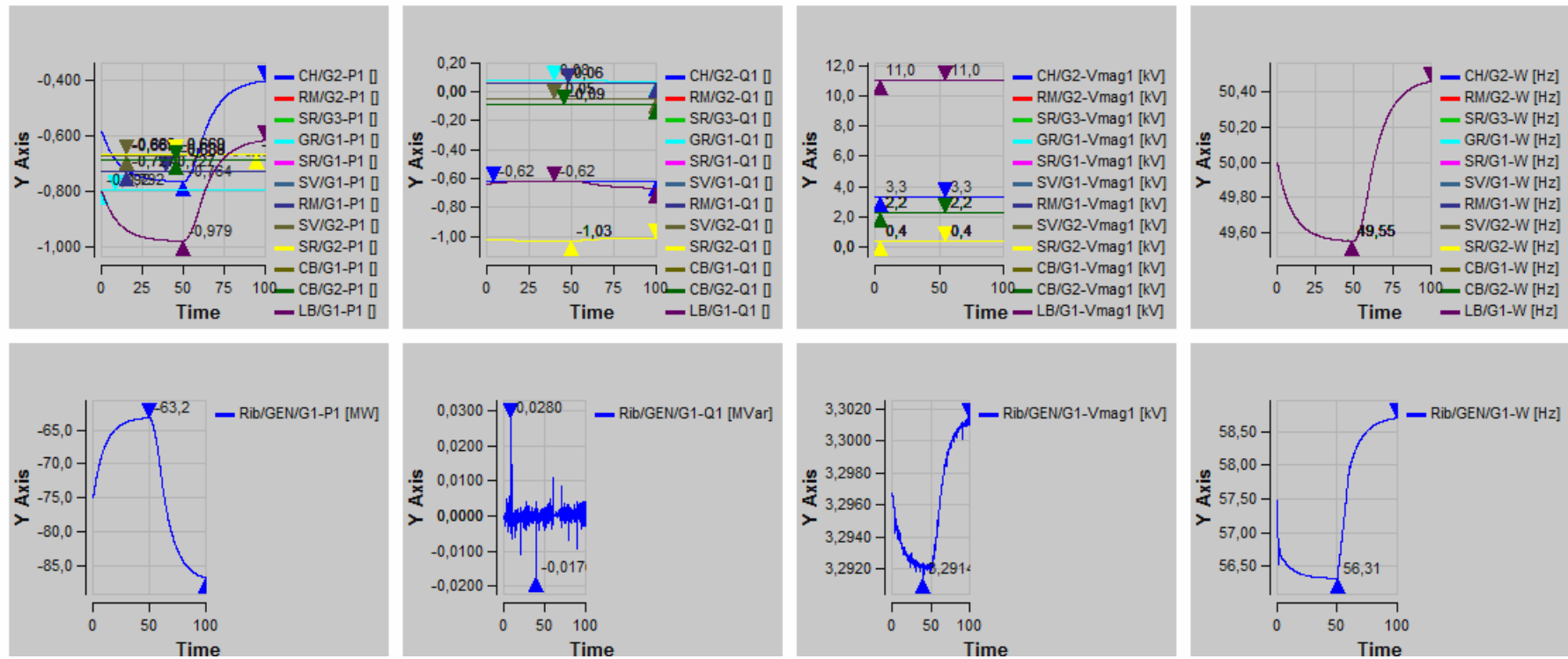


Figure 6.4.: Scenario A, 15% wind speed drop

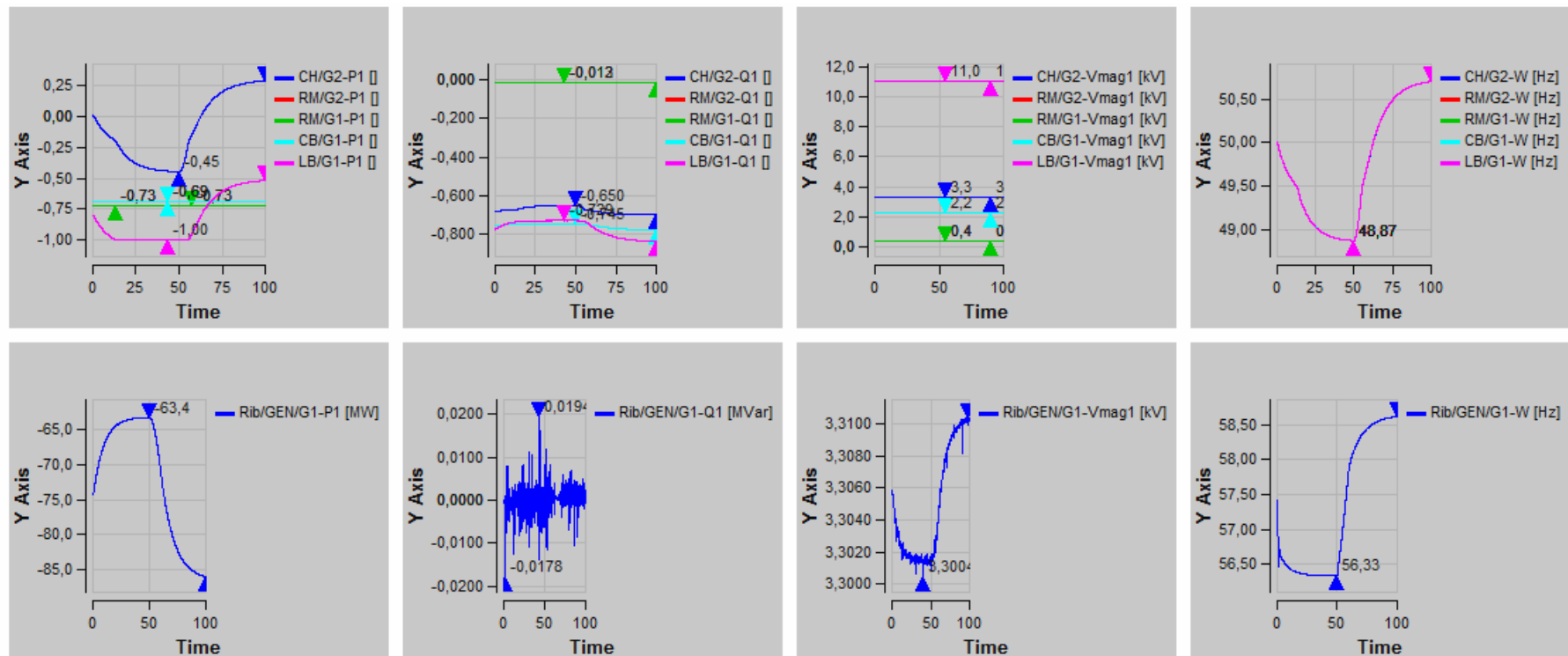


Figure 6.5.: Scenario B, 15% wind speed drop

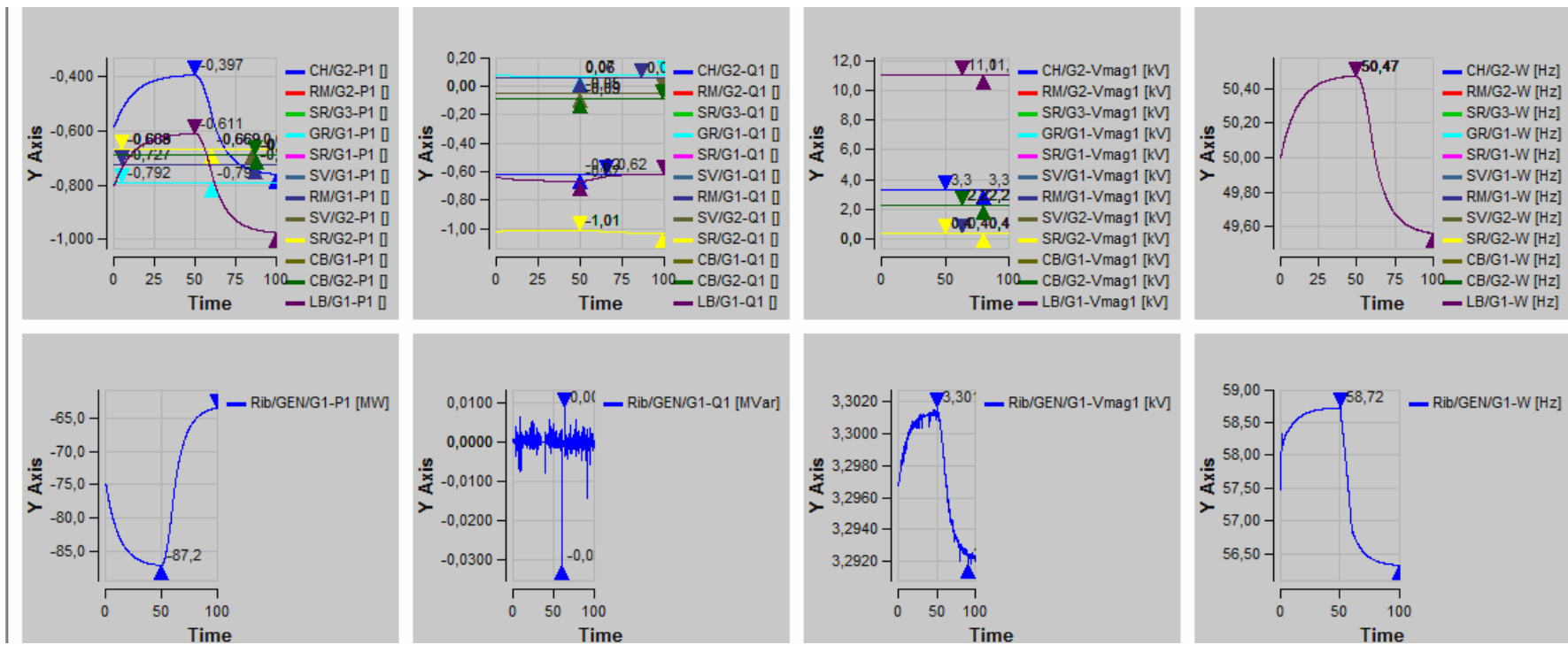


Figure 6.6.: Scenario A, -15% wind speed drop

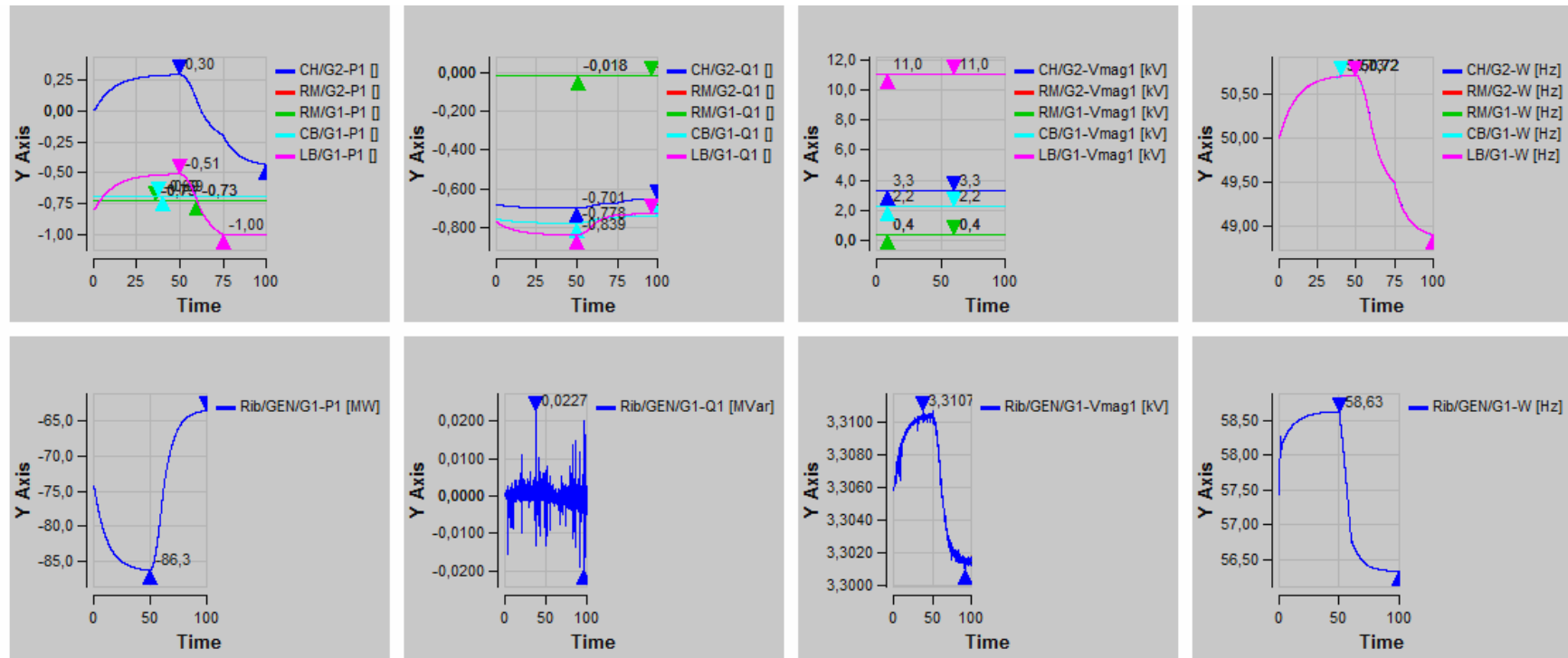


Figure 6.7.: Scenario B, -15% wind speed drop

6.2.2. Active load variation

The transient response was analyzed for an active load variation at Cane Hall feeder. The results are shown in figure 6.8 to 6.11. It was simulated that after one second the active load of feeder Cane Hall suddenly increases for about 20% from 9,000kW to 10,800kW, or decreases by 20% to 7,200kW, respectively. In the simulation, the power factor stays constant at 95%. The load change is equal to a 10% load increase or decrease of the overall system.

As the active load increases, the frequency of the synchronous generators drops. The frequency deviation causes an impact of the diesel governors. The governors increase the fuel injection as well as the active power output of the diesel units LB/G1 and CH/G2. Scenario A, 50% wind and 50% diesel+hydro power, and scenario B, 70% wind and 30% diesel+hydro power, remain stable after 20 seconds of simulation.

Further simulations with higher active load variations show that higher wind penetration has no negative impact on the active load variation robustness. The generators first remaining instable are the hydro units RM/G1 and RM/G2. The induction generators absorb the load variation better due to their slippage than the synchronous generators of the hydro units. As soon as sufficient spinning reserve is supplied, power quality problems are not likely to be caused by the active power variation.

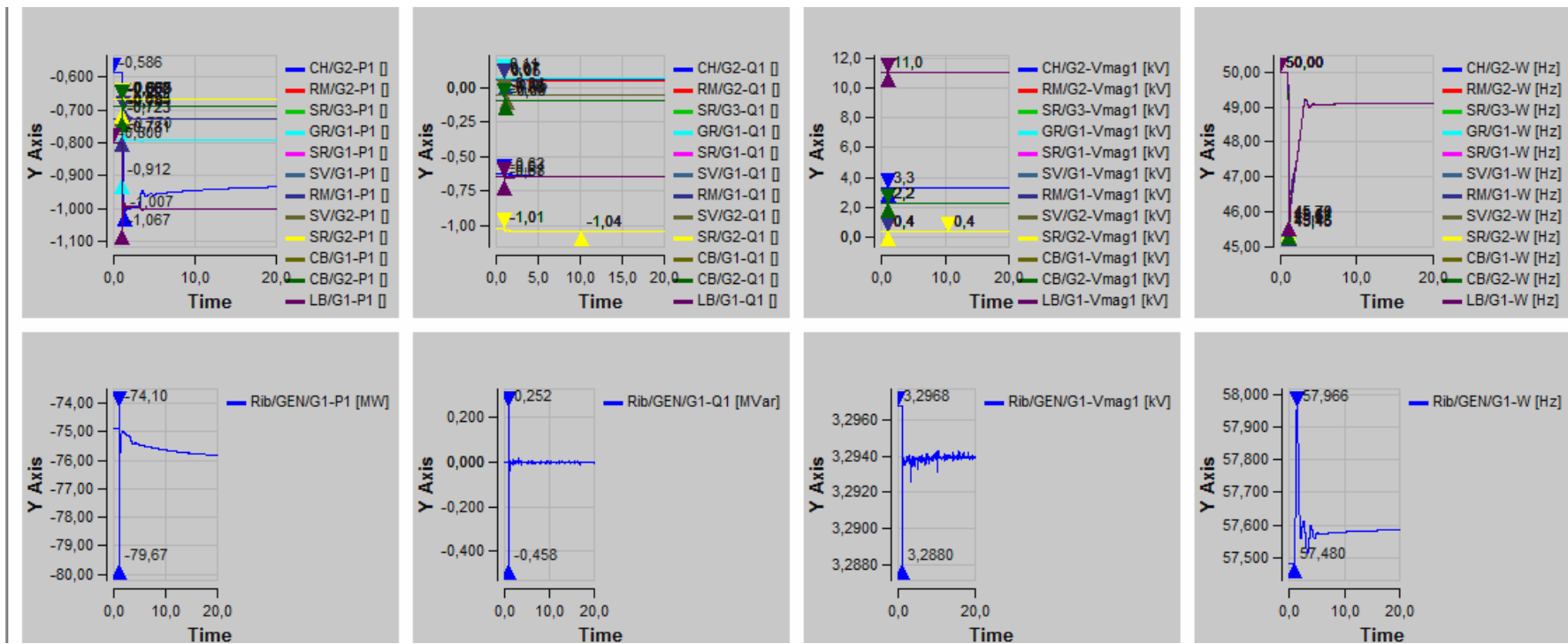


Figure 6.8.: Scenario A, +20% active power drop at Cane Hall

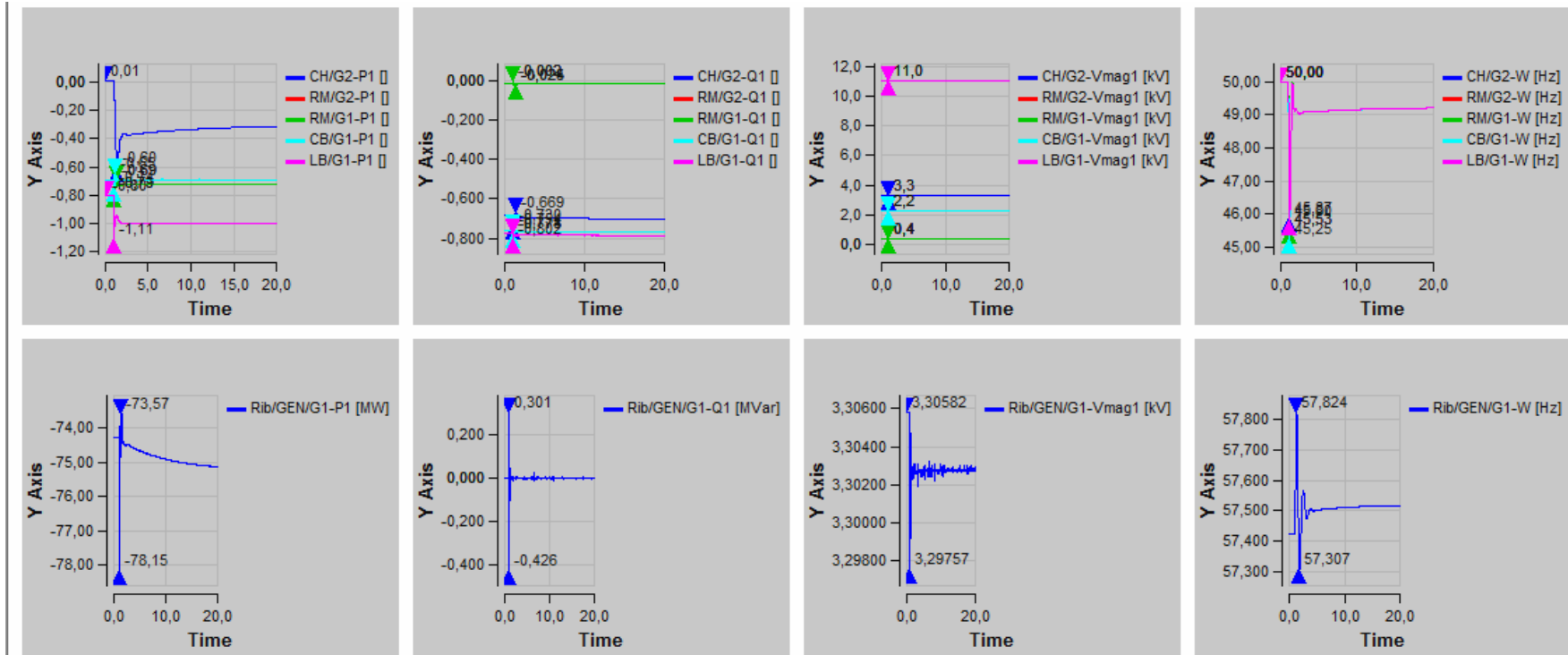


Figure 6.9.: Scenario B, +20% active power drop at Cane Hall

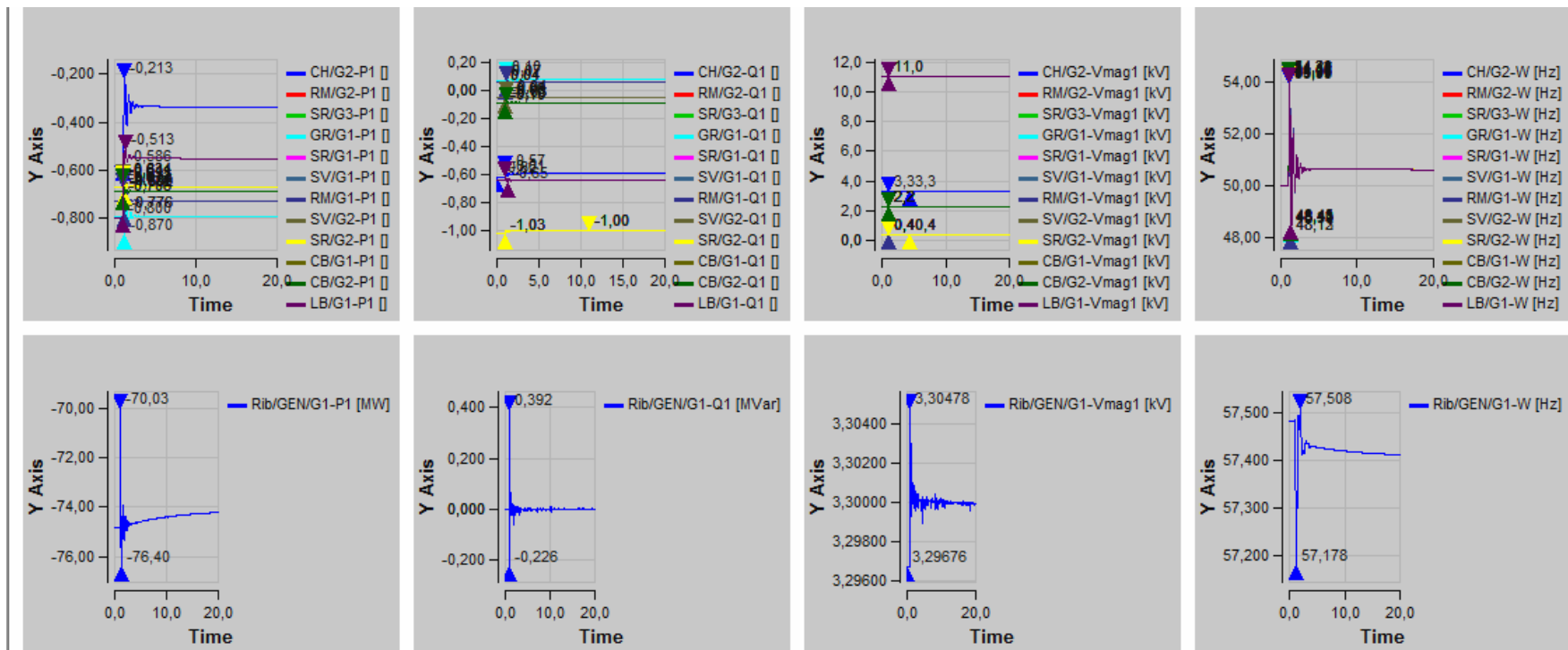


Figure 6.10.: Scenario A, -20% active power drop at Cane Hall

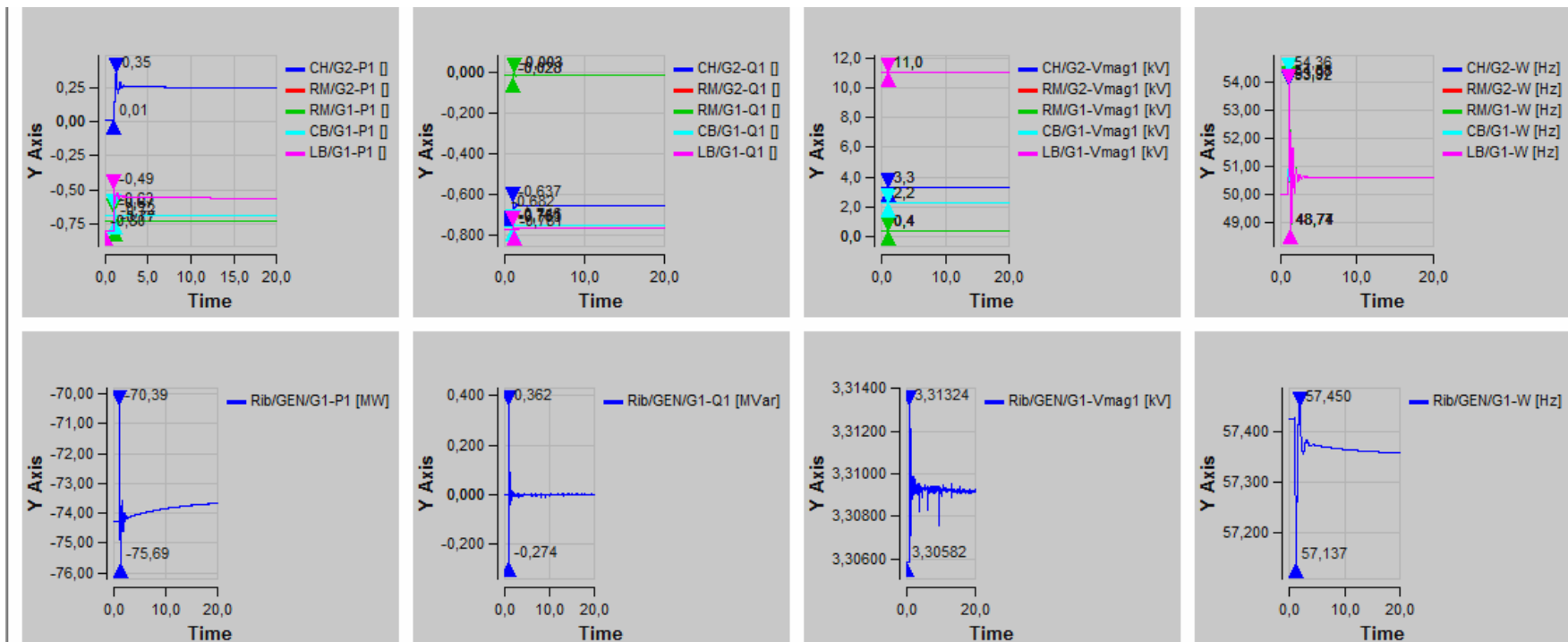


Figure 6.11.: Scenario B, -20% active power drop at Cane Hall

6.2.3. Reactive load variation

The transient response has been investigated for a reactive load change at Cane Hall feeder. The results are shown in figure 6.12 and 6.13. The reactive load of feeder Cane Hall suddenly increases by 20% from 3,000 kW to 3,600 kW, and after 10 Seconds by an additional 35% to 4,860 kW. The power factor changes from 95% to 92.8% to 89.9%. The change of reactive load can be caused by switching loads with a weak power factor.

As the reactive load increases, the reactive power contribution of the diesel units increases. The scenario A remains stable after 50 seconds of simulation. In scenario B the generator CB/G1 and the wind generators Rib/GEN/G1- 12 enter in an unstable situation, and the simulation aborts. In comparison to the synchronous generators of the hydro and diesel units the induction generators of the wind turbines are not able to change their reactive power output. The synchronous generators' reactive power supply is regulated by the exciter current. This causes a better control ability of scenario A. To enable a higher wind penetration a synchronous condenser could supply reactive power and support or replace the existing synchronous generators.

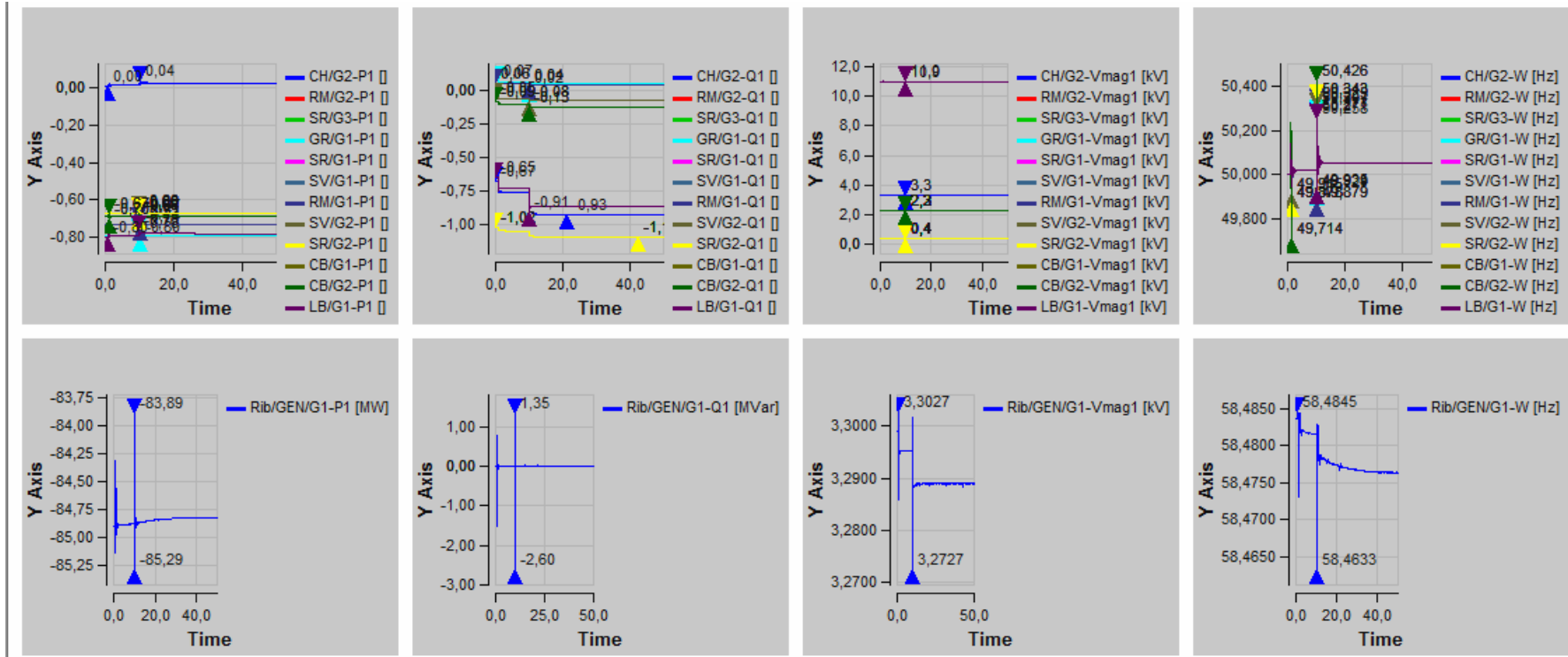


Figure 6.12.: Scenario A, 2 step reactive load increase (start: 3,000kW, 1 sec: 3,600kW, 10 sec: 4,860 kW)

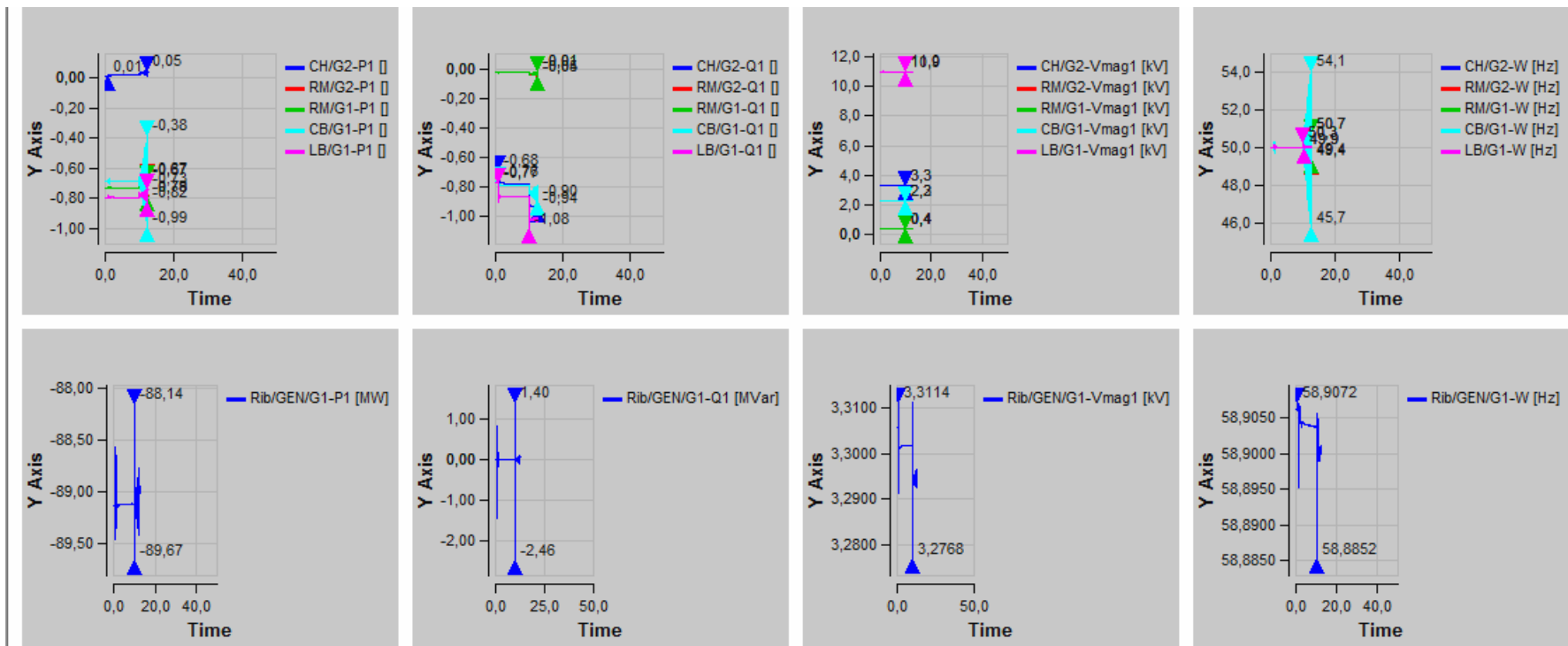


Figure 6.13.: Scenario B, 2 step reactive load increase (start: 3,000kW, 1 sec: 3,600kW, 10 sec: 4,860kW)

6.3. Wind generator concepts

The selection of the wind generator concept is critical for the impact on the power quality of the system. Several concepts provide different control abilities. The assessment of the wind generator impacts is based on a GIZ and DigSilent analysis of 2009 [17].

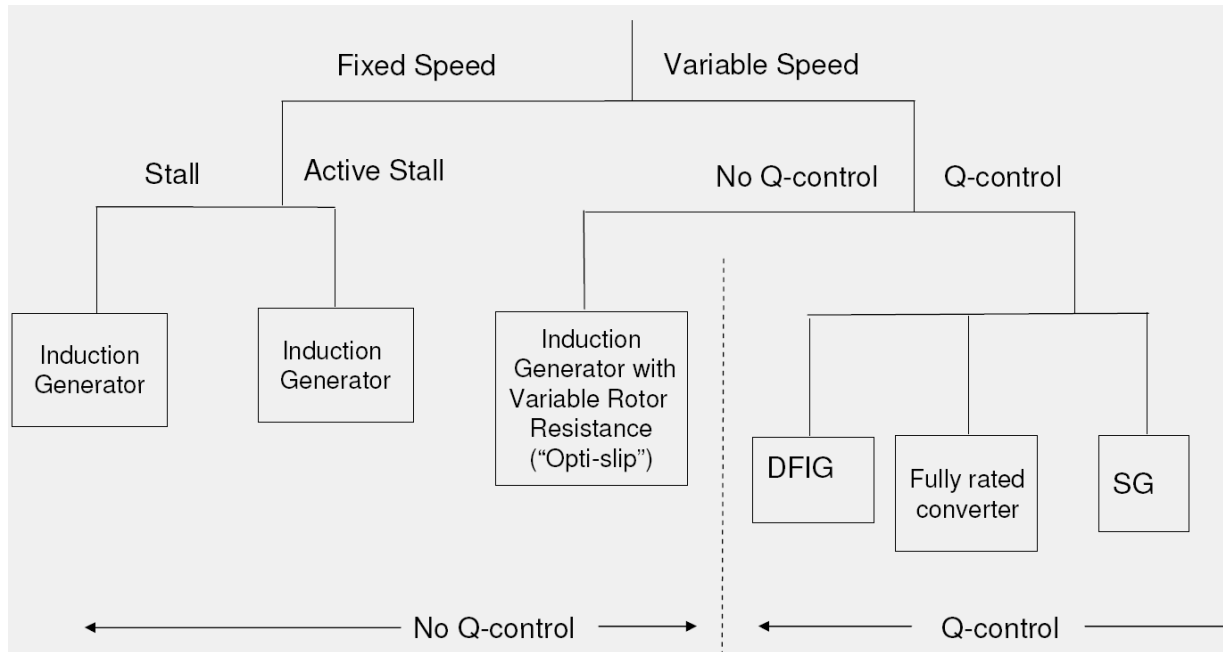


Figure 6.14.: Wind generator concepts with and without reactive power control (“Q-Control”)

Figure 6.14. shows the different wind generator concepts and their classification. The concepts are classified as variable and fixed speed concepts. They are also classified due to the stall control concepts and their reactive power control ability (“Q- Control”). The three existing concepts are passive stall, active stall and the pitch control. With a passive stall, the power of the wind turbine is limited by the aerodynamic characteristics of the turbine; active stall wind turbines limit their power additionally by decreasing the pitch angle. With pitch control the power of the wind turbine is limited by increasing the pitch angle.

The operation of fix speed wind turbines with passive stall is different to the operation of variable speed turbines.

Fix speed turbines start up with an open breaker if the wind speed is higher than the cut-in wind speed. After that, the breaker is closed and the turbine operates with a constant blade angle over the whole wind speed range. In case of large wind speeds the power is limited by the aerodynamic profile of the blade.

Variable speed wind turbines also start-up with open breaker if the wind speed is higher than their cut-in wind speed. They close their breaker and operate at the maximum power coefficient when wind speed is below the turbines rated wind speed. If the wind speed is above the rated limit they operate at a limited power output constraint by power electronics converter and pitching.

The main advantages of variable speed concepts are lower cut-in wind speeds, higher efficiency, especially at low wind speeds, and lower power variations compared to fixed speed turbines. The disadvantage is that they are more expensive. The use of induction generators is only possible at fix speed operation and requires stall control. Using an induction generator also requires additional reactive power compensation. The additional devices that are required for reactive power compensation can be thyristor switched capacitors (TSC) or static synchronous compensators (STATCOM). Because of the risk of dynamic voltage collapse, wind generators based on induction generators are typically asked to disconnect in case of voltage dips.

In the GIZ/ DigSilent workshop, four main concepts have been investigated regarding their behavior after a voltage drop in a high voltage system. The wind generator concepts that have been analyzed are

- direct coupled synchronous generator with variable gear box (SynG),
- fixed speed induction generator (IG),
- double fed induction generator (DFIG), and
- generators with fully rated converter/ direct drive (CDS).

The voltage drop to 80% of the rated voltage occurs for 1.5 seconds.

The results (figure 6.15) show that, depending on the concept, there is a significant impact on the power quality of the electrical grid. Since a generator with fully rated converter (CDS) regulates the voltage deviation very quickly, the synchronous generator with variable gear box (SynG) gets

more excited by the voltage dip and shows the highest oscillation in the active power compared to the other generators. The ability to deliver reactive power to the grid is strongly dependent on the wind turbine technology. According to their fault-ride-through behavior, the concept of DFIG and the fully rated converters are recommended for the use in weak electricity grids.

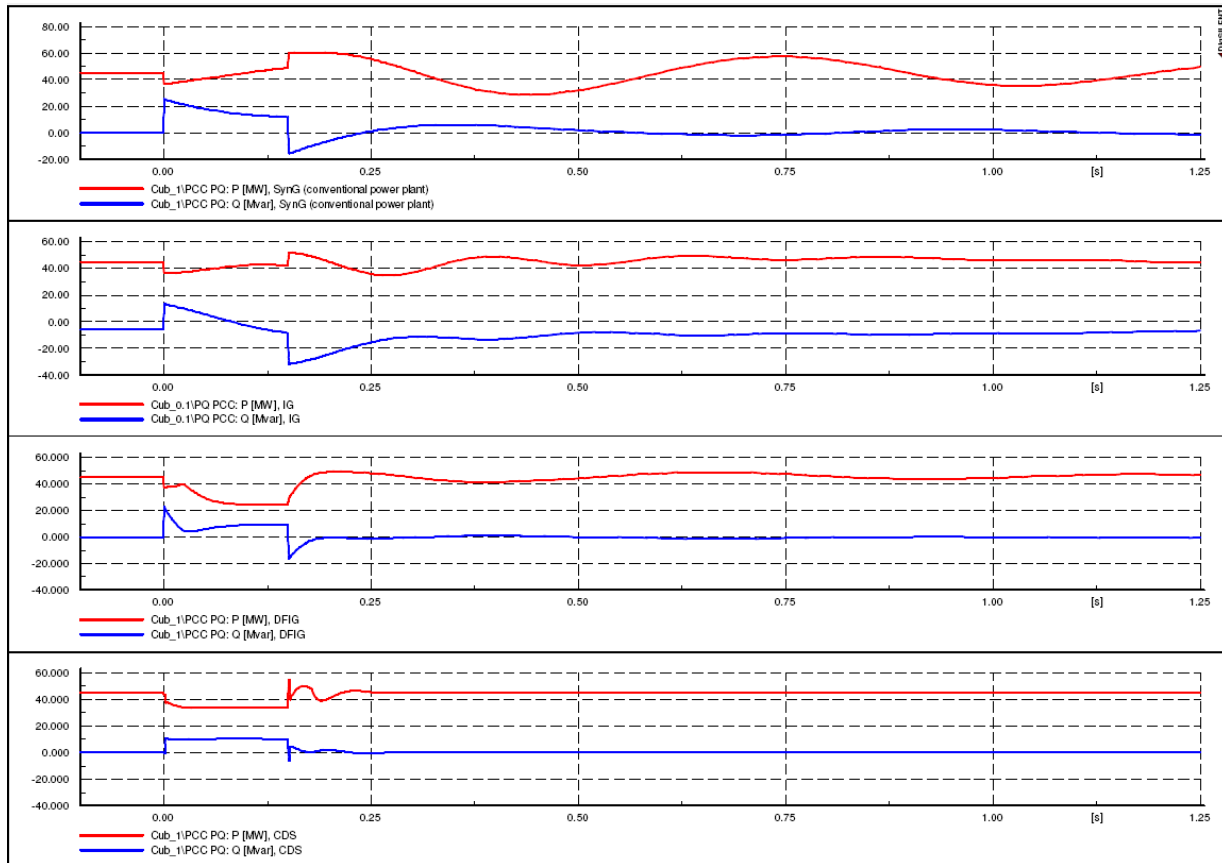


Figure 6.15.: Voltage dip on different wind generator concepts [17]

7. Conclusion - Recommendations for higher VRE penetration

The use of renewable sources to generate electrical energy in isolated EPSS may significantly affect the operational characteristic of the grid, the generation units and inevitably their performance reliability. This study describes the main constraints for VRE in St. Vincent’s EPSS according to the reliability and power quality. An Excel based methodology has been developed to calculate the possible VRE penetrations regarding the constraints. For each constraint, a strategy to circumvent the limitations has been described in chapter 5. The strategies require technical and/or operational changes. Each change requires, beside specific investment cost, a specific time for implementation and operation within the system. Hence, they are broken down into three groups: short, mid and long term measures.

The objective is to maximize the VRE penetration rate in the EPSS. To achieve this, the following is recommended:

- Wind turbine: the wind generator should have a minimal impact on the power quality. Hence, the generator concept is critical and has to be chosen carefully. According to the assessment of chapter 6.3. According to their fault-ride-through behavior, the concept of DFIG and the fully rated converters are recommended for the use in weak electricity grids.
- Wind park connection: Results in other studies have shown that voltage fluctuations in cases of disturbances or grid faults are less with higher reactance resistance ratios (X/R ratio) of the grid. Therefore the wind park should be connected to a “strong” point in the network with high interconnection. Transmission systems have higher X/R values compared to distribution systems. This causes less efforts for reactive power control to support the voltage level [7]. Hence, a connection point to the 33kV transmission system e.g. at Cane Hall S/S would provide a higher grid strength than a connection to the 11kV system.
- Dispatchable hydro operation: The dispatch hydro operation like it is in St. Vincent’s EPSS is based on the daily demand curve. The output power of the dispatch unit is increased in the hours of maximum demand. The penetration of VRE can be increased if the operation

of the dispatch hydro units is not driven by demand but by the variable generation. Dispatch hydro operation should be based on the weather and VRE yield forecast. During high VRE penetration the hydro dispatch units should not provide active power but spinning reserve. That would reduce the spinning reserve demand of the dispatch diesel units in Cane Hall. The VRE penetration limit would increase. To use this advantage the amount of dispatchable hydro units should be as high as possible. One option could be to use the reservoir of the South river power plants for dispatchable operation.

- Diesel unit properties: Diesel units that have to be replaced should be peaker instead of base load units. New diesel units should be capable for low load operation to allow a maximum spinning reserve supply during high VRE penetration. For a more flexible operation of multiple diesel generator sets, smaller diesel units should be chosen.
- VRE forecast: Weather forecast would allow a more precise VRE yield forecast. This is necessary to estimate the required spinning reserve due to VRE sources. The VRE spinning reserve criteria C and D are based on the worst case VRE power outage. A precise forecast would allow reducing this reserve and especially the secondary reserves. Additionally a forecast system would allow operating the hydro dispatch unit according to the VRE yield instead of demand. A forecast system would also be necessary in later setups for a “diesel switched off” operation based on storage systems. To assess and manage the diesel backup systems, a forecast system is necessary to estimate the need for further capacities under long periods of low VRE penetration and low storage conditions.
- Grid code: Currently no grid code exists for the St. Vincent’s EPSS. A grid code that defines the requirements for VRE sources assures that the installed VRE technologies are based on recent technology regarding e.g. fault-ride-through behavior or reactive power supply. This is important for the TSO, otherwise the VRE units cause additional risk of power outages during grid faults like voltage dip or short circuits. A grid code should at least define the compensation of the wind turbine’s own reactive power demand, the reactive power supply in dependency of the voltage dip and the maximum power output of VRE units.

- Synchronous condenser: To allow “diesel off” mode, a synchronous condenser is required to contribute reactive power and control the voltage. In a standard parallel operation reactive power and voltage control is done by the diesel generators.
- Battery storage: As long as no storage capacity is available, the maximum penetration of all generating units is limited by the maximum demand. Hence, the use of storage like pumping hydro or batteries disconnects the power penetration from demand. “Diesel off” mode is only possible if storage facilities compensate the fluctuation of VRE generation caused by their variability. In case of a diesel off mode the “battery” controls the frequency.
- Flywheel storage: Flywheel storages reduce the short term fluctuation in the energy flow caused by wind or solar variation and improve the life time of batteries. In combination with batteries as long term storages, flywheels reduce the fluctuation in power, voltage and system frequency and improve the power quality and reliability.

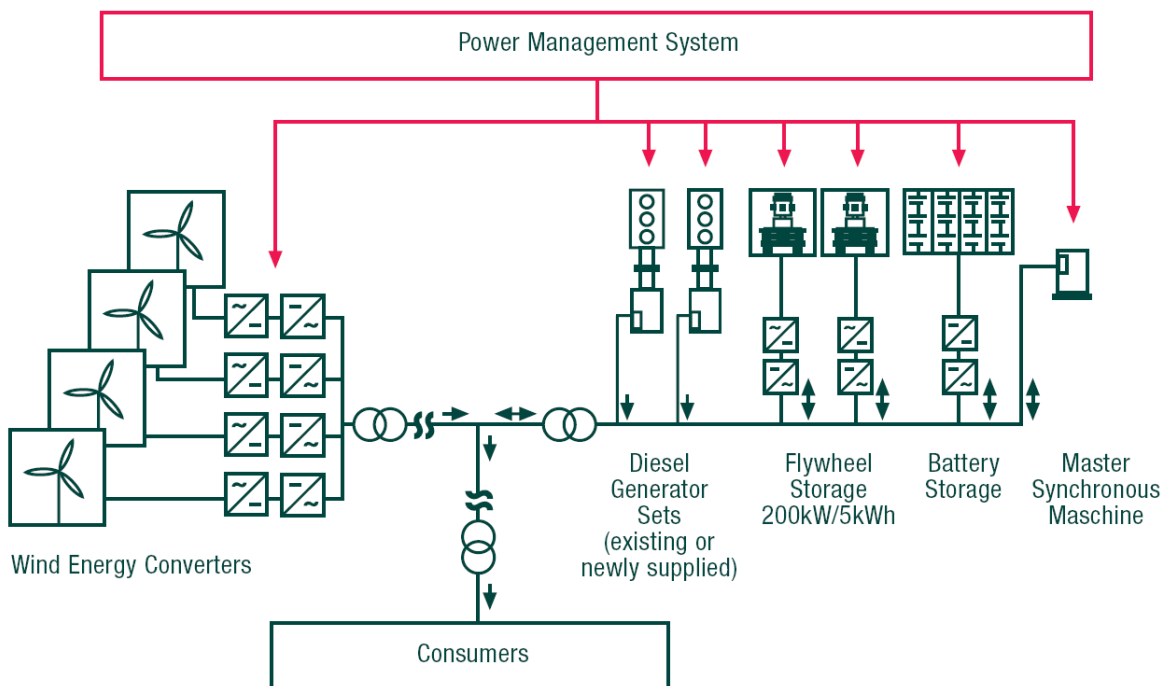


Figure 7.1.: Full integrated wind diesel system [Source: Enercon]

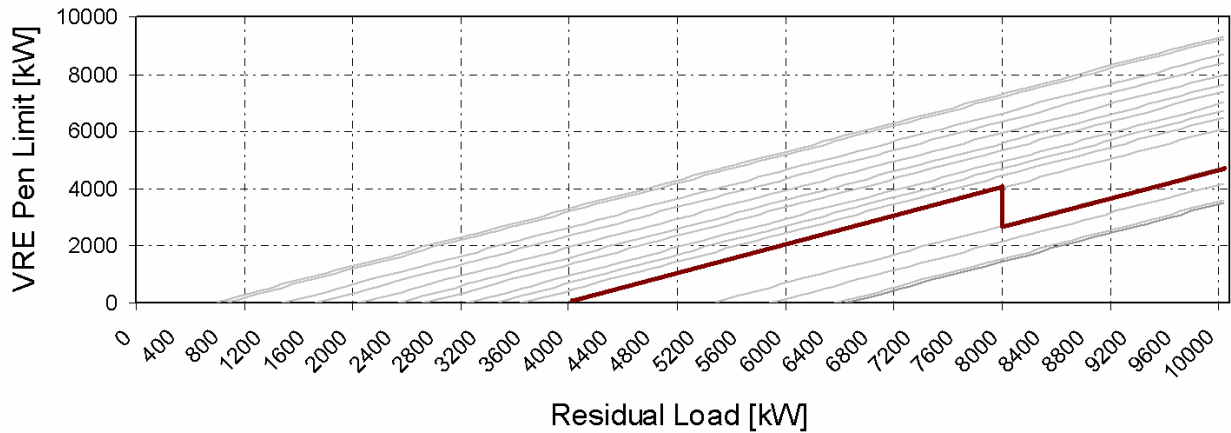


Figure 7.2.: VRE penetration limit (red line) for recent EPSS (required Spinning reserve (SpR) 4,000kW)

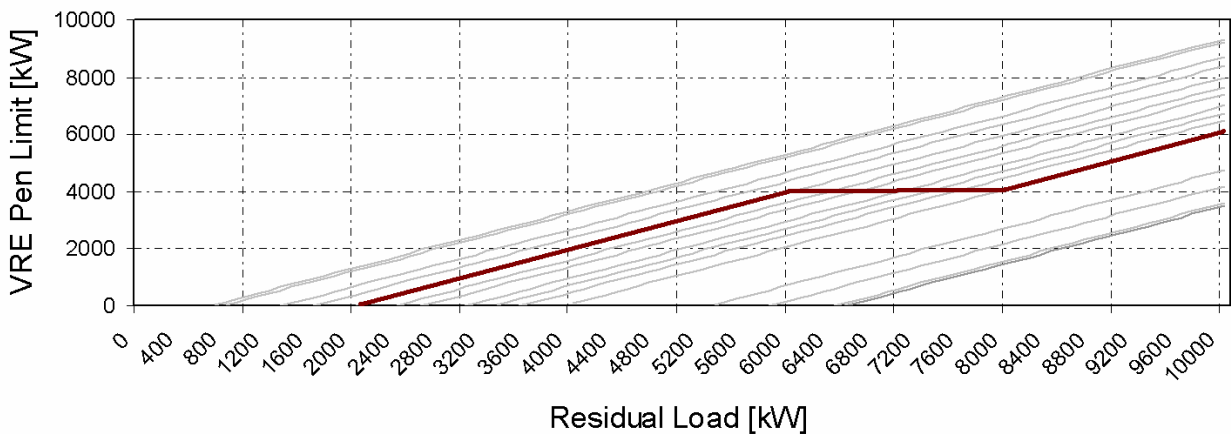


Figure 7.3.: VRE penetration limit (red line) for low load diesel (25% loading) (required SpR 4,000kW)

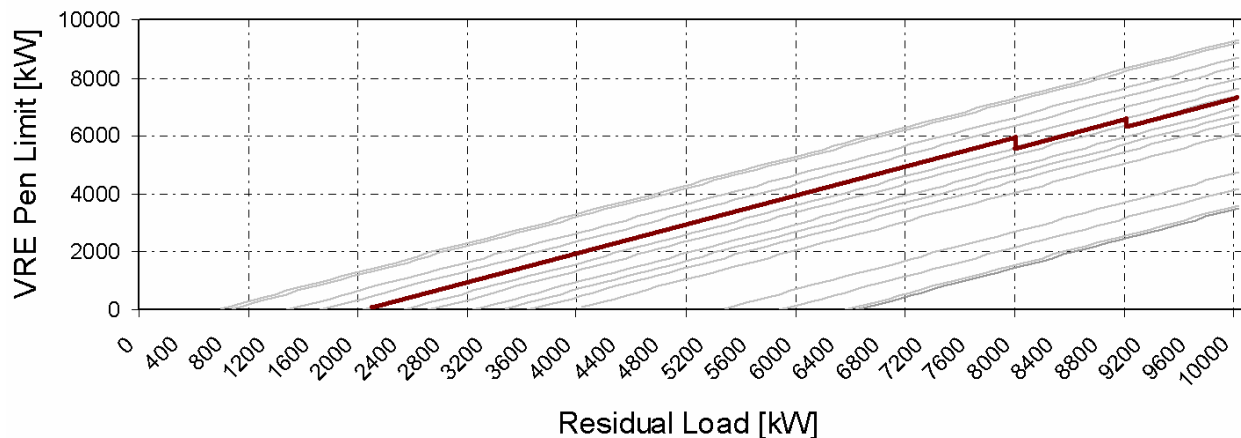


Figure 7.4: VRE penetration limit (red line) including synchronous condenser (MSM) (required SpR 4,000kW)

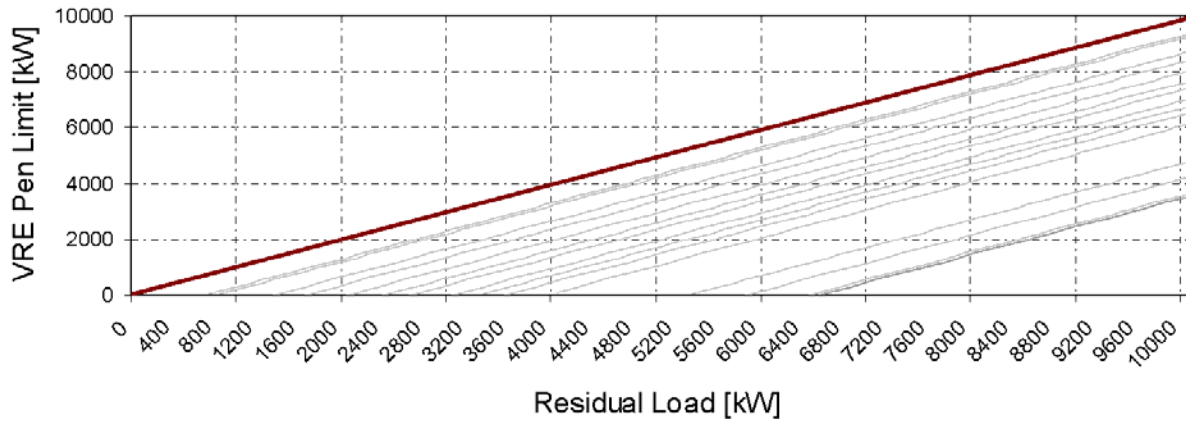


Figure 7.5.: VRE penetration limit (red line) including idling diesel and MSM (required SpR 4,000kW)

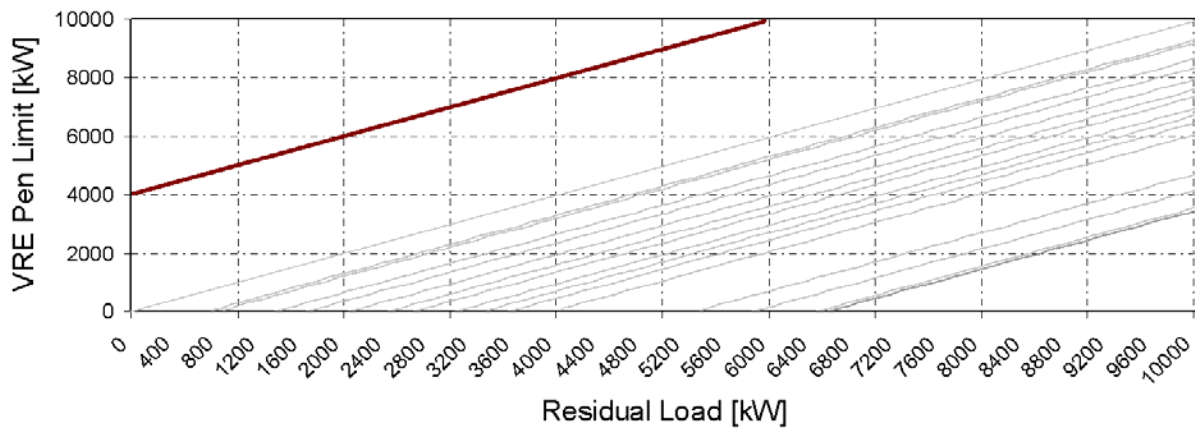


Figure 7.6.: VRE penetration limit (red line) including storage (battery, flywheel), MSM (required SpR 4,000kW)

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Annex

Machine Constant	Turbo Generator	Hydro Generator	Synchronous Condensor	Synchronous Motor
X_d	1.1	1.15	1.80	1.20
X_q	1.08	0.75	1.15	0.90
X'_d	0.23	0.37	0.40	0.35
X'_q	0.23	0.75	1.15	0.90
X''_d	0.12	0.24	0.25	0.30
X''_q	0.15	0.34	0.30	0.40
X_2	0.13	0.29	0.27	0.35
X_0	0.05	0.11	0.09	0.16
r_{sdc}	0.003	0.012	0.008	0.01
r_{sac}	0.005	0.012	0.008	0.01
r_2	0.035	0.100	0.05	0.06
T'_{d0}	5.6	5.6	9.0	6.0
T'_d	1.1	1.8	2.0	1.4
T''_d	0.035	0.035	0.035	0.035
T_a	0.16	0.15	0.17	0.15

Figure A.1: Induction of several generator types [Source: University Idaho]

Generation Type	Regulator V Max (pu)	Regulator V Min (pu)	V Rate of Change (pu/s)	Filter TC (s)	Exciter Gain	Exciter TC (s)	Ceiling Voltage (pu)	Min Voltage (pu)	Regulator Amplifier TC (s)
Hydro	6.000	na	na	0.020	1.000	1.000	2.727	na	na
Diesel	10.400	na	na	0.020	1.000	0.380	4.727	na	na

Generation Type	Exciter Sat @ 75%	Exciter Sat @ 100%	AVR Sat Factor	IEEE Model	Forward Gain	Forward TC (s)	Feedback Gain	Feedback TC (s)	Feedback Amplifier TC (s)
Hydro	1.100	1.200	na	2	400.000	0.020	0.100	0.800	1.000
Diesel	1.100	1.200	na	2	977.000	0.100	0.039	0.600	0.380

Figure A.2.: Automatic voltage regulation data [Source: VINLEC]

Figure A.3: Setup of generators in NEPLAN simulation [Source: VINLEC, University Idaho for blue digits]

	Richmond		Cumberland				South Rivers			Lowmans Bay				Cane Hall											
	RM/G1	RM/G2	CB/G1	CB/G2	SV/G1	SV/G2	GR/G1	SR/G1	SR/G2	SR/G3	LB/G4	LB/G2	LB/G3	LB/G1	CH/G2	CH/G3	CH/G4	CH/G5	CH/G7	CH/G8	CH/G9	CH/G10	CH/G11	CH/G12	
S_N [kVA]	687.5	687.5	581.25	581.25	800	800	1830	343.75	343.75	400	5375	5375	5375	5375	1577.5	0	4053.8	4062.5	1837.5	0	4725	1600	5250	1600	
U_N [kV]	400	400	2200	2200	2200	2200	2200	400	400	400	1100	1100	1100	1100	3300	0	1100	1100	415	0	415	11000	415		
P_{Nenn} [kW]	550	550	465	465	640	640	1464	275	275	320	4300	4300	4300	4300	1262		3243	3250	1470		3780	1280	4200	1280	
P_G [kW]	555	550	465	465	535	535	1650	230	230	250	3000	3000	3000	3000	1420	3650	2200	2200			2800		3200		
Q_G [kVAr]	-168							150	150	174	188	200			680	1770	770	770			1448		1500		
cos phi	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
n_{nenn} [rpm]	600	600	1000	1000	1000	1000	1500	750	750	750	750	750	750	750	750	600	600	1500			750	1500	750	1500	
P_{min} [% P_{Nenn}]	50	50	0	0	0	0	0	50	50	50	91.8	91.8	91.8	91.8	0		91.8	91.8	0		91.8	0	91.8	0	
P_{max} [% P_{Nenn}]	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130		130	130	130		130	130	130	130	
X_d [%]	185.507	185.507	239.057	239.057	239.057	239.057	100.000	####	####	####	26.887	26.887	26.887	26.887	95.117	39.314	46.793	46.793	178.909	####	28.402	178.909	34.286	178.909	
X_q [%]	75	75	75	75	75	75	75	75	75	75	108	108	108	108	108	108	108	108	108	108	108	108	108	16.571	108
X_d' [%]	46.377	46.377	33.670	33.670	33.670	33.670	10.929	84.302	84.302	72.500	4.151	4.151	4.151	4.151	19.658	4.754	9.645	9.645	11.883	28.000	6.116	11.883	5.771	11.883	
X_q' [%]	75	75	75	75	75	75	75	75	75	75	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
X_d" [%]	28.986	28.986	23.569	23.569	23.569	23.569	6.557	63.954	63.954	55.000	2.461	2.461	2.461	2.461	12.048	3.886	5.427	5.427	8.33333	17.333	4.508	8.33333	3.84762	8.33333	
X_q" [%]	34	34	34	34	34	34	34	34	34	34	15	15	15	15	15	15	15	15	15	15	15	15	15	4.81905	15
X₍₂₎ [%]	29	29	29	29	29	29	29	29	29	29	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
X₍₀₎ [%]	18.841	18.841	22.000	22.000	21.886	21.886	7.104	37.791	37.791	32.500	0.441	0.441	0.441	0.441	8.561	5	4.144	4.144	6.68724	17.333	3.556	6.68724	1.94286	6.68724	
R₍₀₎ [%]	12	12	12	12	12	12	12	12	12	12	5	5	5	5	5	5	57	57	5	5	57	5	5	5	5
XI [%]	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
T_{d0}' [s]	2.500	2.500	3.000	3.000	7.100	7.100	9.150	2.500	2.500	2.500	3.770	3.770	3.770	3.770	3.190	3.975	4.630	4.630		1.320	4.270		7.630	3.6	7.630
T_{d0}" [s]	0.024	0.024	0.270	0.270	0.057	0.057	0.067	0.020	0.020	0.020	0.044	0.044	0.044	0.044	0.020	0.084	0.057	0.057	0.056	0.040	0.040	0.056	0.040	0.021	0.056
T_{d0}' [s]	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
T_{d0}" [s]	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060
T_d' [s]	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.800	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
T_d" [s]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
T_d' [s]	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
T_d" [s]	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
R_{Stator} [OHM]	0.725	0.725			0.842	0.842	0.273	1.453	1.453	1.250					0.317	0.123	0.123	0.123		0.667	0.106		0.257	0.257	
R [OHM]	0.417	0.417	0.292	0.292	0.313	0.313	0.250	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.396	0.458	0.458	0.458		0.458		0.250	0.458	0.250	
T_J [s]	0.320	0.320	0.012	0.012	0.028	0.028	0.082	0.016	0.016	0.020	0.204	0.204	0.204	0.204	0.072	0.192	0.178	0.178		0.036	0.208		0.086	0.232	
H [s]	0.160	0.160	0.006	0.006	0.014	0.014	0.041	0.008	0.008	0.012	0.204	0.204	0.204	0.204	0.036	0.099	0.089	0.089		0.018	0.104		0.043	0.116	

	Load [kW]	Power Generation											
		Base Load				Variable				Flexible			
		High-Merit/ Base-Load	Combustion [kW]	Hydro Base Load [kW]	Geothermal Power [kW]	Wind	PV	Hydro	Combustion				
				Wind Power [kW]	PV Power [kW]	Mid-Merit	Hydro Dispatchable/ Reservoir [kW]	Low-Merit/ Peaking	Combustion [kW]				
P _{load,min}	11545	Rated capa [kW]	3440	2240	0	No of Turbines []	4.92	inst PV [m2]	32750	Rated capa [kW]	3674		
P _{load,Avg}	15924	Installed [kW]	4300	2800	0	Installed [kW]	3690	Installed [kW]	3930	Installed [kW]	3674	Max Requ [kW]	8759
P _{load,Peak}	20465	Amount of Peak [%]	16.81	16.81	0.00	Amount of Peak [%]	18.03	Amount of Peak [%]	15.36	Amount pf Peak [%]	17.95	Amount of Peak [%]	19.82
		Spinning Reserve [%Un]	20.00			Peak Limit [%]	100			SpinRes Supply [%]	100		
		Spinning Reserve [%]	4.20		0.00					Spinning Reserve [%]	0.00		
		Penetration [%]	21.60	14.07	0.00	Penetration [%]	23.20	Penetration [%]	5.82	Penetration [%]	11.30	Penetration [%]	24.01

BLGen No[] night	1	Comb- BL night [%]	80	Geoth - BL [%]	80
BLGen No[] day	1	Comb- BL day[%]	80	Avg Res Load [kW]	3824
Idle [0-OFF, 1-ON, 2-ON]	0	Hydro BL [%]	80	ResLoad, Min [kW]	2039

Spinning Reserve - Max Requ [kW]	CR A 10% Pload	2047	Spin Res Requ [kW]	3440
	CR B Largest unit	3440	Min Out of Prat[%]	50.00
	CR C Wind slack	3336	Min Out Requ [%]	50.00
	CR D Solar slack	2338	Storage/ Dem mngt	no need
	CRC>CRB	CRB min	CRD>CRB	CRB min

Load per Feeder	KT-25% PF88.3	CH-50% PF95	SR-15% PF99.6	LB-10% PF84.8
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MaxΔResL [kW/min]	36.2	MinΔResL [kW/min]	-85	MaxΔPower [kW/min]	202	MinΔPower [kW/min]	-403
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Wind inst Pen [%]	32
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PV inst Pen [%]	16.85
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Abs Pen [%]	100
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Total RE Pen [%]	54.38
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Wind speed	STRONG BREEZE
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Healthy MaxΔ	Healthy	Healthy MinΔ	Healthy
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Index:	Setup	Dispatch	Non-Disp
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Figure A.4: Extract of insert panel of Excel based methodology

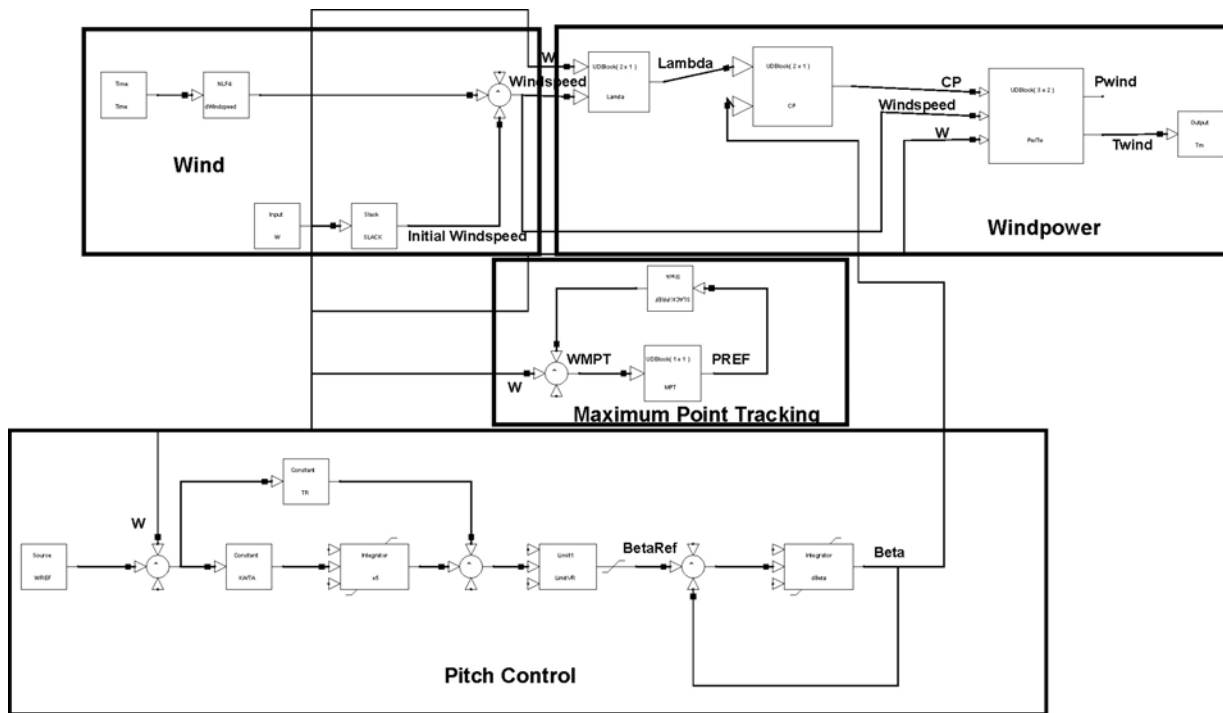


Figure A.5: NEPLAN model for DFIG Turbine [Source: NEPLAN]

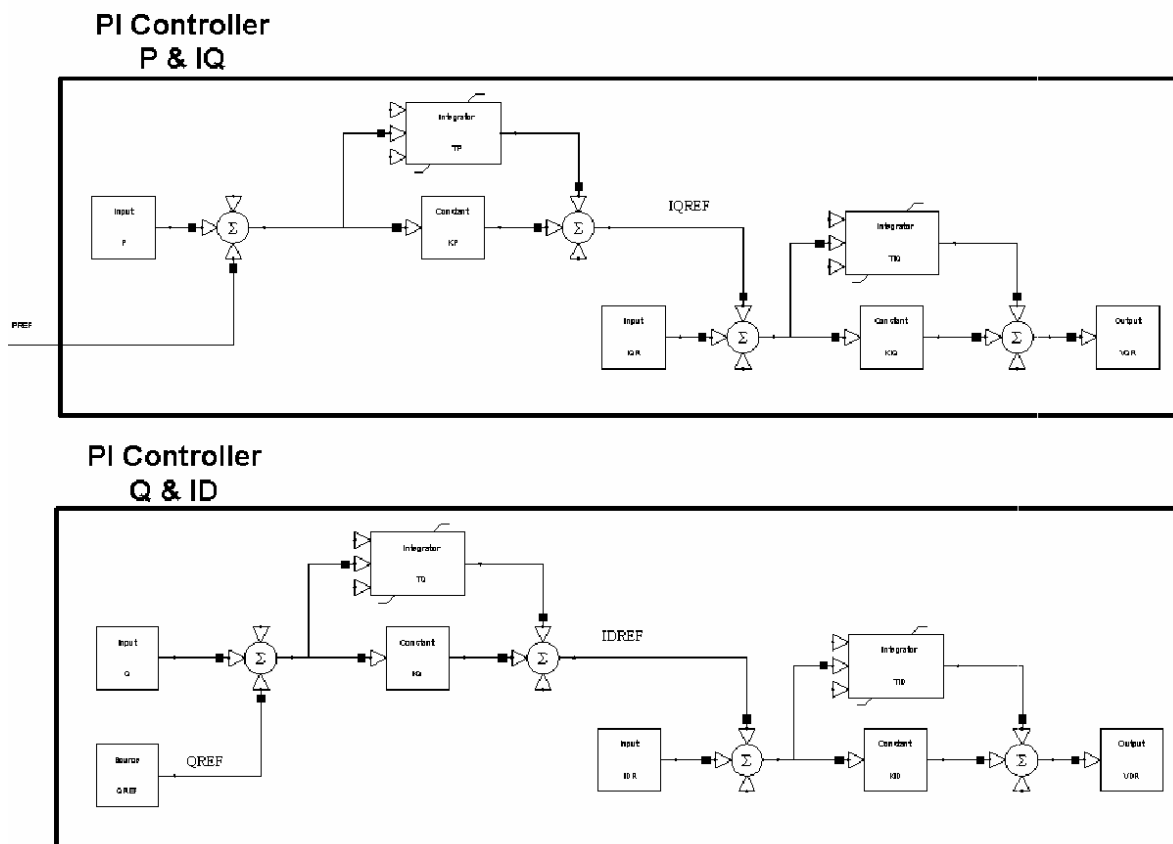


Figure A.6: NEPLAN model for DFIG governor [Source: NEPLAN]

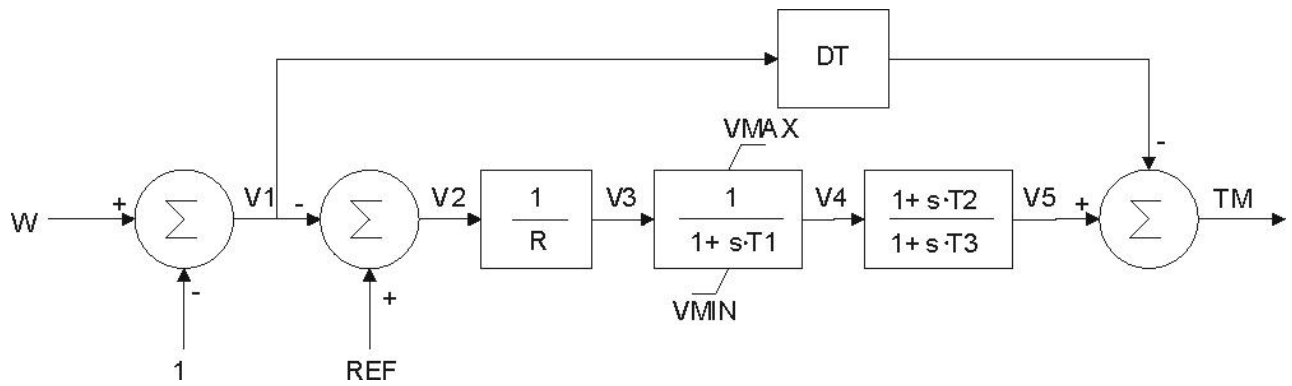


Figure A. 7: NEPLAN model for governor TGOV1 [Source: NEPLAN]

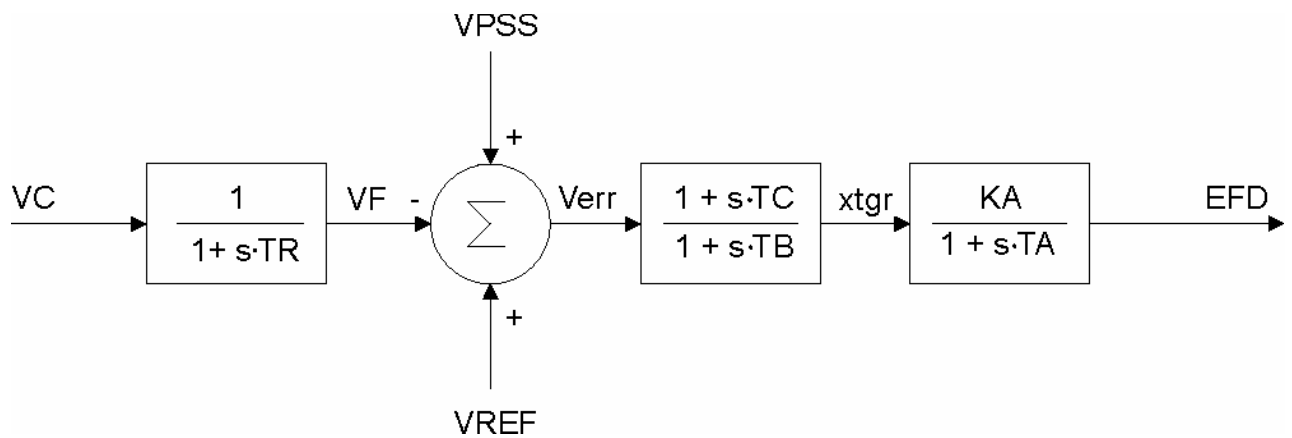


Figure A. 8: NEPLAN model for AVR exciter simple [Source: NEPLAN]