Dynamic Study of Bonaire Island Power System: Model Validation and Project Experience

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***Abstract*—Bonaire island, part of the Netherlands Antilles, is located off the north coast of South America near the western part of Venezuela. The power supply on Bonaire is characterized by a high penetration of wind energy. The contribution on a yearly average is more than 40% and on the peak days the contribution rises up to even 70% of the total generated energy. As a small and closed power system without continental inter-connection, the power supply on Bonaire is facing many interruptions predominantly due to the short circuit faults in the 12 kV distribution system. To improve the power system reliability on Bonaire island, DNV GL was requested to advise on the practical system performance enhancement measures. In this article, the dynamic model validation against a 12 kV three phase fault and single phase to ground fault is performed. Furthermore, the transient dynamic system study results are discussed for the critical scenario with the maximum wind energy production. Eventually the improved protective relay settings as well as the wind turbine controller settings are proposed and confirmed by the dynamic simulation results under the same scenario.**

Keywords: Airco Load, Dynamic Model Validation, Load Shedding, Inertia

I. Introduction

Bonaire island, part of the Netherlands Antilles, is located off the north coast of South America near the western part of Venezuela. The power supply on Bonaire is characterized by a high penetration of wind energy. The contribution on a yearly average is more than 40% and on the peak days the contribution rises up to even 70% of the total generated energy. As shown in Fig. 1 the Diesel power plant as well as the battery energy storage system (BESS) are located at the Northwest coast of Bonaire island while the wind farms Morotin 1 and 2 are installed at the Northern coast. The 30kV distribution backbone is shown as the thick black line, extending to the load center distribution substations at DEN LAMAN, STAD, INDUSTRIAL TERRAIN and WEB NOBO.

The power supply on Bonaire is facing many interruptions with consumers disconnected for several hours. In the past 6 years, several events, dominantly short circuit faults in the 12 kV distribution system, resulted in load shedding or sometimes led even to a blackout. Analysis of the events indicate that during the fault the power output of the wind farm drops to nearly zero, while at the same time the power demand of the power system increases. The system frequency plummets rapidly and the frequency based protection load shedding scheme is triggered to prevent a black-out. A major part of the consumers is disconnected and reconnection may take 1-3 hours, depending on time and location.

Fig. 1. Bonaire Island Power System Overview

To improve the power system reliability on Bonaire island, DNV GL was requested to advise on the practical system performance enhancement measures based on the historical fault records and available system data. To address the challenges on the Bonaire island power system, DNV GL performed a dynamic computer model simulation study. The Bonaire power system, including the ContourGlobal generation at Karpata and Morotin, the 30 and 12 kV network and the system load was modelled in the network simulation software PowerFactory 15.2. Also, dynamic models of the generation controllers and load shedding scheme were included. In addition to the system load model, the air-conditioning units were modelled since these can behave disastrous during system recovery.

The rest of this article is organized as follows: Section II provides the Bonaire power system single line diagram (SLD), where major system components such as wind power

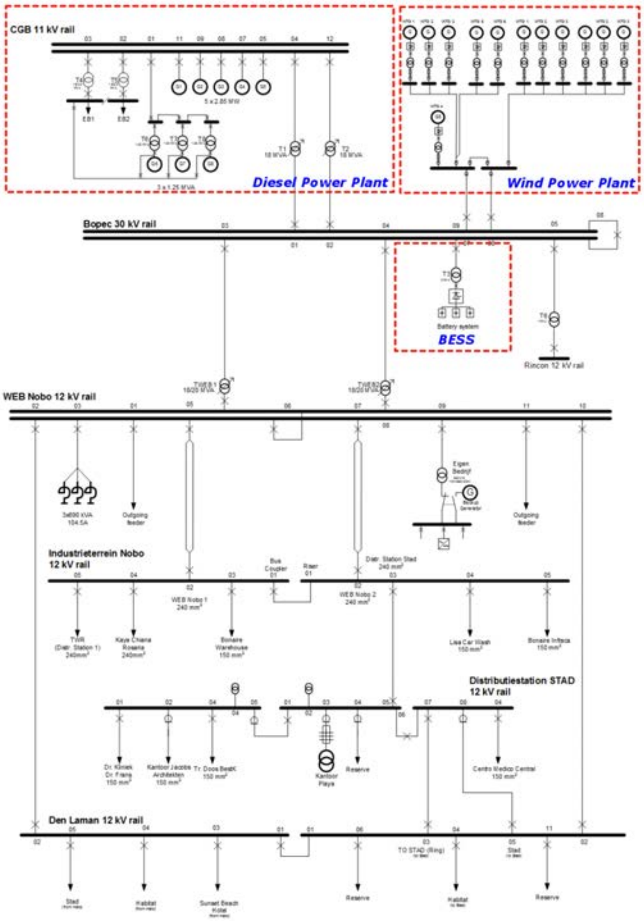


Fig. 2. Bonaire Island Power System Overview Single Line Diagram

plant, diesel power plant, battery energy storage system, and 30/12 kV distribution grid are shown. Following the overall Bonaire island power system description, Section III demonstrates the dynamic model validation against an actual three phase and single phase to ground fault record. The dynamic study results are summarized in Section IV with key findings. Conclusions are drawn in Section V.

II. System Description

The power supply on Bonaire is characterized by a high penetration of wind energy. Currently 5 diesel generators (total capacity 14MW) and 12 wind turbines (total capacity 10.8MW) operated by ContourGlobal generate electricity for Water and Electricity Bonaire (WEB). The power plant includes 5 diesel generators of 2.85 MW each, 3 backup diesel generators of 1 MW each, located at Karpata, and 12 wind turbines of 0.90 MW each located at Morotin. Power is transferred from Karpata to load centre Kralendijk over 15 kilometres by 30kV cables and stepped down to the 12 kV load centre connection. The main distribution voltage is 12 kV. Fig. 2 gives an overview of the Bonaire power system.

III. Dynamic System Model and Validation

To study the dynamic behavior of the Bonaire island power system, a dynamic RMS model was built in Powerfactory 15.2 on the basis of the static vision power system model of WEB Bonaire [1]. The dynamic model is validated by comparing the voltage and the frequency simulation results during the short circuit events with the fault recordings of same events in the past. Special attention is given to the dynamic model of the system load, in particular the non-linear behaviour of the wide-spread air conditioning units.

Three Phase Fault Model Validation

A 12 kV feeder three-phase fault incident record was used to validate the computer model dynamic behavior. Fig. 3 and Fig. 4 demonstrate the overall system frequency and voltage response following a three-phase fault at the 12 kV feeder. In this incident, the frequency drop has caused the activation of the under frequency relay after 400ms, as a consequence approximately 3233kW of load was shed.

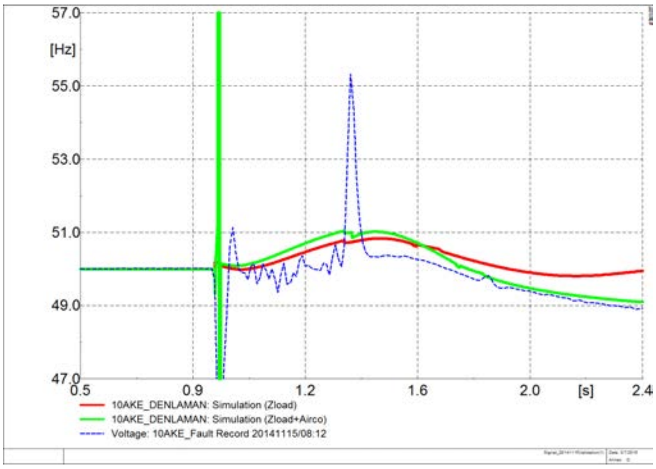


Fig. 3. Overall system frequency response at 12 kV fault record (blue-dotted), simulation results with impedance load (red-solid), and simulation results with arico load (green-solid)

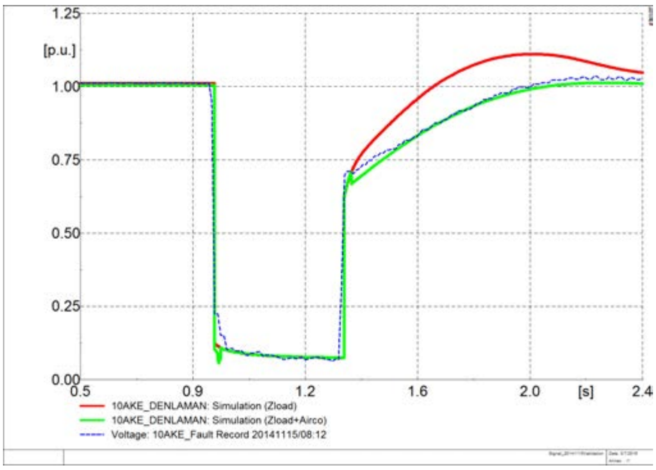


Fig. 4. Overall system voltage response at 12 kV fault record (blue-dotted), simulation results with impedance load (red-solid), and simulation results with arico load (green-solid)

In Fig. 3 and Fig. 4 the red solid lines present the voltage and frequency curve with only pure impedance load, while the green solid line shows the voltage and frequency curve with a combination of pure impedance load and Airco load. The blue dotted lines indicate the voltage and frequency extracted from the fault record at 12 kV feeder. From the plot above, for the voltage comparison a good match can be found between the fault record and the simulation (Zload+Airco). Slow voltage recovery is carefully represented by the Airco load portion with high reactive power consumption following the system voltage recovery. With the pure impedance load case (red solid line), the voltage recovery is rapid and followed by voltage overshoot till 1.1pu. During the fault, the calculated frequency from voltage fault record is jittering due to averaging window calculation method used for the post-processing. As a result, the frequency plot validation shall focus on matching the frequency trend following the fault clearance. Following the fault clearance, the simulation results (Zload+Airco) quickly decrease as a result of the airco load active power rise following the voltage recovery plus the slow recovery of wind turbine in the zero power mode (ZPM). Eventually a good match can be found between the calculated frequency fromthe voltage fault record and the simulation results (Zload + Airco). When the network is simulated with the pure impedance load, the frequency drop is insignificant and system will resume 50Hz when the network is settled following the fault recovery.

Single Phase to Ground Fault Model Validation

A single phase to ground fault occurred on the 12 kV feeder. Over-current protection relay was triggered and the feeder is cleared afterwards. During the fault period (roughly 450 ms), the system frequency plummeted and the under frequency load shedding was triggered. This event was recorded by the protection relay as shown in Fig. 5. The frequency (red) plummeted from 50 Hz to 46 Hz within 400 ms (i.e. ROCOF=10 Hz/s) whilst the active (blue) and reactive power (green) consumption in the network jumped during the fault. The fact that the active power consumption increases during the fault period is quite interesting and unique to low inertia small island power system. Typically, for a large inter-connected power system, the total kinetic energy buffer provided by all the synchronous generators in the system is large. In this case, local disturbances (e.g. generator trip, load rejection, short circuit fault etc.) cause only mild frequency variation thanks to the total system mechanical inertia. However this is not the case with the low inertia island power system, such Bonaire island grid. During the single phase to ground fault, the remaining voltage in the system is relatively high, and the fault current running through the fault path (i.e. fault impedance) and the 12 kV side transformer neutral grounding resistor could cause significant power losses/consumption and result in rapid frequency decrease as shown in Fig. 5.

In this case, the dynamic simulation model validated for the three phase fault is calculated for the event of single phase to ground fault (note: the dynamic network model parameters are kept the same as in the three phase fault validation). This validation exercise focuses on the single phase to ground fault period, where multiple under frequency load shedding protections are triggered. Comparing Fig. 5 and Fig. 7 (upper plot), frequency drop (down to 46Hz) during single phase to ground has been represented in computer simulation software with sufficient accuracy. Comparing Fig. 6 and Fig. 7 (lower plot), the voltage drop and voltage recovery are quite similar.

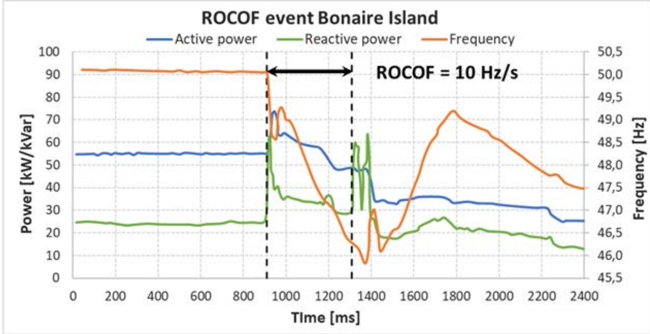


Fig. 5. Fast ROCOF Event Triggered by a 12kV single phase to ground fault on the Bonaire island grid - (red) system frequency y axis on the right side, (blue) system active power consumption, (green) system reactive power consumption

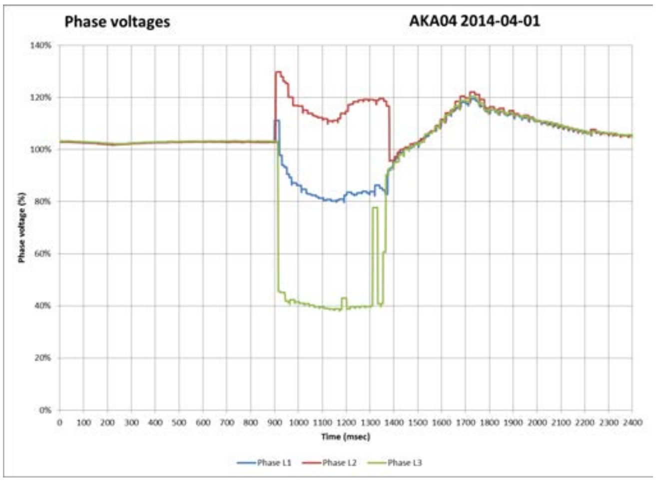


Fig. 6. Three Phase RMS Voltage - 12 kV System Substation WEB NOBO

The three phase fault and the single phase to ground fault model validation both demonstrate good dynamic accuracy of the computer simulation model. Furthermore, the validated dynamic model provides a solid foundation to perform dynamic power system analysis on the Bonaire power system and improve the future power supply reliability on the

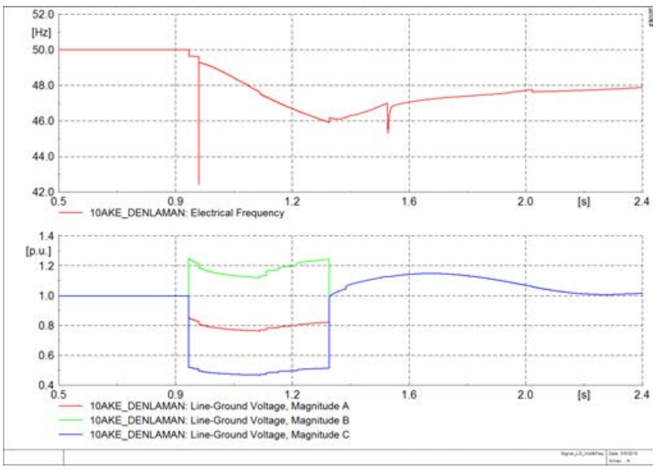


Fig. 7. Simulation plot of single phase to ground fault validation (upper) simulated system frequency measured at 12 kV WEB NOBO, (lower) simulated three phase system RMS voltage at 12 kV WEB NOBO

Bonaire island with optimized relay and controller settings.

IV. Dynamic Simulation Study Results

The main part of the dynamic study is performing simulations of short circuit events at the selected 12 kV load centre for several future dispatch scenarios restricted by the technical boundaries elaborated in Section II. Powerfactory 15.2 is used to build the overall dynamic power system model and validated against historical fault record as detailed in Section III. Firstly the dynamic system study is performed and the results of the simulations are analysed. Next the settings of the load shedding scheme and wind turbine controllers is adapted and simulation are repeated for the most critical scenarios and events. The objective is to determine which settings lead to a reduction in load shedding hence improve the overall power supply reliability on the Bonaire island.

A. Dispatch Scenario

Three dispatch scenarios are defined, all assuming a system peak load of 14 MW:

- Reference scenario: all generation by diesel generators, no renewable generation. This scenario represents actual periods with low wind and traditional generation without renewable energy.
- High wind scenario: only 2 diesel generators running, which is minimum operation practice, maximum wind generation and no PV generation. This scenario represents actual periods with high wind.
- only 2 diesel generators running at minimum output, 5 MW of PV generation and remaining by wind generation. PV generation is considered as possible future addition to the power supply on Bonaire.

The specifics of the scenarios are summarized in Table I.

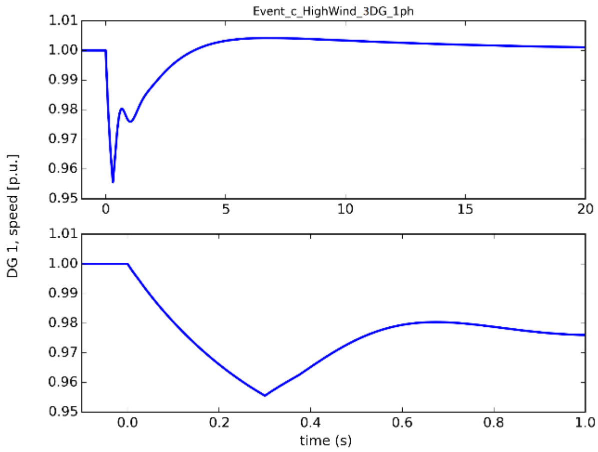
B. High Wind Scenario Simulation Results

As observed from the dynamic study, the high wind scenario is less critical than the reference scenario with respect to the frequency drop. This suggests that with more diesel generators in operation, the frequency drop could be larger. Simulations for the High wind scenario with 3 generators in operations are performed and compared with the simulations with 2 generators in operation, see Fig. 8. With 3 generators, the frequency drop is higher than with 2 generators in operation, although the system inertia is higher. As to be expected, the voltage performance improves with 3 generators in operation.

Event_c, fault impedance 2 ohm		Frequency (DG Speed)			Voltage (12 kV WEB Nobo)			
		CB open (0.3 s)	1 s	5 s	min.	CB open (0.3 s)	1 s	5 s
1-phase to ground	HighWind_3DG	95.5%	97.6%	100.3%	40.0%	90.0%	104.0%	100.0%
	HighWind_2DG	99.7%	103.0%	103.0%	27.4%	72.0%	77.0%	78.0%
2-phase	HighWind_3DG	101.0%	99.8%	99.1%	26.0%	75.0%	90.0%	92.0%
	HighWind_2DG	103.9%	99.3%	101.8%	26.0%	76.0%	57.3%	53.9%
2-phase to ground	HighWind_3DG	97.5%	99.4%	99.3%	26.0%	70.0%	90.0%	92.0%
	HighWind_2DG	99.6%	104.3%	103.0%	21.0%	70.0%	76.0%	78.0%
3-phase	HighWind_3DG	97.6%	100.8%	99.2%	30.0%	65.0%	87.0%	92.0%
	HighWind_2DG	101.8%	101.0%	101.6%	9.8%	58.0%	56.0%	54.0%

Fig. 8. Comparison results High wind scenario with 3 and 2 generators in operation - yellow indicates unsatisfactory system dynamic performance

The cause of the higher frequency drop is probably caused by the higher remaining voltage during the fault and the higher short circuit current. The higher remaining voltage results in a higher load during the fault and the higher short circuit current results in higher active power losses in the short circuit path. See Fig. 9 (frequency) and Fig. 10 (voltage) for the graphs for 1 phase to ground fault response for the scenarios with 3 and 2 diesel generators in operation respectively.



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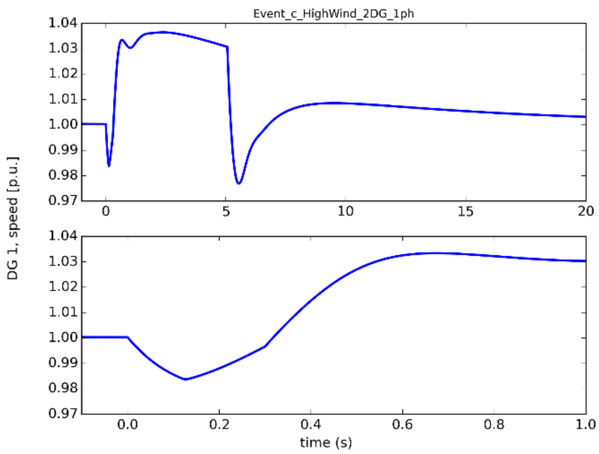


(b)

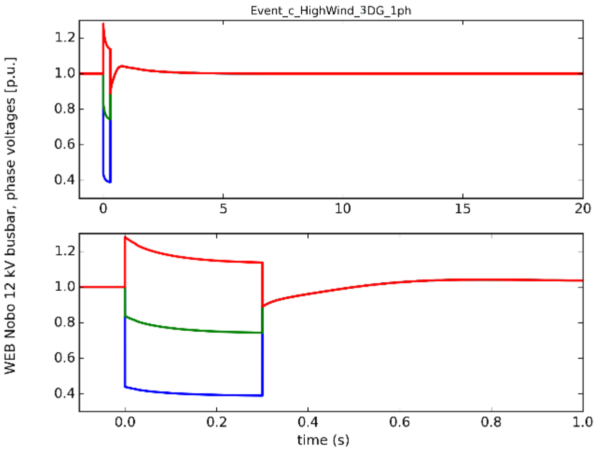
Fig. 9. High wind 1 phase to ground fault, generator speed with - (a) 3 generator (b) 2 generator

The dynamic simulations indicate that scenarios with high PV and high wind penetration do not recover from short circuit faults because the system voltage after fault clearance does not recover (see Fig. 10(b)). Wind farm and diesel generators will trip by under-voltage protection. To prevent a total black-out, load shedding based on low voltage is also required. The current load shedding based on the frequency is therefore not sufficient.

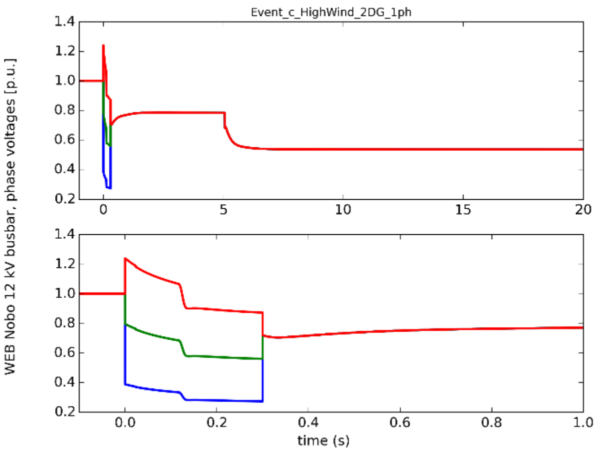
It is interesting to note from the dynamic study that the short circuit faults to ground (1-phase-ground and 2-phase-ground) with fault impedance (overhead line) will cause frequency drops because of the increase of active power consumption caused by the fault current flowing through the fault current path. Despite increased inertia as a result of increased number of diesel generator, the system can experience lower frequency nadir as a result of extra active

TABLE I
DYNAMIC STUDY SCENARIO SPECIFICATIONS

Scenario	System Load (MW)	No. diesel generators	diesel generator dispatched output (MW)	Wind Farm (MW)	PV Farm (MW)
Reference	14	5	2.4	0	0
High wind	14	2	2.5	9	0
PV max	14	2	1.4	6.2	5



(a)



(b)

Fig. 10. High wind 1 phase to ground fault, system 12 kV voltage with - (a) 3 generator (b) 2 generator

power consumption caused by the fault current (See Fig. 9(b) and Fig. 9(a)).

Load shedding on the under frequency is not required as per the simulation findings. However, since there is a risk of tripping of wind turbines, PV and diesel generators on the low frequency nadir, it is necessary to maintain the load shedding on frequency. The pick-up frequency settings can be reduced and moved closer to the trip settings of generators and wind turbines.

C. Enhanced Dynamic System Performance

This paragraph concerns the load shedding protective relay settings modification to improve the Bonaire power system reliability. Firstly, as a result of the detailed dynamic simulation study performed, improvement of settings is proposed. While the new under-voltage load shedding scheme is added, the existing under-frequency is kept with extended pickup level. In the next paragraph, the dynamic simulation study is repeated for the critical scenario with high wind and 2 diesel generators, simulation results confirmed the effectiveness of proposed new settings as the system voltage can successfully recover following the fault clearance.

Bay	Proposed U-shedding (%/s)	Proposed f-shedding (Hz/s)	Bay	Proposed U-shedding (%/s)	Proposed f-shedding (Hz/s)
10AKE07	85% / 1.1	48.0 / 0.4	10AKB04	85% / 0.7	47.3 /0.1
10AKE05	90% / 1.3	48.0 / 1.0	10AKC05	85% / 0.8	47.1 / 0.1
10AKE04	85% / 0.5	47.7 / 0.1	10AKC04	85% / 0.9	46.9 / 0.1
10AKB03	85% / 0.6	47.5 / 0.1			

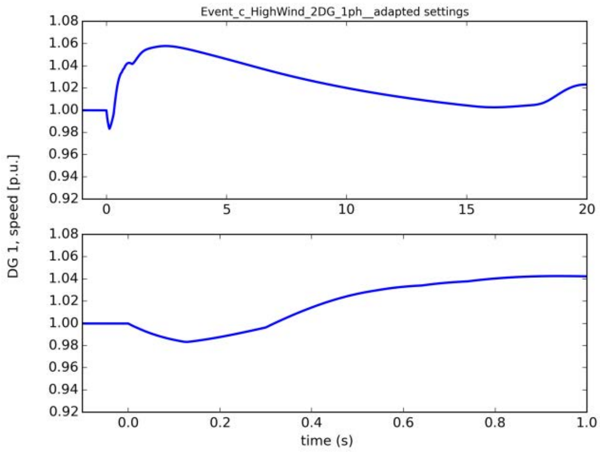
Fig. 11. Proposed protective relay frequency/voltage load shedding scheme

Conclusion from the simulations is that the under-frequency load shedding settings can be changed. Frequency pick-up levels should be reduced, but under voltage load shedding shall be added to prevent a voltage collapse of the system. The proposed setting modifications are summarized as per Table in Fig. 11, where under-voltage settings are new; these are not included in the existing scheme. The Time delay between the steps is graded with 0.1 seconds to be faster than the 30 kV under-voltage tripping delay of 0.95 seconds. The voltage pick-up levels are based on the simulations performed, see next sections. The frequency settings are changed in general by reducing the existing frequency pick-up levels with 1 Hz. Apart from the load shedding schema, also improvement of controller settings of the wind turbines is advised to make use of the total available short term frequency range of the wind turbines to prevent tripping on frequency: over frequency at 57 Hz, under frequency at 43 Hz. Additionally, the dynamic power-frequency control function is activated to automatically reduce gradually the wind turbine output for frequencies above 50.2 Hz.

High Wind 2 DG Event_c		Frequency (generator speed)			Voltage (12 kV WEB Nobo)			
		CB open (0.3 s)	1 s	5 s	min.	CB open (0.3 s)	1 s	5 s
1-phase to ground	New settings	99.6%	104.2%	104.6%	27.4%	72.1%	90.7%	93.8%
	Old settings	99.7%	103.0%	103.0%	27.4%	72.0%	77.0%	78.0%
2-phase	New settings	103.9%	105.8%	104.7%	25.9%	75.9%	91.1%	94.9%
	Old settings	103.9%	99.3%	101.8%	26.0%	76.0%	57.3%	53.9%
2-phase to ground	New settings	99.5%	105.7%	104.9%	21.2%	71.0%	90.6%	95.0%
	Old settings	99.6%	104.3%	103.0%	21.0%	70.0%	76.0%	78.0%
3-phase	New settings	101.8%	107.5%	105.1%	9.5%	57.9%	89.6%	96.2%
	Old settings	101.8%	101.0%	101.6%	9.8%	58.0%	56.0%	54.0%

Fig. 12. Simulation results with improved wind turbine controller and load shedding scheme settings, compared to existing wind turbine controller and load shedding scheme settings - yellow indicates unsatisfactory system dynamic performance

With the proposed changes on the load shedding scheme and the wind turbine controller, see Table in Fig. 11, dynamic simulations for the High wind scenario with short circuit fault are repeated. The results are summarized and compared with the results for the existing wind turbine controller setting without under-voltage load shedding (see Table in Fig. 12). These simulations show the effectiveness of the improved load shedding scheme. No frequency load shedding occurs. Voltage load shedding is activated to prevent low system voltages and voltage collapse. It is interesting to look at the difference in the frequency and the voltage response between the new and the existing settings. With the new settings the frequency response is initially the same as with the existing settings, see bottom graphs of Fig. 13(a) and Fig. 13(b) (mind the Y-scale difference). The response from 1 second onwards, see top graphs of Fig. 13(a) and Fig. 13(b), is smoother for the new settings. With the existing settings the frequency drops suddenly at 5 seconds, caused by the tripping of the wind farm on under-voltage.



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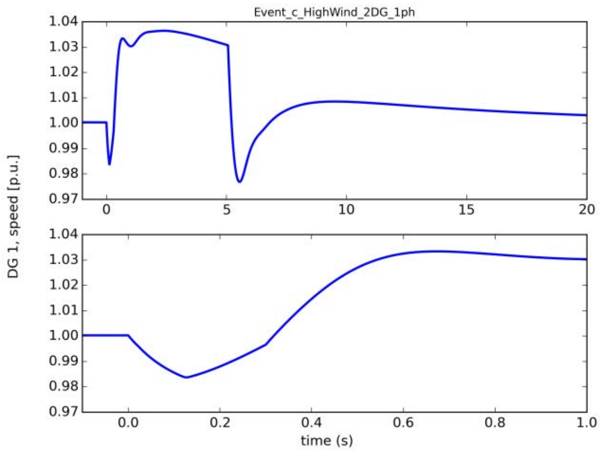
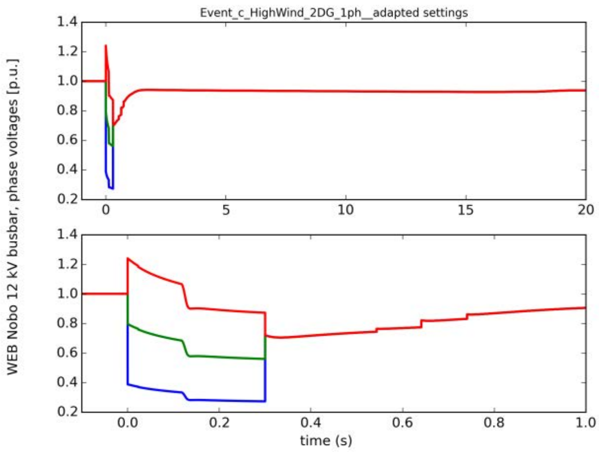


(b)

Fig. 13. High wind 1 phase to ground fault with fault impedance, generator speed for - (a) improved settings (b) old settings

With the existing settings the system voltage will not recover after fault clearance and the system will collapse (voltage collapse), see Fig. 14(b)). With the new settings the voltage will recover, see Fig. 14(a), the voltage recovers due to 3 successive load shedding at 0.55, 0.65 and 0.75 seconds.



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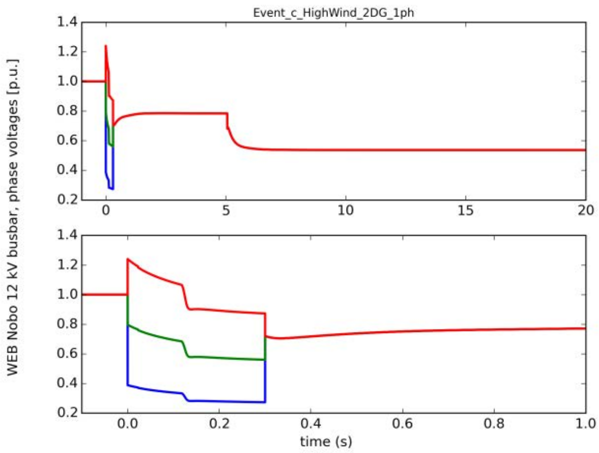

(b)

Fig. 14. High wind 1 phase to ground fault with fault impedance, system 12 kV voltage for - (a) improved settings (b) old settings

V. Conclusions

Dynamic simulation study of the Bonaire power system show that the system does not survive short circuit faults in the high wind (9 MW) and high PV (5 MW) scenarios. The main reason is that the system voltage does not recover after clearance of the fault and wind turbines and PV will trip on the low voltage. To prevent the system collapse, load shedding based on under voltage is required in addition to the existing under-frequency load shedding scheme.

Dynamic model validation demonstrated, next to the power generation units dynamic controller modelling, the importance of dynamic load modelling. In the case of Bonaire power system, the airco modelling is essential for the emulation of motor stalling effect following fault recovery, which could potentially cause delayed voltage recovery or lead a total system voltage collapse.

Short circuit fault with fault impedance (representing an overhead line) causes frequency drops because of the sudden increase of active load during the fault. Load shedding on under frequency may not be required according the calculations, but there is a risk on tripping of wind turbines, PV and diesel generators on the low frequency.

Acknowledgment

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