Report

P13032

Grid and System Integration Study for El Salvador

July 2013

prepared for

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1	22/07/13	J. Horne/M. Pöller	Markus Pöller	First draft report
2	29/07/13	Jonathan Horne	Markus Pöller	Update following comment from client
3	03/02/13	S. Tatiana Orellana	Jonathan Horne	Update following last comment from client

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1 Introduction

1.1 Background

MPE has been commissioned to investigate the impact of 195.2 MW of non-synchronous renewable generation which is planned to be connected to the El-Salvador electricity grid by approximately 2016. This will be comprised of 72 MW of wind generation, and 123.2 MW of photovoltaic (PV) generation.

This is the first time that this type of technology has been connected to this system at utility scale ratings. Questions have therefore been raised as to the impact of this new generation, both on the existing synchronous generation, and the El-Salvadorian electricity system itself. As all the generation is due to connect by 2016, the focus of these studies has been to assess the maximum possible impact for the specific generation, connected at the locations and voltages specified, for the years 2016 and 2019.

In addition, as the grid operator of El-Salvador has never before specified standards for wind or PV generation, either through grid code or connection agreements, MPE have been asked to provide some high level minimum requirements. The aim of these is to minimise or eliminate any impact on the stability or security of the El-Salvador grid without limiting the marketplace of suppliers.

This report contains the conclusions of the studies completed, together with the proposed minimum requirement for the new non-synchronous wind and PV generation.

1.2 Scope of Work

In order to gauge the impact of the new renewable generation the following types of study have been undertaken:

- Intact system load flow analysis
- Contingency analysis (considering line loading and bus voltage)
- QV analysis at various busses in the El-Salvadorian system
- Dynamic simulation considering transient and oscillatory stability
- Some specific dynamic simulation considering frequency stability

2 Network Data Supplied & Preparation of the El-Salvador and SIEPAC Model

The El-Salvadorian electricity system is connected to several other Central American countries (plus Mexico) via the newly constructed 230kV 300MW SIEPAC transmission line. The countries included are as follows:

- Guatemala
- El-Salvador
- Honduras
- Nicaragua
- Costa Rica
- Panama
- Mexico (connected via 400kV to Guatemala but not officially part of the SIEPAC line)

2.1 PSS/E Data Supplied by the Client

Due to the interconnected nature of the El-Salvadorian grid it was necessary to simulate the entire ‘SIEPAC’ region to properly gauge the impact of the new renewable generation. The client therefore supplied the following data:

- Detailed PSS/E data for the El-Salvador system for the following scenarios:
    - 2013 minimum load dry season (March)
    - 2013 maximum load dry season (March)
    - 2013 minimum load wet season (September)
    - 2013 maximum load wet season (September)
    - 2016 minimum load dry season (March)
    - 2016 maximum load dry season (March)
    - 2016 minimum load wet season (September)
    - 2016 maximum load wet season (September)
    - 2019 minimum load dry season (March)
    - 2019 maximum load dry season (March)
    - 2019 minimum load wet season (September)
    - 2019 maximum load wet season (September)
- simplified & combined PSS/E data for the SIEPAC region for the following scenarios:
    - 2014 minimum load dry season (March)
    - 2014 maximum load dry season (March)
    - 2014 minimum load wet season (September)

- 2014 maximum load wet season (September)
- 2015 minimum load dry season (March)
- 2015 maximum load dry season (March)
- 2015 minimum load wet season (September)
- 2015 maximum load wet season (September)

Given that the renewable generation was not due to connect until 2016, and that the El-Salvador system did not change dramatically between 2013 and 2016, it was decided not to proceed with studying the 2013 system, and instead to focus the allocated time on the 2016 and 2019 years which are the only years which will reveal any impact of the new renewable generation.

2.2 Preparation of the Networks

The consultant combined the closest cases for each scenario – 2015 SIEPAC data with the 2016 and 2019 detailed El-Salvador data. In the majority of cases the transfer on the SIEPAC line was maintained at approximately zero as per the current operating procedure. However, in selected scenarios maximum export and maximum import (up to 200 MW) was simulated in order to ensure that the new renewable generation did not cause any unforeseen issues under these extreme operating conditions. More information can be found in the dynamic simulation results section of this report.

Note that for the steady state studies (load flow, contingency analysis and QV analysis) only the detailed El-Salvador system was considered as the neighbouring countries have little or no impact on the contingencies studied. However, external grid representations of the active and reactive power flow to / from El-Salvador were included as if the SIEPAC countries were connected.

Following an initial review of the data supplied by the client it was noted that there was some dynamic data missing for some for the existing generators in El-Salvador, in particular for the 2019 cases. Following a request from the consultant, the client proposed to use similar data from other existing plants. For the majority of plant listed below no dynamic data was included in the PSS/E information provided by the client. The specific type of data which was missing included dynamic data for the generator itself. In addition information about AVRs / PSSs / governors was also missing. The SOYA-G1 machine did have a PSS/E GENCLS generator model (constant internal voltage) included however this is not recommended for use during dynamic simulations. An overview of the missing and replacement data is given as follows:

1. In the 2016 networks:
    a. 21106 5NOV-U6 used generator, AVR & governor data from 21104 5NOV-U4
    b. 21164 AHUA-U4 used generator, AVR & governor data from 21161 AHUA-U1
    c. 20301 SOYA-G1 used generator, AVR & governor data from 21373 NEJA-G3
2. In the 2019 networks:
    a. 21106 5NOV-U6 used generator, AVR & governor data from 21104 5NOV-U4
    b. 21164 AHUA-U4 used generator, AVR & governor data from 21161 AHUA-U1
    c. 21191 CHAPA-U1 used generator, AVR & governor data from 21181 15SE-U1

d. 21215 BERL-U5 used generator, AVR & governor data from 21214 BERL-U4

e. 21216 BERL-U6 used generator, AVR & governor data from 21214 BERL-U4

f. 21401 CHINA_U1 used generator, AVR & governor data from 21215 BERL-U4

g. 20301 SOYA-G1 used generator, AVR & governor data from 21373 NEJA-G3

This exercise also highlighted that the supplied data contained synchronous machine representation of some of the new proposed non-synchronous renewable generation. This was completely removed by the consultant as they were to be replaced with more appropriate models. The generators which were removed were as follows:

1. In the 2019 networks:
    a. 21113 MET-EOL
    b. 21173 CGRA-FV
    c. 21183 15SE-FV

Figure 1 below shows an example of the El-Salvador power grid in 2016 without any non-synchronous renewable generation connected. The 230kV SIEPAC line is shown in red, the 115kV system shown in green, 46kV in dark blue, 23kV in light blue and 13.8kV in purple.

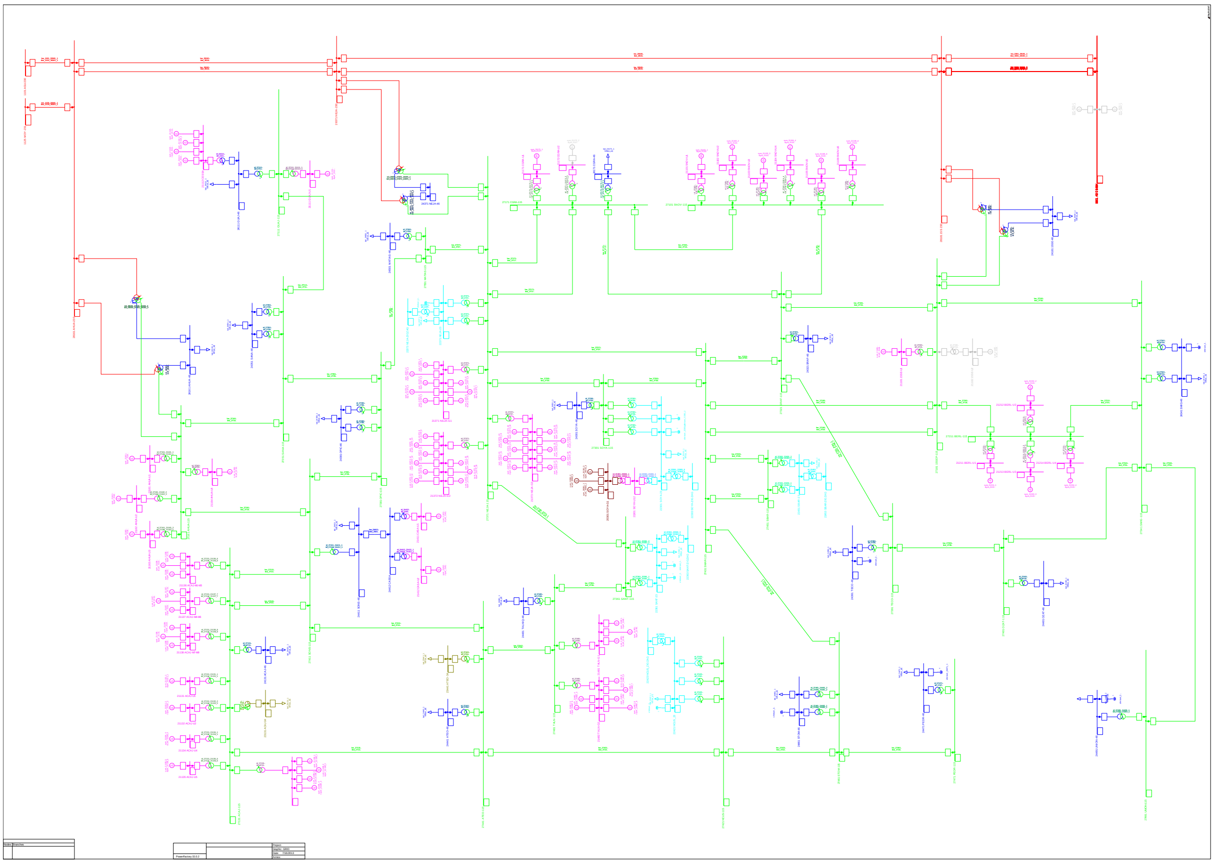


Figure 1 – Schematic of the El-Salvador power grid in 2016 (no non-synchronous renewable generation shown)

2.2.1 Supplied merit order and disconnection of synchronous plant

The client supplied a typical merit order based on dispatch of plant today in 2013. Following discussion with the client this merit order was updated to include missing plant and new plant (in the 2016 and 2019 cases). This was then further modified to align with the generator naming and grouping contained in the supplied PSS/E data. This final agreed merit order can be seen in Annex 1.

The merit order was used to determine which existing synchronous generation should be disconnected or reduced in output to allow for the connection of the renewable generation. In all cases it was assumed that the renewable generation was at its maximum output (195.2MW) in order to gauge the maximum impact, both from this new generation and the displacement of existing synchronous generation. For each case in 2016 and 2019 the dispatch as provided in the PSS/E data was compared with the merit order and the appropriate generation was selected for disconnection / power reduction in the renewable cases. The marginal plant (highlighted in yellow in Annex 1) was reduced so that the volume of synchronous generation reduction was exactly 195.2MW. Note however that due to minimum generation limits, some cases have two marginal plants, both reduced in output. The final generation dispatch, as agreed with the client, is also contained in Annex 1.

3 Renewable Generation Information & Models Used

This section contains details of the wind and PV generation which is expected to connect to the El-Salvador system as supplied by the client. In addition, it contains details of the models used for both steady state and dynamic simulation as introduced by the consultant, together with some general details about the primary plant configuration which is typical in these applications. Note that the more specific requirements for the new generation can be found in the ‘connection conditions’ section of this report.

3.1 Renewable generation information supplied by the client

The generation type, connection location and rating (MW) of the new non-synchronous renewable generation is shown in Table 1 and Table 2 below. It is assumed that all generation will be installed and commissioned by 2016.

Escenarios a Evaluar Parques Eólicos (Grid connection aprox. January 2016)			Subestación
Proyecto	Potencia	Subestación de Conexión	Identificación PSSE
PE1	42.0 MW	Guajoyo	27111 GUAJ-115
PE2	30.0 MW	Ateos	27441 ATEO-115

Table 1 – Proposed wind generation in El-Salvador

Escenarios a Evaluar Energía Solar Fotovoltaica (Grid connection aprox. January 2016)			Subestación
Proyecto	Potencia	Subestación de Conexión	Identificación PSSE
SFV1	14.2 MW	15 de Septiembre	27181 15SEP-115
SFV2	3.0 MW	Guajoyo	27111 GUAJ-115
SFV3	15.0 MW	La Unión	27491 UNION-115
SFV4	10.0 MW	Tecoluca	27391 TECO-115
SFV5	6.0 MW	Ateos	27441 ATEO-115
SFV6	50 MW	La Unión	27941 UNION-115
SFV7	20 MW	Acajutla	27131 ACAJ-115
SFV8	5 MW	Nuevo Cuzcatlan	27421 NCUS-115

Table 2 – Proposed PV generation in El-Salvador

Figure 2 shows the location of the new wind and PV renewable generation (highlighted in green) in the El-Salvador network schematic.

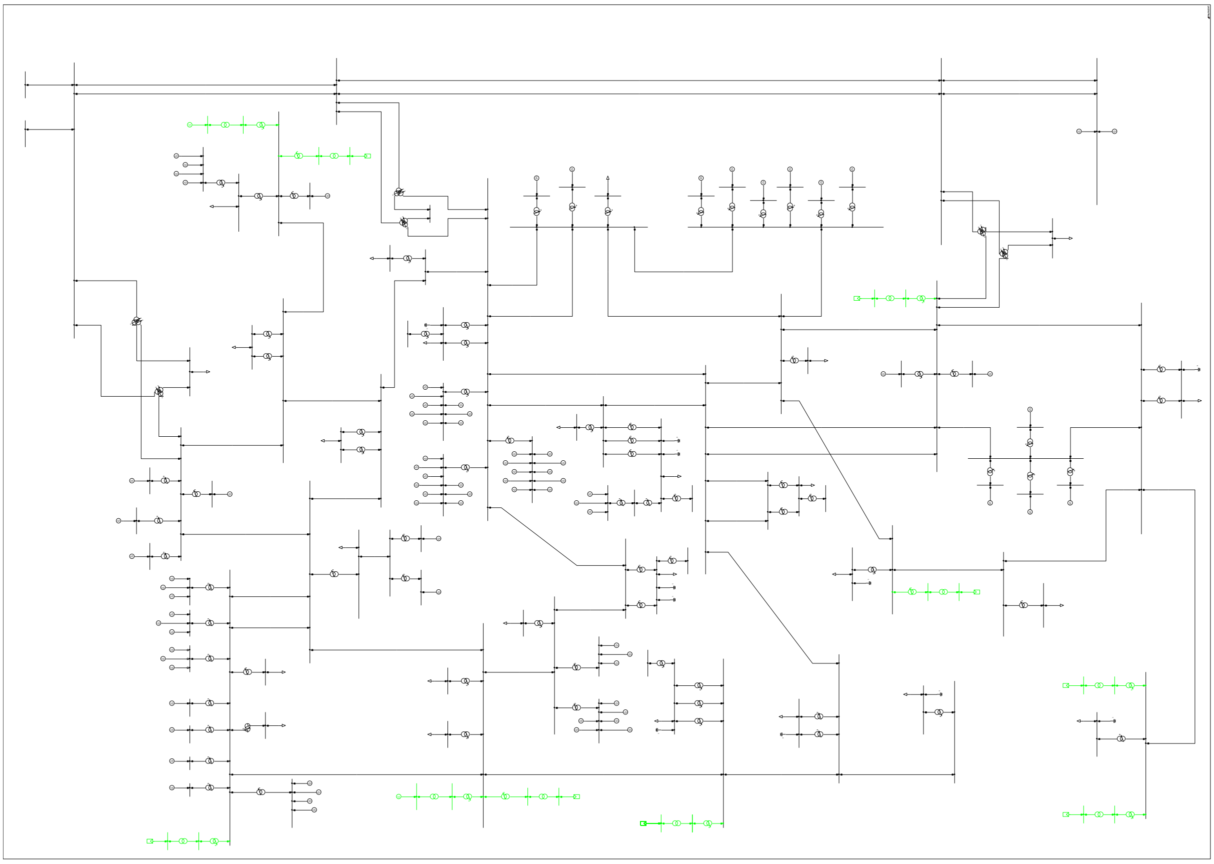


Figure 2 – 2016 El-Salvador network with new wind & PV renewable generation location shown in green

3.2 General primary plant configuration

In order to model renewable generation for these studies (before detailed design information is known) it is necessary to make some assumptions about the type and performance of the generation, and the performance of the entire renewable 'power station' up to the point of connection at 115kV.

Power system analysis packages typically include 'generic' models for this purpose, which provide a very good representation of the response of the generation for whole power system analysis purposes.

In systems, in which Connection Conditions for wind and PV generation exist, these 'generic' models have to be adjusted in order to comply with the requirements of the relevant Connection Conditions. In the particular case of El Salvador, Connection Conditions for wind and PV generation don't exist yet and therefore, a specification for the behaviour of wind and PV generation during normal operation conditions and in the case of grid disturbances is missing. For closing this gap, key elements of corresponding Connection Conditions have been proposed by the consultant (see section 6) and the models have been adjusted in a way that they will comply with the proposed Connection Conditions.

Hence, the results of all studies are only valid under the assumption that the actually installed wind and PV farms will comply with the Connection Conditions proposed in this report or, at least, that the actual behaviour will not substantially deviated from these requirements.

Generally, it is recommended that models of wind and PV generation are compared with the performance of the actual plant after procurement, i.e. when the manufacturer can provide detailed model data for the equipment, and then again where appropriate after commissioning to ensure that they can be considered an accurate representation of the real plant. This activity can be performed in a number of ways:

1. By the manufacturer
2. By the system operator comparing a manufacturer specific model with the generic model
3. By a combination of either 1 or 2 plus post commissioning testing

If the 'generic' model is found to be a good match then typically it is better to use this as they are often more robust and require less computational effort to run than manufacturer specific models.

A typical arrangement of a utility scale wind farm is shown below in Figure 3. This layout can equally apply to a PV farm with the wind turbines replaced by grouped PV modules. The turbines / modules are normally arranged in a string formation with numbers of turbines / modules depending on their location, rating, and the rating of the cables chosen. All strings lead to a common collector busbar, and then one or more transformers to transform to the utility voltage (in this case 115kV).

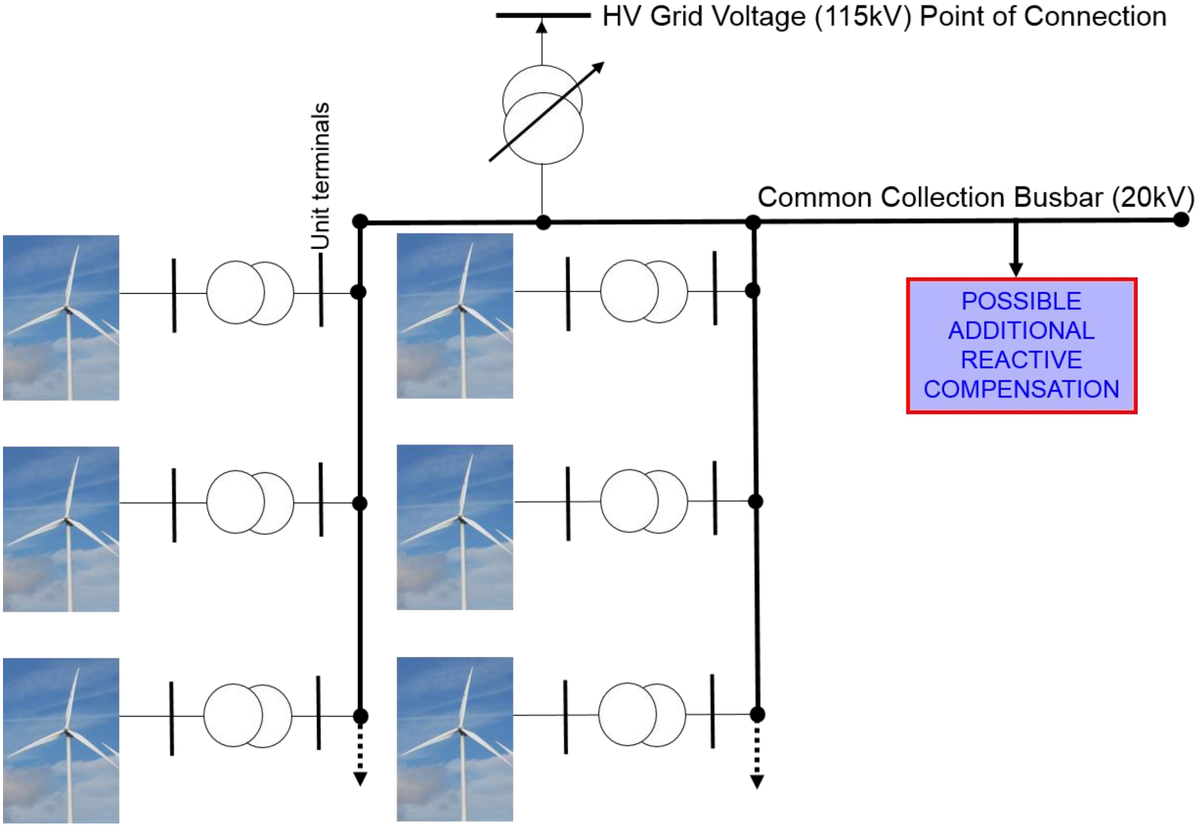


Figure 3 – Typical Wind Farm (or PV farm) Layout Configuration

For the PV farm installations the interface to the grid will be via a DC to AC converter as shown in Figure 4, which converts the DC generated by the PV arrays to AC for power injection into the grid. This configuration has many benefits including the ability to provide reactive power (both generating and absorbing) and in particular very rapid control / injection of fault current to support the grid during faults.

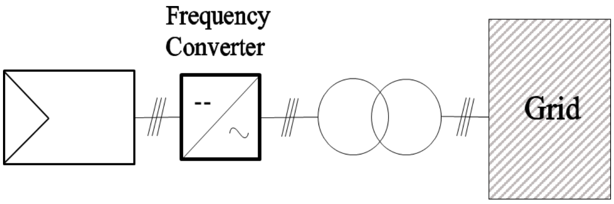


Figure 4 – Typical PV converter arrangement

For the wind farm installations it has been assumed that due to the size of the installations, the turbines will be modern power electronic controlled type. These types have the advantage of superior fault ride through and reactive power provision compared to simple induction generator type wind farms. For the purposes of this report it has been assumed that the wind turbines are DFIG type (as shown in Figure 5) as they have marginally worse fault current injection control and active power recovery post fault clearance when compared to the fully rated converter type. This therefore ensures that the maximum possible impact on the grid is assessed.

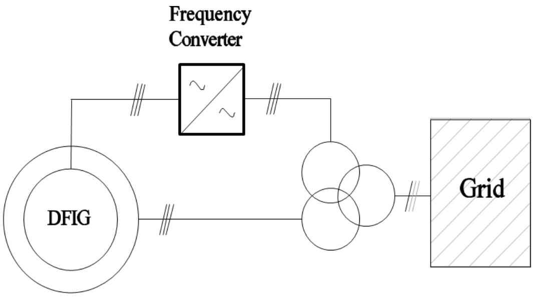


Figure 5 – Typical DFIG wind generator configuration

For both wind and PV installations it has been assumed that the reactive capability of the overall wind farm can achieve 0.95 power factor leading (absorbing) and lagging (exporting) at the point of connection (115kV).

Typically the wind turbine / PV module unit transformers have off-load tap changers and are set depending on their location in the wind farm string. Once set they are typically not varied unless the configuration of the farm substantially changes at a later date. They transform the voltage from around 400 – 1000V up to the range 11 to 33kV. For this report 400V is used for PV generation, and 690V used for the wind generation for the LV voltages. In both cases 20kV is used at the MV voltage with each unit transformer having 6% impedance.

The grid transformer will normally have an on-load tap changer controlling the MV voltage to a value of 1pu (20KV). The reason for this is that the reactive capability of modern wind turbines and PV converters is heavily dependent on the AC terminal voltage. An example voltage dependent capability curve is shown in Figure 6. Here the x-axis shows reactive power in per unit, and the y-axis shows active power in per unit. Note how the exporting (lagging) MVAr is limited with increasing terminal voltage. It is therefore important that the transformer should have sufficient taps to control the MV voltage to 1pu for all possible HV voltages (for example +/- 10% variation at 115kV) in order to maintain the reactive capability of the turbines. Optionally two 50% (or higher) rated grid transformers can be used if increased connection security is desired. However for modelling purposes the overall effect is the same.

In the case of these simulations a single grid transformer with impedance of 15% has been used. Note that depending on the turbine / PV converter manufacturer the reactive power provision of the wind turbines / PV converters may not be sufficient to meet the required 0.95 power factor at the point of connection. Therefore Figure 3 shows a typical location for additional reactive compensation if required. This can take the form or switched or static compensation (inductors / capacitors) or possibly STATCOM or SVC devices. These options can have some additional benefit by reducing the active power losses within the wind farm as they can reduce the distance the required reactive power must be transmitted. However they will typically require a greater capital expenditure in the first instance.

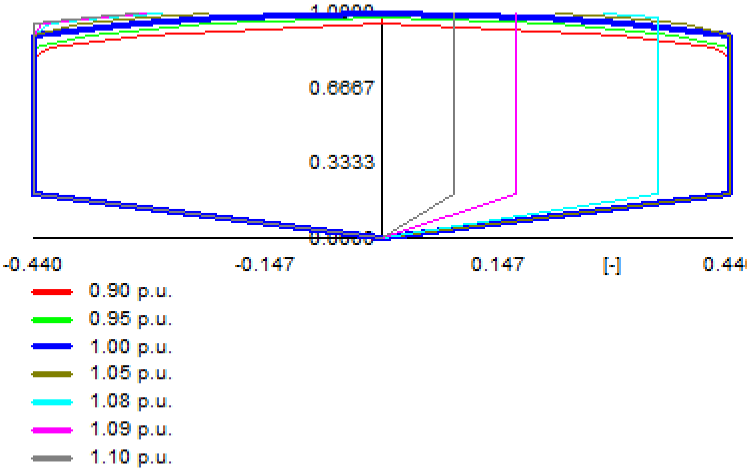


Figure 6 – Typical voltage dependent reactive power capability curve for wind or PV generation

3.3 Voltage control methodology

The wind / solar farm will be small compared to the 115kV network it is connected to. Therefore direct control of the 115kV voltage to a target value is not appropriate as it would normally result in the wind / PV farm operating at full leading or full lagging MVAr for the majority of time. Instead it is typical to control reactive power export based on a voltage target (at 115kV) and a reactive power slope. An example of this approach can be seen below in Figure 7. In this example there is a target of 1pu and a slope of 4%. Therefore, if the point of connection voltage is at 1pu (115kV) then the wind / PV farm will operate at unity power factor (0 MVAr) at the point of connection. If the point of connection voltage drops to 0.96pu then the wind / PV farm will export MVAr equivalent to 0.95 power factor (calculated on rated MW). Conversely if the point of connection voltage increases to 1.04 then the wind / PV farm will import MVAr equivalent to 0.95 power factor. Typically the system operator can adjust the target and slope to achieve different MVAr or response to voltage changes, although normally only the target is adjusted in operational timescales. In the simulations for this report a target of 1pu and a slope of 4% have been used.

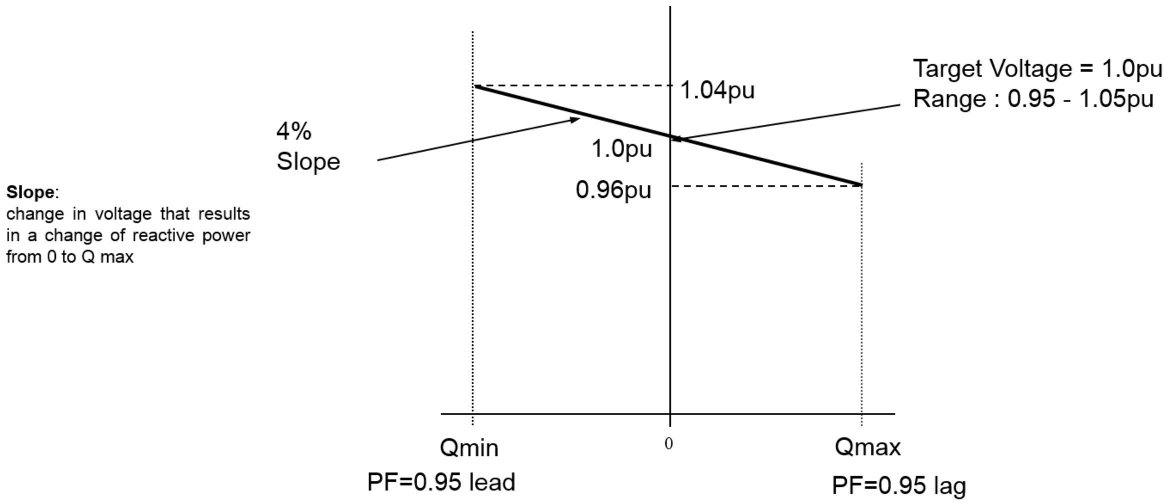


Figure 7 – Voltage control slope approach

The normal approach for achieving this type of control is for the wind / PV farm to use a type of central controller. A high level description of this type of control is shown in Figure 8. Here the point of connection voltage and reactive power (from the wind / PV farm) is measured and signals passed to the farm central controller. The controller then automatically adjusts the reactive power output of turbines / PV converters or any additional reactive compensation equipment in order to achieve the required reactive power at the point of connection. This control loop typically operates in normal SCADA timescales (over a few seconds). In the simulations for this report the voltage control slope and target approach has been included for load flow, contingency analysis and QV curve analysis, however it has not been include for any dynamic simulations as it is assumed to be too slow to provide any real benefit in this instance.

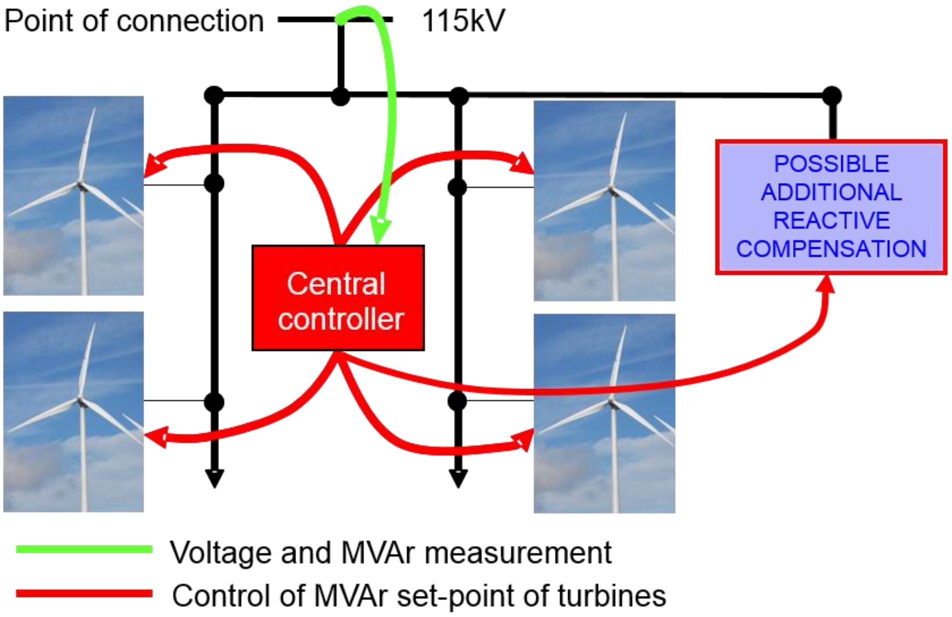


Figure 8 – Central controller approach to achieve voltage target and slope control

3.4 Wind / PV farm dynamic fault performance

The main characteristics of this type of generation during system faults relate to the following aspects:

- Fault ride through ability
- Reactive current support during fault
- Active power recovery post fault clearance

3.4.1 Fault ride through ability

It is essential that the new wind / PV generation is capable of remaining connected during the most severe plausible network faults. A synchronous machine has a ‘natural’ limit to ride through faults, mostly dependent on AVR performance, general machine design and current operating condition. If this limit is breached the machine will pole slip and be disconnected from the system. A modern DFIG or full converter wind turbine, or PV converter will have a pre-programmed voltage – time curve. If the operating point transitions outside of the curve the farm will disconnect from the system. It is not practical / economic to have these curves set at exceptionally long timescales, however it is essential that a network fault does not disconnect vast volumes of renewable generation. Therefore a balance must be achieved between what the system requires, and what the majority of manufacturers can deliver. Based on the results of the simulations conducted for this report, and from information supplied by the client (in particular the maximum expected transmission fault clearing time of 150ms), a suitable curve for El-Salvador has been proposed in the connection conditions section of this report (see section 6) which the majority of major manufacturers should be capable of meeting.

3.4.2 Reactive current support during fault

In order to support the transmission system during faults (similar to synchronous generator action with AVR support) it is essential that the wind / PV farms are specified to provide rapid reactive fault current injection. This helps to maintain voltage in areas remote from the fault location, and also aids with voltage recovery immediately on fault clearance. Typically there is a minimum requirement to inject up to rated current, although some manufactures can provide up to 1.2 times rated current for short periods for voltage drops near the wind / PV farm which are severe. Typically full converter wind turbines and PV converters can provide this fault current very rapidly following detection of fault (within a few ms). However DFIG wind turbines can take longer due to temporary high voltages induced on the rotor side converter. The models used here assume that the wind generators are DFIG type (to give the worst, but a realistic fault current performance) and that both the wind and PV generators provide no more than 1pu reactive current for terminal voltages which decrease by more than 0.5pu from the pre-fault value. A more detailed specification for fault current provision can be found in the section on connection conditions in this report (see section 6).

3.4.3 Active power recovery post fault clearance

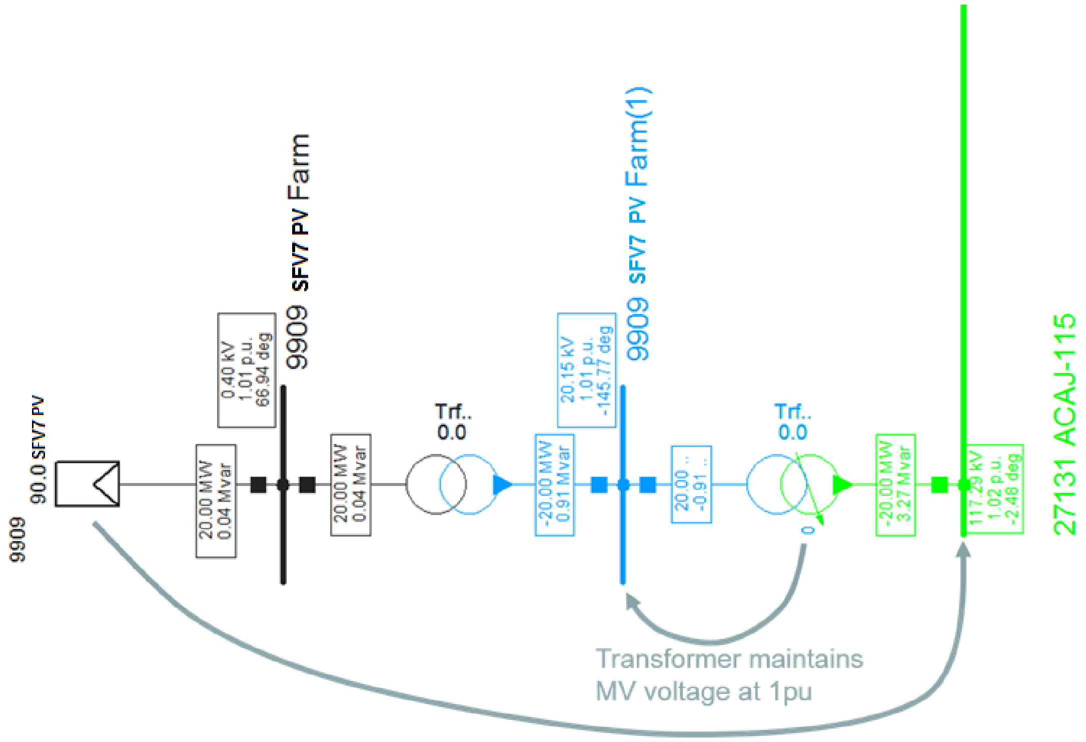
During a fault the wind / PV generation will reduce active power injection into the grid in order to provide capability for reactive power injection, and to avoid voltage collapse from injecting active power into a fault. For wind generators this will cause the rotor to speed up. For longer faults the pitch mechanism may start to respond which could result in an active power decrease post fault. In order to maintain frequency stability, and / or to avoid potential cascade tripping of tie-lines (e.g. SIEPAC line) it is common practice to require the wind / PV generation to restore active power generation in a specific time scale. Details of the requirements can be found in the section on connection conditions in this report (see section 6).

3.5 Wind / PV farm construction in power system analysis software

When studying wind / PV farm generation in power system analysis software where the entire electricity network is represented it is typical practice to aggregate the individual wind turbine or PV modules into one. This improves computational performance and simplifies the set-up procedure, for example if different active power outputs are to be simulated. Additionally, the behaviour of individual turbines / modules inside the wind farm is not of importance during full network simulations. Instead it is the performance of the wind / PV farm as a whole which is the key factor to consider.

3.5.1 Steady state wind / PV model

Figure 9 indicates how the basic steady state model is constructed for a PV farm. An identical representation is used for the wind farms. This Figure contains an aggregated representation of the PV farm module and unit transformer up to 20kV. The grid transformer is represented as in reality. As previously described, the wind generator / PV module controls the reactive power at the point of connection based on a target of 1pu and a slope of 4%. The grid transformer then maintains the 20kV busbar at 1pu in order to allow the wind / PV farm to maintain the best possible reactive range.



Transformer maintains MV voltage at 1pu

PV farm controls reactive power output at point of connection based on target and slope

Figure 9 – Example of PV farm construction in power system analysis software when conducting full system simulations

3.5.2 Dynamic wind / PV model

The high level block diagram of dynamic model of the wind and solar farms is shown below in Figure 10 and Figure 11 respectively. These represent all of the dynamic behaviours as discussed in this section of the report.

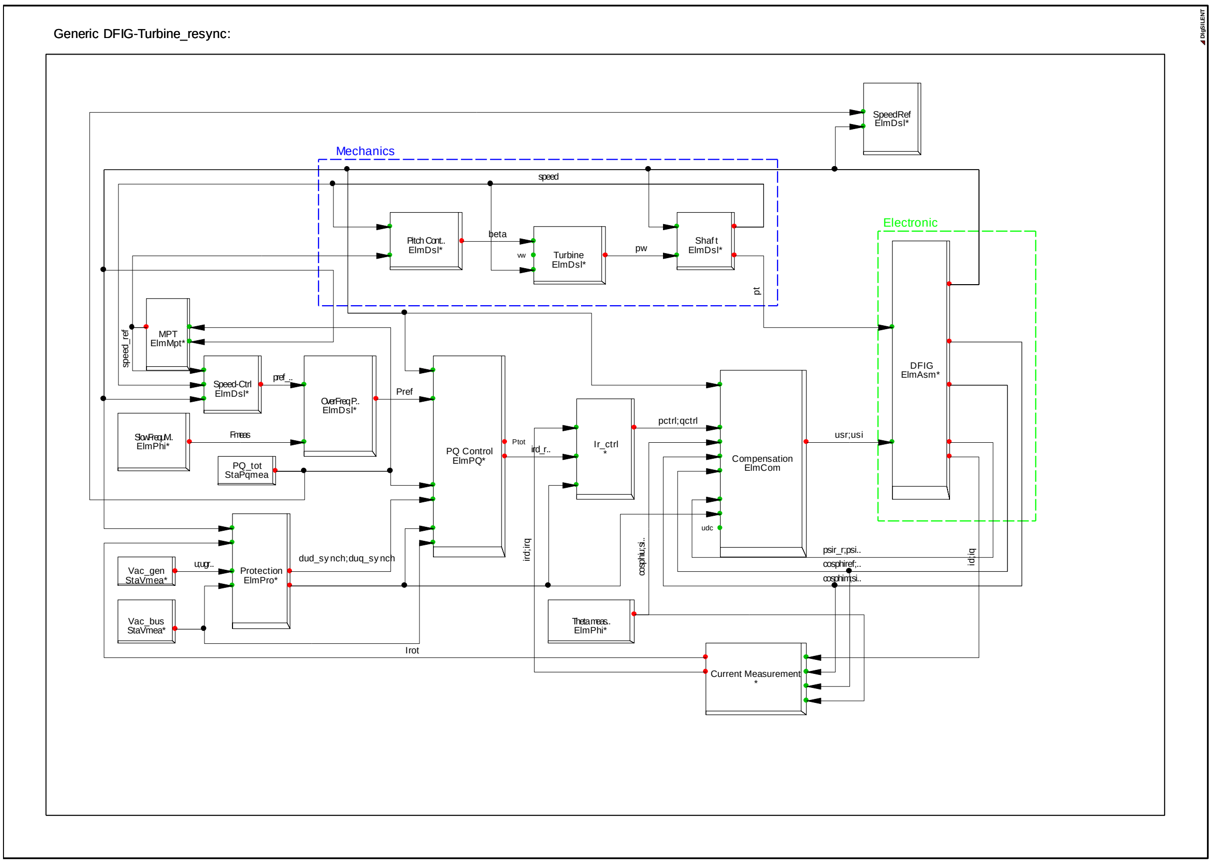


Figure 10 – High level DFIG block diagram

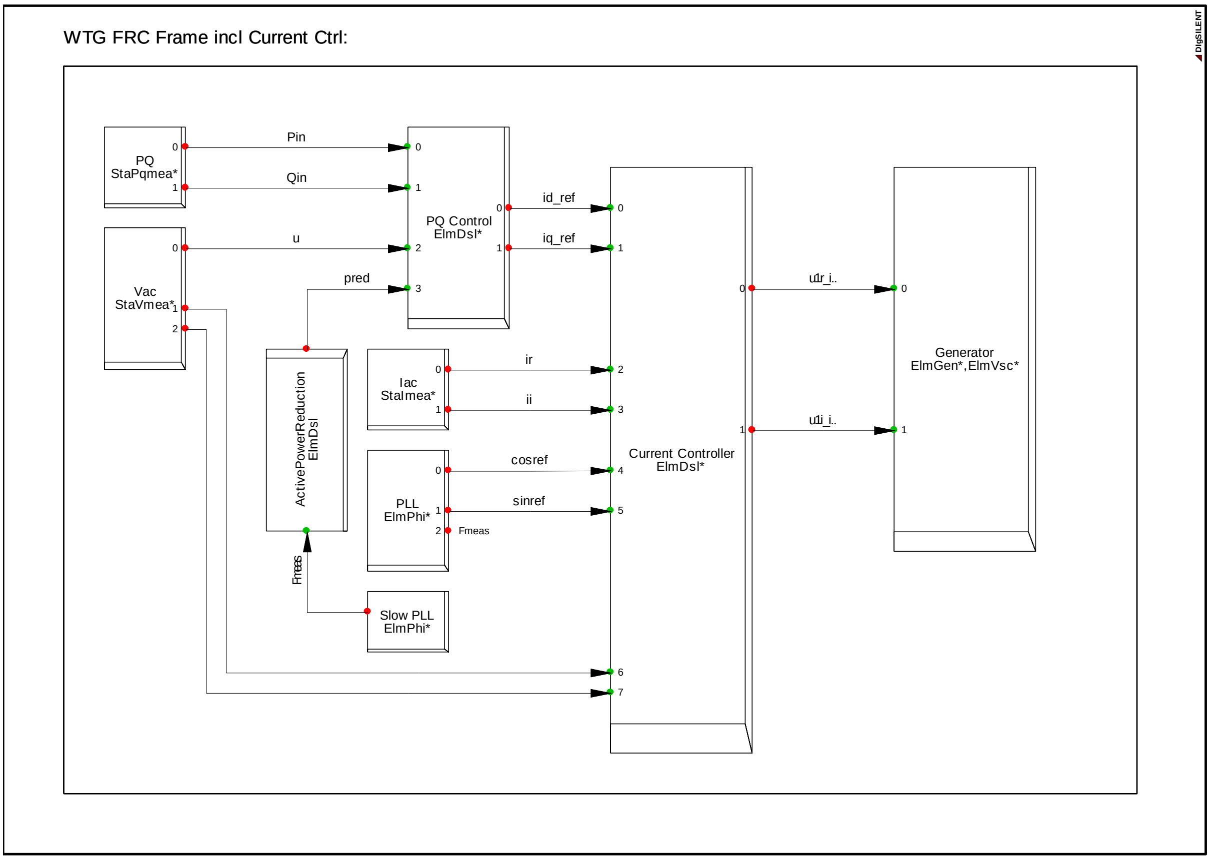


Figure 11 – High level PV block diagram

4 Review of methods for mitigating system overloads

The results contained in this report indicate that on occasion there may transmission line overloads post-fault. This section details some typical methods for managing overloads in these circumstances. These methods are typically applied in European power grids, and in particular in Great Britain. It is suggested that the client review these methods, and provided they can be allowed depending on the operating and regulatory rules of El-Salvador, they can then proceed with a cost benefit analysis to ascertain if any ‘new’ methods could be of use in order to maximise grid usage without requiring physical reinforcement.

The types of actions discussed in this section are as follows

- Pre-emptive manual pre-fault action
- Manual post fault action
- Automatic / special protection scheme actions including
    - Intertrips
    - Fast runback schemes
- A note on dynamic line rating equipment

4.1 Pre-emptive manual pre-fault action

Based on information provided by the client, this is the method which is currently applied in the El-Salvador grid. It involves performing contingency analysis (either on the worst case scenario during planning timescales, or based on the real time state of the power system during operational timescales) and then reducing the output of a specific generator or group of generators, in order to avoid a contingency causing an overload post-fault.

This has the advantage of being a relatively simple method which does not require any special equipment. However, it may mean that the power system is operated in a non-optimal way where low cost generation is constrained, and expensive generation is the only option to replace it. This is particularly the case if there is only renewable generation, with ‘free’ fuel, behind the overload.

4.2 Manual post-fault action

Transmission lines typically have relatively long thermal time constants allowing a small or moderate overload to be permitted for a short period of time. Provided the overload is below the operating point for protection this can allow manual post-fault action to relieve the problem. It is normal practice to be aware of which contingencies cause overloads so the operator can be aware of actions which he must take relatively quickly.

The advantage of this method is that the power system is operated in a more economic manner, and action only has to be taken if the specific contingency occurs. However, operators must be prepared to take action quickly, and it relies on having good knowledge of the protection settings of the line to avoid undesirable line tripping and possible cascade tripping, or system splitting.

4.3 Intertripping

If a post-fault overload occurs, a system to generator intertrip can be utilised to relieve the overload. This is typically termed a ‘special protection scheme’ and is fully automatic, not requiring system operator action. It is normally integrated with new power stations where the cost of a line upgrade or installation of new lines could make the construction of the power station un-economic. The power station may therefore accept an agreement requiring intertripping, rather than pay the cost of a system upgrade.

The procedure operates in the following manner; once the system protection detects a fault on the line (or lines) which is part of the contingency (or contingencies) which cause the overload of concern, it sends a signal to the power station / specific generator to be intertripped. This therefore requires good communication links between the specific contingency location and the generator. The signal is typically sent directly to the generator circuit breaker which opens immediately, thereby relieving the line overload. This method can also be used if there is a stability problem caused by the specific contingency, as the action is both automatic and very fast.

Utilising intertrip functionality has the advantage of being a fully automatic and robust method of mitigating a system issue such as a transmission line overload. It avoids having to take pre-fault action for specific contingencies and therefore operating the system in a non-economic manner. It addition, it can often be substantially more cost effective than reinforcing the power system where otherwise new transmission lines would be required.

However, increasing the frequency of synchronous generator trips does not come without penalty. The sudden ‘shock’ of full load rejection does impact on the life of the generator and associated equipment. Therefore it is normal practice to arm / select different generators within the scheme after each operation, and often the generator is compensated following a trip. Typically the intertrip is only ‘armed’ when contingency analysis indicates that an overload will happen, as otherwise unnecessary tripping of generation may occur. It is also important to ensure that tripping of generation is not in excess of the maximum allowed single loss of generation to avoid excessive frequency deviations, or overloading on tie-lines such as the SIEPAC line.

4.4 Fast runback scheme

Provided the constraint is only a thermal overload (not stability), and there are modern converter controlled renewable plants which can relieve, or are a direct cause of the overload, a fast runback scheme could be used. This utilises the ability of the converter control to ramp power very quickly down to zero. The signal is received by the wind / PV farm central controller (not the circuit breaker as with the intertrip approach). The controller then ramps the power to zero. Typically this is achieved in under 10 seconds. If for some reason they cannot achieve zero within this time then an automatic trip of the wind / PV farm breaker occurs as a backup. This approach has been tested and is in operation at multiple wind farms in Great Britain in order to avoid costly system upgrades. Typically it is only applied for overloading local to the generator to have certainty that the action will solve the issue, and to avoid long distances for the communication links.

This approach has the benefit of rapid power reduction to relieve the overload without the ‘shock’ to a power station of a sudden trip. In many cases it also means that you continue to get voltage control from this plant (if it can still provide MVAr down to zero output) thereby helping to manage post contingency voltages in the area. Similarly to the intertrip approach it also avoids the need to take pre-fault action, and in many cases may avoid the need to upgrade existing transmission lines, or install new lines. Following initiation of a fast runback the system operator can take action to re-dispatch existing plant to relieve the overload, then permitting the renewable generator to return to full output. Alternatively if this is not possible, it may be the case that the renewable generator can be returned to part load operation until such times as the faulted line is back in service. Typically the renewable generator is compensated for operation of this scheme due to the inconvenience of not being able to produce full available output.

4.5 A note on dynamic line rating equipment

A system operator will typically produce seasonal transmission line ratings (e.g. summer, autumn, winter etc.) based on the conductor type and construction together with typical ambient conditions such as air temperature and solar radiation on the line. However these values are normally very conservative. Dynamic line rating equipment can more accurately estimate the temperature of the line based on actual parameters on the day (both line measurements and meteorological data such as ambient temperature, wind speed, solar radiation). This can ‘release’ substantial additional capacity which can be used both pre and post-fault. There is of course a capital cost for this equipment, so it is typically only used on corridors where heavy congestion can occur regularly pre-fault. However, this equipment is starting to be deployed in circumstances where system reinforcement (line upgrades, new lines etc.) would simply cost too much compared to the cost of the project. Some equipment can also be integrated with automatic options for power reduction of generators behind the constraint. Some example suppliers include, but are not limited to, the following three references [1], [2] or [3]. Please note that these references are provide for information only and do not represent an endorsement of the equipment.

5 Analysis of simulation results

This section contains an overview of the simulation results conducted as part of this project. Due to the high volume of results the majority of the raw data is contained in the Annexes of this report, however important examples have been repeated in this section.

5.1 Load flow analysis

For each of the cases in 2016 and 2019 the intact system has been investigated. The base case generator dispatch is as per the supplied PSS/E data. The base case is compared with the case with the new non-synchronous renewable generation, with the appropriate disconnection of synchronous plant so that generation-load balance is maintained. The full results of base and renewable case dispatches are contained in Annex 1. These contain all the voltages (at each end) and loading of all transmission lines in El-Salvador.

Table 3 below contains an overview of the cases considered. This includes the total system generation and load and the calculated active power losses of the El-Salvador system for both the base and renewable cases. Note however that in general, the supplied data did not contain information relating to copper losses, or no-load losses of transformers, therefore the values below are almost exclusively transmission line losses. In most cases there are very small changes in the transmission line losses, however in both the 2016 dry cases, and the 2019 maximum load dry case there are substantial reductions in losses. This is due to the dispersed nature of many of the new renewable generation sites, and therefore better utilisation of the transmission system.

	Generation, Active Power	Generation, Reactive Power	Load P(U)	Load Q(U)	Losses	Change in Losses	CASE
	MW	Mvar	MW	Mvar	MW	MW	
2016 MAX LOAD WET SEASON	1133.79	200.44	1113.01	351.03	20.52		BASE CASE
	1133.34	205.40	1113.01	351.03	20.86	0.34	RENEWABLE CASE
2016 MIN LOAD WET SEASON	508.07	51.96	500.83	144.39	6.73		BASE CASE
	507.92	70.50	500.83	144.39	6.58	-0.16	RENEWABLE CASE
2016 MAX LOAD DRY SEASON	1121.74	224.31	1113.01	351.03	27.95		BASE CASE
	1112.56	203.21	1113.01	351.03	18.76	-9.18	RENEWABLE CASE
2016 MIN LOAD DRY SEASON	521.06	-21.40	500.83	144.39	11.57		BASE CASE
	516.31	-27.61	500.83	144.39	6.82	-4.74	RENEWABLE CASE
2019 MAX LOAD WET SEASON	1296.20	286.69	1269.01	400.22	28.13		BASE CASE
	1296.19	320.67	1267.23	400.22	29.90	1.77	RENEWABLE CASE
2019 MIN LOAD WET SEASON	567.16	8.07	571.06	164.59	11.59		BASE CASE
	567.15	29.98	570.45	164.59	12.19	0.60	RENEWABLE CASE
2019 MAX LOAD DRY SEASON	1303.82	359.39	1268.90	400.22	31.47		BASE CASE
	1303.81	353.32	1276.00	400.22	24.36	-7.11	RENEWABLE CASE
2019 MIN LOAD DRY SEASON	605.42	-33.89	571.07	164.59	10.31		BASE CASE
	605.41	-17.06	570.64	164.59	10.73	0.42	RENEWABLE CASE

Table 3 – Overview of all cases considered including generation, load and losses in El-Salvador for the base and new renewable generation cases

In general the results of the load flow analysis suggest that for the pre-fault case the inclusion of the new renewable generation does not impact on system operation to any great extent. All bus voltages can be adequately maintained within the pre-fault limits of 0.95 to 1.05 per unit, and no lines become overloaded. Table 4 shows an overview of the most heavily loaded line in each of the case and for each of the base and renewable cases.

	Generation, Active Power	Generation, Reactive Power	CASE
	MW	Mvar	
2016 MAX LOAD WET SEASON	48.63	lne_27211_27341_1	**BASE CASE**
	44.40	lne_27181_27211_1	**RENEWABLE CASE**
2016 MIN LOAD WET SEASON	43.25	lne_27181_27211_1	**BASE CASE**
	61.63	lne_27181_27211_1	**RENEWABLE CASE**
2016 MAX LOAD DRY SEASON	75.57	lne_27131_27411_1	**BASE CASE**
	48.26	lne_27411_27441_1	**RENEWABLE CASE**
2016 MIN LOAD DRY SEASON	59.03	lne_27131_27411_1	**BASE CASE**
	60.87	lne_27181_27211_1	**RENEWABLE CASE**
2019 MAX LOAD WET SEASON	53.88	lne_27361_27371_1	**BASE CASE**
	65.94	lne_27181_27211_1	**RENEWABLE CASE**
2019 MIN LOAD WET SEASON	68.20	lne_27181_27211_1	**BASE CASE**
	85.56	lne_27181_27211_1	**RENEWABLE CASE**
2019 MAX LOAD DRY SEASON	76.29	lne_27131_27411_1	**BASE CASE**
	62.57	lne_27181_27211_1	**RENEWABLE CASE**
2019 MIN LOAD DRY SEASON	68.82	lne_27181_27211_1	**BASE CASE**
	89.20	lne_27181_27211_1	**RENEWABLE CASE**

Table 4 – Overview of the most heavily loaded transmission lines (pre-fault)

Note that in some cases the displacement of conventional synchronous generation relieves the most heavily loaded lines, and in others the renewable generation increases the heavily loaded lines. The most common appearance is for the line ‘lne_27181_27211’. Particularly in the 2019 cases this line is often the most heavily loaded. In the 2019 minimum load dry season case it is loaded as high as 89.2%. The location of this line is shown below in Figure 12. It connects the BERL synchronous power station with the main system. This power station is extended by two units between 2016 and 2019 cases, contributing to the increase in loading. In addition the inclusion of the CHINA_U1 geothermal, SFV3, SFV4 and SFV6 PV farms on transmission lines to the south and east cause more of the generation from BERL to be exported along this heavily loaded line. Although this line is heavily loaded, the contingency analysis has indicated that the line will only become overloaded by 2% when considering contingency C15 and C16. This is at a level which (assuming the correct rating data has been supplied) could be managed operationally by reducing the least cost unit (either pre or post-fault) so that the line does not become overloaded for these contingencies. This will be discussed in more detail in the following section on contingency analysis.

In summary, the load flow analysis does not suggest any significant problems due to the new non-synchronous renewable generation. A transmission line loading concern has been identified, although this is mostly due to a combination of new synchronous generation together with 3 new PV farms.

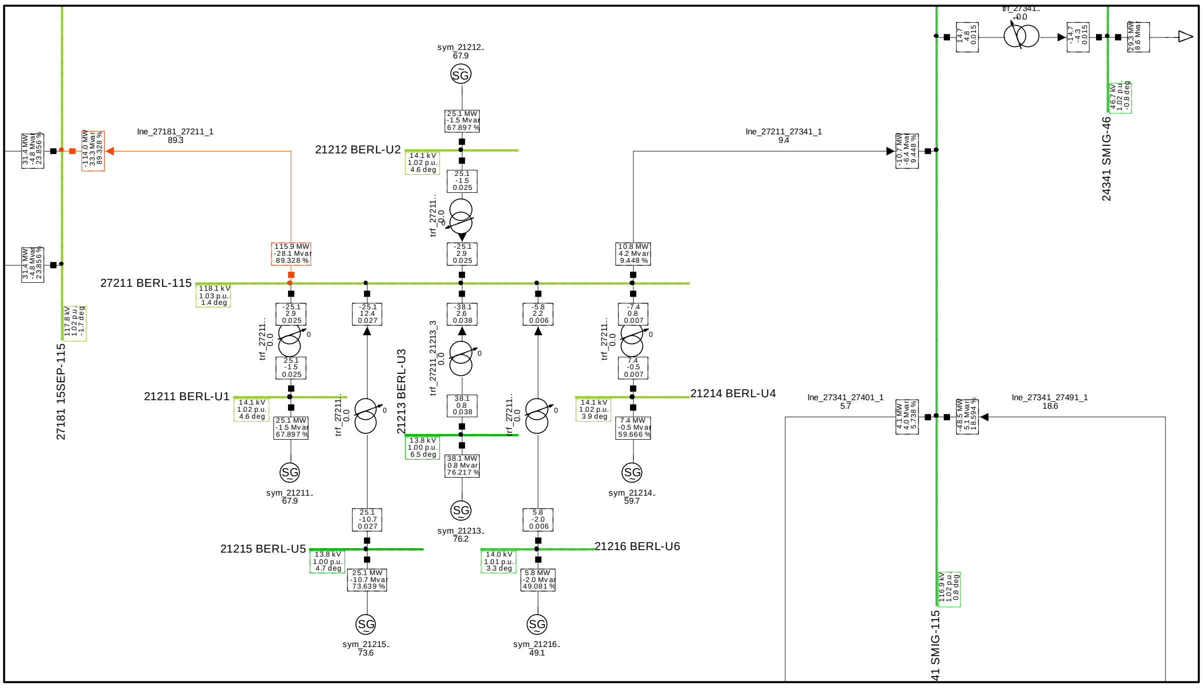


Figure 12 - Heavily loaded line in pre-fault case

5.2 Contingency Analysis

Contingency analysis was conducted for all cases, including both base and renewable cases, for the years 2016 and 2019 in order to gauge any impact from the inclusion of the new non-synchronous renewable generation for credible line and generator outages. Line loading together with bus voltage was monitored to ascertain if any post contingency impact was outside of operational post-fault limits. Note that as no transformer loading information was provided, the loading of transformers was not investigated. The limits applied to busses and lines are as follows:

- 0.95 to 1.05 per unit pre-fault bus voltage permitted
- 0.9 to 1.1 per unit post-fault bus voltage range permitted
- 100% post fault transmission line loading permitted

The full results of the contingency analysis, as contained in Annex 2, show all lines with a loading in excess of 50% (either pre or post-fault), together with all busses with a post fault voltage below or above 0.95 or 1.05 per unit voltages respectively. Note that the pre-fault voltage ranges have been applied for reporting purposes to ensure that there are no bus voltages which are just inside the post fault limits. The following sections provide a brief overview of each case result.

5.2.1 2016 Maximum Load Wet Season

In the base case the double circuit contingency C31 is the most severe, loading lne_27171_27321_1 to almost 100%. With the new renewable generation included the loading increases to just over 100%, however the variation is so small and would be sensitive to the actual load on the day. It can therefore be assumed that the impact of the new renewable generation in this case is negligible and this contingency would have to be managed operationally either by pre-fault dispatch adjustment, or assuming the line has a temporary overloading capability, by post fault operations. If this is considered to be a real overload then any of the following plant would be prime candidates for power reduction: CGRA_U1, CGRA_U2 or 5NOV_U6.

All other contingencies, in both the base and renewable cases maintain line loading levels below 77% and therefore can be considered not to present an issue.

There are no voltages post fault which drop below or above 0.95 or 1.05pu respectively in the base case. In the renewable case bus 27421 NCUS-115 does drop just below 0.95 however the impact is minimal and this is well within post-fault operational ranges.

5.2.2 2016 Minimum Load Wet Season

In the base case the maximum loading achieved is 80.62% for lne_27171_27321_1 during the double circuit contingency C31. In the renewable case a different n-1 contingency, C9 is the most severe loading lne_27181_27211_1 to 70.61%. Therefore in this case the renewable generation dispatch actually improves the utilisation of the grid. However, in either case the post fault loading is well within limits and therefore neither is of concern.

In this case both the base and renewable cases have identical busses which drop below 0.95 per unit. As this occurs in both cases it can be deduced that the renewable generation has little or no impact on the voltage regulation in this case. This voltage drop is still well within the post fault limits and so isn't considered to be an issue.

5.2.3 2016 Maximum Load Dry Season

In this example there are some severely overloaded lines in the base case caused by contingencies C5 and C3. Overloading up to 129.34% occurs on lne_27131_27411_2 (C5), 121.78% on lne_27411_27441_1 (C3), 120.89% on lne_27131_27411_1 (C3) and 120.52% on lne_27131_27411_2 (C3). It is proposed that these contingencies would need to be managed pre-fault by generator pre-fault power reduction or by generator inter-trip if these specific contingencies occur. Key generators to reduce in power or inter-trip would be ACAJ_U5, ACAJ_U4 or CASA_U2, although more than one generator trip would be required due to the severity of the overload. If this is considered to be a credible overload then reinforcement of the impacted lines is suggested to avoid ongoing operational restrictions.

In the renewable case the maximum loading occurring for C3 is 82.69%, indicating that under this operating scenario the change in generation dispatch relieves the overloads and avoids the need for pre-emptive action or inter-trip arming.

The most severe voltage deviation is down to 0.93pu at 21372 NEJA-G2, however this is the same in both the base and renewable cases. All other reported deviations are only just below 0.95 and therefore in this example the impact of the generation on post-fault voltage regulation can be considered to be negligible.

5.2.4 2016 Minimum Load Dry Season

In this case there is a small base case overloading to 101.05% caused by contingency C5. Again, this is a relatively small overloading and would be dependent on the short term overloading capability of the affected line lne_27131_27411_2. ACAJ_U1, U2 or U4 would be prime candidates for pre or post fault power reduction to relive the overload post fault if the overload is considered to be credible. In the renewable case there are no violations. The maximum loading occurring is 73.04% for contingency C11. Therefore, the renewable case can be said to improve the post-contingency loading.

There are no bus voltages reported below or above 0.95 / 1.05pu. In the renewable case there are no busses reported below 0.95, and 4 busses reported to be just above 1.05pu. However these are minor and well within the post fault contingency range and can therefore be considered not to be a problem.

5.2.5 2019 Maximum Load Dry Season

Similarly to the 2016 maximum load dry season case there are severe overloads in the base case which are again relieved by the revised generation dispatch in the renewable case.

The largest voltage deviation reported is to 0.93pu at 27421 NCUS-115. However this is present in both the base and renewable cases. Some of the other base case low voltage deviations are no longer present in the renewable case, however there is one minor excursion above 1.05 at 27211 BERL-115. In all cases the deviations are well within limits and the renewable generation has no impact or even a moderate improvement in the voltage regulation post fault.

5.2.6 2019 Minimum Load Dry Season

In the base case the maximum loading achieved is 97.61% on lne_27181_27211_1 for contingency C9. In the renewable case there are some minor overloads for C13 (103.9%), C16 (103.29%) and C15 (102.33%) all on lne_27181_27211_1. This line was identified in the load flow analysis as being heavily loaded pre-fault due to new synchronous generation together with the new non-synchronous generation. Although the occurrence of maximum solar export at minimum load is unlikely to happen, the line in question can become heavily loaded in other cases. This can be managed in a number of ways following identification of a potential issue using actual operational pre-fault contingency analysis. Either it can be managed by de-loading an appropriate plant (usually the most costly) pre-fault to avoid the overload post fault. Alternatively, if the overload is modest it will most likely be in the short term overload capability of the line, and can be managed with a generator re-dispatch post fault. If an automatic procedure is required then a selected generator can be inter-tripped where by a special protection scheme is put in place to disconnect a specific generator if that specific contingency occurs. Another potential and often preferred method is to install a ‘fast runback’ scheme at one of the wind or PV solar farms which is behind the constraint. As modern wind and solar converters have exceptionally fast active power control, they can be set to reduce power very rapidly upon receipt of a signal from the system operator. This signal is normally automatically produced once the specific contingency has occurred. That way there is no power reduction pre-fault, and it avoids complete disconnection of a generator in the case that the contingency does occur. For the contingencies in these overloaded cases the 9908 SFV6 PV plant is the best candidate for relieving the overload post fault, and therefore a fast runback scheme could be implemented. Once the overload has been relieved a manual re-dispatch of the synchronous generation can be initiated, and the PV plant can be allowed to return to full available output. This permits the fast response of the converter controlled plant to be utilised, but limits the impact of constraining ‘free’ renewable generation.

There were no voltage deviations above or below 1.05 / 0.95pu reported for either the base case or the renewable case.

5.2.7 2019 Maximum Load Wet Season

In the non-renewable case the maximum loading occurs for contingency C31 on lne_27171_27321_1 (97.25%). However in the renewable case there is an overload observed for the same contingency on lne_27321_27431_1 (108.1%). Due to the location of the overload and the meshed nature of the El-Salvador system there are four renewable plants responsible for this overload. In particular it is a combination of 9906 SFV4 PV, 9908 SFV6 PV, 9905 SFV3 PV and 9903 SFV1 PV as shown below in Figure 13 - Overloaded line (shown in red) together with the four different renewable generators responsible. It would however be more effective to reduce the output (either pre or immediately post contingency) of the synchronous generators CGRA_U1, CGRA_U2 or 5NOV_U6. Again, if done post-fault, this would be achieved automatically by inter-trip if the temporary line overloading doesn't allow for time for manual system operator action to take place. It is not recommended to install a fast runback scheme in this instance as it would require communication with multiple generators over large distances.

There are number of voltage deviations below 0.95pu, although none above 1.05pu. The most severe is down to 0.91 (with a 5% voltage step from the pre-fault case) at 27421 NCUS-115, however this is still within the post-fault limits and is identical in both the base and renewable cases. There are a number of additional low voltages reported in the renewable case however many of these are just below 0.95 and are not considered to be an issue.

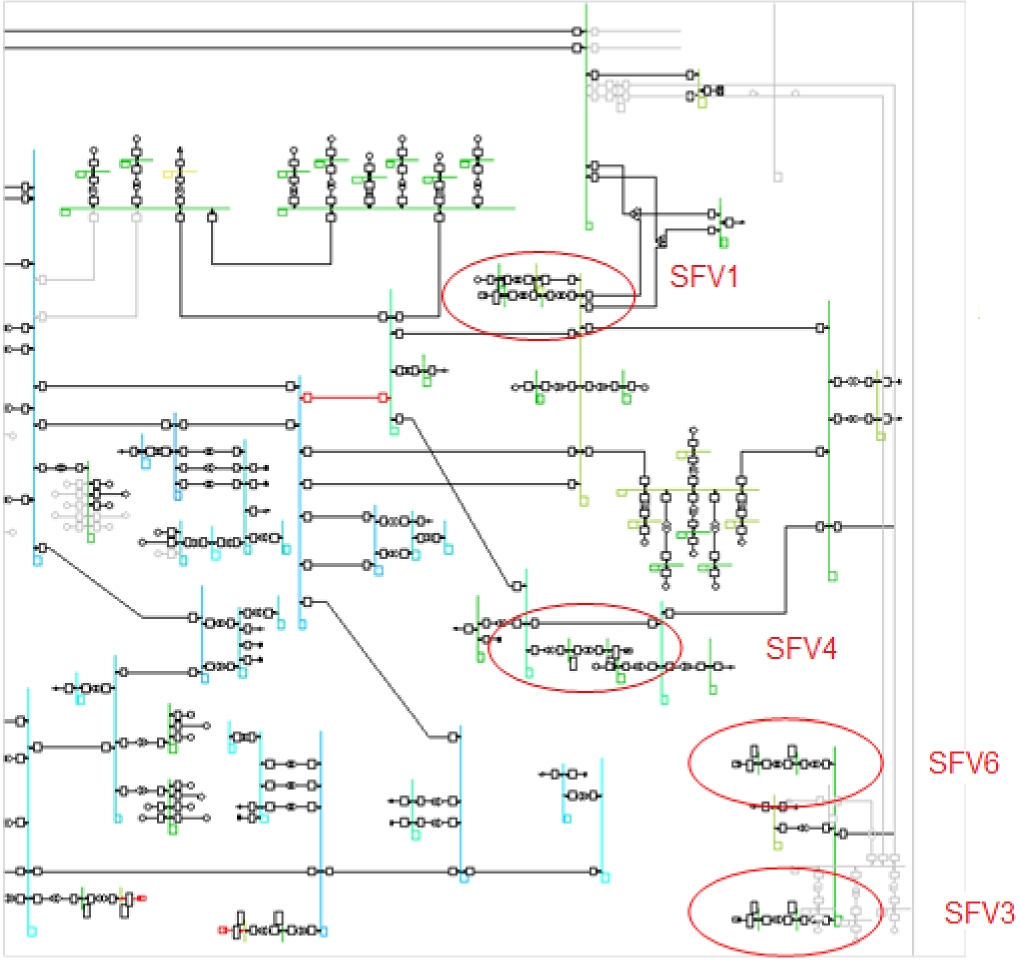


Figure 13 - Overloaded line (shown in red) together with the four different renewable generators responsible

5.2.8 2019 Minimum Load Wet Season

In the base case the maximum loading is 94.37% for contingency C9. In the renewable case C16 and C15 cause minor overloads to 101.11% and 100.53% respectively. If these are deemed to be real overloads then 9908 SFV6 PV or 9905 SFV3 PV would be prime candidates to relieve the overload. However the likelihood of maximum output during minimum load conditions means that this particular case may not occur.

There are no low voltages reported below 0.95pu in the base case, and the low voltage violations reported for the renewable case are at the terminals of generators which have been disconnected based on merit order for the renewable case, and can therefore be ignored. There are three voltages reported above 1.05pu in both the base and renewable cases at 24471 PEDR-46, 27471 PEDR-115 and 24461 STOM-46. Although these are marginally worse in the renewable case (approximately 0.01pu) these are still within post fault operational limits and the impact of the renewable generation on post-fault voltage performance can be considered to be negligible.

5.2.9 Summary of Contingency Analysis Studies

From the contingencies considered, and based on the information provided by the client, any impact on the post fault voltage performance of the El-Salvador system due to the new non-synchronous generation (including the corresponding displacement of synchronous generation) can be considered to be negligible.

It has however been noted that busses in the region of 22471, 27461 and 27421 appear regularly in the contingency analysis results in relation to contingencies C7 and C10. The situation seems to worsen in the 2019 scenarios under high load, with voltage step changes up to 5%. This indicates that this area is particularly weak and would be a candidate for additional reactive equipment. The renewable scenario does not worsen the problem, in fact in many cases it actually improves it due to additional renewable plant with voltage control such as 9910 SFV8 PV. However this plant is small and is unlikely to be connected directly to 115 kV in reality, therefore cannot be relied upon for fixing this issue. For the avoidance of doubt this is an issue which is in the base case and is not caused by the new non-synchronous renewable generation.

In respect of the transmission line loading, there were several cases where lines were loaded above 100%. In some of these cases the overloading was in the base case, and in others it was in the case with the new renewable generation. Table 5 contains the cases which have lines loaded above 100%. For each case the highest line loading is shown for both the base and renewable case. Also shown is the ‘delta’ between the base and renewable cases. A positive number indicates that the renewable case reduces the most heavily loaded lines, and a negative number indicates that the renewable case increases the most heavily loaded lines.

Case	Max loading in base case	Max loading in renewable case	Improvement due to renewable case
2016 Maximum Load Wet Season	99.81%	100.37%	**-0.56%**
2016 Maximum Load Dry Season	129.34%	82.69%	**46.65%**

2016 Minimum Load Dry Season	101.05%	73.04%	**28.01%**
2016 Maximum Load Dry Season	130.7%	93.66%	**37.04%**
2019 Minimum Load Dry Season	97.61%	103.9%	**-6.29%**
2019 Maximum Load Wet Season	97.25%	108.13%	**-10.88%**
2019 Minimum Load Wet Season	94.37	101.11%	**-6.74%**

Table 5 - Cases with transmission line loading in excess of 100%

In the case where the base case is overloaded, the inclusion of the new renewable generation relieves this overloading by displacing synchronous generation and supplying the load from less congested areas of the grid. In the cases where the renewable generation causes overloading, the amount is relatively minor. However, these are extreme examples and represent the maximum possible impact as the new renewable generation is modelled at full output, which is not often the case for 'variable' generation such as PV or wind.

In each case either pre-emptive re-dispatch of generation, or post fault manual operator or automatic action may be required depending on the standard operational practices of the El-Salvador system operator. Key generators have been proposed for power reduction / disconnection to help relieve the overloads for each example. Note that some of the overloads are marginal, and provided the transmission lines have temporary overload capability, can be managed post fault using operational instructions. This is a preferential approach as it only impacts on operational costs if the contingency does occur. Alternatively dynamic line rating equipment could be installed on the overloaded lines to calculate a 'real time' line rating which is usually significantly higher than those used for planning or operational purposes. More information on the potential options can be found in the conclusion.

As a general comment, the renewable generation improves / relieves the overloads in some cases, and make them moderately worse in others which is to be expected with differing generation dispatch / location. The cases studied here are extreme in the fact that all renewable generation is modelled at full output and the most likely operational point will be somewhere in between the base and renewable case. For this reason, a system operator will, in line with good industry practice, perform contingency analysis based on the current and near real time future state of the power system and take action accordingly. Out of the large number of contingencies considered, only a small number of issues have been raised, all of which can be mitigated / managed by the proposed methods.

5.3 QV Analysis

QV analysis is typically used to ensure that the reactive ranges of generation are adequately specified in order be able to maintain voltages within limits during a range of contingencies. As many of the PV farms are relatively small their individual impact on voltage regulation is minimal. In addition, it would be normal practice that they would be connected to lower voltages, rather than directly to the 115kV transmission system as advised by the client. Therefore only the larger (>=20MW) PV and wind farms have been selected for analysis to ensure that the proposed reactive range is sufficient. This gives a total of four sites:

- 9908 SFV6 PV
- 9909 SFV7 PV
- 9901 PE1 WF
- 9902 PE2 30MW WF

For each of the selected generators they have been placed into unity power factor control mode in turn, and a range of PV curves produced for each of the consultant specified contingencies. These contingencies are listed below in Table 6 and have been specifically chosen in order to have the biggest reactive power / voltage control impact on each of the four renewable projects. Note that due to their close proximity SFV7 and PE2 use the same contingencies.

For renewable plant	Contingency
SFV7 & PE2	9907 SFV5 PV
SFV7 & PE2	lne_27131_27411_2
SFV7 & PE2	lne_27131_27441_1
SFV7 & PE2	lne_27161_27411_1
SFV7 & PE2	lne_27411_27441_1
SFV7 & PE2	lne_27421_27441_1
SFV7 & PE2	lne_27441_27481_1
SFV7 & PE2	trf_27131_21137_7
SFV7 & PE2	trf_27131_21139_1
SFV6	lne_27181_27341_1
SFV6	lne_27211_27341_1
SFV6	lne_27321_27391_1
SFV6	lne_27341_27401_1
SFV6	lne_27391_27401_1
SFV6	shntswt_24491_1
SFV6	sym_21182_2
SFV6	sym_21213_3
SFV6	Trf(7)
PE1	lne_27161_27351_1
PE1	lne_27161_27411_1
PE1	lne_27351_27381_1

PE1	lne_27381_27501_1
PE1	sym_21161_1
PE1	sym_21171_1
PE1	tr3_28161_27161_24161_1
PE1	tr3_28371_27371_24371_2
PE1	trf_27111_21111_1
PE1	trf_27111_24111_1

Table 6 - List of project specific contingencies for QV analysis

An analysis of the results indicates that for the four selected renewable generators, the 2019 maximum load wet season case has the largest voltage deviations, and they are therefore used as examples in this section. The remainder of the results can be found in Annex 3.

Figure 14 shows a result for the PE1 wind farm for this particular case. Here the green contingency is the most severe (outage of lne_27161_27351_1). The graph shows that if the PE1 wind farm were to operate in unity power factor mode while at full output, this contingency would cause a voltages drop from the base case voltage of 0.956pu to 0.908pu (by reading across the Q=0 line). However by including a reactive range of +/- 0.95pu the contingency would cause the voltage wind farm to export at its full lagging limit, and the post fault voltage would be improved to 0.941. This result indicates that although the 0.9pu post-fault was not breached, it was very close. Therefore provision of voltage control at this station is required, and a range of +/- 0.95pu is sufficient to manage this appropriately given the generation scenario in this case.

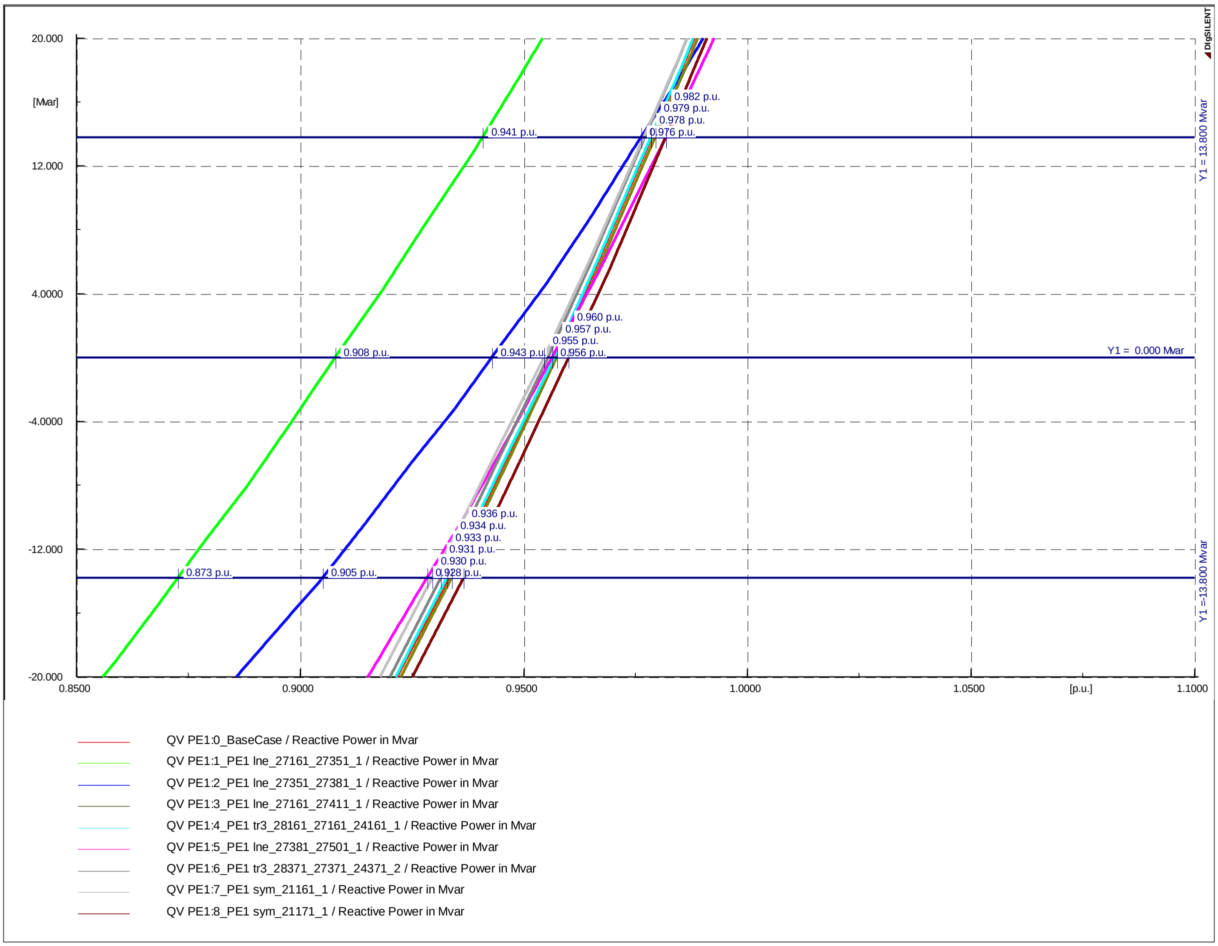


Figure 14 - QV curve for PE1 - 2019 Maximum Load Wet Season

Figure 15 contains a similar result for the SFV7 PV farm. In this example the slope of the curves are exceptionally steep and very close together. This indicates that this is a very strong part of the network, and indeed there are several generators connected to the same bus (ACAJ). Therefore it is very difficult for SFV7 to impact significantly on the voltage of this bus.

This result indicates that in the studied cases provision of reactive power / voltage control from this site is arguably not necessary. However, as these high level voltage control / reactive power requirements are considered standard in many countries, the inclusion here of both services is still advised. The reason being is that it helps to maintain system reactive reserves, future proofing the El-Salvador system, particularly if some dispatch cases could occur in future, for example moderate import via the SIEPAC line where additional synchronous generation would be disconnected from this bus.

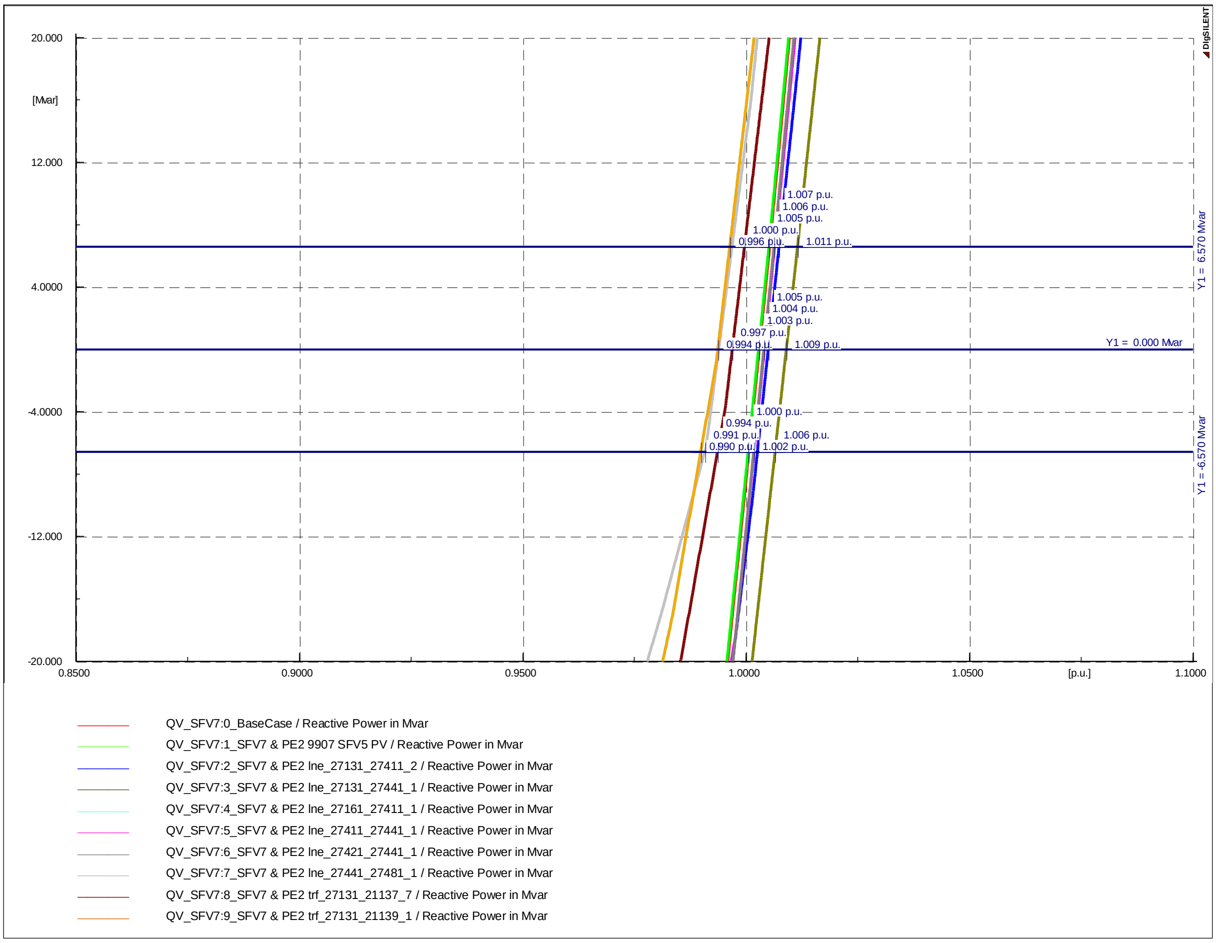


Figure 15 - QV curve for SFV7 - 2019 Maximum Load Wet Season

The results for PE2 are shown below in Figure 16. The only significant contingency of lne_27441_27481_1 is depicted by the blue line. In this case the line connecting PE2 to the nearby TALN synchronous generation is lost. Although the voltage drop at Q=0 is still within post-fault limits, the provision of full lagging power factor in this case would improve the post-fault voltage profile. Therefore, for the same reasons as discussed for SFV7, the +/- 0.95pu reactive range with droop voltage control is considered adequate and is recommended for the PE2 site.

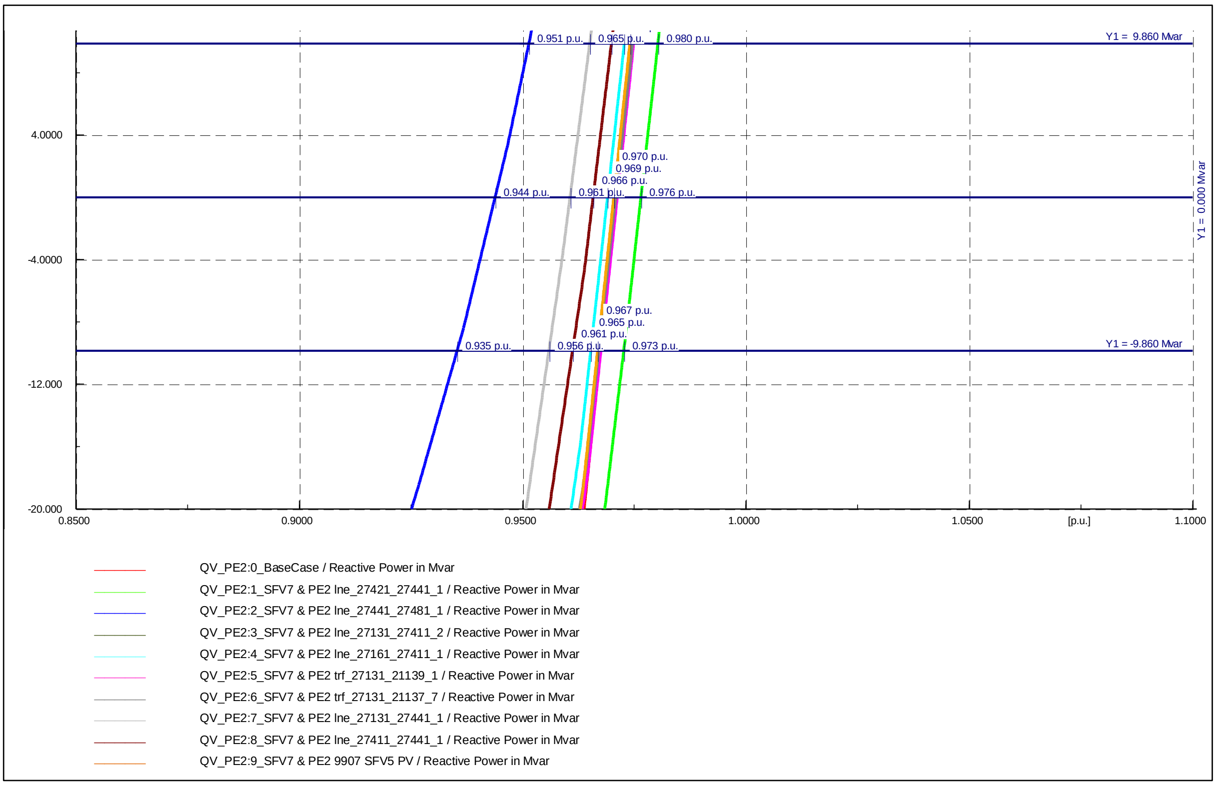


Figure 16 - QV curve for PE2 - 2019 Maximum Load Wet Season

Results for the SFV6 plant are shown in Figure 17. Despite being at the end of a 50km transmission line, the voltage regulation at this bus is still relatively good with the deviations for the studied contingencies being relatively small. This is partly due to the SFV3 plant and the nearby BERL synchronous plant. Although operation in unity power factor does not highlight any voltage violations outside of post fault ranges, provision of voltage control does assist in the voltage regulation post-fault at this node and is therefore recommended.

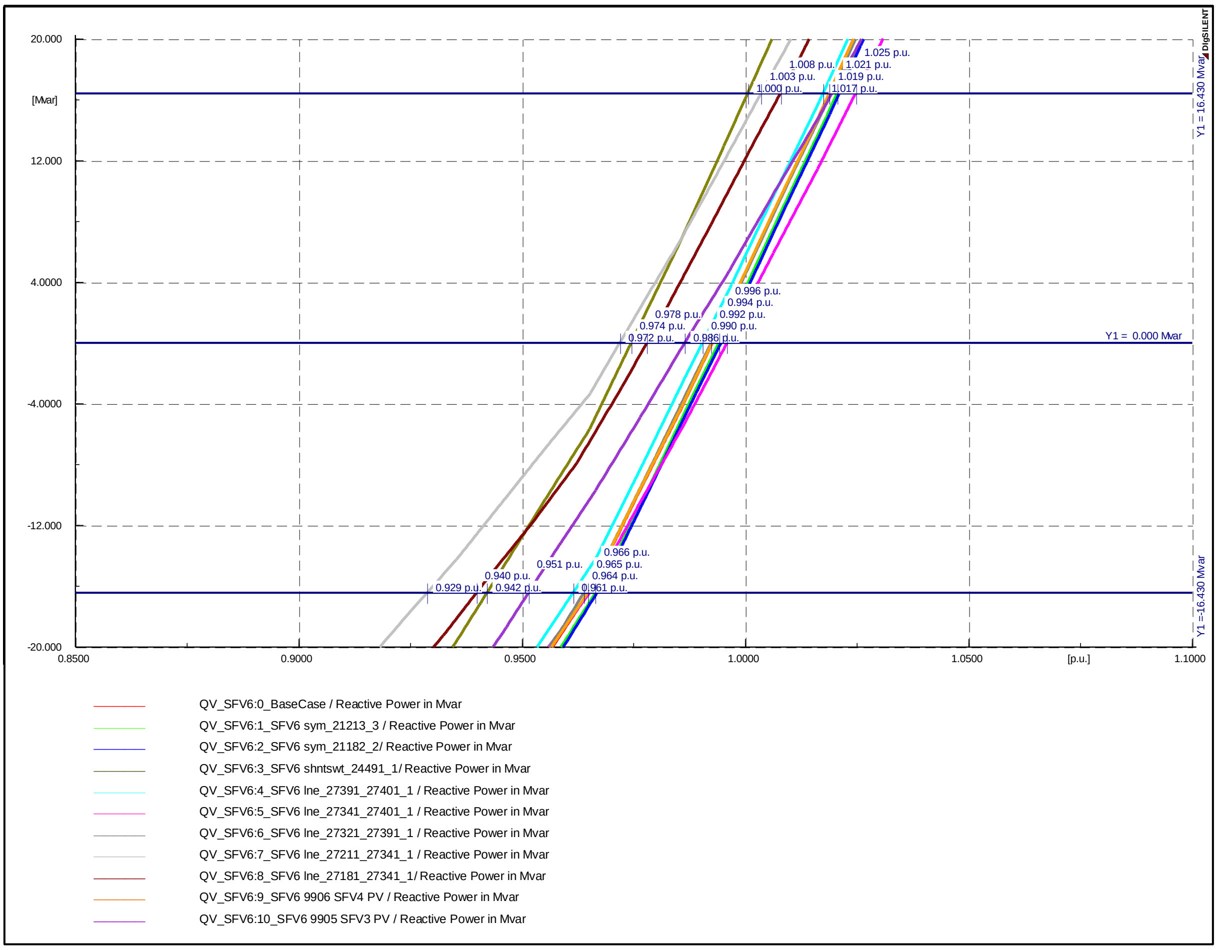


Figure 17 - QV curve for SFV6 - 2019 Maximum Load Wet Season

In conclusion it can be stated that for each of the large renewable plants studied, and for each of the cases as supplied by the client, a +/- 0.95pu reactive range is sufficient to control voltage sufficiently with post-fault voltage limits. There is no evidence to suggest that any of these plants require additional reactive capability. There is a potential argument for a reduced reactive range, or operation in reactive power mode, however this is not recommended as it decreases overall system reactive reserves. In addition, future system operational scenarios may have different system dispatches where entire synchronous power stations are disconnected due to SIEPAC imports etc. Reactive range of this magnitude, together with droop voltage control is considered an industry norm in many countries with the majority of established manufacturers being capable of delivery of this service. Therefore in order to provide some 'future proofing' of the El-Salvador system, applying a clear and transparent standard requirement for all transmission connected non-synchronous plant is advised by the consultant.

5.4 Dynamic Simulation Analysis

For verifying the impact of planned wind and PV generation in El Salvador on

- Transient stability
- Short-term voltage stability

- Frequency stability (in the case of islanding of the system of El Salvador) extensive simulation studies have been carried out based on the models described in section 2 and section 0.

Stability studies for the system of El Salvador can generally be divided into studies relating to:

- Local stability aspects in the 115kV system of El Salvador
- Regional stability aspects relating to the interoperability of all systems connected to the SIEPAC line.

Because at present, the SIEPAC line is operated with zero transfer (export/import) and only used for frequency and voltage stabilisation of the connected countries, no regional stability issues have to be expected.

For the year 2019, it can be expected that a market for power exchange between the countries connected to the SIEPAC line will be in place and therefore, situations with high import and high export of the system of El Salvador have been studied as well.

However, for really studying the impact of renewable generation on global stability aspects in the interconnected SIEPAC-system it would be required to:

- Consider planned renewable generation in all countries connected to the SIEPAC line
- Consider a regional network model for the year 2019. As described in section 0, only a regional model for the years 2014 and 2015 could be provided for the purpose of these studies.

Because of these modelling limitations, results of regional stability studies are only of very limited significance.

5.4.1 Methodology

Based on the contingency analysis results (see section 5.2) critical contingencies have been identified and analysed by dynamic simulations considering short circuits on the sending end of the corresponding line with a subsequent trip of the line after 150ms. A critical contingency has been defined as a contingency that leads to considerable line loadings (above 70% of rated current). These faults have been simulated for all cases according to section 2.1 (base case scenarios), with and without planned renewable generation plants, and the results have been compared for identifying the impact of planned renewable generation plants on system stability.

For analysing the robustness of the system, special “stress scenarios” have been defined, such as maximum export from El-Salvador (high inertia, high loading of SIEPAC line) or maximum import to El-Salvador (high import, minimum short circuit level/reactive support in El Salvador, high loading of SIEPAC line) that deviate from the base case scenarios according to section 2.1. For those scenarios, only a few contingencies that have been considered to be of particular relevance have been analysed.

5.4.2 Results of Simulation Studies, Year 2016

The result of all simulation studies for the year 2016 is depicted in Annex 4. Each graph uses the same contingency numbering terminology as used for the contingency analysis. A complete list of the contingencies and the corresponding numbers can be found in Annex 2. These results show:

- Response of renewable generation plants (voltage, active and reactive power)
- Response of synchronous generation plants (voltage, active and reactive power)

- SIEPAC-transfer (active and reactive power flows).

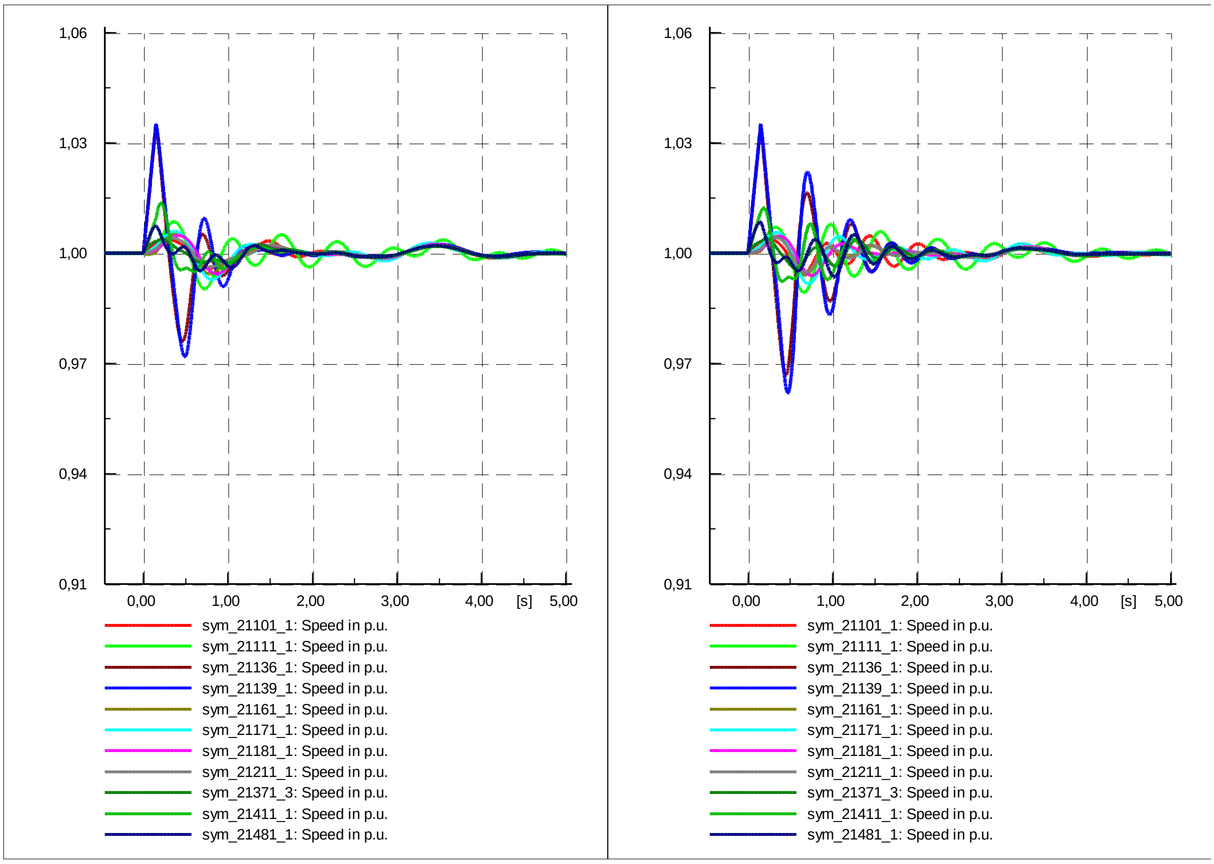


Figure 18: Speed of generators in El Salvador for the case without new renewable generation (left) and with planned renewable generation plants (right), case: Max Dry 2016

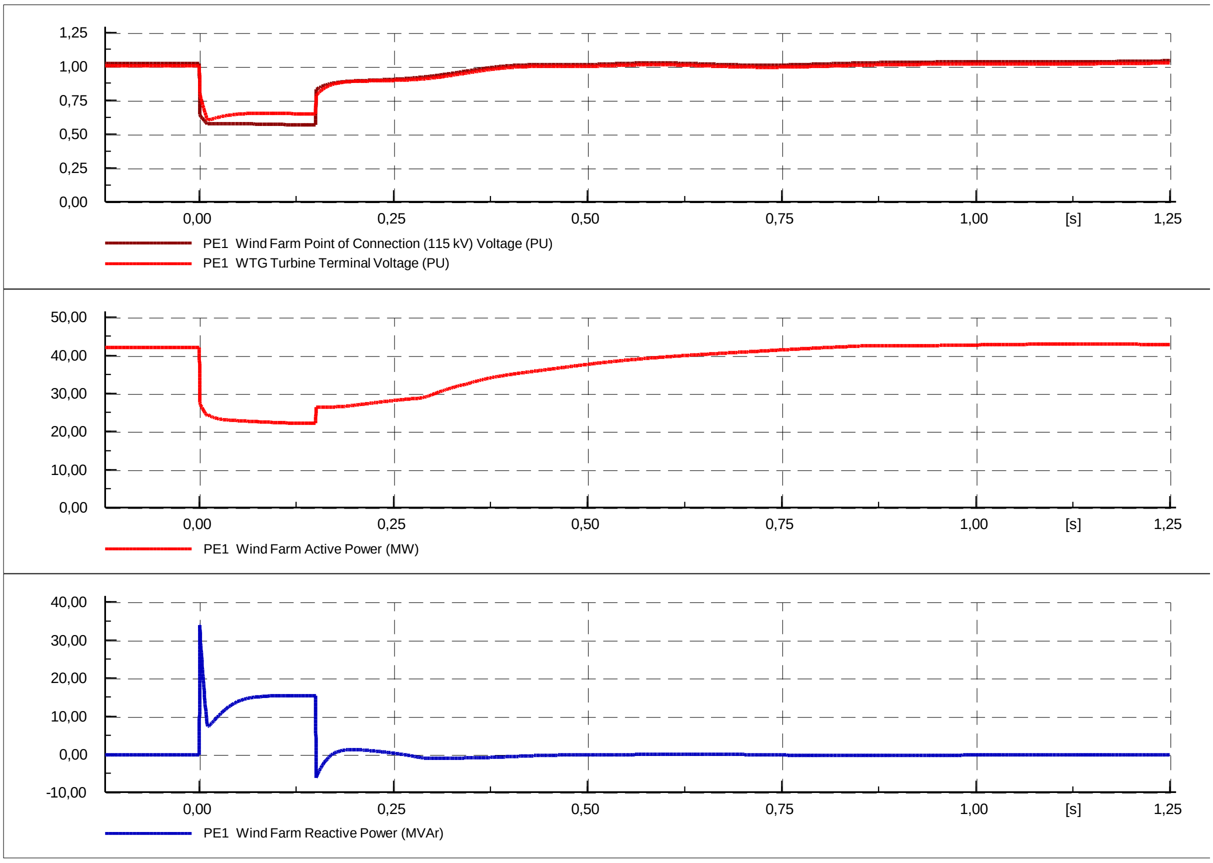


Figure 19: Response of PE1 Wind Farm to a voltage dip

Transient Stability (Local)

Generally, the system shows a very stable response to all simulated faults, meaning that critical fault clearing times are largely above 150ms.

The introduction of the planned wind and PV farms doesn't have a significant impact on transient stability of the system, which is also due to fact that the addition of renewable generation doesn't change the loading of lines significantly (see section 5.2).

Besides this, all renewable generation plants are supposed to be equipped with converters and controllers that are compliant with the principles outlined in section 7 resulting in a very supportive response. Figure 19 shows the response of PE1 wind farm to a voltage dip with a retained voltage of around 60%. The wind farm immediately responds to the voltage dip with an increased reactive power supply supporting the grid voltage while reducing active power.

During voltage recovery, the wind farm operates at around zero reactive power exchange, which means that it behaves neutral with regard to voltage recovery.

Active power is restored to pre-fault level in under 1 second.

Oscillatory Stability (Local)

In most cases, a slight reduction of damping of local modes in the grid of El Salvador can be identified when planned renewable generation plants are included, and the selected synchronous generation is displaced. However, damping of oscillatory modes is still considered good and no special measures for mitigating this issue will be required.

Regional Stability:

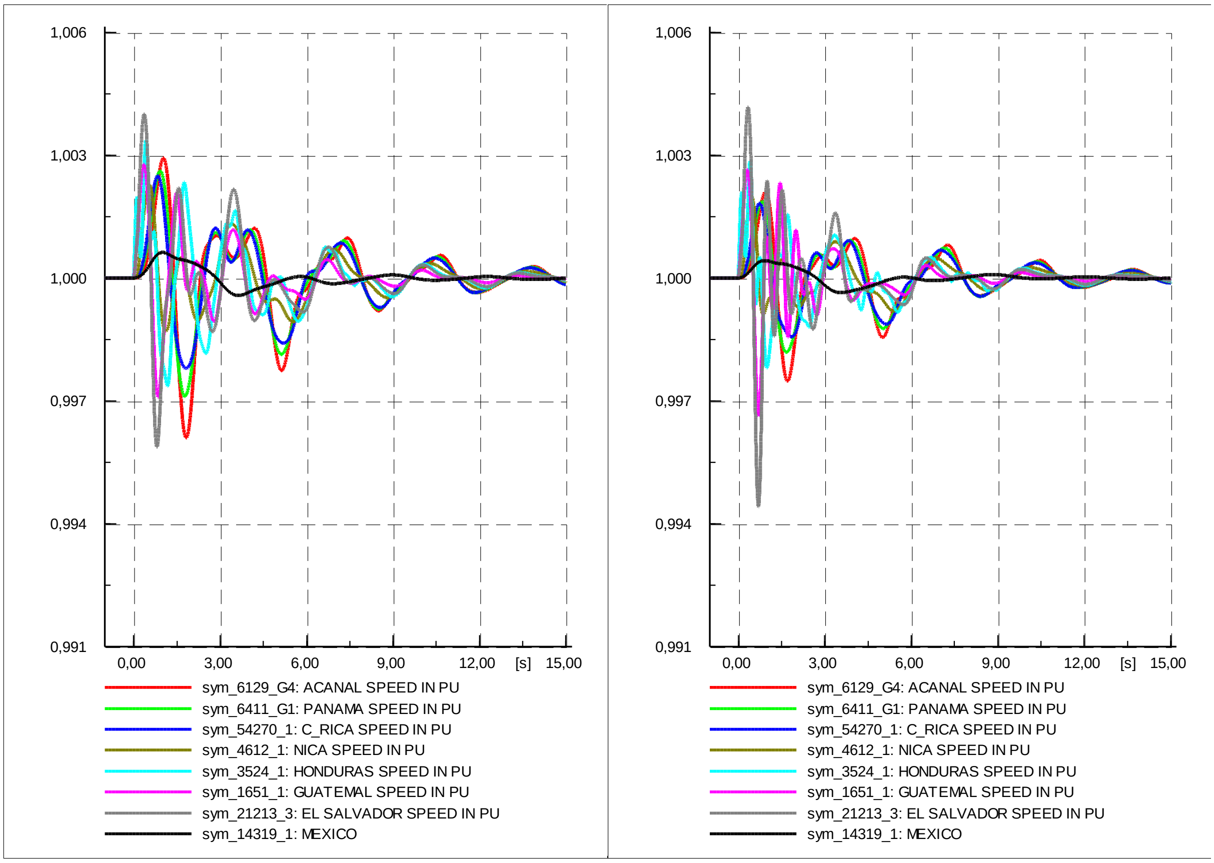


Figure 20: Inter-area oscillations on the SIEPAC system for the case without planned renewable generation in El Salvador (left) and with renewable generation in El Salvador (right): Max Dry 2016

Whereas a slightly negative impact of the planned renewables on the damping of local oscillations could be identified, there is almost no or even a slightly positive impact on the damping of inter-area oscillations noticeable.

However, in the case of zero power transfers, inter-area oscillations should generally not represent a serious issue.

5.4.3 Results of Simulation Studies, Year 2019

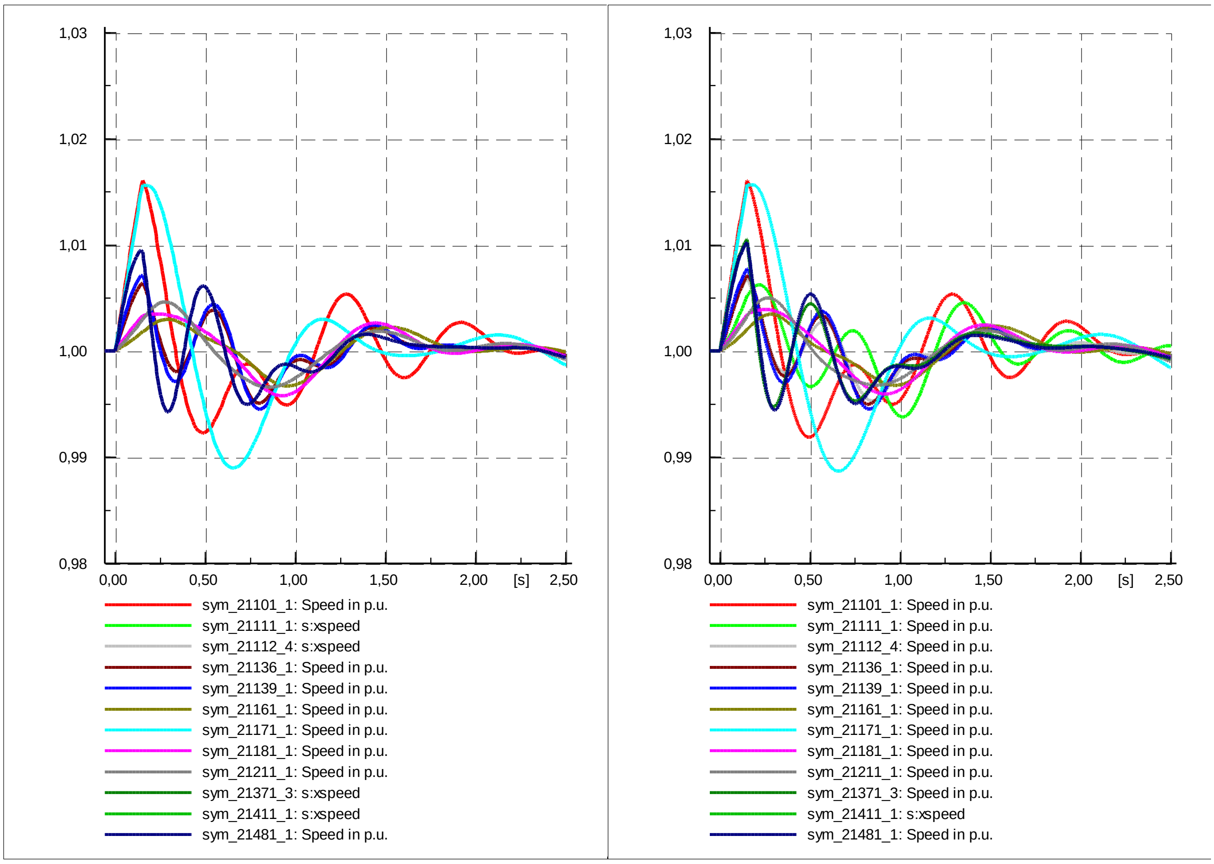


Figure 21: Speed of generators in El Salvador for the case without RE (left) and with planned renewable generation plants (right), case: Max Wet 2019

The results of all dynamic simulation studies for the year 2019 are depicted in Annex 5.

The summary of the presented simulation results is therefore the same as for 2016:

- There is no considerable impact on transient stability aspects
- There is no considerable impact on the damping of local or regional oscillatory modes.

Generally, the impact of the planned renewable power plants on transient and oscillatory stability in 2019 is even lower than in the year 2016 because the installed renewable generation capacity remains constant while load and conventional generation increases between these two years. Hence, the penetration of renewable generation is lower in the 2019 cases than in the 2016 cases.

5.4.4 Results of frequency stability studies

Frequency stability in the case of a complete loss of the SIEPAC interconnector was studied for the year 2019, when it can be expected that the power transfers over the SIEPAC interconnector will be possible. For assessing the impact of the planned renewable generation plants on the initial frequency rate of change, the following cases have been studied:

- Max load, max. import
- Max load, max export

The max. import and max. export scenarios were defined by an export and import of around 200MW respectively.

5.4.4.1 High Frequency Response

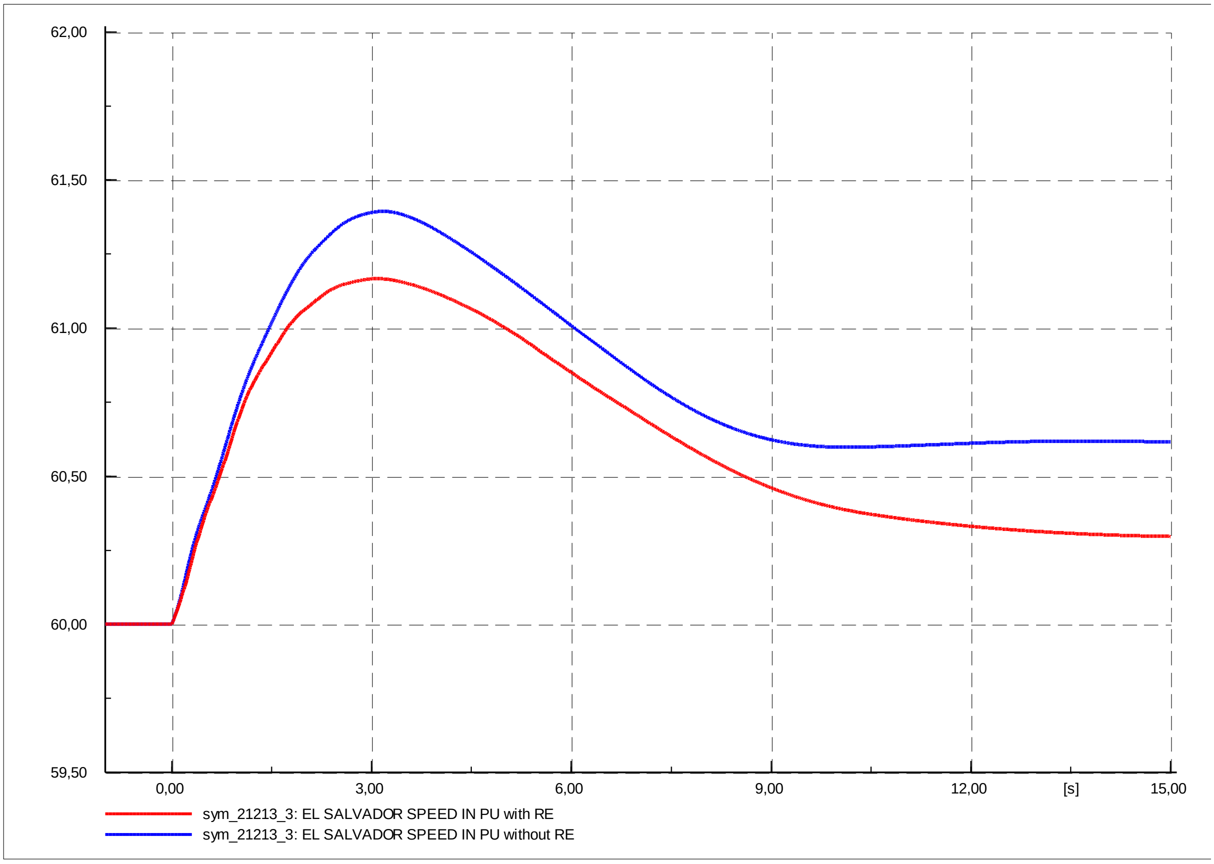


Figure 22: Frequency for High Export and sudden loss of SIEPAC interconnector

The high export case with renewable generation was defined by adding the planned renewable generation plants and balancing of the additional generation capacity by disconnecting synchronous generators outside El Salvador.

The high export case without renewables has been modelled by switching synchronous generators in El Salvador on and balancing off the additional generation capacity by disconnecting synchronous generators outside El Salvador.

The resulting frequencies in case of a sudden disconnection of the SIEPAC interconnector (Min Wet case) are depicted in Figure 22. As this figure shows, the high frequency excursion is higher for the case without renewable generation, even when the system inertia is larger in this case.

This can be explained by the fast active power reduction of all renewable generation plants in the case of high frequencies according to the requirements as described in section 6 of this report, and specifically in Figure 27. By quickly reducing active power production in the case of frequencies above 60.5Hz, the renewable generation plants can greatly limit high frequency excursions.

5.4.4.2 Low Frequency Response

For simulating the frequency response of the system in the case of low frequencies a case with maximum import has been defined.

However, a case with maximum import in the presence of large renewable generation represents a quite unrealistic scenario because only with a drastic reduction of conventional generation, such high imports are feasible in the presence of high renewable generation.

Because many synchronous generators have been disconnected in the max. import/ high renewable generation case, the level of fast reactive power reserve is very low resulting in voltage problems, which would have to be resolved through the addition of reactive compensation devices.

Figure 23 shows frequency in El Salvador during the first seconds following a sudden disconnection. Basically, one would expect a faster frequency rate of change in the case with high renewable generation compared to the situation without renewable generation because of the higher system inertia. However, because of the mentioned voltage problems, load is initially reduced (see upper picture in Figure 23) because of its voltage dependence, which compensates the reduced system inertia.

If the response of the system to a sudden islanding in the case of high power imports is of relevance to the actual operation of the system, it is recommended to carry out additional studies using a model that considers frequency dependence and voltage dependence of the load more precisely than the model that was the basis of the studies presented in this report.

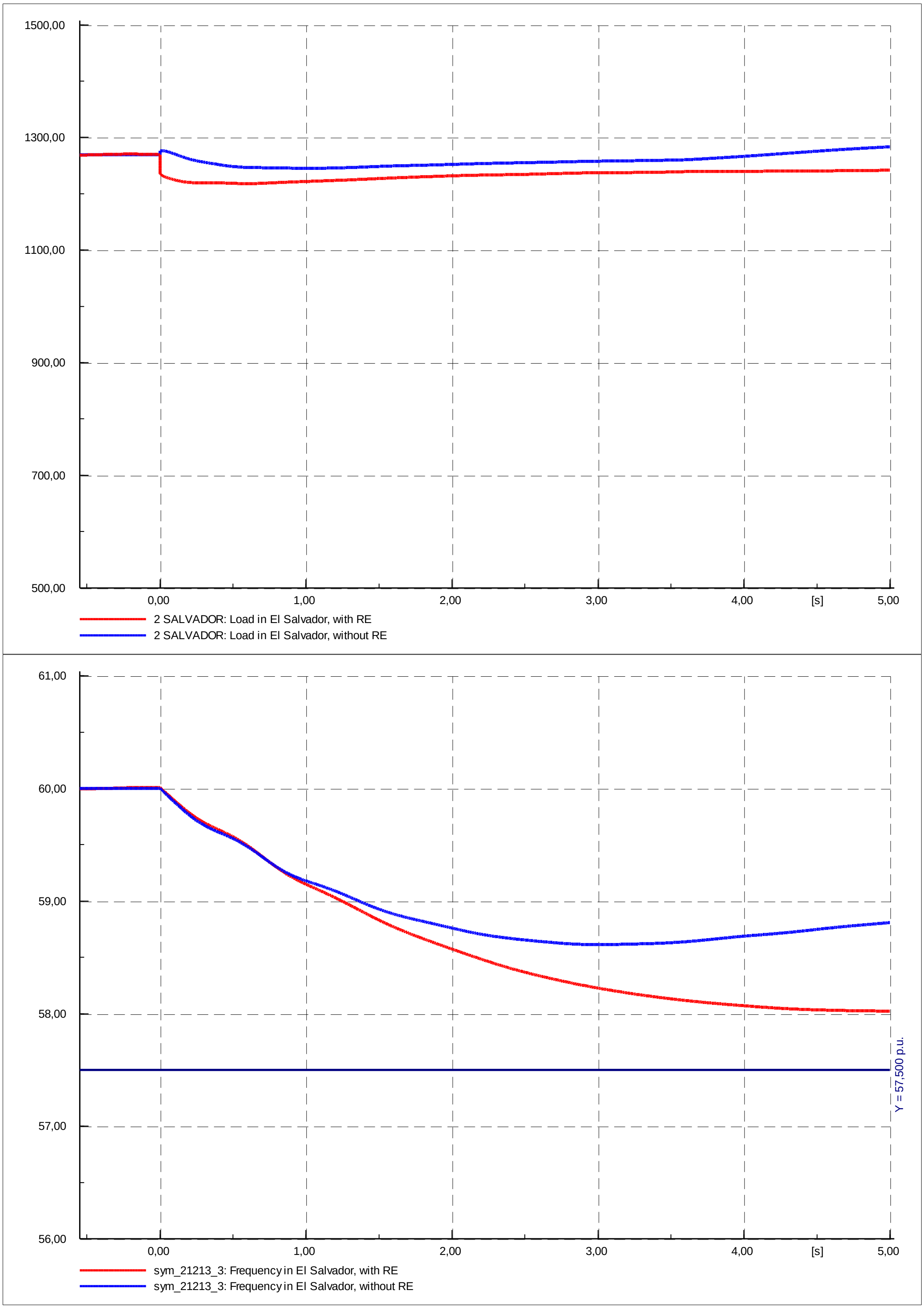


Figure 23: Load and Frequency in case of sudden disconnection of the system of El Salvador in case of high import (200MW)

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6 Proposed Connection Conditions for the New Non-Synchronous Renewable Generation

6.1 General

When connecting wind and PV generation to a power system the definition of appropriate grid code Connection Conditions is essential for the following reasons:

- In most cases PV and wind power plants are installed by IPPs (Independent Power Producers) requiring a clear specification of the interface between the IPP's power plant and the public utility grid.
- PV and wind generators are (in most cases) based on power electronics converters having a highly controllable response to grid disturbance. Hence, in contrast to conventional synchronous generators, the short-term response of PV and wind generators doesn't follow physical principles but are defined by an engineered controller. It is therefore essential that a clear 'specification' is defined via grid code Connection Conditions and where appropriate, bilateral agreement requirements.

Generally, when defining such Connection Conditions the following aspects should be considered:

- The Connection Conditions should ensure that wind and PV generation supports system stability and system security.
- Conversely, the requirements shouldn't be unnecessarily high resulting in increased / unnecessary costs for PV and wind generation.
- PV inverters and wind generators are produced at large scale. This means that especially in countries with relatively small markets for PV inverters and wind generators, technical requirements that deviate from international standards, which will require specific developments, tests and certification will substantially increase costs or may substantially reduce the choice of manufacturers willing / able to participate in that region.

Based on these criteria, the following section proposes a set of technical requirements for wind and PV generation that is as much as possible in-line with corresponding international standards. Furthermore, they will help to ensure that stability and security of the power system of El Salvador is maintained for the studied and other operational scenarios, or if / when non-synchronous generation levels continue to increase.

6.2 Technical Requirements

Connection conditions for wind and PV generation should cover a large variety of aspects, such as:

- Ranges of frequency and voltage
- Reactive power capability
- Reactive power/voltage control
- Response to frequency disturbances
- Response to voltage disturbances
- Power quality aspects

- Protection and control
- Monitoring and signalling
- Grid code compliance studies, tests and monitoring
- Data provision

The following sections summarize the main aspects of Connection Conditions for wind and PV generation connected to HV systems (115kV) in El Salvador, as they are relevant for the reported studies.

6.2.1 Frequency Ranges of Operation

Frequency ranges of operation determine the frequency range around the nominal value where all generation must remain connected. These should be in-line with corresponding frequency ranges as specified in grid codes for conventional generators in El Salvador (which should also be aligned for all countries connected to the SIEPAC line due to the corresponding common system frequency).

In 60Hz systems, these ranges could typically be:

$$57{,}5\text{Hz} < f < 61.5\text{Hz}$$

The normal frequency of operation can be in a range of:

$$59{,}5\text{Hz} < f < 60{,}5\text{Hz}$$

However, it should be highlighted again that it is not advisable to define different frequency ranges for different types of generation in the same synchronous area. Therefore it is strongly recommended that frequency ranges of operation for wind and PV generation should be the same as for any other generator in the system of El Salvador and the wider SIEPAC region.

6.2.2 Voltage Ranges of Operation

As in case of frequency ranges of operation, voltage ranges of operation should be in-line with corresponding standards and operational practice of El Salvador.

The maximum continuous voltage of operation in 115kV systems is 123kV (6% above nominal voltage). Hence, it is recommended to specify the voltage range of operation as follows:

$$104\text{kV} < v < 123\text{kV}$$

6.2.3 Reactive Power Capability

The studies presented in this report have been carried out under the assumption that all PV and wind farms are able to cover a reactive power range of cosphi=0,95 leading/lagging at the wind farm connection point under rated conditions for active power production and voltage.

The required maximum and minimum reactive power capacity in the case of voltages different from nominal voltage is depicted in Figure 24.

In the partial load area, between 20% and 100% of the *Available Installed Capacity* (installed capacity of all units not being on outage, e.g. for maintenance), it is required that wind and PV farms can vary reactive power at the PCC continuously in a range between the maximum and minimum reactive power limit according to Figure 24, as shown in Figure 25 (for nominal voltage).

For active power levels below 5% of the *Available Installed Capacity*, it is required that reactive power at the PCC remains in a tolerance range Q=+/-5% based on the *Available Installed Capacity* (see also Figure 25)

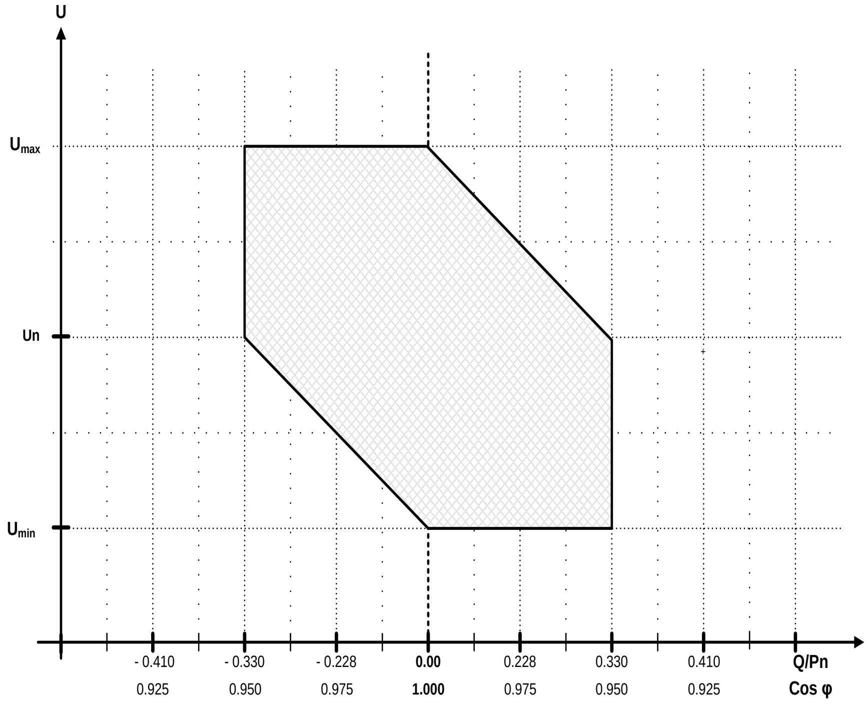

Figure 24: Proposed Reactive Power Capability vs. Voltage Requirement

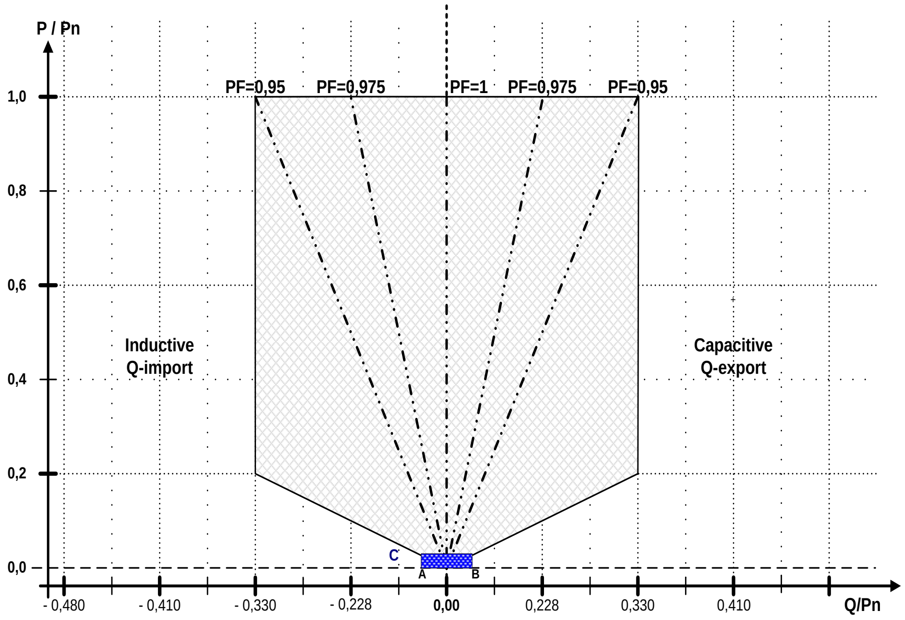

Figure 25: Reactive Power Capability in the partial load area for nominal voltage

6.2.4 Reactive Power/Voltage Control

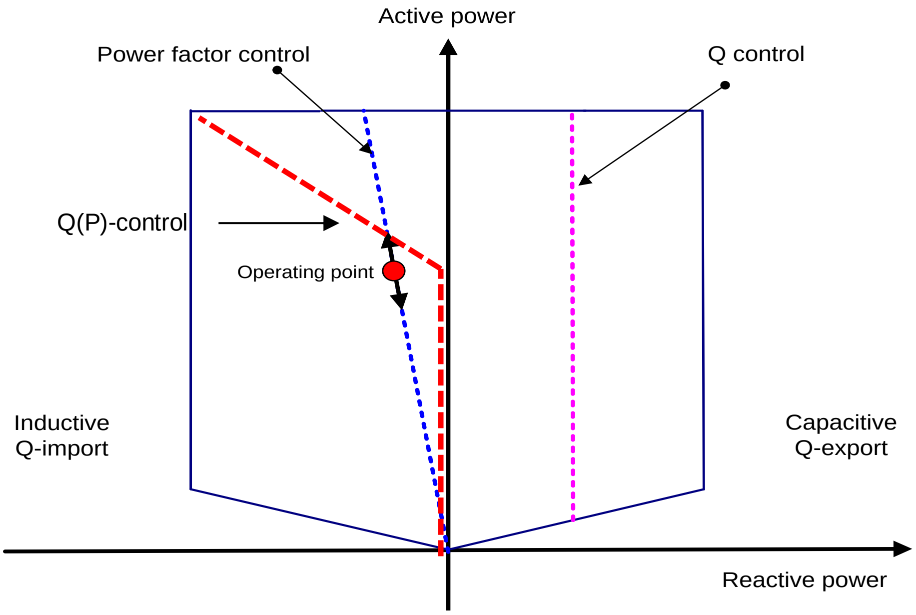

Figure 26: Q-control, Q(P) control and power factor control modes

Wind and PV farms should support the following reactive power/voltage control modes:

- Q(U)-control (see also Figure 7)
- Q-control (fix Q setpoint, see Figure 26)
- Q(P) control (see Figure 26)
- Power factor control (cosphi-control, see Figure 26)

For wind and PV farms connected to the 115kV system, the Q(U) control mode should be applied so that they contribute to the reactive power reserve of the system.

For smaller wind and PV farms, which will be connected to the LV side of the corresponding substations, power factor control or constant Q control will be sufficient.

Besides the required control modes it is important to clearly specify dynamic performance requirements for voltage control.

Requiring fast reactive power/voltage control capability at the point of connection (e.g. in the time frame of a few seconds) will typically require additional dynamic reactive power compensation devices (e.g. STATCOMs). It will not be possible to support the reactive power control capability by switched shunts or automatic tap changers of transformers and typical SCADA control times of wind / PV farm controls.

In the case that time frames of >30s up to a few minutes will be specified, most wind farms and PV farms will be able to comply with reactive power requirements just by using the reactive power range of the wind turbine generators or PV inverters and potentially additional switched compensation devices (e.g. MSCs), which leads to much lower capital expenditure costs of this type of generation.

Because no short-term voltage stability issues could be observed in any of the short-term stability studies, it is recommended to only require slow reactive power/voltage control requirements, e.g. in the time frame of approximately 30s for moving reactive power between the leading and lagging reactive power limits.

6.2.5 Response to Frequency Disturbances

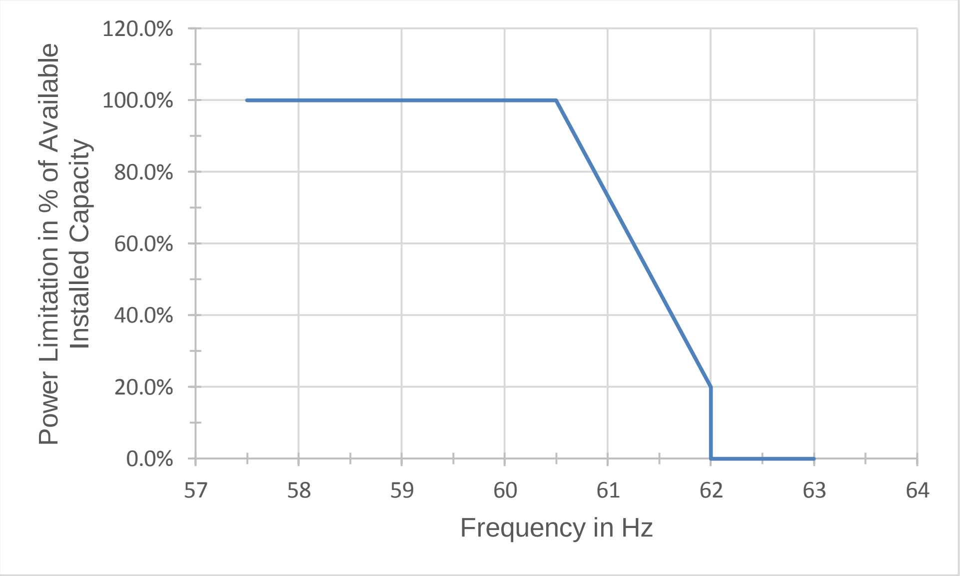

Figure 27: Power Curtailment Function for High Frequencies

In some countries, e.g. in the U.K. (see [4]) or South Africa (see [5]) large wind and PV farms (U.K.: >50MW) are required to have the technical capability for participating in primary and secondary frequency control (low and high frequency response).

Technically, modern wind turbine generators and PV inverters are able to contribute to primary and secondary frequency reserve. However, providing reserve means that the power production has to be curtailed for making corresponding low frequency response available. Because the primary energy of wind and PV generation is ‘free of charge’, contribution of these generators to active power reserves is usually not economical as long as there are sufficient conventional power plants in the system that can provide the required active power reserves.

Because the planned penetration levels of wind and PV generation in El Salvador are still far away from displacing so many conventional power plants that the remaining conventional power plants couldn’t deliver the required active power reserves, it is not recommended to require primary and secondary frequency control capabilities of wind and PV farms at this stage.

For limiting high frequency excursions, a frequency dependent active power curtailment function, as depicted in Figure 27, should be required. This requirement corresponds to international standards and doesn’t result in significant additional costs but on the other side contributes substantially to a stabilisation of frequency in the case of high frequency excursions, as they may occur in the system of El Salvador if the connection to neighbouring countries is suddenly lost during high export scenarios.

6.2.6 Response to Voltage Disturbances

With regard to the required response of wind and PV plants to voltage disturbances, the following aspects are important and have to be specified:

- Low Voltage Ride Through Capability (LVRT): Requirement to remain connected during low voltage disturbances.
- High Voltage Ride Through Capability (HVRT): Requirement to remain connected during high voltage disturbances (e.g. after fault clearance)
- Voltage support during LVRT and HVRT situations
- Limitation to the permitted reactive power absorption during voltage recovery
- Requirements for the active power restoration during voltage recovery

6.2.6.1 LVRT and HVRT Requirement

For avoiding the situation where large amounts of wind and PV farms disconnect in case of system wide voltage dip (e.g. caused by a fault on a 115kV transmission line), it is important to include LVRT and HVRT requirements in Connection Conditions for wind and PV generation.

Without a strict LVRT requirement, the results of the stability studies presented in this report would not be valid.

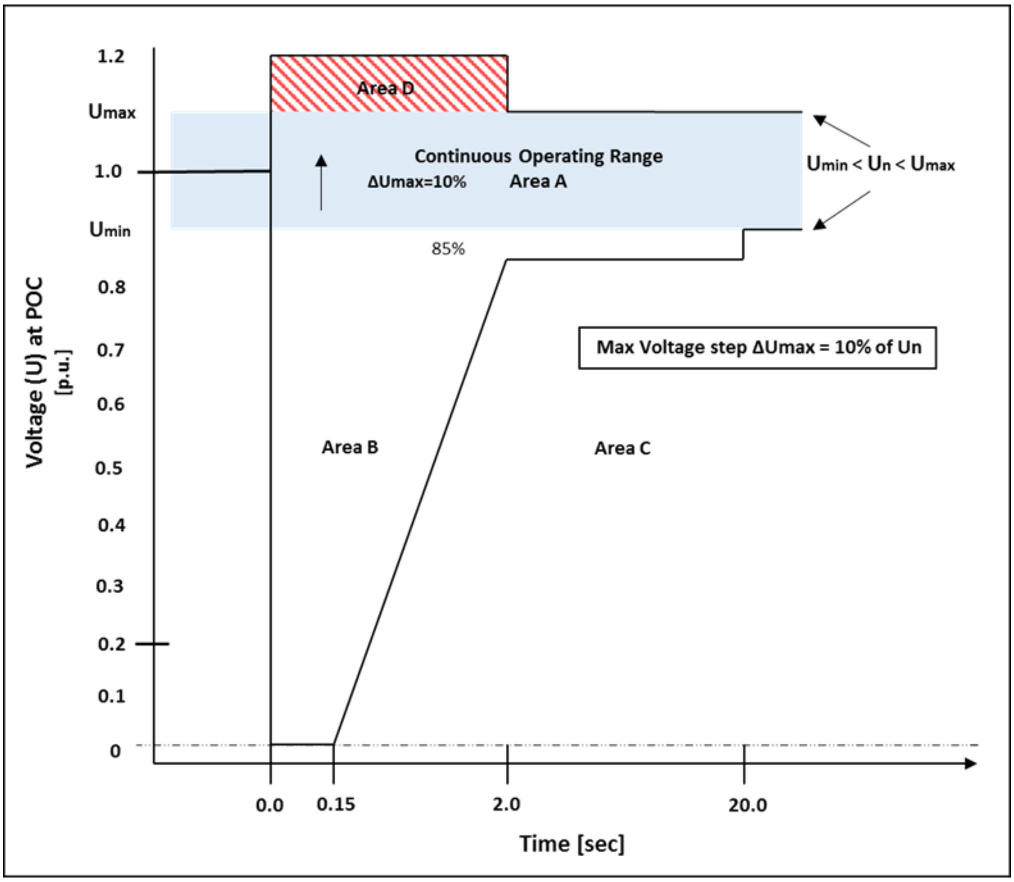

Figure 28: Recommended LVRT and HVRT Requirement

LVRT and HVRT requirements are usually specified in terms of upper and lower limit curves. As long as the voltage at the point of connection remains within the specified limits, no disconnection of wind or PV farms is allowed.

The recommended curve is depicted in Figure 28. Essentially, this curve specifies the following limits:

LVRT:

- As long as the voltage remains with the Continuous Operating Range (Area A in Figure 28) no disconnection from the grid is permitted.
- In the case of a retained voltage equal to zero for a maximum of 150ms (aligned with the required critical fault clearing time of the system of El Salvador), no disconnection from the grid is permitted.
- As long as the voltage remains above the lower limit curve according Figure 28, no disconnection from the grid is permitted.
- In the case of asymmetrical faults, the lower limit curve according to Figure 28 represents the lowest value of the three phase voltages.

HVRT:

- The wind or PV farm must remain connected as long as the voltage remains below 120% for a maximum of 2s (Area D of Figure 28), subject to a Voltage Step of no more than 10%.
- Voltage Step defines the difference between the post-disturbance voltage and the continuous pre-fault voltage (e.g. defined by the 1 minute average value).
- In the case of asymmetrical surges, the upper limit curve according to Figure 28 represents the highest value of the three phase voltages.

This HVRT requirement will ensure that there will be no disconnection of any wind or PV farm after fault clearance, especially during low load situations, when short over-voltages can be observed in the system of El-Salvador.

6.2.6.2 Voltage Support during LVRT and HVRT situations

Especially with increasing levels of wind and PV generation, it is not sufficient that wind and PV farms stay connected during LVRT and HVRT situations, but it is also necessary that they actively support voltage during these events. This is to avoid a case where the voltage dips become deeper and voltage surges higher with increasing penetration levels of wind and PV.

Such voltage support can be achieved by injecting or absorbing reactive currents in the case of low voltages or high voltage respectively.

Most wind turbine generators and PV inverters apply a fast PQ-control (at turbine / PV converter level) as long as the voltage is within the normal range of operation. For those generators, a reactive current injection/absorption requirement according to Figure 29 leads to behaviour that is highly grid compatible. This requirement is in-line with the corresponding German requirements and therefore supported by most modern wind turbine generators and PV inverters on the market.

The objective of the proposed dynamic voltage support requirement is the following:

- The transition between normal operation and LVRT/HVRT operation must be “bump-less”: Hence reactive current is specified in terms of Additional Reactive Current and not in terms of an absolute reactive current requirement. The Additional Reactive Current must be added to the pre-fault reactive current and is equal to zero at the transition points between normal operation and LVRT/HVRT operation.
- For supporting a “bump-less” reactive current control, it is explicitly specified that reactive current support must be in proportion to a voltage dip/surge. Hence, the curve according to Figure 29 does not represent a minimum requirement for the provision of reactive current but a target value of a corresponding controller.
- It is not required to control the additional reactive current very accurately. It is just necessary that there is a proportionality between voltage variation and Additional Reactive Current. Therefore, a relatively wide tolerance band around the target value is specified.
- Reactive current support must be a fast control function. Hence it must be realized in the local controller of each individual wind turbine generator or PV inverter. For this reason, the additional reactive current and voltage according to Figure 29 apply to the local LV terminal of a wind turbine generator or PV inverter (and not to the point of connection).
- Reactive current must be provided sufficiently fast. Dynamic voltage support would be useless if the settling time of the reactive current control would be longer than typical fault clearing times. For this reason, a corresponding dynamic performance requirement has been specified.

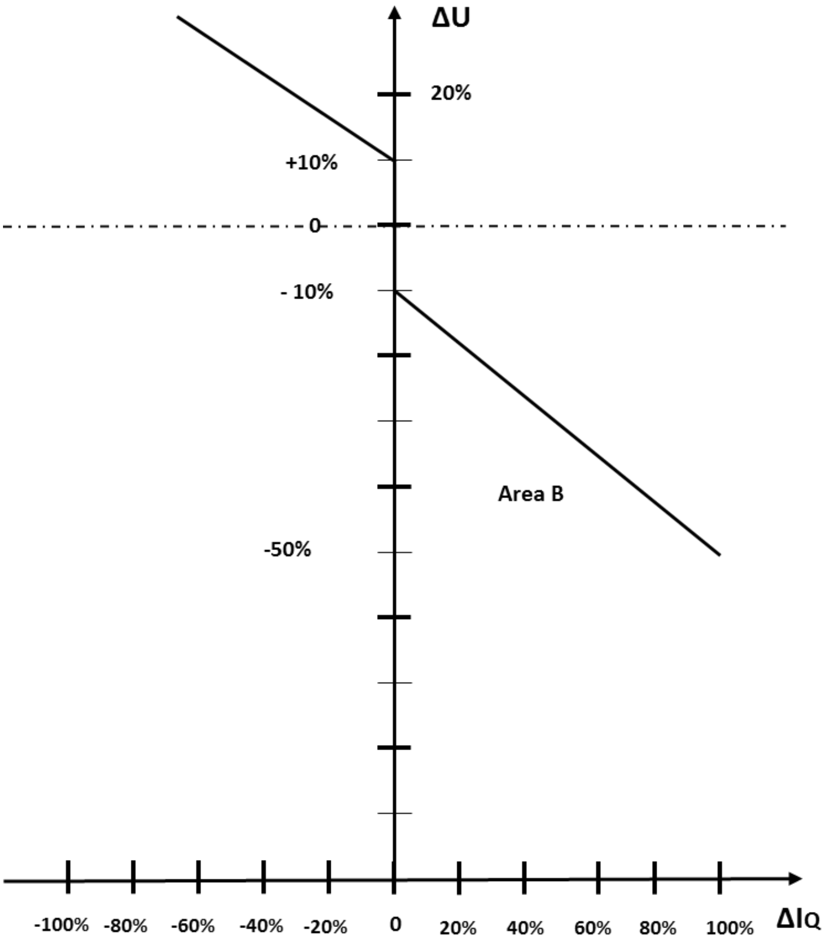

Figure 29: Reactive Current Support during LVRT and HVRT conditions

For clearly specifying the dynamic voltage support requirement the following wording is proposed:

a. In connection with symmetrical fault sequences in areas B and D of Figure 28, wind and PV farms shall have the capability of delivering an additional reactive current in proportion the voltage change ΔU, as illustrated in Figure 29.

b. The factor of proportionality between additional reactive current and voltage deviation is named K ($\Delta I_Q = K\Delta U$). The factor K must be settable in the range of $0<K<10$.

c. The additional reactive current ΔI_Q according to Figure 29 shall be injected in addition to the pre-fault reactive current.

d. The voltage deviation ΔU is defined as being the difference between the post-fault and the pre-fault voltage.

e. Both, pre-fault current and pre-fault voltage are defined by the 1-minute average of the positive sequence component of the fundamental frequency value of current and voltage respectively.

f. The post-fault voltage on which basis the voltage deviation ΔU is calculated is the positive sequence component of the voltage at the point of connection.

g. The additional reactive current shall be injected as a positive sequence component.

h. After 100ms, the additional current shall remain within a tolerance band of ±20% around the value according to Figure 29.

i. The absolute value of the current in each phase that is injected into the grid can be limited to the rated current of the wind or PV generator.

j. The reactive current requirement applies to retained voltages (post-fault voltages) greater than 10%. Below 10% the current of the wind or PV farm can be set to zero.

k. As long as a wind or PV generator operates in Area B of Figure 28, the active current I_P shall be reduced in proportion to the voltage change ΔU.

Wind turbine generators or PV inverters having fast voltage controllers without dead-band (as they become more and more common in future) should be fully supported, even if they don't comply with each of the above sentences. Their normal control functionality ensures that during LVRT or HVRT situations a reactive current in proportion to a voltage change will be provided to the system. Note that typically a 'K' value of 2 is commonly used in many countries.

6.2.6.3 Reactive Power Absorption during Voltage Recovery

Modern wind turbine generators, such as DFIG or wind turbine generators with fully rated converter can be designed in a way that they don't absorb reactive power during voltage recovery and hence, don't have any negative impact on voltage recovery (as it used to be the case for old, fix speed wind turbine generators).

For ensuring that every wind turbine generator or PV inverter behaves correctly during voltage recovery a corresponding statement should be included into the Connection Conditions, e.g.:

- During voltage recovery, a wind farm or PV farm must not absorb more reactive power than prior to the fault (reference for pre-fault reactive power: 1 minute average).

6.2.6.4 Active Power Restoration during Voltage Recovery

During a LVRT situation it is permitted to reduce active power to zero for:

- Allowing a wind or PV converter to use its fully capacity for reactive current support
- For avoiding short-term voltage instability in the case of nearby faults.

As soon as a fault has been cleared and voltage recovers, it is important to ensure that active power production of wind farms and PV farms is restored to pre-fault levels sufficiently quickly for avoiding subsequent frequency problems.

When looking at corresponding international requirements, the following observation can be made:

- In smaller, isolated systems (e.g. the U.K. transmission system), there is a requirement for fast active power recovery (e.g. 0,5..1 s) subsequently to a fault, because frequency stability is in the center of interest.
- In large, interconnected power systems (e.g. the central European interconnected system), relatively slow active power requirements are common (e.g. 10s in Germany) because frequency stability is not a big concern here and slow active power recovery has a positive impact on transient stability aspects.

Generally, the following statements can be made:

- Fast active power recovery requirements have a positive impact on frequency stability but no or even negative impact on transient stability aspects.
- Slow active power recovery requirements have a rather negative impact on frequency stability but positive impact on transient stability aspects.

Because no transient stability problems could be observed in the presented studies, it is recommended to ask for a rather fast active power recovery time, which would help in situations, in which the system of El Salvador operates in isolated mode, when the SIEPAC line is not available. Therefore it is recommended to include the following statement in the Connection Conditions for wind or PV generation:

- Upon the termination of a LVRT event, when voltage is back into Area 4 of Figure 28, each VRPP shall restore active power to at least 90% of its pre-fault value within at least 1s.

6.2.7 Other Requirements

Other requirements, especially with regard to:

- Power Quality Aspects
- Protection and Control
- Monitoring and Signalling
- Grid Code Compliance Studies, Tests and Monitoring
- Data provision

have to be included in Connection Conditions for wind and PV generation as well but are not related to the scope of the studies presented in this report. It can be assumed that corresponding requirements exist for conventional generation in El Salvador and that these requirements can also be used for wind and PV generation, where applicable.

7 General Recommendations for the El-Salvador & SIEPAC System (Including Data Model)

In general the quality of the El-Salvador PSS/E data supplied has been high. However in the course of the project the consultant has noted a few areas where it may be beneficial to make some improvements, or to check that the data entered is correct. This applies both to the El-Salvador data and the wider SIEPAC system data. In addition there are a few recommendations, not related to the impact of the new renewable generation, which are proposed in this section.

1. Some of the dynamic models for new plant (in 2019) will need to be updated once the detailed design data is known.
2. Points relating to transformers in El-Salvador:
    a. Many of the transformers with auto-tapping have very wide voltage dead-bands for example 0.875 to 1.125 per unit. Is it suggested that the client check that these settings reflect reality

  - **b.** Some transformers (without auto-tapping) have taps available but the voltage per tap is exceptionally large (values ranging from 3% to 24% have been noted). The client should check these values if they are to be used in simulations.
  - **c.** It is suggested that transformers have proper rating values attached to permit contingency analysis to monitor transformer loading
  - **d.** It is suggested that transformers data is improved to contain on-load and no-load active power losses

3. It is suggested that governor data should be based on tested / actual response rather than generic parameters as this is often vastly over optimistic
4. New non-synchronous renewable generation performance should be checked against the generic models used (usually by the manufacturer) and either
    - **a.** Custom manufacturer models used or
    - **b.** As long as the performance lines up then generic models can continue to be used
5. The client should consider operational procedures in cases when contingency analysis shows heavy pre-fault loading of line ‘lne_27181_27211‘
6. The client should investigate the overloaded base case results from the contingency analysis and ensure processes are in place to manage them in line with the normal operational procedures of the El-Salvador grid operator.
7. The wider SIEPAC system does contain a variety of suspicious data. For example:
    - **a.** transformers with exceptionally low impedance
    - **b.** transformers with exceptionally high impedance
    - **c.** generators without dynamic models
    - **d.** generators with non-standard impedances and time constants
    - **e.** modelling of cables does not always include a capacitive component
    - **f.** Nicaragua wind turbines should be aggregated for computational performance reasons

    It is therefore recommended that a full review of the wider SIEPAC data is performed to allow all countries to model impact on their own systems adequately. This is especially important before the flows on this line are increased.
8. The client should consider installation of additional voltage support at busses in the region of 22471, 27461 and 27421 following the results of the contingency analysis which indicated contingency voltage deviations close to the post-fault limit and with a large voltage step change, particularly in 2019 (not due to the renewable generation).

8 Conclusions

The impact of the addition of 195.2MW of new non-synchronous renewable wind and PV generation to the El-Salvadorian electricity grid has been extensively investigated in this report. Due to the meshed and relatively lightly loaded El-Salvadorian grid, together with the additional security of the SIEPAC line it can be stated that this new renewable generation can be accommodated provided that it meets the defined high level connection conditions outlined in this report. Some minor potential overloading of lines due to the new renewable generation has been identified, particularly in later years as the system load increases and new synchronous generation is added to the system. However these violations represent extreme conditions coincident with full renewable generation output. Even if they were to occur they can easily be managed by re-dispatch of generation (either pre or post fault) in line with normal system operation procedures.

Dynamic simulation studies for various operating conditions and fault cases lead to the conclusion that the planned renewable generation plants only have very minor impact on system stability. In more detail, the conclusions of the stability studies can be summarised as follows:

- No considerable impact on transient stability could be identified
- Very minor negative impact on the damping of local oscillatory modes has been found
- The impact on the damping of inter-area oscillations can be neglected.
- A positive impact on the system response to high frequency excursion could be identified, which is due to fast high frequency response of the renewable generation plants, as required by the proposed connection conditions.

The studies presented in this report analyse the impact of planned renewable generators on the electricity grid of El Salvador.

Studies relating to the impact of the variability of wind and PV generation on system balancing and generator dispatch are not covered by the studies presented in this report and still have to be carried out. Those studies will require time series data of wind and PV generation, as well as data relating to load variation and constraints of the conventional generator dispatch (min. up and down times, start-up times, shut-down times and associated costs).

9 References

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10 List of Annexes

- Annex 1: Generator Dispatch Tables
- Annex 2: Results of Load Flow/Contingency Analysis Studies
- Annex 3: Results of QV-Analysis
- Annex 4: Results of dynamic simulation studies, year 2016
- Annex 5: Results of dynamic simulation studies, year 2019