STANDARD OPERATIONAL PROCEDURES FOR SOLAR PARKS

VOL. V
GRID INTEGRATION OF SOLAR PARKS

THE EUROPEAN UNION'S FOREIGN POLICY INSTRUMENTS (FPI) PROGRAMME FOR INDIA

GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

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IBF International Consulting, EQO-NIXUS (OCA Global) and IDOM.
Grid integration and management of solar parks

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VOL. V

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Table of contents
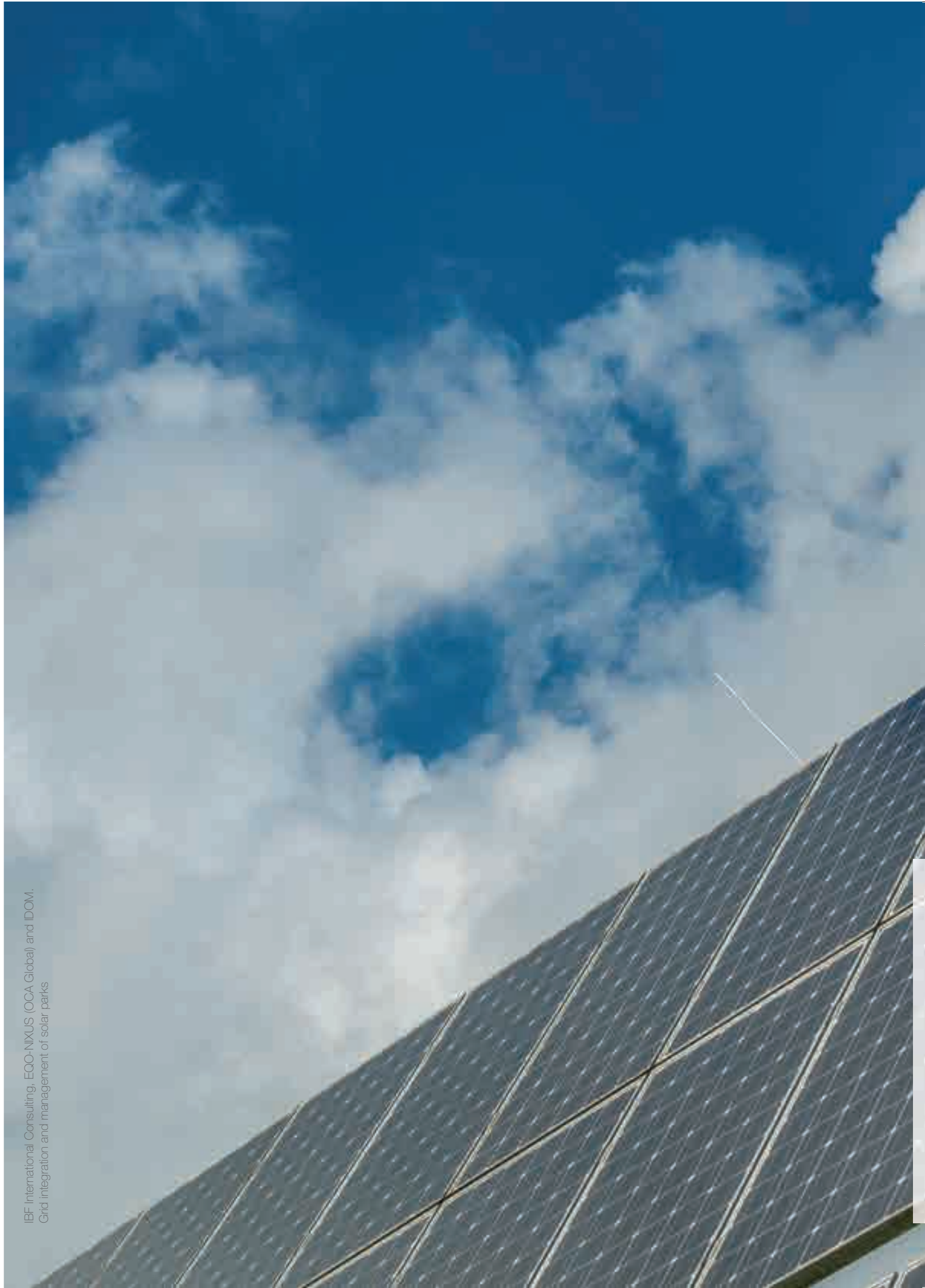
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Grid integration and management of solar parks

INTRODUCTION

This document intends to cover the integration of intermittent renewable energies in an existing electrical system and in particular of solar parks. This will include aspects related with the Solar parks operation and control but also in some aspects related to the Transmission System. The delivery of power from Solar parks to the transmission system is related with the security of the electrical system.

The first aspect to consider is how the Indian Electricity Grid Code (IEGC) sees the solar parks and regulates them. It will be followed by the technical aspects of the Solar parks integration. The problems are of two levels;

◈ Global - maintenance of the energy balance of the power system and the consequences when this balance is lost.

◈ Local - related with the closer network to the solar park connection to the transmission system with special consideration to voltage and flows control.

The following aspects to be considered are the monitoring, scheduling and forecast of the generation of the solar park and the information management.

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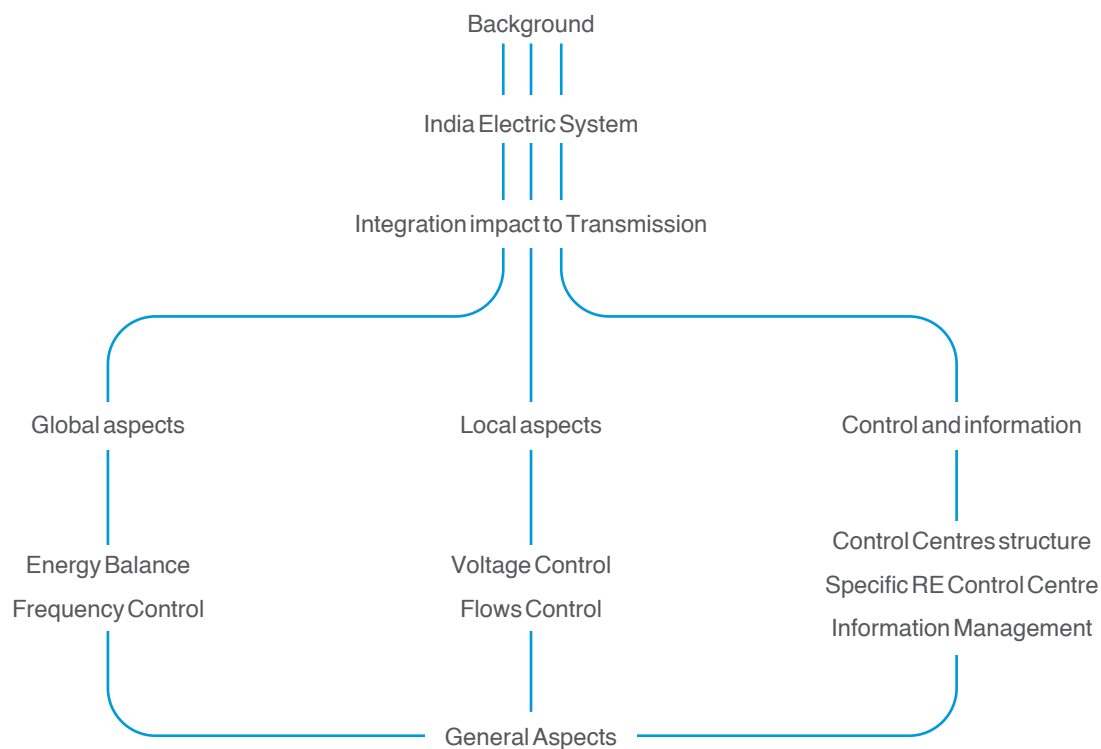
Background

India Electric System

Integration impact to Transmission

Global aspects   Local aspects   Control and information

Energy Balance   Voltage Control   Control Centres structure
Frequency Control   Flows Control   Specific RE Control Centre
                                                 Information Management

General Aspects

# INDIA ELECTRICAL SYSTEM

In India, the ownership of the high and medium voltage transmission systems is shared between the Power Grid Corporation of India (PGCIL), the state transmission utilities and the private sector. PGCIL has assets in all states and is currently planning and implementing the Green Energy Corridor to be able to evacuate intermittent power to main load centers. Each state transmission grid is managed by the state transmission company with interfaces with PGCIL's substations and grid.

India electricity grid code

On mid-2016, the Ministry of Power made public the "Report of the Technical Committee on Large Scale Integration of Renewable Energy, Need for Balancing, Deviation Settlement Mechanism".

This document includes operational technical changes that will require important changes on States regulation.
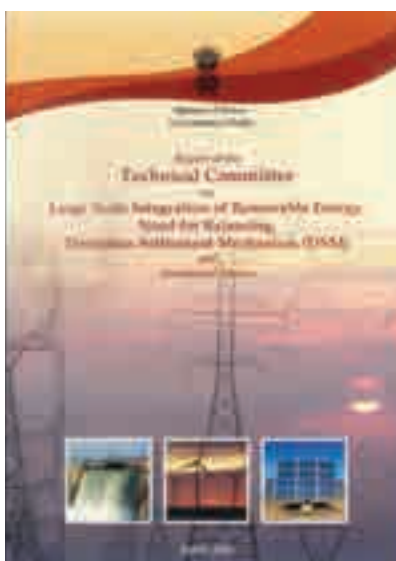
Some states already started those changes but they are not fully coincident, in some aspects they are diverging. An example of this are the different penalties for forecast deviations between Andhra Pradesh and Gujarat.

Andhra Pradesh

Sr. No.	Absolute Error in the 15-minute time block	Deviation Charges payable to State DSM Pool
1	<= 12%	None.
2	> 12% but <= 20%	At Rs. 0.35 per unit for the shortfall or excess energy for absolute error beyond 12% and upto 20%.
3	> 20% but <= 28%	At Rs. 0.35 per unit for the shortfall or excess energy beyond 12% and up to 20%. + Rs. 0.70 per unit for balance energy beyond 20% and up to 28%.
4	> 28%	At Rs. 0.35 per unit for the shortfall or excess energy beyond 12% and up to 20%. + Rs. 0.70 per unit for shortfall or excess energy beyond 20% and up to 28%. + Rs. 1.05 per unit for balance energy beyond 28%.

Gujarat

Sr. No.	Absolute Error in the 15-minute time block	Deviation Charges payable to State DSM Pool
1	<= 10%	None.
2	> 10% but <= 20%	At Rs. 0.50 per unit for the shortfall or excess energy for absolute error beyond 10% and up to 20%.
3	> 20% but <= 30%	At Rs. 0.50 per unit for the shortfall or excess energy beyond 10% and up to 20%. + Rs. 1.00 per unit for balance energy beyond 20% and up to 30%.
4	> 30%	At Rs. 0.50 per unit for the shortfall or excess energy beyond 10% and up to 20%. + Rs. 1.00 per unit for shortfall or excess energy beyond 20% and up to 30%. + Rs. 1.50 per unit for balance energy beyond 30%.

It is a challenging environment when the regulation is in evolution and being implemented differently on different states. Nonetheless what is clear is that:

1. Regulation is approaching some market oriented aspects like:

    a. Solar Generators shall produce a day ahead generation forecast. For two days ahead the error could be reasonable, while for three days ahead the error would not be acceptable.

    b. The qualified coordinating agencies (QCA) will be held financially accountable for the penalties according to the deviation versus the forecast.

    c. Solar (and wind) generators may be represented by a single QCA.

2. The Ancillary Services will be moving also to Market Oriented procurement. The regulation will likely move the frequency control from manual to computer oriented. The use of Load Frequency tools could be mandatory in the medium term.

Under this condition and with states diverging in their regulation as well as others delaying their decision, it is recommended to analyse the regulation from other states as other demanding aspects such as frequency control may also be changing.

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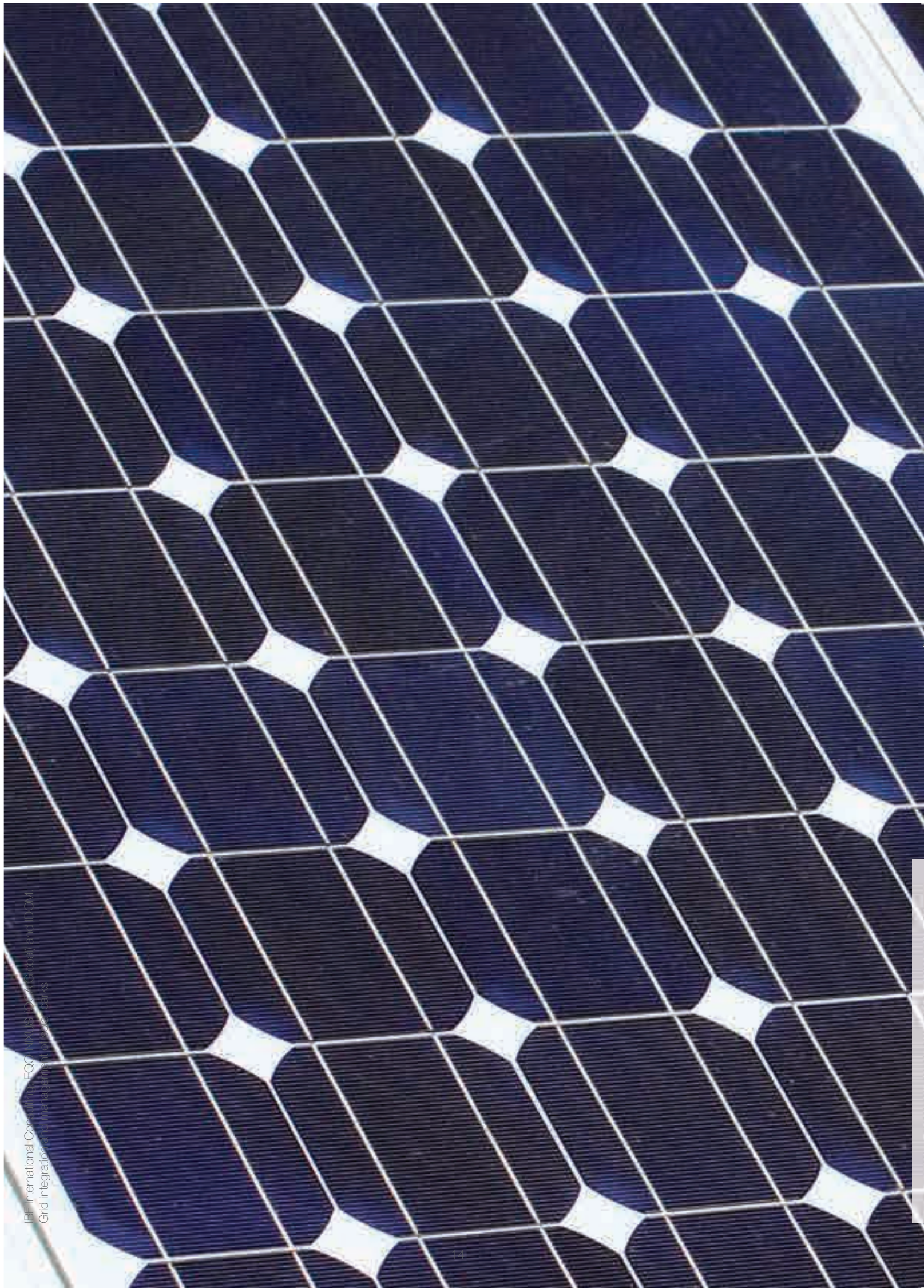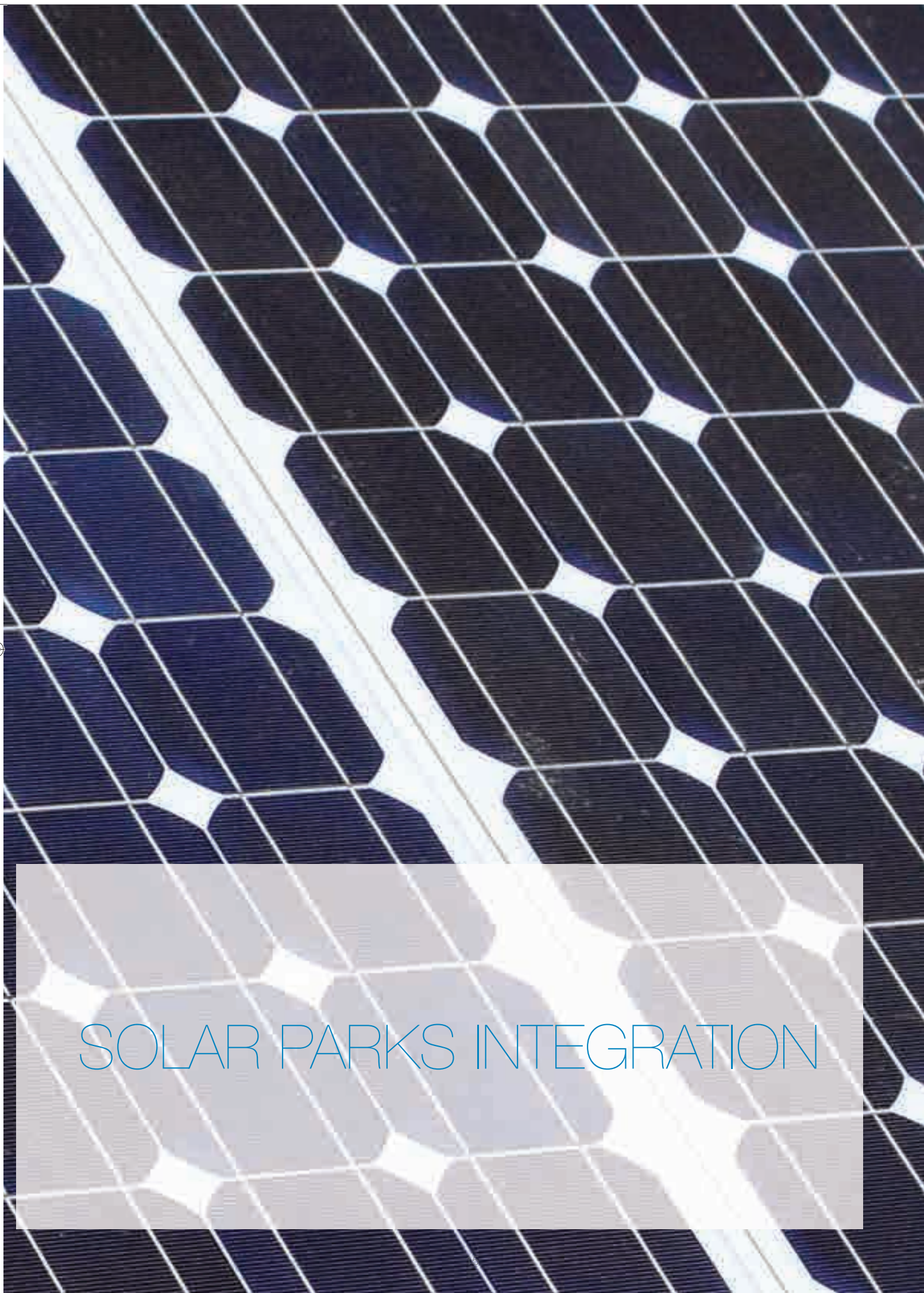
SOLAR PARKS INTEGRATION

The impact of integration of solar parks into any system can be found in two main aspects of system security:

◈ **Global level:** variations of generation versus the scheduled, will require more ancillary services than conventional generation, specially reserves, and depending of the size of the deviation, it will also impact the system frequency. All these aspects will impact all interconnected systems.

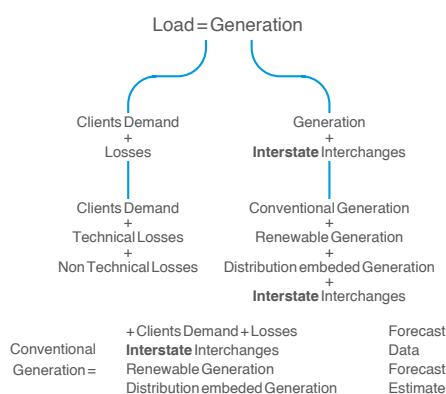◈ **Local level:** flows will change during the day or night in comparison with the values registered before the solar park connection. Also, voltage control will require more resources, controlling it up or down. Both of these aspects impact only the parts of the grid closer to the solar parks.

Global problems require global solutions. The unscheduled variations of generation represent a mismatch between load and generation. These deviations are corrected by the Ancillary Services as the first automated corrective action (for example fast tertiary control), but will require rescheduling of the generation.

The physical manifestation of this unbalance is a frequency deviation, as large as the generation deviation. This frequency deviation will impact the full interconnected system and in case of India it will concern all states.

The schedule of conventional plants is a function that depends of the load forecast in the system and the amount of non-scheduled generation, including the intermittent renewable energy generation and some potential "must run" units, as shown in the next schema:

$$Load = Generation$$

Clients Demand + Losses	Generation + **Interstate** Interchanges
Clients Demand + Technical Losses + Non Technical Losses	Conventional Generation + Renewable Generation + Distribution embeded Generation + **Interstate** Interchanges

Conventional Generation = + Clients Demand + Losses   Forecast
Interstate Interchanges   Data
Renewable Generation   Forecast
Distribution embeded Generation   Estimate

This graphic shows how important the intermittent Renewable Generation forecast is for the conventional generation scheduling and consequently the System Security. Local problems require local solutions. The flows and voltage problems are felt by the closer electrical area of the network, but it still impacts the state interconnections, independently of the ownership of the network.

The main aspects of the local impacts are:

◈ **System congestions.** The introduction of new big solar parks into any existing system will produce important changes in flows into the system during low load or peak periods. To avoid that this aspect may introduce restrictions to the solar park operation, the system shall be expanded or reinforced. It is important for the solar park to be rolled out taking into consideration the network expansion so that the solar park availability will not be impacted in a transitory form or in permanent congestion.

◈ It is important to verify that there are no voltage problems under normal conditions and that the system will survive during allowed voltage levels included in the Security Criteria without introducing generation constrains. In case of restrictions, some countermeasures shall be applied either temporality or permanently.

◈ **Voltage Control.** While the system is dimensioned to support maximum installed Renewable Generation, during night hours, the solar park will not produce and in consequence, lines going out of the park will be lightly loaded, becoming a generator of reactive power, increasing the voltage during a period where voltage is particularly high. The impact is unlikely to be meaningful at the system level, but it may have impact at the local level. Contrary to this situation are peak hours, with generally low voltage in the system and lines heavy loaded which will tend to further reduce the voltage.

In general, global problems shall be solved at interstate level, requiring a coordination between the actions taken at Central level and at States level, while local problems shall be solved at the intra-state level, requiring a coordination by the state load dispatch centers.

Global impacts

The following aspects will be analysed in detail

◈ Energy balance.

◈ Intermittent renewable energy generation forecast.

◈ Frequency control.

◈ Protections settings for voltage ride through capability.

Energy Balance

The generation scheduling as a result of the Energy Balancing is done in two steps. The first step is done at a **central level**.

The National Load Dispatch Centre, has been assigned by law to have the following functionality, among others:

i) In exercise of the powers conferred at section 176 (2) (d) of Electricity Act, 2003, Ministry of Power, Government of India vide notification dated 2nd March, 2005 had constituted National Load Despatch Centre at national level for optimum scheduling and despatch of electricity among RLDCs and the centre will be located at New Delhi with back-up at Kolkata.

ii) The National Load Despatch Centre shall be the Apex Body to ensure integrated operation of the national Power System and discharge the following functions.

◆ Supervision over the RLDCs.
◆ Scheduling and despatch of electricity over inter-regional links in accordance with Grid standards specified by the Authority and Grid Code specified by the Central Commission in coordination with RLDCs.

The Regional Load Despatch Centers (RLDC) schedule the generation of some power plants, mostly owned by NTPC, or with some special operative conditions (like IPP's, must run…) and its generation is assigned to the states with long term contracts. If this electricity is rejected by the States, some penalties are applied.

The second and final step is done at the State level. At State level, the final Energy Balance will be performed considering:

◈ The interchanges with other States as communicated by the RLDC's.

◈ The Load Forecast.

◈   The Renewable Generation Forecast.

◈   The needs of Ancillary Services, specially Voltage Control and short circuit current values.

◈   The grid constrains either structural or by maintenance.

◈   The System Security, fulfilling the Security Criteria.

◈   The power plants availability.

◈   The scheduling procedures from priority lists to optimization processes to decide the State operated units set point.

The Qualified Coordinating Agencies (QCA) shall facilitate the information required by the Load despatch Centres at state level to adequately balance the generation with consumption and estimate the required ancillary services.

Solar generation is primarily an energy resource which cannot be dispatched like conventional generation. In more traditional utility operations, predictions of system load for the next hour, day, week, etc. are essential for programming supply resources so that total costs are minimized while maintaining system reliability and security. Incremental costs due to the uncertainty in the timing and quantity of energy delivery from intermittent renewable energy generation facilities in operational time frames can be reduced with better short-term forecast. Solar generation forecasts and the appropriate use of those predictions by the load despatch centres in scheduling functions and real-time operating practices will reduce the uncertainty.

As the penetration of renewable energies continues to increase and become a central piece of the energy mix, it will become increasingly important to consider ways to more efficiently operate power systems to accommodate significant amounts of such a variable resource. In situations where resource decisions are made according to various market signals, prediction of intermittent RE generation will be important for those who operate the markets and are in charge of system security and reliability.

Whether by direct action of an operating entity or responding to market signals, electrical supply resources in any defined area must be managed, scheduled, and operated to provide the desired levels of system reliability and security. Furthermore, to minimize the overall cost of electricity to consumers in this area, the supply resources must be utilized in a manner that leads to the lowest total production cost. Meeting these objectives and at the same time honouring the countless constraints on individual generating units resulting from contractual obligations requires the ability to continually assess the present state of the system and predict future states hours or days in advance.

Uncertainty in the operational planning time frame can lead to defensive operating strategies and higher costs. Solar generation without forecast will increase the uncertainty in the short-term forecasts of the system, leading to higher operating costs. In real-time operation, additional reserves might be allocated to cover the uncertainty in the hours-ahead, again with higher costs.

In control areas with multiple intermittent RE generation facilities, forecasts must be generated for each plant on schedules appropriate for real-time management of the control area as well as short-term operational planning activities such as unit commitment or reliability monitoring. Given that the plants in a single control area may likely be exposed to the same general meteorological conditions, a wider geographical perspective on intermittent RE resource conditions is essential for forecasting.

Intermittent renewable energy generation forecast

Because of the introduction of solar PV generation, two main factors impact the operation of the power grid: diurnal cycle and localized effects. Diurnal effects are widespread, usually predictable, and relatively slow-varying events. Localized effects may induce sharp changes in output of individual plants, which are caused by low, fast-moving clouds, rain or sand/dust storms.

Specifically, the irradiance measured at certain location may vary around 80% in a very short-term period (minutes). However, it is possible to assume, in the worst scenario, a ramp of 50% of the power per minute for 10 to 20 MW PV plants spread across a large area (square km). For larger plants having a wider geographical distribution, this effect could occur over a longer time frame with lower magnitude.

Observation of 1-minute duration data shows that variability is essentially uncorrelated for about 1 MW PV arrays located at least 1 km apart. The geographical extension of the power plants over larger areas leads to lesser correlation of cloud-induced ramps, even over larger timescales such as 5, 10 or 60 minutes. Therefore, variability in irradiance (and consequently PV generation) can be strongly mitigated when PV generation is geographically distributed across the grid. In fact, sharp ramp rates observed by irradiance sensors or in data collected at individual small PV plants show irrelevant effects at the transmission level. A solar park will behave differently due to its size and relative narrow geographical location.

- ◈ In the case of extreme weather events, like large sand storms or monsoon rains, being usually predictable, specific countermeasures can be taken in advance when necessary, such as:

  - ◆ Temporary increase of power reserve.
  - ◆ Preventive power curtailments.

Energy Storage Systems installations can mitigate these problems as well; the installation of energy storage systems near a solar plant, solar park or on system-wide scale should be investigated through a cost-benefit analysis. All the above-mentioned actions (storage, preventive power curtailments and reserve increase) were successfully undertaken by some European transmission system operators or (mainly in Germany and Italy) during a solar eclipse in 2015.

In PV forecasting, weather variables that should be considered for day-ahead estimation are:

- ◈ Irradiance.

- ◈ Temperature.

- ◈ Wind speed and direction.

Irradiance has the higher statistical correlation with the Actual Produced power.

PV-generator: Normalized Output Power vs. Irradiation (hourly measurements during 1 month)
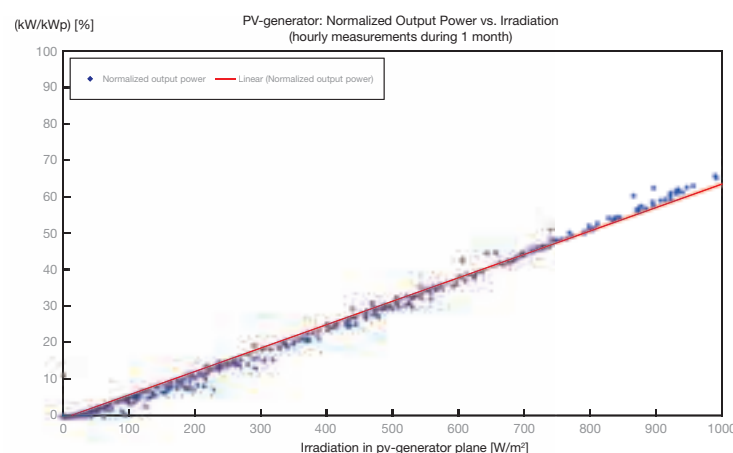
While the statistical correlation of the temperature and the generation is much less significant, it is clear that temperature impacts the generation by decreasing the efficiency of the PV plant.
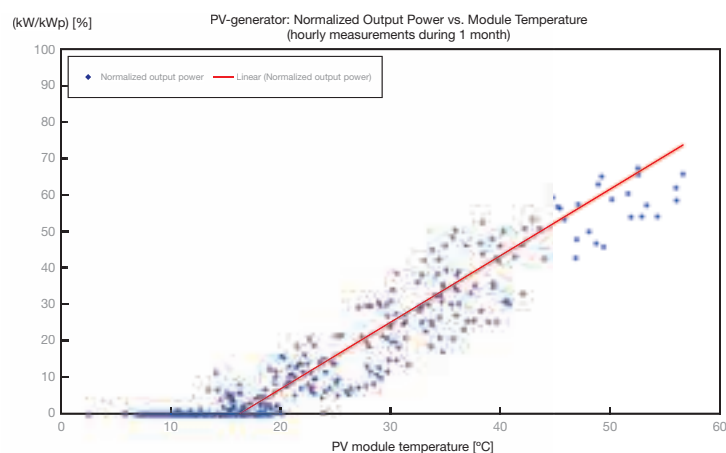
Correlation between power and temperature

Several methodologies can be applied to PV forecasting, using both parametric methods (such as linear/ multiple regression or time series) and artificial intelligence methods (such as neural networks and fuzzy logic). It is also possible to extrapolate the total generated power by monitoring a certain number of "representative" units in each area. PV short-term variability should also be considered during forecasting and towards this end the following is recommended:

◈ Embed the confidence interval calculation in the PV forecast algorithm;

◈ Study past behavior using actual output and weather records;

◈ Perform very short-term predictions with updated data.

👍 Verify the regulatory obligations of QCAs in the Solar parks to perform forecast and the responsibilities (including penalties) in case of deviations between the real generation and the forecast.

👍 QCAs may decide to provide generation forecast, but may also rely on the SLDC's forecast.

Frequency Control

Maintenance of the frequency among acceptable limits is a common job for all interconnected states and systems. The first action is to match the generation to the actual load.

The frequency can be controlled by the generators either manually or automated, The first one provides a basic control with low quality of the frequency at a reasonable cost while the second provides a very efficient control at a much higher cost.

Manual Control

This methodology consists in a precise load forecast and a consistent schedule of generation. Unavoidably deviations in the demand forecast or in the generation will modify the load – generation balance that will produce fluctuations in the frequency. Its magnitude will be a function of the difference between the load and generation with regards to the size of the load.

To correct those deviations from the pre-set frequency value, some manual actions are taken either from the Load despatch Centre or directly by the power plants, increasing or decreasing the generation as a response to a lower or higher frequency values.

Those methods to correct sensitive values of the frequency will never maintain the frequency at its precise value or correct the "electric hour" as examples.

Automated Control Load

In comparison with the previous system, the load – frequency control has as a mission, maintain the frequency value as close as the pre-set value as possible, with a computer driven system for the generation control.

The system tries to correct potential deviations, first the interchanges deviation as a difference between the scheduled and the actual interchange. By comparing both values, the difference is the error between the programmed and actual, generation also known as Area Control Error (ACE). This value is split between the power plants that provide secondary reserve which will receive signals to raise or lower the generation if the actual value is lower or higher than the scheduled one.
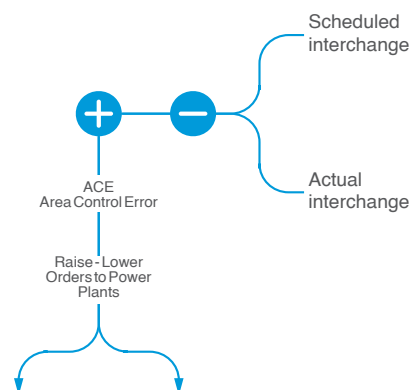

The objective of this automatism is to maintain all interconnected systems fulfilling its interchange contracts inside acceptable limits and correct deviations as soon as they are detected.

Within this system there is not a corrective cooperation among the participants. In case one system deviates and is not able to correct, no other system will do it. The frequency will deviate until the whole system recovers all its margins.

To correct this situation and to establish a cooperation between the participants as soon as the deviation is produced, a second branch is added to the previous schema: the frequency deviation correction.

The frequency deviation is multiplied by a factor called "bias frequency" that represents for each participant inside the synchronous area the weight of the load regarding the frequency, measured in kW/Hz. The Bias Frequency is a function of the size of the synchronous system and the size of each subsystem. The addition of the deviations for interchanges, detected only by the system deviated, and the frequency, detected by all interconnected systems, will provide positive reactions on all systems. When the frequency comes back to normal the rest of the systems will stop their support and the deviated system shall correct or reprogram its interchanges.
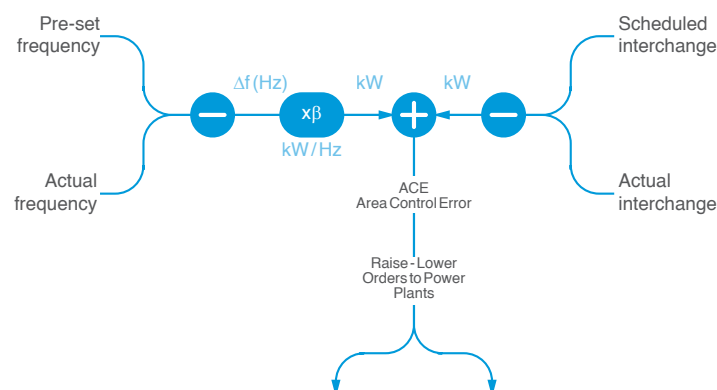
Comparison

Both options are effective and have been used in different transmission systems. To decide which one is more convenient for one system, some aspects shall be considered:

a. Load – frequency regulation is a more expensive system operation, equivalent to maybe the cost of the reserves required to maintain the frequency as closer as possible to the set point.

b. Load – frequency regulation results in a much more stable system and the potential oscillations are minor.

c. Wave quality is better in the case of a close control of the frequency while a loose control produces a lower quality wave profile.

d. The frequency stability will facilitate the interchanges among systems and the system operation with different units connected into the system.

> In case it is technically feasible and the Solar park has some energy storage capacity available, evaluate the possibility to participate, in a limited way into the secondary regulation.

## Protections settings for voltage ride through capability

Any short circuit in the system, even correctly eliminated by the protections system will generate a voltage dip. The main characteristics of these voltage dips are their depth and duration. The main aspects that define both parameters are the network conditions, the type of short circuit and the protections used in the system.
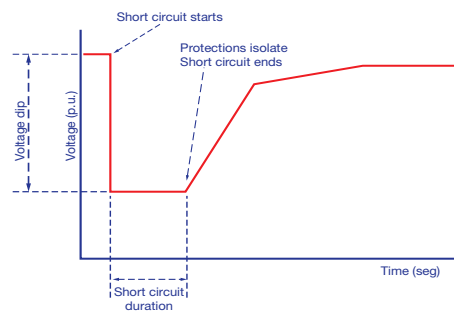
Voltage graph during a fault

The main objective is to study the actual capability of intermittent RE generators to "survive" voltage dips (holes), which is known as fault ride-through capability. In general, the generators will "survive" when the depth and duration of the voltage dip are lower than those the generators can resist, according to their characteristics determined by the manufacturers and the protections settings. Some intermittent RE generators are technologically not adapted to have fault ride-through capability but even others that technologically may resist a voltage dip, may have characteristics or their protections set at values, which will not allow them to remain connected to the system. Solar parks should have fault ride through capability, whose settings may allow them to "survive" or not.

The graph included in recent CEA draft regulation documents, establishes the following profile:
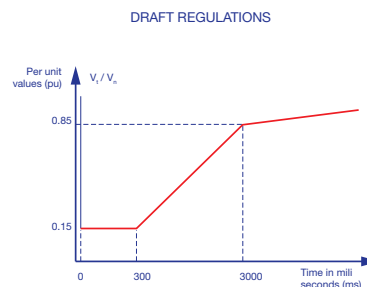
Draft regulations
This graphic is the one mentioned in India Regulations For Grid Connectivity, it shows the time units considered

The graph considers:

a. Short-circuits in bus-bars with Solar parks connection are excluded and not considered as contingencies, and as the system shall survive them, the graph does not reach of the nominal 85% Voltage.

b. The duration of the short circuit could be as much as 0,30 seconds.

i. If we are considering only main protections the durations are below the 0,10 seconds. If considering the failure of a protection the value is also high.

ii. A secondary protection like distance or impedance protection can also work at second or third steps, and could have a duration below the 0,20 seconds. As more challenging the curve selected is, the more demanding for the QCAs in the solar park.
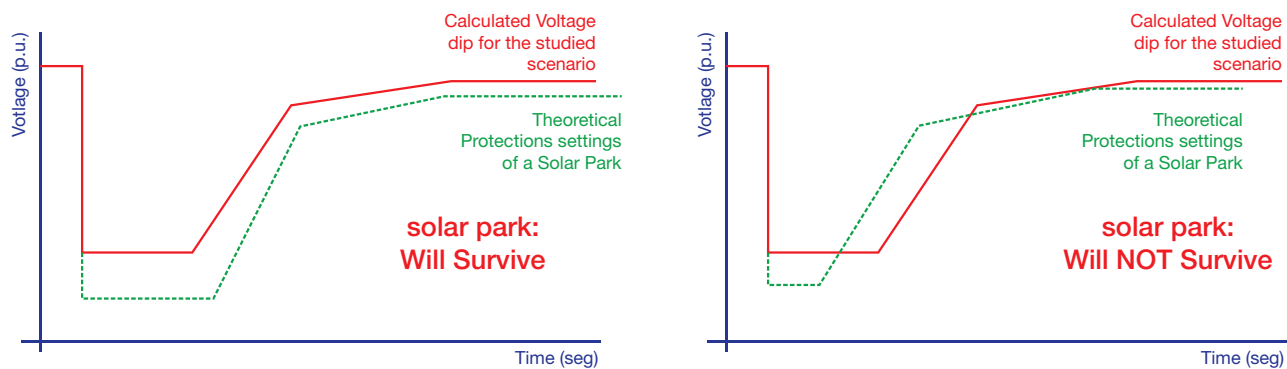
It must be understood that the curve for a certain location during a short circuit depends of many factors and will be different in all network locations as it depends on: resistance of the short circuit, short circuit power in each substation, network topology, impedance and resistance between the short circuit and the substation.

It is recommended for each solar park that the worse conditions shall be considered and studied using a dynamic study and with its results determine the protections settings required.

To calculate the real curve in the Parks locations, the easy way is one of the two following processes:

i. Execute a dynamic simulation of the short circuits in the lines closer to the park substations, using a dynamic load flow, and considering the different protections settings in the Park and lines and transformers in the park proximity.

ii. Use the short circuit analysis tools to analyse the registered values of voltages and flows, during the short circuit.

The best option is to combine the two alternatives.

If those options are not available due to the lack of the dynamic model in case i. or the unavailability of the short circuit analysis tools, an approximation can be calculated from the settings of the network protections. Shortcuts in this process will impact into the solar park survivability to Short Circuits and in consequence to system security.

👍 The worse case scenario for each Solar park shall be studied as Static and Dynamic analysis.

👍 Solar parks should always have protection settings in the power delivery point to the transmission System capable of doing voltage ride through.

👍 Consider the adequacy of the protections settings demanded by the system operator with the Solar park own settings.

Local impact of intermittent RE integration

There is also a local impact, especially in flows and voltage, in the integration of new Solar parks into the electrical system. As solar generation will produce only during day light hours, the low flows will be as stated before during the remaining hours. These changes should be included in the planning of the network.

Flows will be normally very low coming out of the solar park during no sun hours, especially during night hours, when the voltage is higher and the low flows from the solar parks have the effect in the lines that will produce reactive power with a tendency to further increase the voltage. Meantime, during sun hours the Energy flow will be high, when the voltage may be lower in the system, and as consequence lines will absorb reactive power, tending to reduce the voltage.

Both effects will require elements to correct voltage, to increase or reduce voltage depending on the flows.

System Congestion

Under normal conditions and when the solar park generation will be commissioned, the planned network to support it, will be also in service and no congestions are expected.

But nowadays the time to build new lines is higher than to build a new solar plant and even a solar park. This may cause system congestion, during which the operation may have to reduce the solar park potential generation or violate the system security criteria. None of both alternatives is satisfactory.

A third alternative is to install some smart grid solutions to control the network. These smart grid solutions shall be oriented to one of two objectives:

◈ Redirect active flows to avoid congestions during the unavailability of some elements.

◆ Active flow control elements that modify the angle or the impedance of some elements (automated serial shunts, impedance variable transformers.). In both cases the active flows will be modified, avoiding congestions.

◈ Introduce generation rejection elements which will reduce automatically the output of the solar park, and return the system to the limits within the security criteria.

◆ Special Protection Schemes are combined protection's that will react instantaneously, combining different values measured at the same substation (voltages, flows, flow direction…) and reacting when a predefined condition is reached.

These elements can be relocated to other areas. These solutions will maximize the solar park production when a system has a congestion or security violations. For slow development incidents, some manual Defence Plans can be predefined for the operator's use in case the system reaches the specified conditions. All these measures are oriented to avoid curtailment and generation loss.

Unavailability of the network elements

If the network conditions are not the designed ones either because of some delays in the commissioning of network elements or their unavailability for corrective or preventive maintenance, it is possible that the solar park generation may be restricted.

Any restriction to the generation capacity is not only a loss of generation that will need to be substituted by other generation means, but also an economic loss. Reducing the generation in the Solar parks, in this case, avoids system congestions and fulfils the security criteria that otherwise would jeopardize the whole system security.

In case that the potential unavailability or delays introduce restrictions to the solar park generation, verify that all countermeasures have been adopted in order to reduce the generation loss.

Verify that the network expansion or reinforcement is developing as planned and the commitment date is compatible with the Solar park availability.

In case of delays or unavailability of the designed network expansion, verify that it will not introduce restrictions to manage the Solar park full generation capacity.

Voltage Control

The system will require elements to control over and under voltages at different network conditions. There are two potential systems to control voltage:

> i. Controlled by the solar park.
> ii. Using Control Elements installed in the transmission network.

Both solutions are effective and can be used simultaneously.

Voltage and reactive power control by power plants

Initially most regulations didn't impose requirements on voltage control. Regulations were limited to requiring a minimum power factor (typically 0.95 or 0.98) to ensure negligible reactive power exchanges with the grid.

High intermittent RE penetration rates made evident that such requirements were not enough and that it was necessary to require RE to contribute to voltage control. The requirement level varies a lot across countries; but nowadays those who had "soft" schemes are transitioning towards more demanding ones.
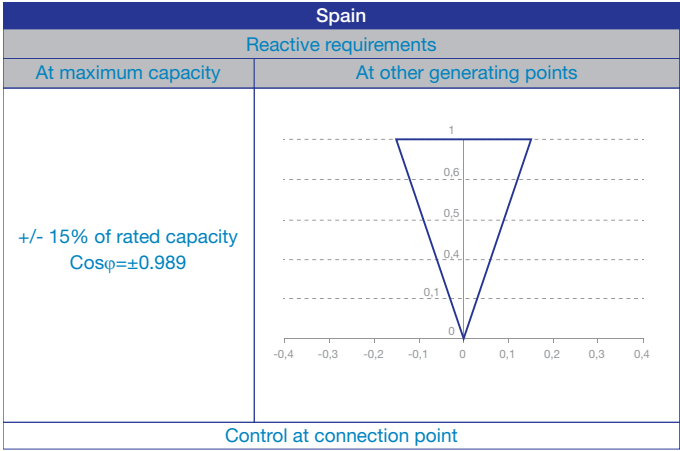
The draft CEA regulations stipulate as follows:

(…)Voltage Regulation in Wind and Solar generating stations:

> a. Wind generating stations/Solar generating stations shall have a continuously-variable, continuously-acting, closed loop control Voltage Regulation System (VRS) i.e. an equivalent to the Automatic Voltage Regulator (A-VR) in conventional machines.

> b. The VRS set-point shall be adjustable in the range prescribed by the appropriate Commission and it shall also be adjustable by Load Despatch Centre via SCADA.

> c. The VRS controller regulation strategy shall be based on proportional plus integral (PI) control actions with parallel reactive droop compensation. The VRS Droop shall be adjustable from 0 to 10%.

> d. The VRS shall be calibrated such that a change in reactive power will achieve 95% of its final value no later than 1 second following a step change in voltage. The change in reactive power shall not cause excessive voltage excursions or overshoot.

> e. The VRS shall be in service as long as the wind / solar generating unit is electrically connected to the grid, regardless of MW output including nil generation from the unit.

> f. The VRS dead band shall not exceed± 0.1 %(....).

For example, the proposal made by ENTSO-E (European Network of Transmission system operators for Electricity) to ACER in Europe states that all generating plants larger than a certain installed capacity shall contribute to voltage control by injection/extraction of reactive power within certain limits, to be defined by each Transmission System Operator (TSO). There is however a consensus among TSOs that all generators shall be capable of controlling at the connection point either: voltage, reactive power or power factor.

As a sample of the requested voltage control for a solar park, is the following graph, which shows the Spanish conditions as indicated in the Operation Procedures (equivalent to the grid code):

Spain	
Reactive requirements	
At maximum capacity	At other generating points
+/- 15% of rated capacity Cosφ=±0.989	
Control at connection point	

European countries, coordinated by ENTSO-E do not agree in this participation and in consequence their grid codes show different participations, including Canada as an non-European System, as can be seen in the following picture:
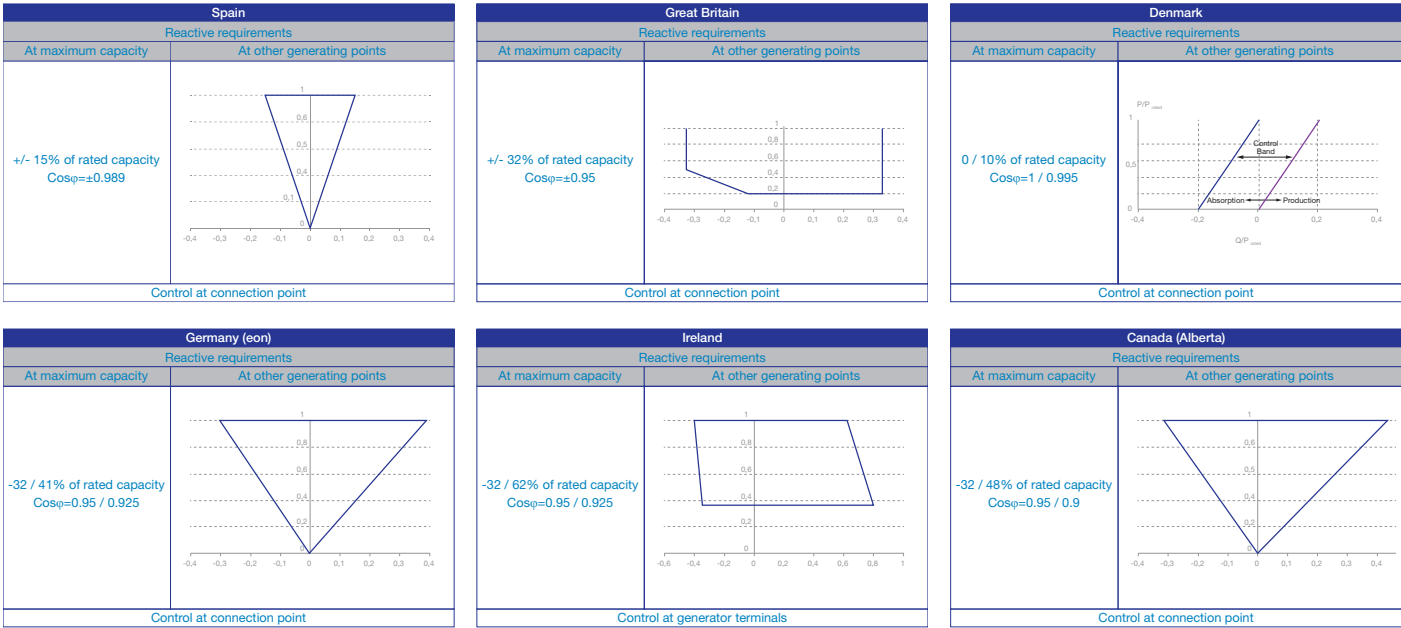
Solar PV inverters can control voltage and provide voltage support in case it is requested. The reactive power capacity is also available though SPDs may be reluctant to do it as they may not be remunerated.

Voltage Control by network elements.

Traditional shunt devices as voltage control will require, as said above, elements to control voltage in both directions and in consequence will require capacitors and reactance's. This may justify economically the use of dynamic elements as:

◈ SVC (Static Variable Compensator). It's an extensively used element which will compensate reactive power by generating or absorbing it, in fixed steps.

◈ STATCOM (static synchronous compensator) elements are a combination of capacitors and reactors. It's a more expensive solution than SVC's but allows a more dynamic control.

Comparison

It must be understood that both solutions, which can be applied simultaneously, will increase the costs in different ways:

◈ The solution of control by the solar plant introduces extra costs in the plant construction and some operation and maintenance costs.

◈ The solution of control by network elements introduces extra costs into the system expansion.

Consider the requirements imposed in the Regulation for Voltage Control and the Solar park Capacity to achieve the values demanded.

In case that there is not enough control capacity, it may be considered to introduce some control elements (SVC's, STATCOM…) and perform a cost analysis.

If there is capacity the solar power developers may consider their participation in the voltage control ancillary services and its remuneration.

System security analysis

The Security Criteria defines the system conditions for normal state. In an electrical system, three states are considered:
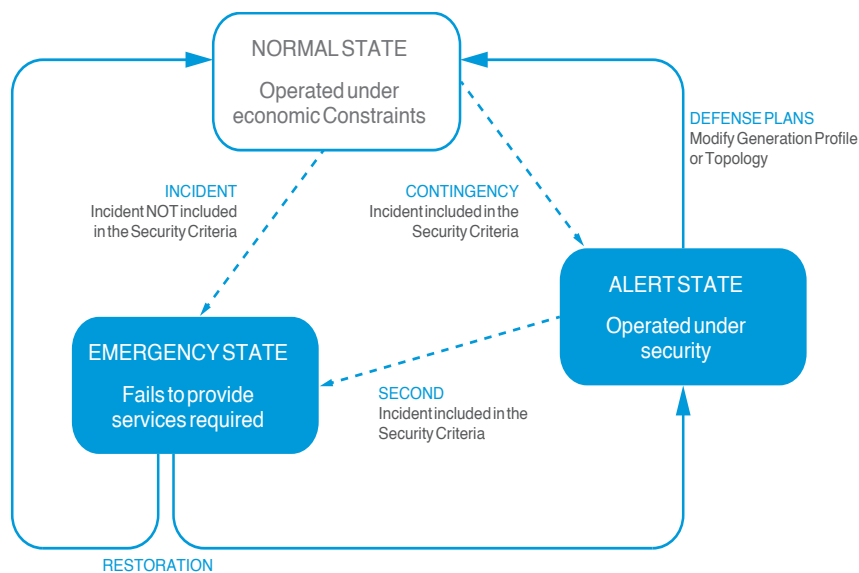
a. The Normal State is defined when the system is operated under economic constrains:

◆ All services are attended (final users, power plants…).

◆ Maximum and minimum voltage acceptable.

◆ Maximum flows in lines and transformers respected.

◆ List of elements which trip (including some simultaneous trips) but will not lead the system to Alert State conditions nor to emergency conditions and in consequence the system will survive. This list is known as contingencies.

◆ Trips not included in the previous list have no guarantee of survival of the system to these incidents.

b. The Alert State is defined when the system is operated under security constrains.

◆ All services are attended (final users, power plants…).

◆ Maximum and minimum voltage acceptable. Limits are less restrictive than in normal conditions.

◆ Maximum flows in lines and transformers. Limits are less restrictive than in normal conditions.

◆ There is no guarantee of survival in case of a second contingency or an incidence not included in the list of contingencies.

c. The Emergency State is defined when not all the clients or services are attended, or voltages or flows are out of limits.

A network security analysis is the process that studies and determines whether the state of the electrical system to take place in a near future (day or hours) is going to survive the incidents that are included in the security criteria. In real time this process considers the security from the actual state to the next few minutes to a few hours. In case that the system is not going to survive, then countermeasures should be taken to make it more secure.

A system must survive to the outages of elements in the system included in the security criteria, which are called "contingencies", while the ones not covered by the security criteria remains as "incident". The security analysis simulates the expected system status, the full list of contingencies, or in some cases the list of the more critical ones, and verify that after the contingency all the voltage values and flows are still inside normal limits, and that no customer or service is lost.

The functional security analysis process is as follows:

1. Inputs:

a. Electrical model: mathematical model of the network, where all physical infrastructure of the network is modelled with their electrical physical characteristics: reactance, resistance, and capacitance.

b. Topology: The electrical network topology is the arrangement or connection of the different elements of the network: bus-bars, generators, lines, cables, transformers, shunts, etc. This topology may be changed with the use of elements designed for this use such as breakers and isolators.

c. Load forecast, active and reactive power, in each node for the period considered.

d. Generation Profile:

i. Uncontrolled generation, like intermittent renewable generation will be forecast.

ii. For controlled generation by other load despatch centres, will be used the results of their scheduling.

iii. For the controlled generation by the transmission system being analysed, it will be the result of the unit commitment or any other scheduling process (market oriented, single buyer, etc.)

2. With those inputs, a base case is generated and a load flow is executed. Load flow output will contain the voltages and angles in all nodes and flows (active and reactive) in all lines, cables or transformers. Generation will be modified in the power plants under regulation or in the swing bus, to adjust the generation to the load plus system losses.

3. The proposed base case will be acceptable if:

a. All voltages are inside limits for a normal state and,

b. All flows are below maximum acceptable flow (current) for a normal state.

    c. All required reserves are met,

    d. The scenario is accepted as feasible and the security analysis could start.

4. The security criteria are the principles that define under which conditions the electrical system shall survive in case that one of the incidents included takes place. In this case the incidents are defined as contingencies. The contingencies list which include any outage inside the security criteria (as example: loss of any line, any transformer, any unit…), represents the practical interpretation of the Security Criteria.

5. In the Contingency Analysis, all contingencies are simulated on top of the base case and if all contingencies result in a system in which:

    a. All voltages are inside limits, for a system under alert state and,

    b. All flows are under maximum acceptable limits under alert state and.

    c. All required reserves are met.

    d.Then the full scenario is accepted and the system state shall be considered as feasible and secure and can be operated under economic constrains which means that in any operation: decision is taken due to its positive impact in the operation costs.

6. If the base case is not acceptable, then inputs shall be changed with the following priority:

    a. Modify generation profile of those units under our control.

    b. Ask to other control centres to modify their generation profile.

    c. Modify the outages list.

    d. Use demand side management, if available.

    e. Execute some selective load shedding.

7. In case that some contingencies generate an unacceptable system state, than as first option:

    a. Modify the base case voltage profile.

    b. Use available tools (smart concepts or ordinary tools) to make the system feasible by correcting the violations.

    c. Modify the base case topology.

8. If those measures are still insufficient, then modify the inputs, with the priorities fixed in point 6, and restart from there.

9. The test and acceptance of the countermeasures can be done manually or in an automated way, following the priority list.

This sequence of Security Analysis shall be executed on:

◈ Operation planning: for day ahead (or any lapse of time from hours to a week, for selected hours). Using forecast values.

◈ Real time, using EMS tools and executing for next minutes to few hours, using the real-time values and modified by short term forecast values.

In all cases the main objective of this process is to guarantee that the system will have all main parameters inside the limits under normal conditions or in the case that one of the outages included in the security criteria takes place.

All this can be resumed in the following graph:
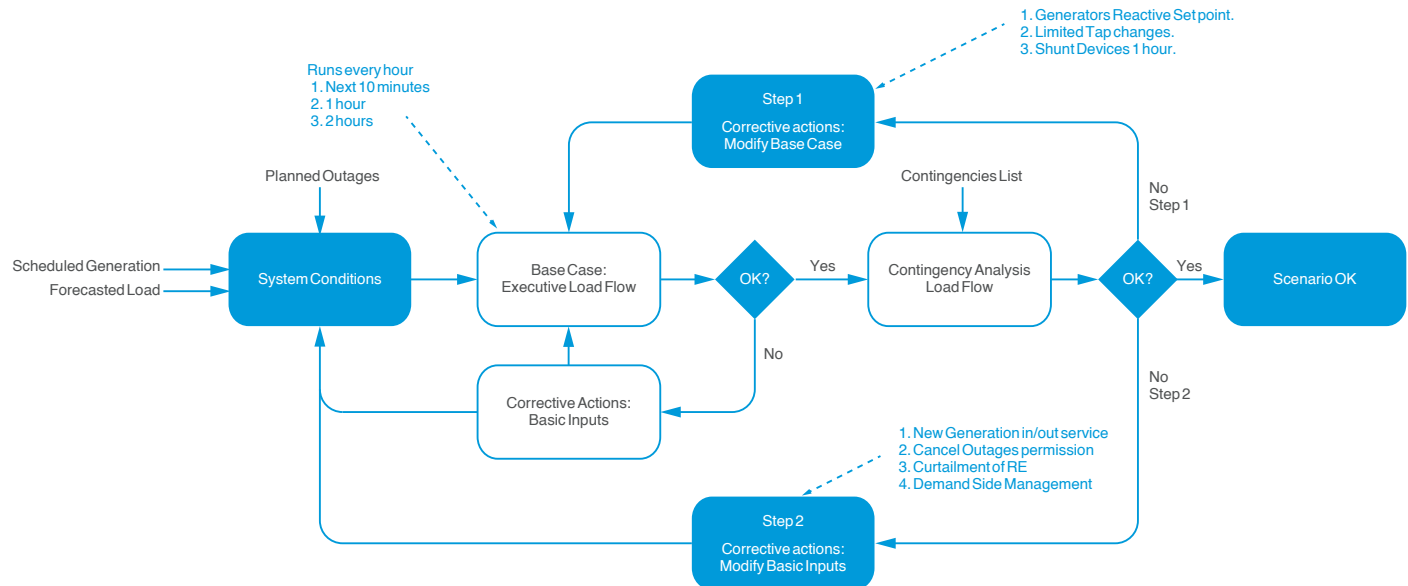
Any incident outside the security criteria may lead the system to a non-acceptable situation or even to a blackout (partial or global). This security analysis is normally performed at two operation times:

◈ On operation planning: when the load is forecast, the generation scheduled and the outages considered. It is executed in general, a week or a day ahead of the time considered and considered for this horizon.

◈ On real time, using the current values of generation and load, or modified according the load forecast for the next minutes to few hours, the generation is based in the actual and/or the last schedule and the topology is the actual topology collected in the SCADA System.

The tools used in both time frames are normally the same or very similar due to the fact that they may be running in different systems, but in any case, with the same functionality and with the same settings.

The solar park potential oscillations are to be added as a new contingency. Potentially the new contingency for large solar parks will require a highest level of reserves and this will make the system operation more expensive.

👍 Decide on the capacity to be considered in the scenarios included in the security analysis and its alignment with the security criteria included in the regulation.

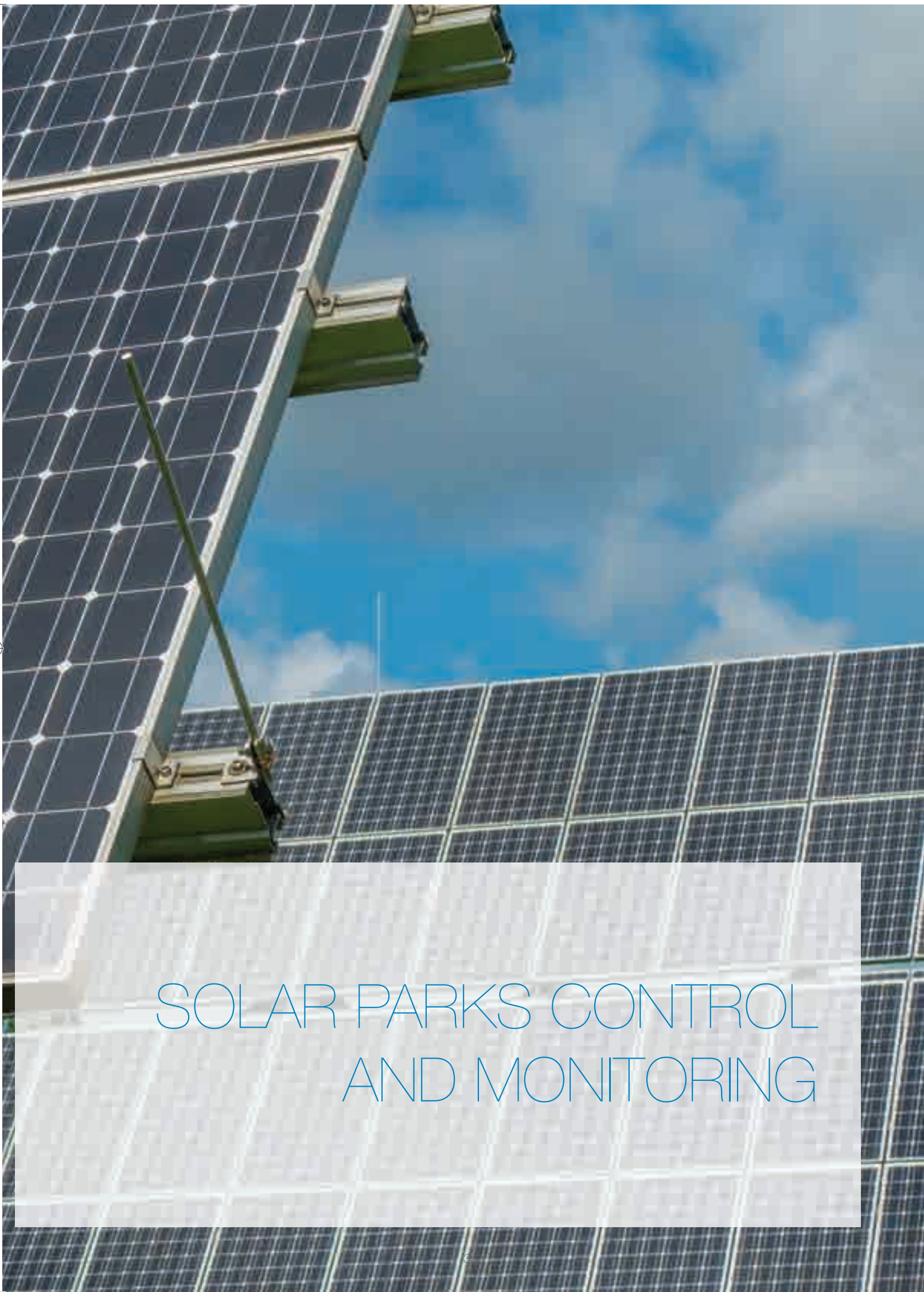👍 Perform a risk analysis for the solar park generation and a risk mitigation study.

SOLAR PARKS CONTROL AND MONITORING

In the structure of load despatch centres in India, we can find the following types and objectives:

◈ National Load Despatch Centre: under POSOCO (Power System Operation Corporation Limited); has the role to schedule and despatch of electricity over the international and inter-regional links in accordance with grid standards specified by the authority and grid code specified by Central Commission in coordination with Regional Load Despatch Centers.

◈ Regional Load Despatch Centre: under POSOCO (Power System Operation Corporation Limited); controls the regional networks (including the green corridor and other interstate networks with high impact into the global system), and coordinates with the State Load Despatch Centres.

◈ State Load Despatch Centre: schedule the main generation elements under the authority of each state with the mission to forecast load and intermittent renewable energy generation in the state control area and schedule conventional generation considering as input the interchanges announced by the Regional Load Despatch Centre.

◈ DISCOM Control Centres or DSOs. Few of them in each state, control the Distribution Networks, under the coordination of the State Transmission Control Centre (some states are now in the process to install the Distribution Control Centres). The equipment in the DISCOM Control Centre's may vary from full SCADA systems, which is equipment for the next generation of DISCOM Control Centres, and some of it is in the process of installation, to less sophisticated, manually operated tools.

◈ 11 Renewable Energy Management Centre (REMC) are being established out of which 7 are in RE-rich States, while 3 are at regional level and one at National level.

The QCAs will monitor, and may forecast the generation of the solar plants inside the solar park and communicate the information to the relevant State Load despatch Centre or even Regional Despatch Center. The communication occurs usually between computers using appropriate protocols over fast communications channels (optical fiber) but in some cases could use other less sophisticated communications resources.

Intermittent renewable control centers

In case of a significant size of intermittent renewable generation, it is recommended to have an intermittent renewable energy control center, either as a separate facility or as an extension of the state load despatch center. Regarding the intermittent renewable energy control centre's, the main functionality is:

1. Intermittent RE generation forecast.

2. Real time monitoring.

3. Static security analysis: curtailment.

4. Dynamic stability verifications.

The intermittent RE control centre should not be considered as an independent control centre, but as an expansion of a load despatch center, and its functionalities, complementary to the existing ones. The objectives of this functionality are to reduce the impact of the intermittent RE generation into the system security and to the quality of the services provided by the electrical system. Several states in India are already implementing Renewable Energy Monitoring Centers (REMC).

Intermittent RE generation forecast

The placement of this functionality closer to the monitoring and other control actions only has advantages.

Intermittent RE generation monitoring

The intermittent RE generation monitoring consists in the data collection, historic time series generation and statistical use of the individual or aggregated generation. The information to be collected is (in addition to the information usually obtained from power plants):

◈ Actual plants generation active (MW) and reactive (MVAr) power.

◈ Actual irradiance, temperature, wind speed and wind direction values. The values must be stored individually with a certain frequency.

◈ Actual voltage and current levels.

◈ Last period energy produced (in MWh and MVArh, coming directly from the meters). If this information is not available, the integration of the instantaneous values may provide a good enough estimation of the energy.

With this information, time series will be created for its use in the different processes in operation planning or real time. It is important to have the time series as "clean" as possible in order not to impose irregularities to future forecasts. CERC is implementing the monitoring of all RE generators, including solar parks, so that the visibility can reach the inverter level, namely.

Static security analysis

When the security assessment detects an expected amount of intermittent RE energy that may produce violations in the security criteria, it will be necessary to take the appropriate actions by the Transmission operator, in order to take back the system to secure conditions. Quite often this will involve actions to limit the amount of generation to be delivered to the system.

When the number of solar parks and the amount of power connected to the network increases the alternative to give voice or manually generate orders to the parks becomes limited, if not useless. The time necessary to execute the decision will be unacceptable. Under these circumstances is unavoidable to have a mechanism that automatically transmits the orders to the solar parks and insures that those orders are automatically executed in order to control the generation in each park.

As intermittent RE generation may suffer permanent variations, it is very complex to use percentages of reduction for each park.

The capacity to send orders to reduce generation in solar parks should be included in the Control Centre functionality.

The procedure to establish this functionality is:

◈ Determine the maximum loss of intermittent RE power, in a single incident, that the system can afford without introducing exceptional measures, to recover from the loss.

◈ In case that the generation exceeds the maximum calculated, the curtailment will be applied, to reduce the actual generation to reach the maximum secure generation level.

◈ To perform the curtailment the load despatch centre shall be prepared with the following functionalities.

- ◆ Capacity to define a maximum acceptable generation, per QCA, per solar park, or per region.

- ◆ The system will split the maximum acceptable generation between the parks included in the affected region, establishing a limit for each one. The algorithm to be used to share the maximum generation allowed between parks must be designed in advance and known by all parties (regarding actual output or total installed capacity).

- ◆ Send individual signals to all parks in the area. The value received will be their maximum generation capacity while the actual conditions persist.

- ◆ In case that one of the parks does not fulfil the order, then its power reduction will be recalculated among the other parks. Penalties could be applied.

- ◆ Send permissive signals to produce as much as possible, when the constrains that caused the reduction disappear.

- ◈ Appropriate communications and protocols shall be dedicated.

  - ◆ The order must be registered and the output monitored.

- ◈ To perform the curtailment the solar park shall be prepared with the following functionalities.

  - ◆ Appropriate communications and protocols shall be dedicated.

  - ◆ Capability to receive set point orders from the load despatch centre.

  - ◆ Capability to execute the orders received, either limiting the generation capacity or recovering the maximum capacity.

- ◈ Establish in the grid code or in the connection agreements, the interfaces and conditions for a solar generation curtailment, compatible with the ones established in the load despatch centre. It should include at least:

  - ◆ Control action to be sent by the load despatch center: maximum output in MW and normalization signal.

  - ◆ Communication facilities and protocol.

  - ◆ Actions to be taken in case that the solar park does not execute the orders received.

👍 Curtailment has an important economic impact. Review the regulation to define the capacity and limitations of the load dispatch centers to restrict the amount of power to be produced in the Solar parks, for security purposes.

👍 In case that curtailment is allowed, define the way and guaranties that the information will be transmitted to the relevant QCAs.

Dynamic stability verifications

The protections settings are dependent of the:

- ◈ The type of short circuit: resistant, metallic, mono or multiple phases.

- ◈ How close is the short circuit, considering the impedance between the solar park and the short circuit.

- ◈ The generation and voltage profiles.

With so many variables the optimal settings will vary. In consequence, a value shall be selected to maintain the same protections settings under any circumstance. Too relaxed settings will allow the trip of the solar parks under small network incidents or far away short circuits while rigid settings will maintain the park in

service under more severe conditions. The settings must be analyzed and the methodology to determine them considered.

> 👍 Apply the same protection settings being used for the settings of the solar plants.

Information management

The origin of the information is always the solar plant that can communicate directly with the solar park, using it as an intermediary. The information to be transmitted is:

- ◈ Analogue values:

  - ◆ Actual generation (Active and Reactive power).
  - ◆ Voltage and current levels.
  - ◆ Flows in any equipment with a voltage higher than 100 kV.
  - ◆ Flows in transformers with a high voltage side equal or higher than 100 kV.
  - ◆ Energy generation with the established frequency (every 15, 30 or 60 minutes).
  - ◆ Weather information in solar park location:
    - · Irradiation.
    - · Temperature.
    - · Wind speed and direction.
    - · Rain.

- ◈ Digital Values:

  - ◆ Trips of breakers due to incidences.
  - ◆ Alarms that carries unavailability of total or partial generation capacity.

> 👍 Enable the communications infrastructure within the Solar parks to provide the required information.

The communications could be done in different ways, the most common and appropriate is through a SCADA system, where the communication shall be established as an interchange between computers with any standard protocol (ICCP or similar).

> 👍 Enable the installation of communications to exchange information.

The information stored has different levels of confidentiality:

- ◈ Public information. Oriented to the public and with the objective to create a positive image of the solar park through its contribution to stop climate change.

- ◈ Information for regulators and civil authorities.

- ◈ Internal information oriented to business control and monitoring.

According with this all information stored shall be correctly identified and the system shall guarantee access to the ones who have the right to it and deny the access in the contrary.

STORAGE

The different roles of the energy storage can be grouped on three main uses:

1. If the storage is operated by the system operator, then it will store the energy when there is excess of generation during low load hours and return the energy to the grid on peak hours. It is basically an economic cycle to use energy surplus on energy shortfall hours or on more expensive generation times. This use shall consider the cost benefit, including the storage performance and possible generation alternatives.

2. Used as source of energy when by any reason there is a lack of energy in the system or other ancillary services, as a way to improve the system's performance and electricity quality.

3. In case that the storage is operated by the PV (or wind) plant owners, and used to avoid potential penalties due to deviations from the scheduled and real generation, The solar plants operating in a market, shall forecast their generation and in case of the real generation deviates in any direction, the deviation will be penalized. To avoid it storage may allow to reduce or cancel such deviations.

This last one is currently one of the main uses for storage installations, where the forecast may be difficult and not too precise and the deviations are expensive.

If the storage is owned by the solar plant operators, then its use will be oriented to provide economic advantages to those companies:

◈ Avoid penalties due to the deviations from scheduled and real generation.

◈ Participate in some extend into some ancillary services, specially reserves, which in market oriented systems are well remunerated.

If the storage is owned by the transmission system operator, then its use will be oriented to provide ancillary services to the system:

◈ Reduce the need of ancillary services provided by generation companies to avoid their costs, especially on the reserves.

The following example shows how storage can be counterproductive for the electrical system in general:
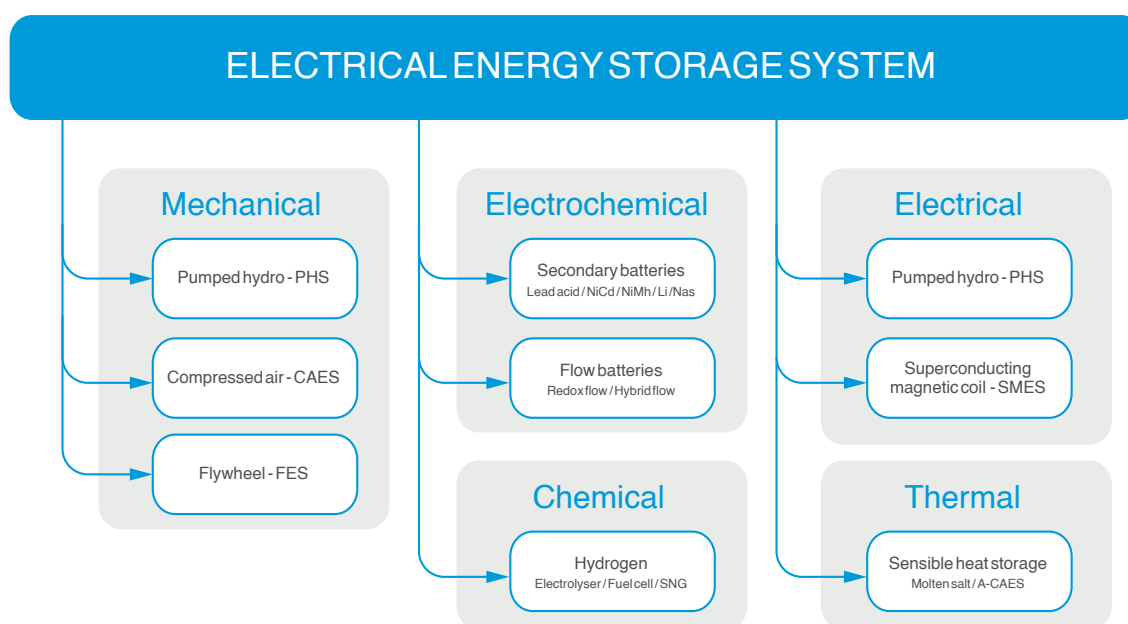
◈ The QCAs in a solar park have under estimated the generation for the next period.

◈ The solar park as a whole will deviate by delivering more energy than scheduled, and will be subject to a penalty.

◈ At the same time, at state level there is an increase in the load that requires extra generation, to avoid potential penalties.

◈ In this case storage will favour Renewable generation and will not benefit the system, or vice versa.

This conflict of interest in the installation of energy storage systems has sparked a debate between experts. Nonetheless the stored electricity could be used in the spot market to actually be sold to match the load needs.
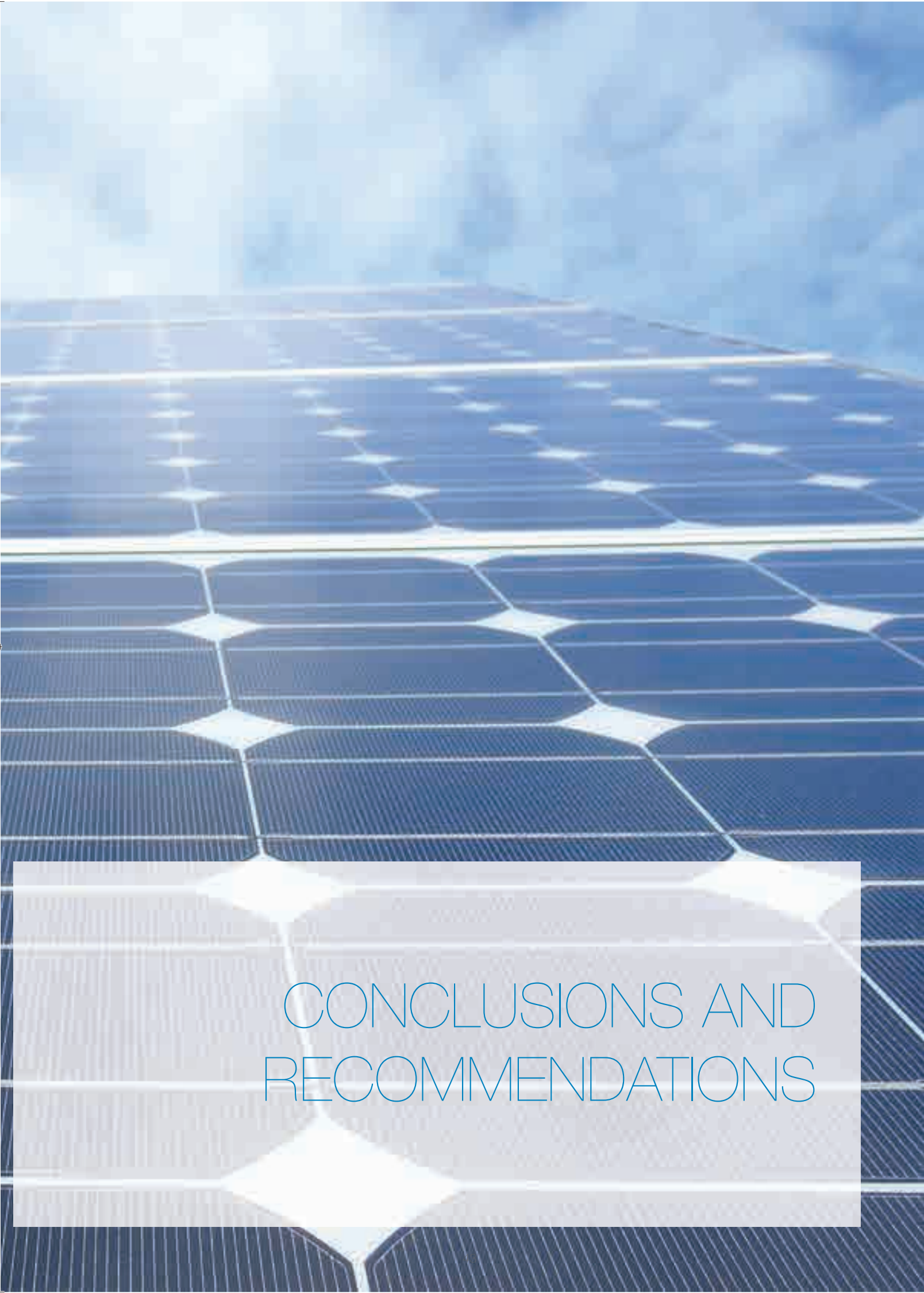
Technologies used

There are commercially available a good number of storage technologies. The most consolidated ones - pumping hydro plants - require a high surplus of energy during low load hours and a good price difference between low and peak load hours. Others as electrical storage are too expensive for a massive adoption, but their cost reduction trend is promising. The more convenient technology is a function of the storage size, charge and discharge conditions, regulatory conditions, including also the cost of schedule deviations.

A resume of the technologies available follows:

ELECTRICAL ENERGY STORAGE SYSTEM

Mechanical

- Pumped hydro - PHS
- Compressed air - CAES
- Flywheel - FES

Electrochemical

- Secondary batteries
  Lead acid / NiCd / NiMh / Li /Nas
- Flow batteries
  Redox flow / Hybrid flow

Chemical

- Hydrogen
  Electrolyser / Fuel cell / SNG

Electrical

- Pumped hydro - PHS
- Superconducting magnetic coil - SMES

Thermal

- Sensible heat storage
  Molten salt / A-CAES

41

CONCLUSIONS AND RECOMMENDATIONS

The system security depends on the solar parks availability and the best possible generation forecast. The solar park generation depends on the system security. In case of violations of the established security criteria, the operators are responsible to take actions to correct such system condition and one of those measures could be the generation limitation or curtailment. This mutual dependency requires that both sides know the decision taking mechanisms for preventive actions. The impact of generation limitation inside a Solar park is too important to be ignored.

A set of recommendations is made:

p.20   Verify the regulatory obligations of QCAs in the solar parks to perform forecast and the responsibilities (including penalties) in case of deviations between the real generation and the forecast.

p.20   QCAs may decide to provide generation forecast, but may also rely on the SLDC's forecast.

p.22   In case it is technically possible and the solar park has available some energy storage capacity, evaluate the possibility to participate, in a limited way into the secondary regulation

p.23   The worse scenario for each solar park shall be studied as Static and Dynamic analysis.

p.23   Solar parks should always have protection settings in the power delivery point to the transmission System capable of doing voltage ride through.

p.23   Consider the adequacy of the protections settings demanded by the system operator with the Solar Park own settings.

p.24   In case that the potential unavailability or delays will introduce restrictions to the solar park generation, verify that all countermeasures have been adopted in order to reduce the generation loss.

p.25   Verify that the network expansion or reinforcement is developing as planned and the commitment date is compatible with the availability.

p.25   In case of delays or unavailability of the designed network expansion, verify that it will not introduce restrictions to the management of with the solar park full generation capacity.

p.27   Consider the requirements imposed in the Regulation for Voltage Control and the solar park Capacity to achieve the values demanded.

p.27   In case that there is not enough control capacity, it may be considered to introduce some control elements (SVC's, STATCOM…) and perform a cost analysis.

p.27   If there is capacity from the solar power developers may consider their participation in the Voltage Control ancillary services and its remuneration.

p.30   Decide on the capacity to be considered in the scenarios included in the security analysis and its alignment with the security criteria included in the regulation.

p.30   Perform a risk analysis for the solar park generation and a risk mitigation study.

p.36   Curtailment has an important economic impact. Review the regulation to define the capacity and limitations of the load despatch centers to restrict the amount of power to be produced in the Solar Parks, for security purposes.

p.36   In case that curtailment is allowed, define the way and guaranties that the information will be transmitted to the relevant QCAs.

p.37   Apply the same protection settings being used for the settings of the solar parks.

p.37   Enable the communications infrastructure within the solar parks to provide the required information.

p.37   Enable the installation of communications to exchange information.