STABLE INTEGRATION OF A 400MW PHOTOVOLTAIC FARM INTO THE JAPANESE POWER SYSTEM – CHALLENGES AND CHANCES

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The German project developer Photovolt Development Partners GmbH plans the erection of a utility-scale photovoltaic power plant on Ukujima, an island in the western part of Japan. The installed capacity of the Ukujima Mega Solar Park is planned at 430 MW (DC). The distance to the grid connection point is approximately 65 km and requires the application of a submarine cable. The grid connection of such a large-scale plant is a challenge both for the project developer and the system operator. The characteristics of the Japanese power system with its split into two frequency areas are unique and need specific considerations regarding the requirements for the system stability. This paper describes the challenges and chances of the Ukujima Mega Solar Park connection with regard to stable operation of the power system from the project developer's perspective and will address the specifics of the development of the project's internal electrical infrastructure and its electrical characteristics.

Keywords: solar energy; large-scale power generation; grid connection; power system stability

INTRODUCTION

Photovolt Development Partners GmbH (PVDP) plans to erect the "Ukujima Mega Solar Park" on Ukujima. The installed capacity of the solar park is planned at ca. 430 MW (DC) to achieve an export capacity of 400 MW at the Point of Common Coupling (PCC). The connection to the public grid is a substation 220kV, belonging to Kyushu Electric Power Co. The photovoltaic farm is to be located on the Ukujima Island; the distance to the PCC is approximately 65 km and requires the application of a submarine cable.

The integration of this project with variable generators and a capacity of 400 MW (AC) into the Japanese 60Hz Power System is a challenge both for the project developer and the system operator. The electrical capabilities of the complete farm allow the submission of control services dedicated to the stability of power systems. The application of these opportunities is comparable to those of conventional power plants and allows the improvement of system stability in general.

The paper is intended to be a contribution for the understanding of a stable interaction between Renewable Energy Systems and stable Power Systems.

CHALLENGES AND CHANCES

The project developer PVDP has to engineer a complete proprietary power network for the transmission of the generated power up to the PCC. The DC network has a length of more than 10km. For the DC-AC conversion more than 400 inverters, each with an installed capacity of 1,000kVA will be installed. The inverter stations that consist of two inverters each are designed for special environmental conditions at the Ukujima Island. The power network comprises a distributed medium voltage (MV) network at Ukujima Island, which connects more than 200 transformer stations. The voltage level of the internal MV network was defined autonomously. The length of the internal MV network is 150km. A power station with a total capacity of 500 MVA at the Ukujima Island will transform the distributed energy up to 220 kV. The transmission of the power to the PCC at Kyushu will be realized with a special advanced transmission system.

The system operator is responsible for a stable operation of the connected power plants. The responsibility is related (but not limited) to a reasonable degree of active power and frequency control, reactive power and voltage control as well as a stable operation of the connected power plants to the grid during network faults (Fault-Ride-Through). Here, the different character of decentralized power resources, like solar, compared to conventional generation has to be considered. Conventional power plant performance metrics are designed for dispatchable generation. Those metrics may be difficult to apply to variable generators such as wind and solar power. However, with increasing plant sizes and higher penetration levels, interconnection and operational challenges become more complex. It has to be mentioned that the specific of the Japanese power system and its split into two independent frequency zones is unique and needs specific considerations regarding the requirements for the system stability.

CHALLENGES OF THE PROJECT DEVELOPMENT

Optimal Design of the MV Network

The development of the optimal design for the internal network is a so-called "green-field" planning process. Doing so, the following main parameters had to be decided:

- MV voltage level
- Topology of the internal network.

As the internal network is completely isolated from other networks, an *optimum for its operation voltage level* had to be defined. The approach for a technical-economical optimum is based on investment and operation figures and requires a consideration of the market availability of the essential assets. Moreover, the results of similar investigations regarding a comparison of different medium-voltage levels were considered [1]. Two main facts led to the decision to use voltage levels lower than 66kV: the non-availability of gas-insulated load-break-switchgears for 66kV and the impossibility to implement switchgears and transformers for voltages of 66kV into the spare space of the given cubicles for the inverter stations. High currents for the transmission of the generated power of 400MW in total up to the first substation showed advantages for the application of the voltage level 33kV compared to 22kV.

The *topology of the internal medium-voltage network* is of a radial structure (Fig. 1). The choice of this type of topology is related to the characteristics of the Photovoltaic (PV) modules - a connection between the different strings is not necessary - and an optimum between the total costs and the reliability for the power transmission. Each string of the radial network is designed for a maximum current of 630A that allows the use of typical gas-insulated load-break-switchgears. A specialty of the design is that, only every third station is equipped with switchgears. All other stations are equipped with medium-voltage fuses only for the protection of the transformers.

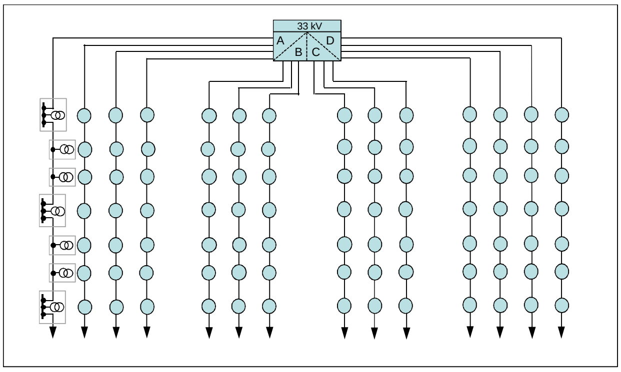

Figure 1: Principle of the internal MV network design

Submarine Power Transmission

The transmission of power of 400MW to the PCC at Kyushu over a distance of 65 km requires the application of a high-voltage submarine cable. In general, two basic technologies are available on the market considering the main parameters for the submarine power transmission - amount of power and length of the route - the HVAC technology and the HVDC technology. Regarding the HVDC technology it has to be considered that the Ukujima Island is not an active power network. Therefore only the HVDC-VSC, not the LCC technology is applicable. For both technologies, the HVAC and the HVDC-VSC technology, worldwide references are available.

A sensitive evaluation of advantages and disadvantages showed that, the application of the HVAC technology is the preferred technical-economical solution for the project related conditions considering CAPEX and OPEX. However, the effect of the use of the HVAC technology for the existing transmission system regarding the topics Power Quality and Electromagnetic Transients had to be studied carefully. Doing so, the Power Quality analysis showed the displacement of the existing network resonance to a critical area around 300Hz (Fig. 2). Within this frequency area harmonic currents can generate inadmissible harmonic voltages.

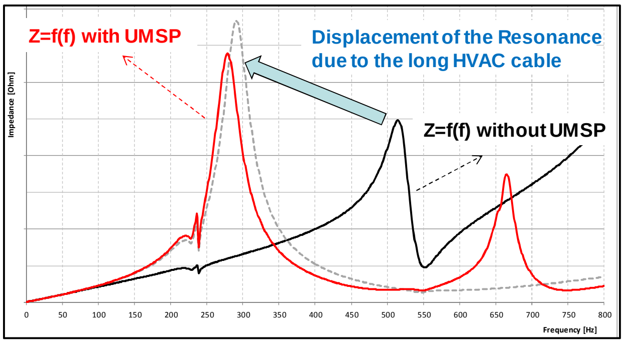

Figure 2: Impact to the Impedance-Frequency-Curve

The process of a final decision about using HVDC or HVAC is still ongoing. All investigations were done with the Power System Analysis Software “PowerFactory” by DIgSILENT, Germany [2]. The main outcome of the detailed system studies were:

- The definition of measures for a secure and stable operation concerning the requirements of JEAC 9701-2012
- The definition of countermeasures for specific electrical phenomena due to the use of a long-distance submarine cable (e.g. harmonic filters to prevent inadmissible harmonic voltages)
- The definition of basic settings of the protection devices.

The outcome of the system studies is the income for the design of an electrical power plant infrastructure that can contribute to a stable operation of the transmission system according to the requirements stated in JEAC 9701-2012 and other international standards.

CHANCES FOR THE POWER SYSTEM’S STABILITY

General Stability Requirements to Generating Units

The intension of the development of UMSP is to provide control services to support the stability of the transmission system. For the following aspects (types) of a power system’s stability the control services shall be provided:

- Frequency stability (balance of the active power)
- Voltage stability (balance of the reactive power).

The third main part of the stability of power systems, the rotor angle stability, is out of the scope for UMSP and can't be influenced.

Based on the transmission system operator's responsibility to keep the stability of a transmission system, the following main requirements to generating units – all Renewables included – are determined in typical grid connection codes (Fig. 3). The relevant code for the grid connection of generating units and Renewables in Japan is JEAC 9701-2012 [3].

Criterion	Description of the Requirement	Stability Type	JEAC 9701
Frequency range	Normal operation 47.5 Hz ≤ f_{r50Hz} ≤ 51.5 Hz or 57.0 Hz ≤ f_{r60Hz} ≤ 61.8 Hz (Europe 48.5 Hz ≤ f_{r50Hz} ≤ 50.5 Hz)	Frequency	✓
Voltage range	Normal operation between 80% ≤ U_r ≤ 120 % (Europe 80% ≤ U_r ≤ 120 %)	Voltage	✓
Active Power Control	Active Power Control within a given Frequency Range	Frequency	✓
Reactive Power Control	Possibility to meet a given P-Q-diagram independently to voltage changes (P-Q-diagram in a voltage band)	Voltage	✓
Fault Ride-Through	Stable connection during network faults within a give time-frame; (injection of a reactive current)	Voltage	✓

Figure 3: Basic stability requirements to generating units

All main requirements concerning the grid connection of generating units and Renewables are included in JEAC 9701-2012.

Stability Requirements according to JEAC 9701

The document JEAC 9701-2012 defines all requirements for generating units to be connected to the Japanese power system (Tab. 1) and therefore have to be applied to each Renewable energy system. The distributed character of Renewables requires is a prerequisite for a stable operation of the power system. The main technical requirements to Renewables systems are described in detail hereinafter.

- Active Power Control

Active power control is used to control the system frequency by changing the power injected into the grid. The frequency is an indicator of the imbalance between production and consumption. New interconnection requirements are now in place to support a smoother response to frequency deviations of PV systems (Fig. 4). Now, frequencies above the rated value lead to a smooth power reduction according to a predefined, characteristic curve, until the generation units are disconnected from the grid at a defined frequency. JEAC 9701-2012 require a stable operation of the generation unit within a given frequency range (Fig. 3). However, requirements for an active power control according to Fig. 4 are still not established within this document.

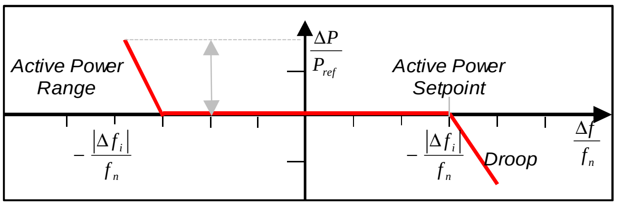

Figure 4: Variation of the power output of generating systems

- Reactive Power Control

The voltage control requirement is used for generating units to supply overexcited or underexcited reactive power at the grid connection point. Each unit should be capable of supplying a proportion of the system's reactive capacity, including dynamic capability, and should contribute to maintain the reactive power balance. Requirements of the Grid Code for reactive power capability claim that the power factor is maintained in a specified range. According to the Japanese Standard JEAC 9701-2012 generating units, including Renewables, with a rated capacity of 50 MVA or higher the power factor has to be in a range of 90% lag to 95% lead from the system's point of view. The leading and lagging power factor values reflect a difference of reactive power. For instance the lagging power factor of generators indicates that, the reactive power is positive from the generator's point of view. However, if it is seen from the system's point of view, the reactive power becomes negative due to the opposite direction of the power flow; therefore the power factor is leading. Likewise, lead and lag of power factor changes depending on the point of view. Voltage regulators as well as measures to control reactive power at the generators and connection points are used in order to keep the voltage within the required limits and avoid voltage stability problems.

- Fault-Ride-Through

Distributed renewable energy systems are expected to be penetrated widely and largely due to agreed global environmental targets. The increased number of installed renewable systems, like PV systems, may impact the stability of the power system in case of network failures. Disconnection from the grid during network failures may worsen a critical grid situation and may threaten the security standards. To avoid this situation, the Fault-Ride-Through (FRT) requirement was established. In the event of network faults outside the protection range of the generating facility, the latter must not be disconnected from the network and has to revert to normal operation when the fault on the power system is cleared. The FRT requirement according to JEAC 9701-2012 (after March 2017) is according to Figure 5.

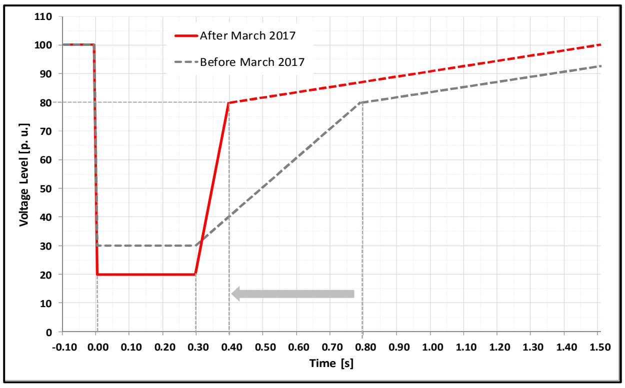

Figure 5: FRT requirement acc. to JEAC 9701-2012

The generation units must not disconnect during a voltage drop down to 20% of U_r and duration of 0.3 sec. It has to revert to 80% of U_r within 0.1 sec when the fault is cleared (0.4 sec faster than before March 2017). The origin voltage before the fault shall be achieved after 1.5 sec.

Ability for Stability Support by UMSP

The ability of UMSP to fulfill the grid code requirements and to provide control services for the stability of the power system will be determined by the inverters mainly. It is intended to use inverters with an installed capacity of 1.000kVA or more. These inverters are already available on the market; their electrical characteristics are known. Using this equipment, UMSP is able to provide the following control services:

- Active Power Control

Each inverter is able to limit the active power due to increased frequencies according to the following sequence (Fig. 6). If the frequency exceeds a threshold (Point 1), the inverter starts to reduce the active power according to a gradient in kVA/Hz, defined by the grid code or the TSO. If the frequency starts to decrease (Point 2), the active power will remain constant up to a new operation point (Point 3). Only from this point a power increase up to the origin value is possible. A farm-centered controller coordinates the activities of each inverter related to the PCC.

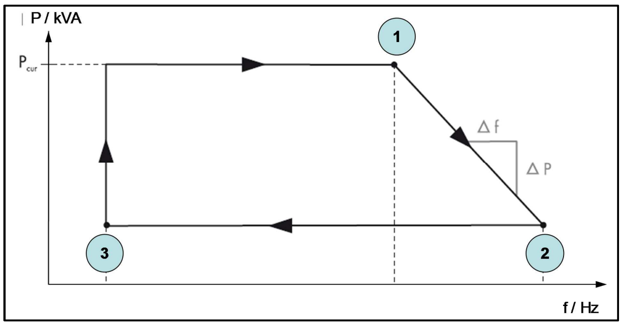

Figure 6: Principle for the active power regulation

- Reactive Power Control

Using the reactive power capability of the inverters, UMSP is able to provide the reactive power at the PCC according to the requirements of JEAC 9701 for all active power export scenarios (Fig 7). The reactive power export of the inverters can be controlled by different parameters (e.g. fixed cos φ, Q=f(P) or Q=f(U)). The farm-centered controller coordinates the reactive power regulation process for each inverter related to the PCC.

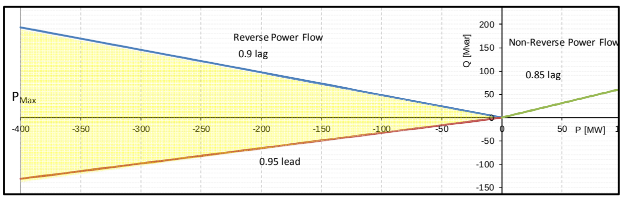

Figure 7: P-Q-diagram for the PCC

- Fault-Ride-Through

The evidence for the fulfillment of the FRT-criterion stated at the grid codes, e.g. JEAC 9701-2012 is carried out according to the following sequence. For each inverter a certified FRT-measure for the relevant inverter type must be available (Fig. 8). Based on this real measure, an electronic inverter model for the FRT behavior will be developed. This model reflects the active and the reactive power during the time period of an external network failure. It has to be verified by an independent certification body and will be provided to the project developer by the inverter manufacturer. The project developer implements this model into its own model of the complete farm. Doing so, the project developer is able to analyze the behavior of the complete farm during an external fault and check, whether the FRT requirement is fulfilled. The analysis is done under consideration of the individual network specifics (e.g. short-circuit power) and the reactive power demand of the farm internal network.

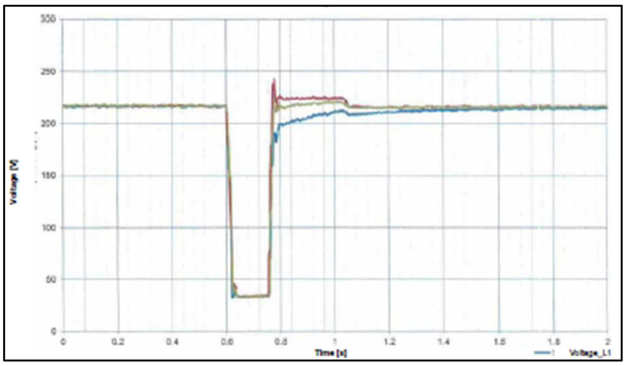

Figure 8: Real FRT measure at LV side

Besides the FRT behavior, the inverters are able to provide an additional reactive current during the network fault in order to support the voltage during the drop. This behavior is not required within JEAC 9701-2012.

SUMMARIZE

The Ukujima Mega Solar Park is able to meet the basic technical requirements to generating units as stated in the Japanese Grid Code JEAC 9701. It is able to provide system services such as:

- Operation of the PV park in a predefined frequency range
- Operation within the defined voltage range and to provide reactive power for the voltage support
- Maintenance of the operation during a fault in the grid (Fault-Ride-Through Capability).

Moreover, UMSP is able to provide additional system services as required by JEAC 9710, such as:

- Active power control during frequency variations
- Infeed of a reactive current during external network faults for an additional voltage support.

The Ukujima Mega Solar Park is able to contribute active to the stability of the Japanese transmission system and to provide all required system services.

References

[1] Carbon Trust; Joint Industrial Project "Offshore Wind Accelerator" *http://www.carbontrust.com*

[2] "PowerFactory", DIgSILENT Germany; www.digsilent.com

[3] Japan Electric Association "Grid Interconnection Code", JEAC 9701-2012