Wind and PV Energy Integration in Distribution Grids and Bidirectional Grid Operations :
A Comparative Analysis in Japan and Germany

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Abstract : Grid operations and key rules enabling integration of wind and photovoltaic systems into the power network system in Japan and Germany were analyzed in this study. The research focuses on reverse power flow from low voltage (LV) and medium voltage (MV) grids to extra-high voltage (EHV) grids. The results showed that German grid operators flexibly transmit and distribute electricity in a bidirectional way, depending on the power output from renewable electricity. German grid operators prioritize purchase of renewable electricity and transmit it to the upstream grid as necessary. Excess electricity from wind and PV systems is physically transmitted to upstream grids and to neighbouring zones as a priority. In Japan, grid operation is unidirectional and uses a downward power flow based on electricity from nuclear power and large-scale coal power plants. Nuclear electricity has the first priority over all other types of electricity to be transmitted downward from 500 kV grids to the lowest voltage grids and to inter-zone tie-lines. Renewable electricity has no legal definition with regard to upstream transmission. Because the Renewable Energy Act in Japan does not oblige utility companies to expand their grid capacity, there are few opportunities for renewable energy sources in the grid system. Therefore, rules for upstream transmission and reinforcement of upstream grids are required for utility companies in Japan.

Keywords : wind energy, photovoltaic energy, grid integration, reverse power flow, upstream transmission, bi-directional grid operation, vertical grid load, priority transmission, grid capacity development

Introduction

Wind and photovoltaic (PV) energy sources are useful ways to reduce CO_2 emissions in the electricity sector. However, distribution grid systems are facing challenges of how best to accommodate wind and PV energy on a large scale because middle and low voltage distribution grids were not originally designed for this purpose. In this study, grid operations in Japan and Germany are investigated, with a focus on key rules that enable wind and PV systems to be integrated into the power network on a large scale by comparing energy policies in the two countries.

First, bidirectional grid operation in the 50Hertz transmission zone in Germany is examined. This research focuses on reverse power flow (Rückspeisung) from low voltage (LV) and medium voltage (MV) grids to high voltage (HV) grids. The relationship between reverse power flow and feed-in from wind and

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PV energy will be examined. Grid data in the 50Hertz zone is used in this part of the study. Second, the key rules that enable reverse power flow from wind and PV energy in Germany will be discussed, including rules concerning grid connection, transmission and upstream transmission of renewable electricity under the Erneuerbare Energien Gesetz (EEG: Renewable Energy Sources Act)[1,2]. Finally, rules concerning connection, transmission, distribution and grid expansion under the feed-in tariff law in Japan will be analyzed. The reforms necessary for the success of this law will be discussed through a comparison with grid integration policies in Germany.

1 Grid operation with high penetration of wind and PV energy in Germany

1.1 Negative vertical grid load and reverse power flow

A positive vertical grid load (VGL) indicates load flow from the 380 kV transmission grid to the 110 kV distribution grid with a voltage decrease through transformers, whereas a negative VGL indicates reverse power flow from the 110 kV grid to the 380 kV grid with a voltage increase through transformers.[3] The value of VGL in this study is defined as the total net sum of electricity through all transformers and tie-lines that are directly connected to the 380 kV grid in the control zone of each transmission system operator (TSO). Reverse power flow can occur in some transformer substations with a large capacity of interconnected wind and PV systems, while some urban or industrial areas have a positive VGL at the same time. Even if the aggregated VGL in a TSO control zone is negative, there is a possibility that transformer substations in some areas will still have a positive VGL. VGLs are given in units of MW/15 min.[4]

In this paper, VGL, tie-line transmission, and international transmission in the 50Hertz and TenneT zones will be examined using grid data in units of 15 min, with the relationship between feed-in from wind and PV energy as a priority. In the 50Hertz zone, wind energy capacity is around 13,4000 MW and PV capacity is 7,400 MW. Data for control area load, VGL, wind feed-in, PV feed-in, international exchange, and feed-in management are shown in units of MW/15 min, according to Sections 13(1)-EnWG and 13(2)-EnWG (German Energy Industry Act). The grid load for each transmission line in the 50Hertz zone is shown in MW/hour. All data are available at the website of 50Hertz GmbH.[5]

1.2 Vertical grid load and voltage levels of wind and PV energy integration

The magnitude and times of the negative VGL have increased since 2011 in the 50Hertz zone (Fig. 1). The amount of negative VGL accounted for 0.68% of the total sum of electricity transmitted between the 380 kV grid and 110kV grid, and hours of negative VGL accounted for 3% of annual hours in 2013. Brown coal, large hydro, and hard coal plants are connected to the 380 kV transmission grids in the 50Hertz zone. However, 91% of wind capacity and almost all PV capacity in the 50Hertz zone is interconnected to the 110kV and lower voltage grid (Fig. 2). Around 76% of PV capacity in the 50Hertz zone is connected to the MV grid, which indicates that feed-in from wind and PV energy satisfies the load demand in the LV and MV grids.

The EEG obliges German grid operators to feed-in and trasnmit electricity from renewable energy sources (RES) as a priority. Therefore, when feed-in from RES exceeds the load demand in the LV (0.23 or 0.4 kV) and MV (20 or 35 kV) grids, the excess electricity is transmitted to the HV grid (110 kV) with a voltage increase. When feed-in from wind and PV energy exceeds the load in the 110 kV grid, excess electricity is transmitted to the 380 kV grid with a voltage increase.

The 380kV/110kV transformers are equipped with on-load tap changers that can control voltage

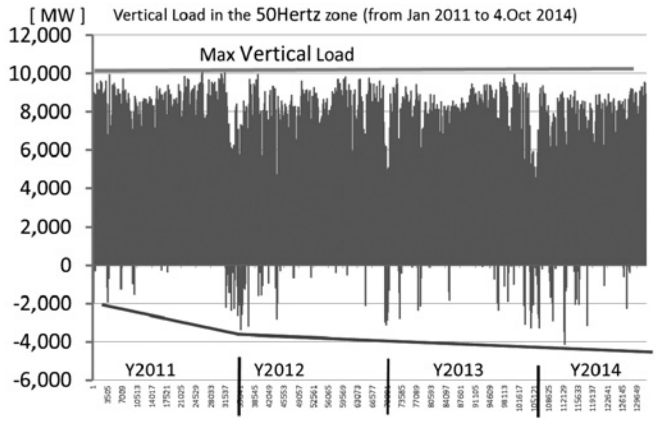

Fig. 1. Vertical load (50Hertz zone, Jan. 2011–Oct. 2014)

Source: Calculated from 50Hertz grid data

changes caused by reverse power flow. In addition, almost all transformers at 380kV/110kV, HV/MV and MV/LV are equipped with both-direction protection systems to deal with reverse power flow. Both-direction protection systems have been installed in the past decade.[6] This is because the EEG (2004 version) obliged German grid operators to transmit renewable energy electricity as a priority. Reverse power flow at 380kV/110kV transformers occurs only when wind and PV feed-in is extremely high and the control area load is low. At HV/MV and MV/LV transformers, however, reverse power flow occurs quite often in distribution areas in which a large capacity of wind and PV systems are interconnected to the grid and the load in the distribution area is low.[7]

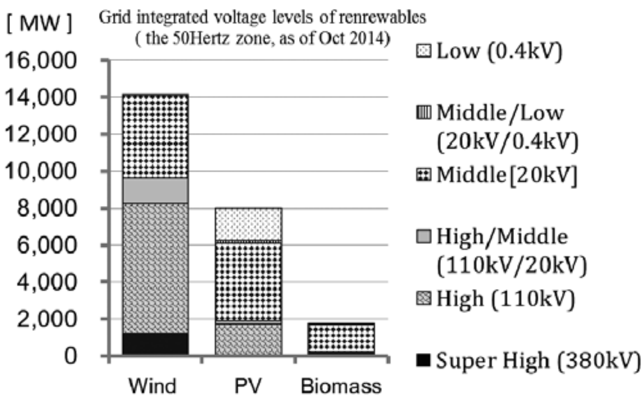

Fig. 2. Integrated voltage levels of renewables (50Hertz, Oct. 2014)

Source: Calculated from EEG-Anlagenstammdaten[8]

1.3 Correlation of wind feed-in, PV feed-in and reverse power flow

Feed-in from wind and PV systems can vary according to weather conditions. However, the EEG requires grid operators to feed-in electricity from wind and PV systems as a priority. Therefore, TSOs must ensure system stability and reliability of the grid, and must adapt to changes of wind and PV feed-in at the same time. Residual load (RL) indicates if wind and PV electricity is fed-in to the grid as a priority, and what amount of the control area load must be satisfied with feed-in from conventional power plants and other renewable power plants.

$$RL = L - (W + PV) \qquad (1)$$

The RL is defined in Equation (1), where L is the load in the control zone [MW]. W is the wind feed-in, and PV is the photovoltaic feed-in [MW]. High feed-in from wind and PV energy and a low load in a control area causes a low or negative residual load and a low or negative VGL (Figs. 3, 4, 5). VGL clearly decreases

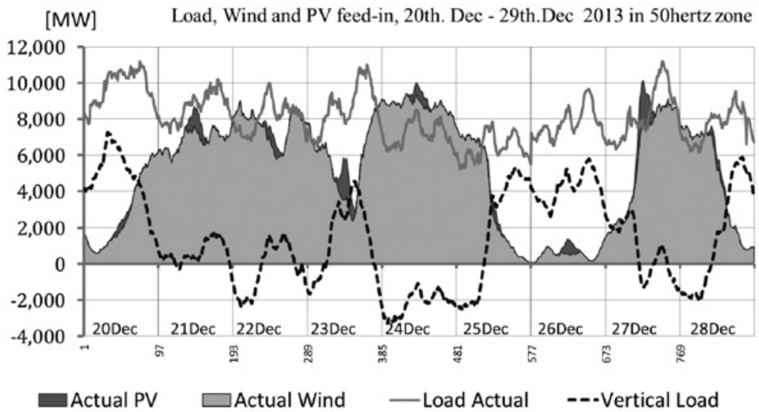

Fig. 3. Vertical grid load and high feed-in from wind energy (20–28 Dec. 2013, 50Hertz zone)

Source: Calculated from 50Hertz grid data

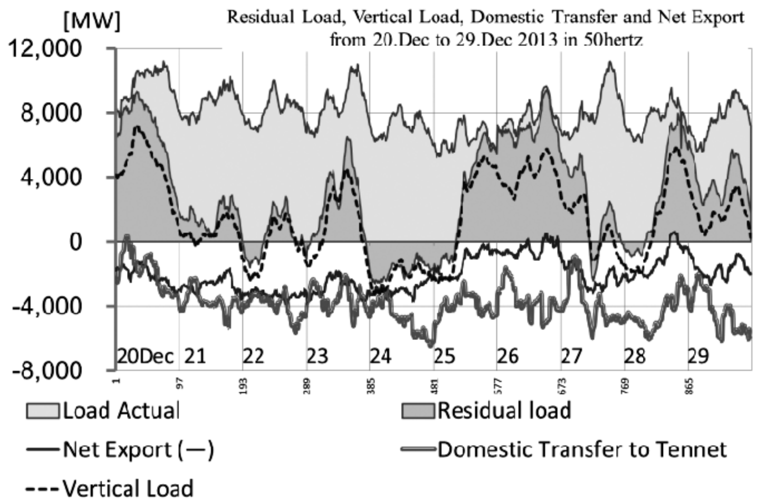

Fig. 4. Vertical grid load, export and transmission to the TenneT zone (20–29 Dec. 2013, 50Hertz zone)

Source: Calculated from 50Hertz grid data

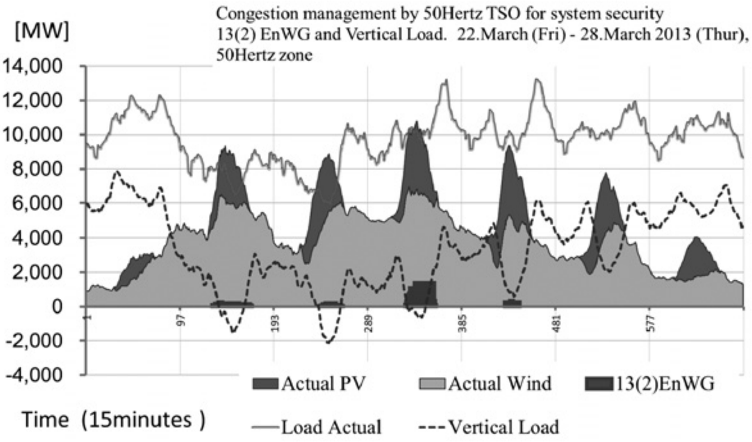

Fig. 5. Grid situation of high wind and PV feed-in, low load, vertical load and curtailment according to Section 13(2)-EnWG (German Energy Indestry Act) (22–28 March, 2013, 50Hertz zone).

Source: Calculated from 50Hertz grid data

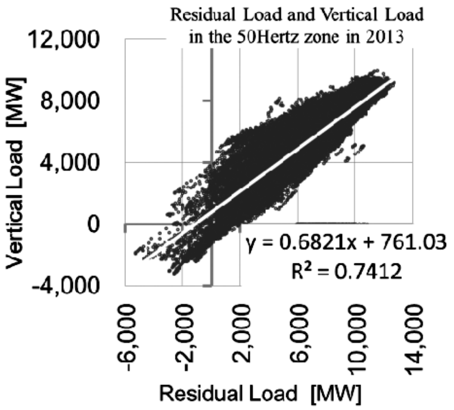

Fig. 6. Residual load and VGL (50Hertz zone, 2013)

Source: Calculated from 50Hertz grid data

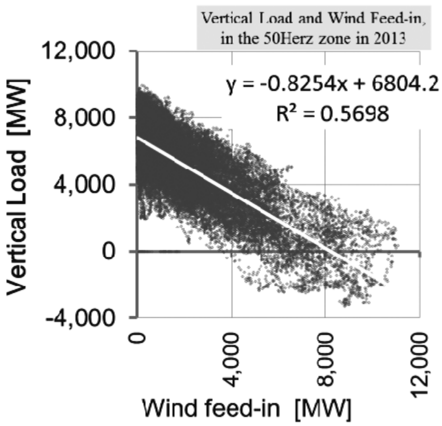

Fig. 7. Wind feed-in and VL (50Hertz zone, 2013)

Source: Calculated from 50Hertz grid data

at a time of low residual load. This is because as feed-in from wind and PV energy in the distribution grid (LV, MV. 110 kV) satisfies the load in each grid, feed-in from the 380 kV to 110 kV grid decreases. Electricity supplied to the 380 kV grid is mainly from brown coal, hard coal, and large hydro power plants in the 50Hertz zone. There is no nuclear power plant in this zone. There is a clear correlation of the residual load and VGL in the 50Hertz zone (Fig. 6). When wind feed-in is high, VGL dereases, and the amount of wind feed-in mainly determines the VGL in the 50Hertz zone (Fig. 7).

1.4 Reverse power flow and use of domestic tie-line transmission

At a time of very high wind and PV feed-in, the VGL in the 50Hertz zone becomes negative at almost all 380kV/110kV transformer substations, except in large cities such as Berlin and Hamburg. Excess electricity in the 110kV grid is transmitted to the upstream 380 kV grid as reverse power flow and to the neighbouring TenneT zone and international zones (Denmark, Poland, and Czech Republic). The capacity for domestic tie-line trasnmission from the 50Hertz zone to the TenneT zone totals around 5000 MW under stable conditions.[9] On the other hand, the capacity allocation for cross-border congestion management in the 50Hertz zone is around 2000 MW (from 50Hertz) with four cross-border connection hubs.

The amount of domestic tie-line transmission from the 50Hertz zone to the TenneT zone is estimated using Equation (2).

$$Tr\text{-}TenneT = (G - L) - Exp \qquad (2)$$

where *Tr-TenneT* is the transmission from the 50Hertz zone to the TenneT zone [MW], *G* is the *g*enerated amount in the control zone, *L* is the control area load [MW], and *Exp* is the net export from the control zone [MW].

Correlations of wind feed-in with domestic tie-line transmission from the 50Hertz zone to the TenneT zone (Fig. 8) and with net export (Fig. 9) are similar. The amount of domestic tie-line trasnmission reached its maximum limit of capacity (Fig. 8) and the net export reached its maximum trasnmission limit (Fig. 9).

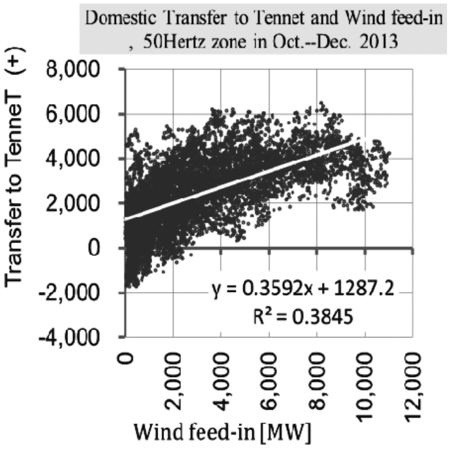

Fig. 8. Wind feed-in and transmission to TenneT zone (Oct. – Dec. 2013, 50Hertz zone)

Source: Calculated from 50Hertz grid data

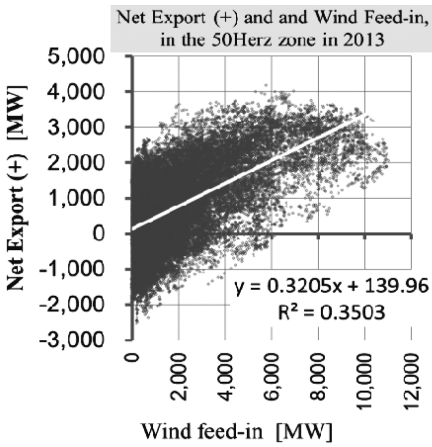

Fig. 9. Wind feed-in and net export in the (50Hertz zone, 2013)

Source: Calculated from 50Hertz grid data

1.5 Tie-line transmission to the TenneT zone and wind feed-in

In a high wind feed-in situation, 50Hertz transmission uses the following three routes to transport excess electricity from wind energy to the TenneT zone: (a) No. 413, No. 414 (Remptendorf-Redwiz), (b) No. 449 (Vieselbach-Mecklar), No. 450 (Eisenach-Mecklar), and (c) No. 491, No. 492 (Wolmirstedt-Helmstedt). This is because a large capacity of the wind energy systems is located in northern areas in the 50Hertz zone.

The grid loads of transmission lines at No. 413, No. 414, No. 449, and No. 450 between 50Hertz and TenneT are shown in Figs. 10(a) and 10(b). Wind and PV feed-in and TSO intervention for system security under Section 13(1)-EnWG and 13(2)-EnWG (German Energy Industry Act) and Section 11-EEG are shown in Fig. 10(c). The amount of power regulated under Section 13(1)-EnWG mainly corresponds to redispatch from conventional power plants. The amount of power regulated under Section 13(2)-EnWG in conjunction with Section 11-EEG is mainly curtailment (feed-in management) of RES electricity.

The solid and dotted lines in Fig. 10(a–c) show 50% and 70% capacity use, which means the grid loads were 50% and 70% of the transmission capacity of each line, respectively. A proviso is that the real transmission capacity can vary according to real-time grid situations. The lines for 50% and 70% capacity use in this paper only indicate the minimum value [MW] for each line in the year 2012. According to an explanation given by 50Hertz Transmission, grid use at less than 50% capacity has no problems in a case of line failure. However, a capacity ≥ 50% to ≤ 70% is close to the limit if line failure occurs. If the capacity use is > 70%, it is at the limit in a case of line failure.[10]

The 50Hertz zone integrates a large capacity of wind and PV energy, in addition to 10 GW for brown coal plants. Therefore, the 50Hertz zone often has excess electricity transmission to the TenneT zone and to cross-border transmission, except at a time of very low wind feed-in, although the grid load in Fig. 10 does not indicate the direction of electricity flow from or to the 50Hertz zone.

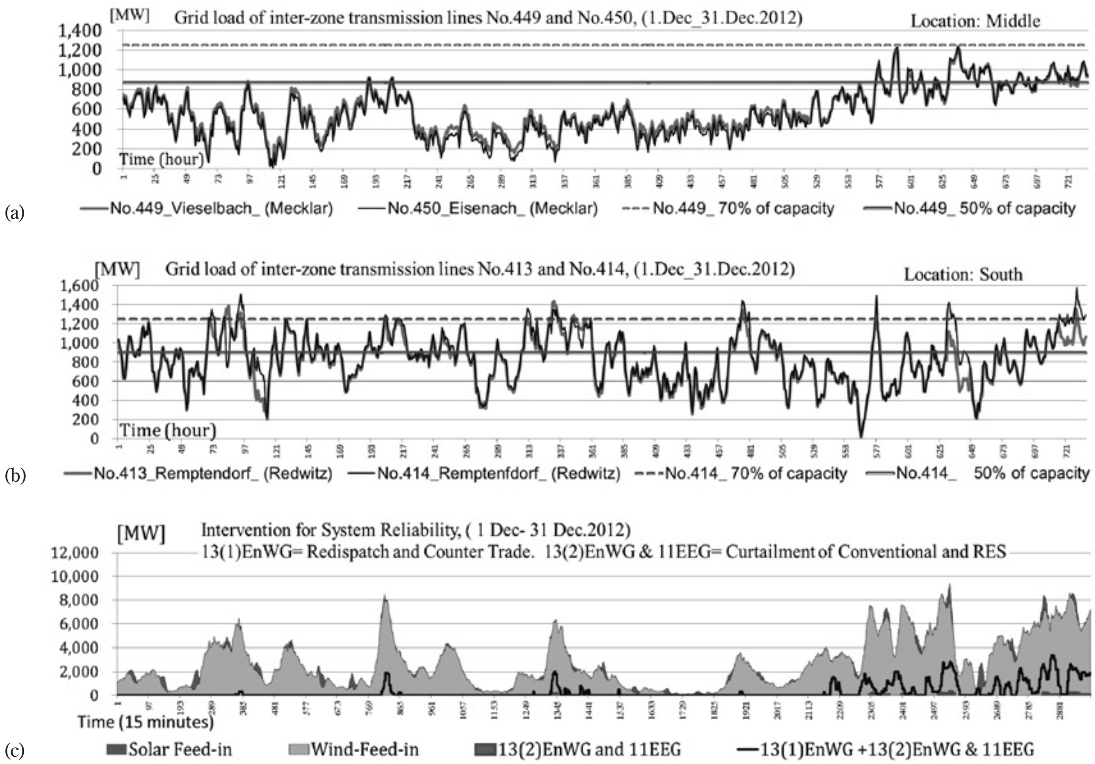

Fig. 10. Grid load of domestic tie-lines between 50Hertz and TenneT in Dec. 2012 by line in hourly values.

(a) Line No. 449, No. 450, (b) Line No. 413, No. 414, (c) wind and PV feed-in and TSO interventions for system security (redispatch and curtailments under s.13(1) and 13(2)EnWG (Energy Industry Act).

Source: Calculated from 50Hertz grid data

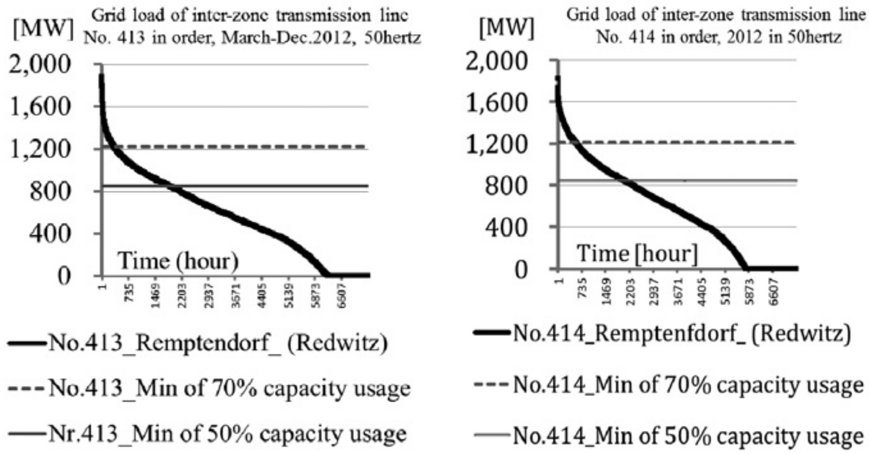

Fig. 11. Grid load of inter-zone transmission lines, No. 413 and No. 414, sorted in order of grid loads (March to Dec. 2012, 50Hertz zone).

Source: Calculated from data for 50Hertz grid load flow by line

The grid load at No. 413, No. 414, No. 449 and No. 450 often reached 50% of the transmission capacity. The grid load of No. 413 exceeded 50% capacity use in 1663 hours and No. 414 in 1620 hours of 7336 observed hours from 1st March to 31st Dec. 2012 (Fig. 11). Based on Figs. 8, 10 and 11, 50Hertz Transmission uses domestic tie-lines to the maximum limit to transmit excess electricity from wind and PV energy.

1.6 Bidirectional grid opertations to feed-in renewable electricity in Germany

A large negative VGL in the 50Hertz zone is caused by combined effects of feed-in from wind and PV energy (Fig. 12). High level capacity use in domestic tie-lines between 50Hertz and TenneT signifies that 50Hertz transmission system operators use domestic tie-lines fully to transmit excess electricity from wind and PV energy as a priority (Fig. 11). Reverse power flow occurs quite often from LV to MV grids and from

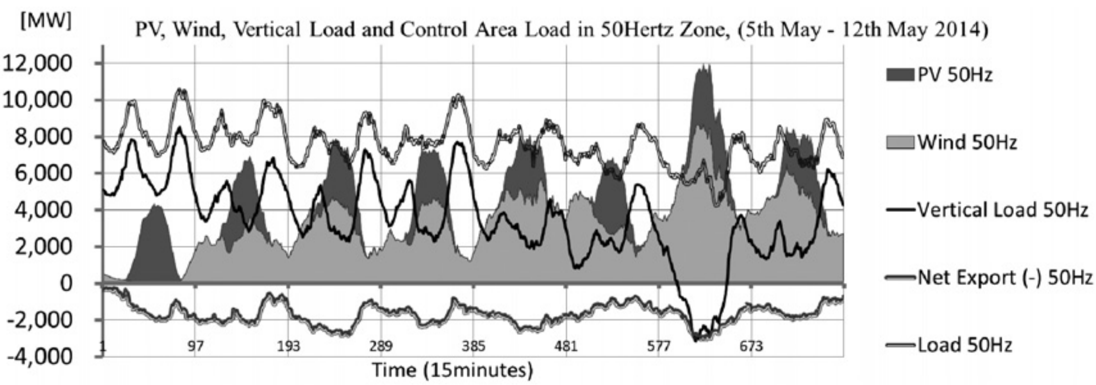

Fig. 12. Negative vertical grid load, wind and PV feed-in in the 50Hertz zone (5th–12th May 2014)

Source: Calculated from 50Hertz grid data

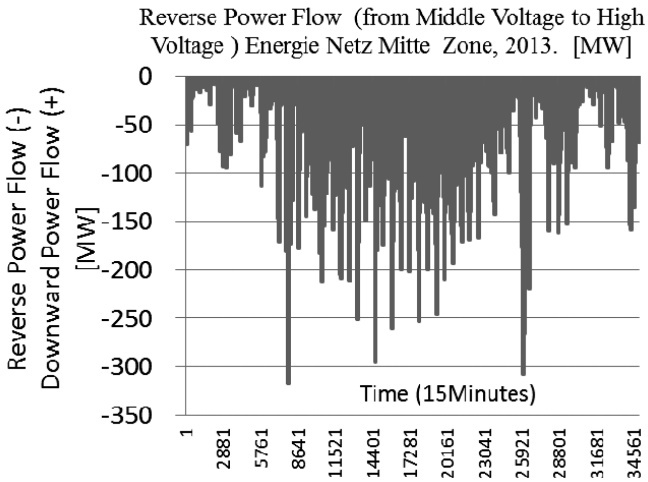

Fig. 13. Reverse power flow from middle volatage to high voltage grids (Energie Netz Mitte zone, measured at HV/MV transformer substations, 2013)

Source: Calculated from data from Energie Netz Mitte

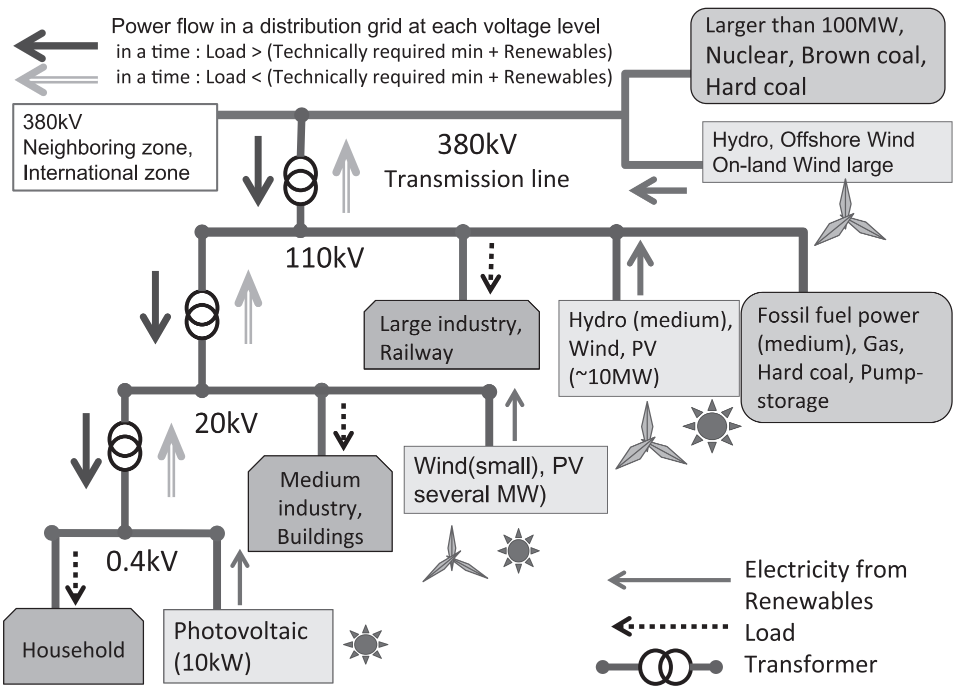

Fig. 14. Reverse power flow from renewable energy plants and voltage levels

Source: Based on interviews with TSOs and DSOs

MV to HV grids (Fig. 13). However, very few distribution grid operators (DSOs) disclose their reverse power flow (Rückspeisung) data in MV grids (20 kV) or LV grids (230 V and 400 V).

These data suggest that German grid operators carry out bidirectional and flexible grid operations to feed-in and transmit renewable energy electricity to upstream grids as a priority, if necessary.[11] A simplified structure of bidirectional grid operation and integrated voltage levels of renewable energy plants in Germany is shown in Fig. 14. This figure is based on several interviews with DSOs and TSOs.

2 Grid integration rules to enable bidirectional grid operations in Germany

The key rules for grid connection, purchase and transmission of renewable electricity and bidirectional grid operations under the EEG (2014 version) are summarized in this section. The EEG requires German grid operators to immediately and even physically, as a priority, purchase, transmit and distribute all of the electricity produced from renewable energy sources or from mine gas (section 11(1)-EEG). The duties of priority purchase, transmission and distribution are imposed on grid operators who are directly connected to renewable power plants and on upstream TSOs connected with renewable plants indirectly (section 11(5)1-EEG). These definitions require upstream TSOs to transmit electricity from renewable energy physically as a priority. This enables reverse power flow of excess electricity from renewable energy from the lower voltage grid to the higher voltage grid.

The EEG requires that German grid operators immediately optimize, reinforce and expand their networks with the available technology to ensure purchase, transmission and distribution of electricity from renewable energy (section 12(1)-EEG). The duty of grid reinforcement is even imposed on upstream grid operators up to a voltage level of 110 kV, even if renewable power plants are not directly connected with them (section 12(1)-EEG). Grid operators are obliged to provide grid connections to renewable power plants, even when purchase of renewable electricity is only possible by optimizing, reinforcing and expanding the grid (section 8(4)-EEG).

It should be noted that, according to the EEG, even upstream grid operators are obliged to carry out grid reinforcement. Hosting capacity increase and optimization of voltage control in the distribution grid (LV, MV and 110 kV grids) are essential to enable reverse power flow from wind and PV feed-in in lower voltage grids. This is because reverse power flow from excess electricity from wind and PV systems often causes voltage rises in distribution grids and transformers, especially at MV/LV and HV/MV transformers in local distribution grids.[12] Therefore, this mandatory capacity expansion imposed on grid operators, including upstream grids, is important to achieve reverse power flow from wind and PV energy systems in distribution grids.

The operator can bring the compensation cost for feed-in management (curtailment) into the calculation of grid charges. However, the grid operator bears the compensation costs of feed-in management, if the operator did not exhaust all options for optimizing, reinforcing, and expanding the grid (section 15(2)-EEG). These strict legal definitions make German grid operators reinforce the grid system to ensure purchase and transmission of renewable electricity. These definitions are the legal basis of enabling reverse power flow of renewable electricity and bidirectional grid operations in Germany.

3 Grid integration policies for wind and PV energy in Japan

The structure of the power system in Japan and grid integration policies for wind and PV energies under the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities (hereinafter, the Renewable Energy Act) are summarized in this section.

First, it should be noted that in Japan the transmission grid systems have yet to be separated from generation businesses. The nine major generation companies (General Utility Companies; hereinafter, the utility companies) own and operate the grid systems in their control zones. These nine companies are 'vertically integrated' power companies that operate all aspects from generation, transmission and distribution to retail of electricity (Fig. 15). These utility companies own 90% of the total generation capacity in Japan, including nuclear power plants (Fig. 16).

There are no legal definitions concerning priority connection and purchase of renewable electricity under the Renewable Energy Act. There is a proviso that when there is a risk to stable supply and grid reliability, the utility companies can reject a connection request from renewable operators (Article 5, paragraph 1, (2)-Renewable Energy Act). Six of the nine utility companies set a capacity restriction on PV and wind energy integration in each control zone (Figs. 17 and 18). There are no legal definitions of the 'priority connection' and 'priority transmission' of renewable electricity under the act. The six utility companies in Fig. 18 are allowed to set curtailment (output reduction) 'without compensation' to PV operators when integration of PV capacity in each control zone exceeds the restriction amount (Article 6, paragraph 7. Enforcement Regulations in the Renewable Energy Act).[13]

The Renewable Energy Act does not obligate utility companies to expand and reinforce the grid system to accommodate renewable energy plants. To increase integration of wind and PV systems, suitable capacity expansion and reinforcement of low voltage grids (0.2 kV), 6.6 kV grids and 66 kV grids are urgently needed, for the following reasons. The voltage levels in the Japanese grid system are 500, 275, 154, 66, 22 and 6.6 kV and 100 and 200 V (with some regional variations in control zones). The inter-zone tie-lines are mainly at 500 kV grids. Nuclear and large fossil fuel plants are connected to 500 kV grids. Hard coal generators and large hydro power generators are connected to 500 kV, 275 kV or 154 kV grids. In contrast, many wind energy systems are interconnected with 66 kV or 154 kV grids. Many PV systems are connected to low voltage, 6.6 kV and 66 kV grids. Therefore, to accomodate wind and PV systems, it is necessary to expand and reinforce low voltage (0.2 kV), 6.6 kV, 66 kV and 154 kV grids.

When wind and PV systems are integrated into the grid on a large scale and in a period of high feed-in from wind and PV energies, excess electricity in each trasnformer substation will cause reverse power flow. This flow will cause voltage increases at transformers and distribution grids, especially in the low voltage and 6.6 kV grids. Therefore, both grid capacity and transformer capacity must be sufficiently expanded and reinforced. Both-direction protections systems and voltage control equipment must be optimized to enable reverse power flow and upstream trasnmission with control of voltage levels in a permissible range. In addition, the regulatory framework in Japan requires utility companies to be obliged to expand and reinforce their grids at their own expense, including upstream voltage grids such as the 66 kV and 154 kV grids, if it is indeed necessary to accomodate the renewable energy plants.

To enable reverse power flow at transformer substations in the 6.6 kV and 66 kV grids, upstream transmission is essential. However, the Renewable Energy Act does not oblige the utility companies to prioritize transmission of renewable electricity to upstream grids.

Wind and PV system operators are strictly limited concerning use of inter-zone tie-lines under the rules of OCCTO (Organization for Cross-regional Coordination of Transmission Operators, Japan). Renewable energy operators are required to use batteries, electricity storage measures or combination of other electricity sources to stabilize feed-in from wind and PV systems[14].

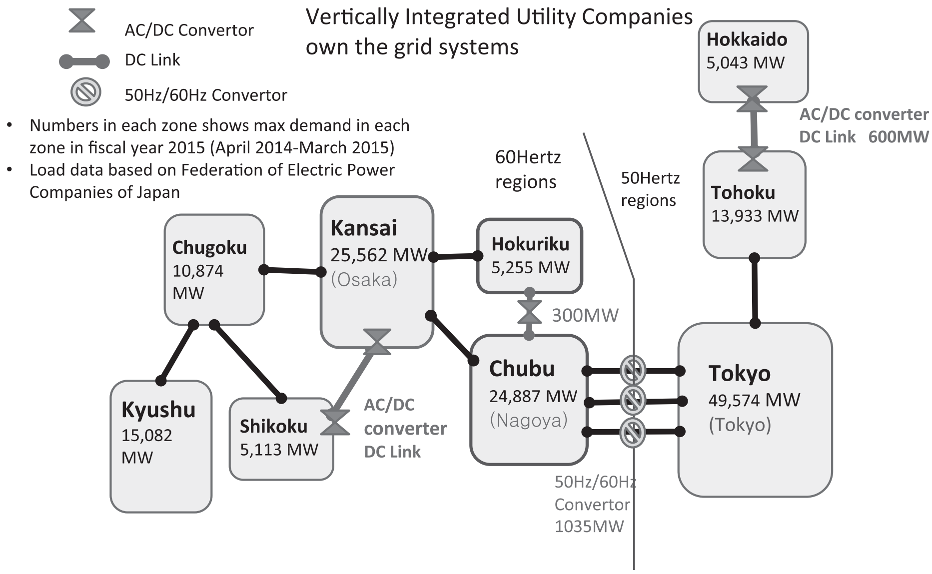

Fig. 15. Grid structure and inter-zone tie lines in Japan

Source: Sammarized from the Interim Report of the Committee on the Master Plan for Reinforcement of Inter-Zone Tie-Lines (Power System Reform Committee, Ministry of Economy, Trade and Industry), 2012. Lood data based on the Federation of Electric Power Companies of Japan.

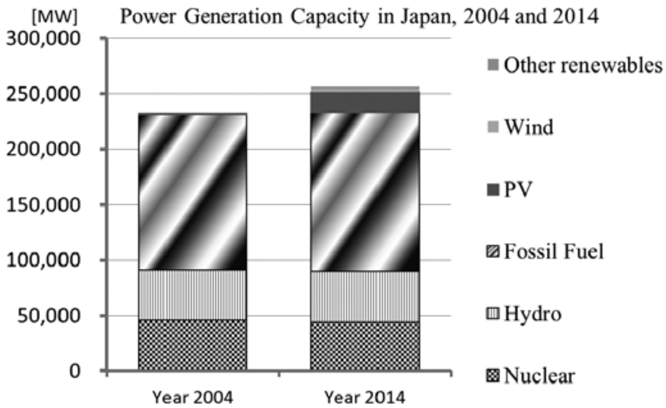

Fig. 16. Generation capacity in Japan in 2004 and 2014

Source: Calculated from power generation statistics from METI, feed-in tariff scheme data disclosure from METI, and Trends in Photovoltaic Applications from IEA-PVPS

In a time of curtailment (suppression of output from generators), renewable electricity has a priority only over fossil fuel plants. However, nuclear electricity always has the first priority over all other electricity to feed-in to trasnmission grids in each zone (under the Renewable Energy Act)[15] and to inter-zone tie-lines (under the OCCTO Network Code). This code states that "long-term cost recovery generation" has the first priority in transmission to inter-zone lines. The network code defines nuclear energy as "long-term cost recovery generation".[16]

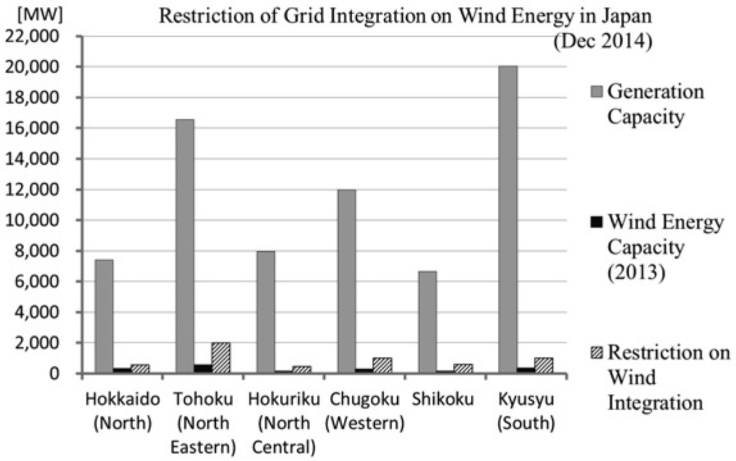

Fig. 17. Capacity restrictions on wind energy integration by major utility companies

Source: Data from METI New Energy Subcommittee, Federation of Electric Power Companies Japan.

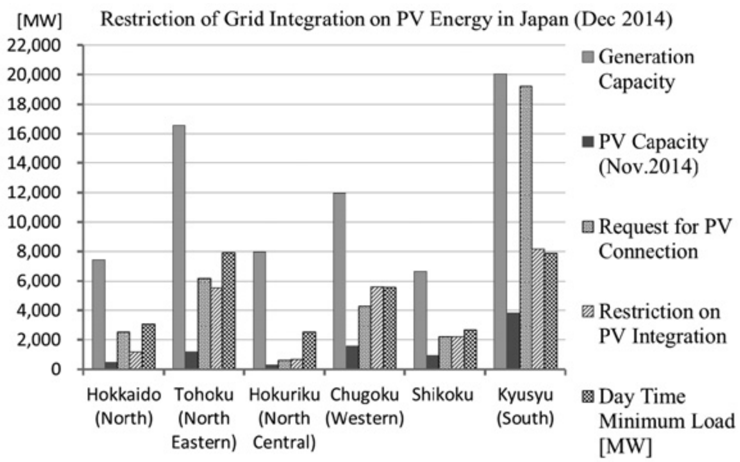

Fig. 18. Capacity restrictions on PV energy integration, requests for connection, and installed capacity

Source: Data from METI New Energy Subcommittee, Federation of Electric Power Companies Japan.

According to the Implementing Regulations in the Renewable Energy Act (hereinafter "Implementing Regulations"), when feed-in from renewable energy generators exceeds demand in each control zone, utility companies can impose curtailments (suppression) of output on renewable electricity. Utility companies can escape from payment of compensation for curtailment for up to 360 hours a year for PV systems and 720 hours a year for wind energy systems.[17] In addition, the regulation exempts the following 'designated utility companies' from the payment of compensation without limitation of hours: Hokkaido, Tohoku, Hokuriku, Shikoku, Chugoku and Kyushu utility companies for PV systems, and Hokkaido and Tohoku utility companies for wind energy systems.[18]

4 Conclusions: Bidirectional grid operation in Germany, unidirectional grid operation in Japan

Grid data in Germany show that German grid operators flexibly transmit and distribute electricity in a bidirectional way, depending on the power output from renewable electricity. Grid operators prioritize purchase of renewable electricity and transmit it to the upstream grid as necessary. Excess electricity from wind and PV systems is even physically transmitted to the upstream grid and to neighboring zones as a priority. German renewable energy law obligates grid operators to expand and develop grid capacity “without delay” to accommodate renewable electricity. This legal framework has enabled bidirectional grid operations.

In contrast, grid operation in Japan is unidirectional and has a downward power flow based on supply from nuclear power and large-scale coal power plants. Nuclear electricity has the first priority over all other types of electricity to be transmitted downward from 500 kV grids to lowest voltage grids and inter-zone tie lines. The utility companies give renewable energy systems very limited access to the grid, and renewable electricity has no legal definition in regard to upstream transmission. Because the Renewable Energy Act in Japan does not oblige utility companies to expand their grid capacity, there are few opportunities for renewable energy sources to penetrate into the grid system in Japan.

The following reforms are necessary in grid integration policies for wind and PV energy on a large scale in Japan. First, generation businesses must be legally separated from grid operation businesses (not only operation of inter-zone tie lines, but also transmission and distribution grids in each zone). Second, utility companies must be obliged to connect renewable energy sources to the grid as a priority over all other energy sources. As long as nuclear power plants supply base power as the first priority, wind and PV electricity cannot penetrate into the electricity supply on a large scale. Third, utility companies must be obliged to expand and reinforce their grids, including upstream grid systems, in a reasonable period of time to ensure purchase of renewable electricity, even if grid expansion and reinforcement are necessary to build a new connection with a renewable power plant. In particular, grid expansion and reinforcement for 6.6 kV, 66 kV and 154 kV grids are essential to ensure wind and PV energy integration. Fourth, utility companies must be obliged to transmit electricity from renewables to upstream grids physically as a priority if this is necessary. Rules for upstream transmission and grid reinforcement of upstream grids must be jointly imposed on utility companies. Capacity expansion of grids is important for utility companies, both to enable reverse power flow from excess electricity of lower voltage grids, and to control voltage levels in a permissible range according to grid technical codes. Capacity expansion is urgently needed for lower voltage grids with which renewable energies are interconnected, and for upstream grids. Fifth, the capacity restriction on grid integration of PV and wind energy must be abolished. Sixth, compensation must be paid for renewable energy operators when curtailment is set on renewable electricity in each zone.

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Notes

1 Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG, 2014) .

2 Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG, 2012).

3 The voltage levels in the German power system are super high voltage (SHV) for transmission grids at 380 kV or 220 kV, high voltage (HV) for distribution grids at 110 kV, medium voltage (MV) for local distribution grids at 20 kV (and 35kV in some regions, since there are regional differences in MV levels), and low voltage (LV) for local distribution grids at 400 V and 230 V, mainly for small-scale consumers.

4 50Hertz: Vertical grid load. available from http://www.50hertz.com/de/Kennzahlen/Vertikale-Netzlast

5 Data used in this study: (a) 50Hertz zone in 2013: Generation ouput, Vertical grid load, Control area load, Wind feed-in, PV feed-in, Maßnahmen nach §13.1 EnWG, §13.2 EnWG, Load flows cross-border, in MW/15 min. (b) 50Hertz zone: Grid load by line, hourly data in MW.

6 Based on interviews with Fraunfoher IWES (in Aug. 2015), Hanse Werke (in May. 2014), Stromnetz Hamburg (in Sep. 2015), 50Hertz, and Amprion (in Sep. 2014).

7 Stetz, T., Kraiczy, M., et. al. Technical and economical assessment of voltage control strategies in distribution grids. Prog. Photovolt. Res. Appl. (2013), DOI: 10.1002/pip.2331

8 50Hertz GmbH: available from http://www.50hertz.com/de/EEG/Veroeffentlichung-EEG-Daten.

9 Information from 50Hertz GmbH. Actual transmission capacity can change according to grid conditions.

10 50Hertz: Explanation on grid load and capacity usage: http://www.50hertz.com/en/Grid-Data/Grid-load

11 Stetz, T., Kraiczy, M. Diwold, K. et al. Transition from unidirectional to bidirectional distribution grids. IEA-PVPS, task 14 (2014).

12 Concerning the voltage rise caused by high PV penetration in the local distribution grid, the necessary grid expansion measures are explained in the following papers: Stetz, T., Kraiczy, M. Diwold, K. Country-specific analysis, Germany. IEA-PVPS Task 14, Subtask 2: *High Penetrations of Photovoltaic Systems in Distribution Grids* (2014). Stetz, T., Kraiczy M., et. al., Technical and economical assessment of voltage control strategies in distribution grids. Prog. Photovolt. Res. Appl. (2013), DOI: 10.1002/pip.2331.

13 Concerning the Designated Utility Companies shown in Fig.18 and the Okinawa Power Company. Implementing Regulations for the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electnicity Utilities.

14 OCCTO: Network Codes of the Organization for Cross-regional Coordination of Transmission Operators, Japan. Article 202, Paragraph 3-(i), (amended April 2016).

15 Implementing Regulations for the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities. Article 6, Paragraph 1, Point 3-(1).

16 OCCTO, Network Codes of the Organization for Cross-Regional Coordination of Transmission Operators, Japan. Article 202, Paragraph 1-(vi), (vii), Article 210, Paragraph 1 (amended April 2016).

17 Implementing Regulations for the Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities. Article 6, Paragraph 1, Point 3-(1).

18 Implementing Regulations. Article 6, Paragraph 1, Point 7.

風力・太陽光発電の配電網への系統連系，双方向潮流対応の系統運用について

―日本とドイツの比較分析―

竹濱　朝美[i]

本稿は，風力・太陽光発電システムを配電網に大量連系するための規則と系統運用について，日本とドイツを比較した。特に，配電網から送電網への逆潮流に焦点を当てて分析した。

ドイツでは，系統運用者（送電会社および配電会社）は，風力・太陽光発電からの電力を，出力状況に応じて柔軟に，低圧および中圧系統から高圧系統へ，さらには，特別高圧系統に逆潮流させる双方向潮流対応の系統運用を行っている。ドイツの系統運用者は，再生可能エネルギー電力を最優先で給電し，かつ，上位電圧系統に優先送電する義務を負う。系統運用者は，風力・太陽光発電からの給電が配電網内の需要を上回る場合，上位電圧系統（送電網）に，物理的にも電力を上流送電し，他の送電区域に地域間送電する。

これに対して日本では，長期固定電源（原子力，大型水力，地熱発電）の電力を500kV 送電系統から低圧系統に，下方一方向潮流で配電する系統運用である。日本では，原子力発電からの電力を他の全ての電源に優先して，給電・配電する。地域間送電線の使用においても，日本では，原子力発電の電力を最優先で送電する規則となっている。

日本では，再生可能エネルギーからの電力を，下位電圧系統から上位電圧系統へ優先的に上流送電（逆潮流）させる規則は整備されてない。日本の再エネ特措法は，一般電気事業者に電力網の系統容量の拡張を義務付けていないため，系統容量の拡張が不十分なままで，再生可能エネルギー電源の連系を制約している。再生可能エネルギー電源を大量に電力網に連系させるには，一般電気事業者に対して，再生可能エネルギー電力の上流送電と電力網の系統増強を義務付ける必要がある。

キーワード：風力発電，太陽光発電，系統連系，逆潮流，上流送電，双方向潮流対応，垂直負荷，優先送電，系統増強

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