Development of Model for Optimal Operation of Power Systems with Large-Scale Integration of Solar Power Generation in Kyushu Region

Ryuji Matsuhashi

Abstract—**Japan has a national goal of reducing greenhouse gas emissions in 2030 to 26% below 2013 levels. Energy efficiency improvement and low carbon power generation technologies will provide the primary source of greenhouse gas reductions. On the other hand, the feed-in tariff (FIT) program that began in 2013 triggered explosive growth of renewable power sources, particularly photovoltaic generations because of its short lead-time and high tariff level.**

However, mass introduction of renewable power sources causes serious instability issues in power systems such as impacts to the transient stability in power systems. Since it could lead to a massive blackout in the worst case, the power system must be carefully managed to maintain the transient stability. Another issue is that outputs of photovoltaic and wind power generations fluctuate, causing frequency instability. These fluctuations must be absorbed so as to keep stable frequency in each power system, which is called LFC, load frequency control.

In this article, we introduced the constraints on the transient stability in the power generation mix in Kyushu region, taking massive installation of photovoltaic systems into consideration. Next we described on our mathematical model of economic load dispatch for Kyusyu district, taking transient stability into consideration. Computed results quantified suppression of photovoltaic generation in each primary grid, and indicated that the suppression concentrated on specific power transmission lines. Furthermore we investigated the way to efficiently utilize the suppressed power, including estimation of economic feasibility to produce hydrogen utilizing electrolysis.

Index Terms—**Low carbon power generation technologies, solar power generation, output suppression, economic feasibility of producing hydrogen, electrolysis.**

I. Introduction

Paris agreements were adopted in COP21, which took place from 30th of November to 13th of December in 2015. Paris agreements are new international frameworks to reduce greenhouse gas emissions from 2020. They are the equitable agreements, in which all nations participate in voluntary reduction of greenhouse gas emissions for the first time in history. Taking Paris agreement into consideration, Abe, Japanese prime minister, determined the plan to mitigate global warming, in which we shall promote total policy packages to reduce greenhouse gas emissions by 26.0% in 2030 compared with to 2013 [1].

METI, Ministry of Economy, Trade and Industry in Japan issued the long-term outlook for energy supply and demand in August, 2015, which is consistent with the above plan to mitigate global warming. METI focused on the significance of power supply constitution and energy conservation in the outlook [2].

In particular, the share of renewable power sources increased up to 22% or to 24%, in which the share of solar power generation is around 7%. Thus the solar power generation is placed as a renewable power source next to the hydraulic power generation.

In Japan, the feed-in tariff (FIT) program, that began in 2013, triggered explosive growth of renewable power sources, particularly photovoltaic systems because of its short lead-time and high tariff level.

However, mass introduction of renewable power sources is causing serious instability issues; solar and wind power generation output fluctuates, causing power system instability, and these fluctuations must be absorbed.

Although we constantly need to balance supply and demand in power systems, output from solar and wind power generation is fluctuated depending on weather conditions. Thus it is difficult to balance supply and demand of power in mass introduction of solar and wind power generation.

In order to solve this issue, we have to establish a novel power operation scheme, in which adjusting ability of each power generation facility is taken into consideration. It is also necessary to transform the energy into hydrogen using electrolysis, which is suppressed due to the constraints of the power system. Komiyama *et al.* studied how to suppress the output of PV, taking adjusting ability of existing power generation facilities [3].

Furthermore, increase of PV capacities influences the transient stability of power systems, since PV does not inertia, which synchronous generators have. In other words, decrease of the synchronous generators due to mass introduction of PV leads to the shortening of the critical clearing time of the power system. Therefore it is necessary to maintain the certain share of synchronous generators such as fossil-fired power plants. In this context, we have to take reduction of CO_2 into consideration as well as the stability of power systems.

Several articles deal with analyses on transient stability of power systems including photovoltaics [4]-[9].

However there are almost no articles dealing with mathematical models, which identify least cost mix of power generation technologies including the constraints on CO_2 emissions and on the transient stability of power systems including photovoltaics. In this study, I developed the novel mathematical model of power systems with constraints on

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CO_2 emissions and on the transient stability, by which active power of photovoltaics is restricted in individual transmission lines. [10] I also took hydrogen production from the restricted active power into consideration. These are principal originalities of this article.

In the power system of Kyushu area present capacity of PV is 6 GW and accredited capacity is more than 18GW, although the present demand in peak period is just 15GW. [11] Thus the capacity of PV is beginning to influence the stability of the power system.

In this article, a novel mathematical model is developed on power system planning, including constraints of power by PV based on evaluating transient stability. Then we analyze relationships between output suppression and hydrogen utilization. As concrete process of developing the model, Kyushu region is divided into four areas based on the WEST30 generators model. [12] Then I develop the model of power system planning, including the constraint of active power by PV. This model determines the least cost mix of power systems, taking both capital expenditure and operation costs into consideration.

II. Methodologies Adopted in This Article

A. Representation of the Power System in Kyushu Based on West30 Generators Model

The model of WEST30 by Japan Society of Electrical Engineering, is a model, in which power systems in western part of Japan is represented with by thirty generators and transforming network connecting them. In this article, we extract the power system of Kyushu region from the WEST30 model, based on the study. [12] Referring also to the information by Kyushu Electric Power Company, we assumed the power system in Kyushu is as shown in Fig. 1. The model of WEST30 was developed based on the power system before 2000, so that it does not necessarily coincide with the present system. The transmitting lines between Seburi and Nishi-kyushu substation was constructed after 2000, which is a significant difference. Therefore we modified the original WEST30 model, taking the above into consideration, as shown in Fig. 1.

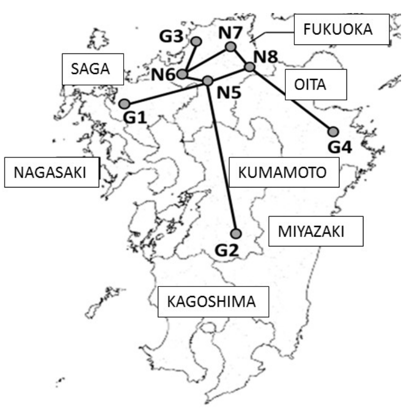

Fig. 1. The model of the power system in Kyushu based on the model of West30.

The generator G1 corresponds to Nagasaki and Saga prefectures. The generator G2 corresponds to Kumamoto, Miyazaki and Kagoshima prefectures. The generator G3 corresponds to Fukuoka prefecture, while the generator G4 corresponds to Oita prefecture. We set the capacities of the above generators based on the present values of individual areas. We name this as the model 1.

Fig. 2 depicts the system, which represents the model 1 with 8 nodes and 8 arches. The left one of the Fig. 2 simply shows the topologic structure of the model 1. The right one extracts node1, node2 and node5 and shows their structure for power transmission. Nodes 1 to 4 correspond to the generators 1 to 4, respectively. Node 5 corresponds to the Chuo substation. Node 6 corresponds to the Nishi-Kyushu substation. Node 7 corresponds to the Kita-kyushu substation. Node 8 corresponds to the Buzen substation. Nodes 1 to 4 are assumed to have electricity demands and PV, while Nodes 5 to 8 are assumed to have neither generators nor electricity demands.

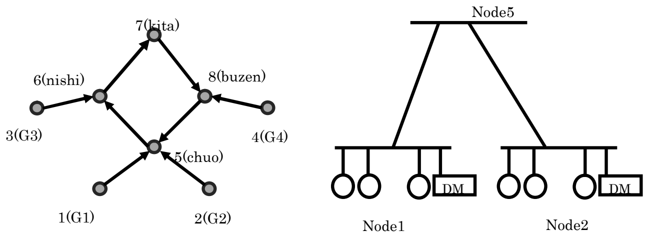

Fig. 2. Network and flow of the power system in Kyushu.

B. Data Settings in the Model Simulating Optimal Operation of Power Systems

Electricity demand is based on the actual data of the year 2013. [13] Power generation by PV is based on the article [13], which estimates it by regional solar radiation data. In the article [13], the authors estimated power generation by PV in the entire Kyushu region. In this article, we divide the power generation in the entire Kyushu into the four areas, Nodes 1 to 4, based on the information of regional PV installation. [11] Table I shows the estimated result on power generation by PV. We estimated wind power generation in the same way as in PV as shown in Table I.

Regarding data on power demand, we estimate them for each node based on the peak demand data of the WEST30 model. The estimated results are shown in Table I.

TABLE I: The Estimated Share of Each Node on the Capacity of the Renewable Power Sources and Power Demand

	G1	G2	G3	G4
PV	17%	45%	25%	13%
WG	32%	61%	4.5%	2.5%
Demand	46%	27%	9%	18%

Table II shows the present capacities of individual power generation technologies of G1, G2, G3 and G4 as described above. These data is based on the homepage of Kyushu Electric Power Company [14].

Adjustment ability of individual power generation technologies are assumed as in Table III based on the article [13]. On the other hand, the requirement of LFC, load frequency control for PV output is assumed in table IV based on the article [13]. Values in Table IV are rates of LFC requirement to PV outputs. The rate of LFC requirement of power demand is assumed to be 3% of total demand.

It is possible to estimate total LFC requirement and adjustment in each time period from the above values. Then when the total LFC requirement is higher than the total LFC adjustment ability, PV output is suppressed, so that the excessive amount of LFC requirement is zero.

TABLE II: THE ESTIMATED SHARE OF EACH NODE ON THE CAPACITY OF THE RENEWABLE POWER SOURCES AND POWER DEMAND

	Coal fired	Gas fired	Gas C. C.	Oil fired	Pumped Hydro
G1(GW)	0.700	0.000	0.000	0.875	0.600
G2(GW)	1.400	0.000	0.000	1.000	1.700
G3(GW)	0.735	1.800	0.000	0.735	0.000
G4(GW)	0.615	0.000	2.295	1.036	0.000

	Run-of-river type hydro	Stored type hydro	Nuclear power	Geo-thermal
G1(GW)	0.145	0.016	3.478	0.000
G2(GW)	1.449	1.407	1.780	0.006
G3(GW)	0.006	0.003	0.000	0.000
G4(GW)	0.041	0.044	0.000	0.152

TABLE III: ADJUSTMENT ABILITY OF INDIVIDUAL POWER GENERATION TECHNOLOGIES

(%)

Coal fired	Gas fired	Gas C. C.	Oil fired	Pumped Hydro
5.5	14.0	1.3	19.0	0.0

Run-of-river type hydro	Stored type hydro	Nuclear power	Geo- thermal
0.0	0.0	1.0	0.0

TABLE IV: RATE OF LFC REQUIREMENT OF PV TO TOTAL PV OUTPUT

January	February	March	April	May	June
0.120	0.159	0.152	0.111	0.120	0.078

July	August	September	October	November	December
0.117	0.109	0.070	0.094	0.125	0.119

In this article, output of wind power generation is taken into consideration. However electric energy generated by wind power generation is much less than by solar power generation, so that the influence of wind power generation to LFC, load frequency control, is very small. Therefore I do not deal with the influence in this article as our future work.

C. *Constraints and an Objective Function for the Power System Model*

This sector deals with constraints and an objective functions in the mathematical model for simulating power systems with minimum costs.

1) *Objective Function*

In this study, the power system is determined, so that the total cost consisting of fixed costs and variable costs.

$$\text{minimize TotalCost} = \sum_{i,g,h,d} \text{Cost}_{i,g,h,d}$$

2) *Constraints on Upper Limits of Output of Generators*

Each generator has its own upper limit of output, and it cannot exceed the limit.

3) *Constraints on changing rates of outputs within an hour*

The changing rates of outputs within an hour have upper and lower limits. The changing rates must be lower than the upper limits and higher than the lower limits.

4) *Constraints on securing of LFC adjustment capacity*

This is a constraint to secure LFC adjustment capacity, which is larger than LFC requirements in each time period.

5) *Constraints on coincidence of supply and demand taking network and flow of power systems*

In this study, we represent power systems in Kyushu with eight nodes and eight arcs. Then we determine power flow on each arc, so that supply and demand coincide on each node.

6) *Constraints on maintaining transient stability*

Active power flow by PV must be less than a certain ratio on each arc by these constraints. We set these constraints so as to maintain transient stability of the power systems. The upper limit of the ratio on active power flow of PV is determined by calculating the critical clearing time in each arc.

III. COMPUTED RESULTS OF THE MODEL SIMULATING OPTIMAL OPERATION OF POWER SYSTEMS

Fig. 3 shows the relationships between CO_2 emissions constraints and costs of power generation. As the constraints become 3 million ton-CO_2, the total cost of power generation increases up to 11.9 yen/kWh. This corresponds to cost escalation of 23% compared with no constraints on CO_2 emissions.

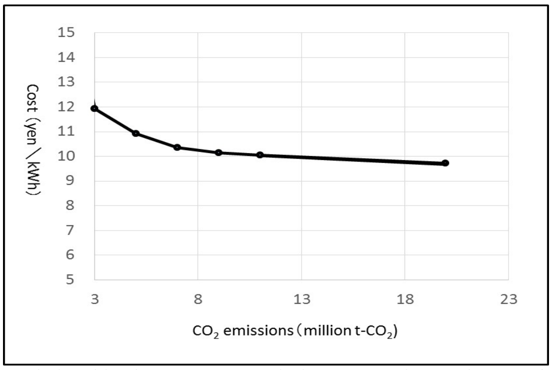

Fig. 3. Relationships between CO_2 emissions constraints and costs of power generation.

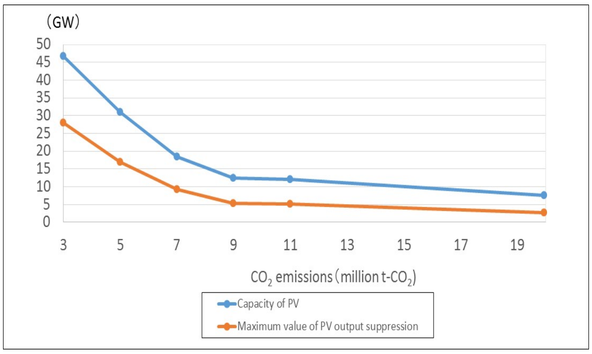

Fig. 4. Relationships between CO_2 emissions constraints, PV capacities and suppression of PV output.

Then Fig. 4 shows that capacities of solar power generation systems increases as the constraints on CO_2 emissions become severer. At the same time, output suppression of solar power generation also increases. It is remarkable that solar power generation is introduced even in no restrictions on CO_2 emissions.

On the other hand, capacity of hydrogen storage sharply increases from the constraint around 5 million ton-CO_2 as shown in Fig. 5.

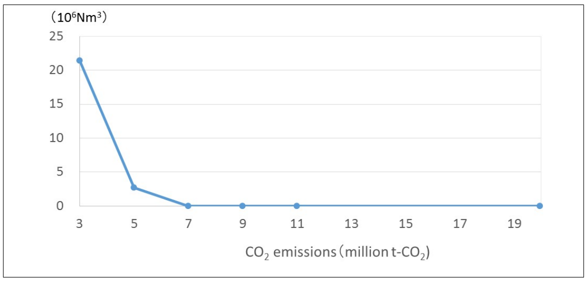

Fig. 5. Relationships between CO_2 emissions constraints and hydrogen storage capacities.

Fig. 6 and Fig. 7 below show the computed results of optimal power operation on a summer day and a winter day without constraints on CO_2 emissions. These results are consistent with simple economic principles, by which power generation technologies with low fuel costs take the base loads and those with high fuel costs take the middle and peak loads. In that sense, summer and winter patterns of operation have common characteristics.

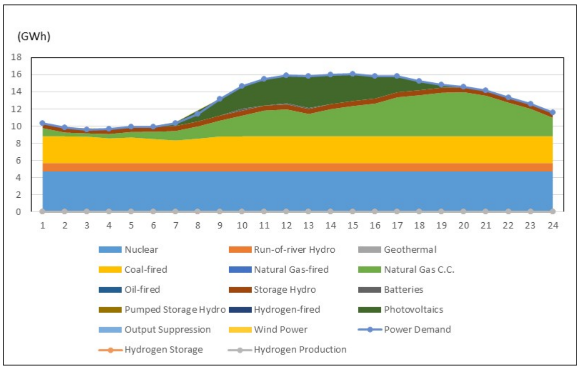

Fig. 6. Optimal power planning on August the first without CO_2 constraints.

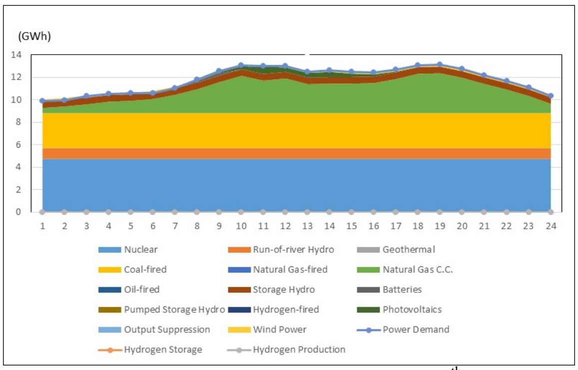

Fig. 7. Optimal power planning on December the 25th without CO_2 constraints.

On the other hand, the two figures below show the computed results of optimal power operation on the same summer day and the winter day with constraints on CO_2 emissions at 3 million ton-CO_2. These results are totally different from those without CO_2 constraints. At the summer day, output of solar power generation are suppressed, although it primarily takes the peak load. Then the suppressed electric energy leads to hydrogen production through electrolysis. As a result, capacity of hydrogen storage increases especially at the daytime as shown in the Fig. 8. While the capacity increases on the summer day, it decreases on the winter day as shown in the Fig. 9. Then power generation using the hydrogen storage take the load throughout the day. As a whole, structures of power supply are more complicated than those without CO_2 constraints.

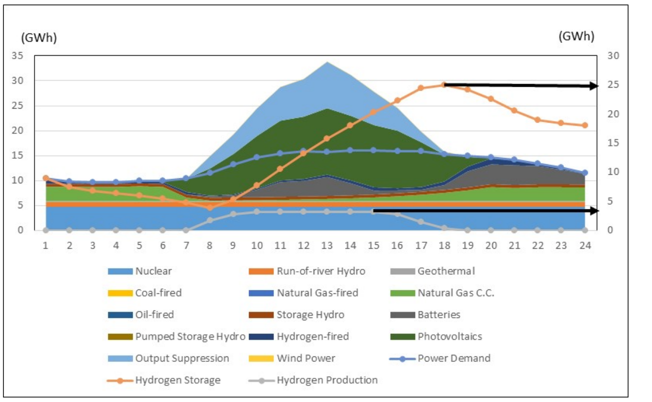

Fig. 8. Optimal power planning on August the first with CO_2 restrictions at 3 million t

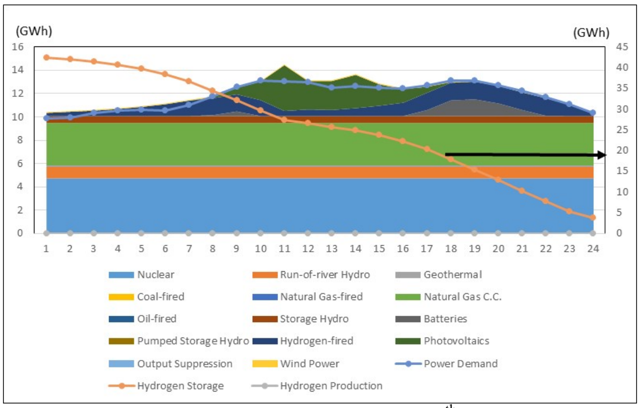

Fig. 9. Optimal power planning on December the 25th with CO_2 restrictions at 3 million t.

The Fig. 10 depicts the volume of stored hydrogen with the CO_2 constraints at 3 million ton throughout the year. Computed results imply that CO_2 emissions could be reduced to 3 million t when PVs were introduced by 47GW. It corresponds to 90.2% reduction compared with 30.5 million t in 2010. This means that combination of renewable energy and hydrogen power generation could be a promising option to reduce CO_2 emissions with maintaining stability in power systems.

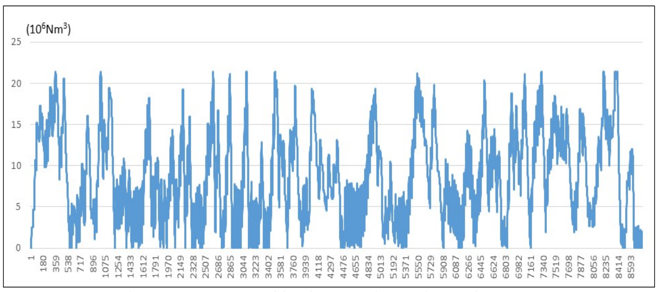

Fig. 10. Storage of hydrogen throughout the year.

There are also technological and economical barriers to realize the system combining renewable energy and hydrogen. In particular, we need large capacity of hydrogen storage of 21 million Nm^3, leading to economic burden. Thus the cost-down of hydrogen storage is a significant future development issue.

IV. Conclusion

1) This article deals with the network-flow model of the power system in Kyushu, representing it with 8 nodes and 8 arcs.
2) The following novel methodology is proposed to maintain stable management of power systems, taking explosive growth of solar power systems into consideration. That is, the network-flow model has upper limits on active power generated by the solar power systems in individual transmission lines so as to maintain transient stabilities of power systems.
3) The novel methodology is applied to the power system in Kyushu region and simulated the optimal operation of power systems. The computed results quantified suppression of electric energy generated by solar power systems, leading to hydrogen production through electrolysis.
4) Thus the combination of renewable energy and hydrogen power generation could be a promising option to reduce CO_2 emissions with maintaining stability in power systems.
5) Technological and economical barriers exist so as to realize the system combining renewable energy and hydrogen. In particular, reduction of hydrogen storage cost is one of the significant development issues.

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