SC C2

POWER SYSTEM OPERATION & CONTROL

10636

Development of New Integrated Stability Control System for Photovoltaics Introduction Expanding Grid Utilizing Artificial Intelligence

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Introduction

- The Nagano-region grid in Japan, which has a total length of about 300 km, comprises 275 kV and 500 kV transmission lines (Fig. 1).
- The grid has strict characteristics in respect of system stability, including normal voltage operation, transient voltage, and transient stability when a fault occurs.
- The integrated stability control (ISC) system, which achieves power system stabilizing control employing on-line information, was installed (Fig. 2).
- The power flow to the 500 kV bulk system is assumed to grow heavier and the system stability to become stricter due to the further introduction of photovoltaics (PVs).

Existing VQC and future problems

- The existing VQC of the ISC system controls the terminal voltages of the Joetsu thermal generators, SCs, ShRs, and 500/275 kV transformer taps in order to maintain bus voltages of 500 kV, 275 kV, 154 kV, and 77 kV classes within their target voltage range.
- The control method has three problems in Table I when power flow in the Nagano region becomes heavier due to the further introduction of PVs.

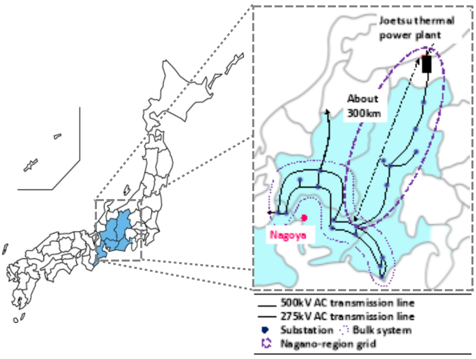


Fig. 1 Nagano-region grid in Japan.

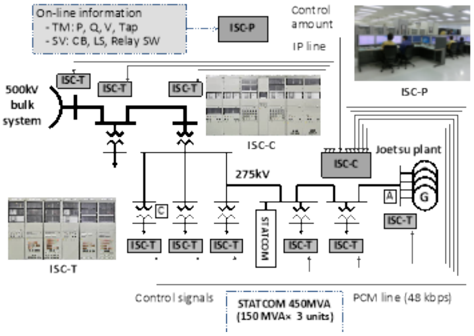


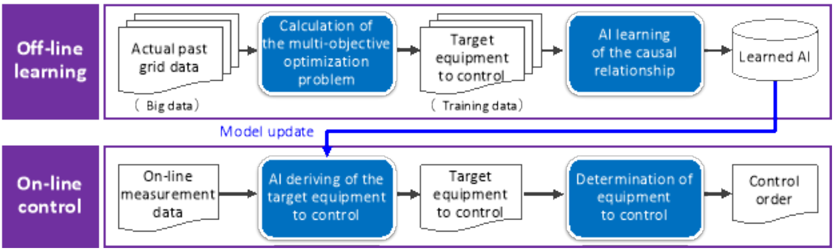
Fig. 2 System configuration of the ISC system.

Table I Future problems in the Nagano-region grid.

Problem	Detail
Severe over-voltage	• Reactive power loss increases when the power flow to the 500 kV bulk system becomes heavier, which leads to lower bus voltages of 500 kV or 275 kV classes. • The SCs connected to the grid increase in order to maintain bus voltages within their operational range. • As a result, the risk of over-voltage increases when a route cut-off fault occurs.
Frequent operations of LRT taps, SCs, and ShRs	• When outputs of PVs change steeply, LRT taps, SCs, and ShRs operate frequently when VQC is carried out in order to maintain bus voltages. • As a result, maintenance costs may rise.
Large amount of generator tripping	• Power flow to the 500 kV bulk system becomes heavier and thus transient stability worsens when a fault occurs. • In this condition, the amount of generator tripping will likely increase.

Overview of new VQC with AI

- The feature of the new VQC method is that AI is applied to solve each problem (Fig. 3).


Off-line learning

Actual past grid data (Big data) → Calculation of the multi-objective optimization problem → Target equipment to control (Training data) → AI learning of the causal relationship → Learned AI

Model update

On-line control

On-line measurement data → AI deriving of the target equipment to control → Target equipment to control → Determination of equipment to control → Control order

Fig. 3 Overview of the new VQC method with AI.

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VQC: Voltage and reactive power control, LRT: Load ratio control transformer, SC: Static condenser, ShR: Shunt reactor

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Off-line learning of new VQC

<Calculation of the multi-objective optimization problem>

- The target equipment to control is determined by solving the multi-objective optimization problem subject to the constraint conditions shown in Table II.
- The target equipment to control is derived by selecting equipment based on the sensitivity to the weighted value of objective functions E in order to minimize it.

$$E = \sum_{i=1}^{6} w_i f_i \,, \quad w_i: \text{weight}$$

- The sensitivity is calculated as the amount of change of the objective function's values by controlling SCs, ShRs at substations, and the terminal voltages of the Joetsu thermal generators.
- The number of operations of LRT taps, SCs, and ShRs has a trade-off relationship since SCs and ShRs should be operated in order to maintain bus voltages within the dead band of LRT taps to prevent LRT taps from operating.
- The new VQC method introduces a target range for bus voltages of 154 kV and 77 kV classes in the multi-objective optimization problem (No. 5 of Table II) to adjust the balance between the number of operations of LRT taps, SCs, and ShRs.

<AI learning of the causal relationship>

- The target equipment to control determined by the multi-objective optimization is used as training data for AI learning of the causal relationship.
- A multi-regression model is used as AI since the model can maintain necessary accuracy for on-line VQC and has high interpretability for the AI output compared to other AIs.

$$y = \sum_{i=1}^{n} a_i x_i + b$$

y: Number of SCs and ShRs connected to the grid, value of the terminal voltages of the Joetsu thermal generators.
x_i: Active power of transmission lines, and active power and reactive power of substation transformers

On-line control of new VQC

<Overview>

- The data on the target equipment to control is derived by inputting the on-line measurement data to the AI.
- The equipment to control is determined by using the data on the target equipment to control derived by the AI and on-line measurement data (Fig. 4).

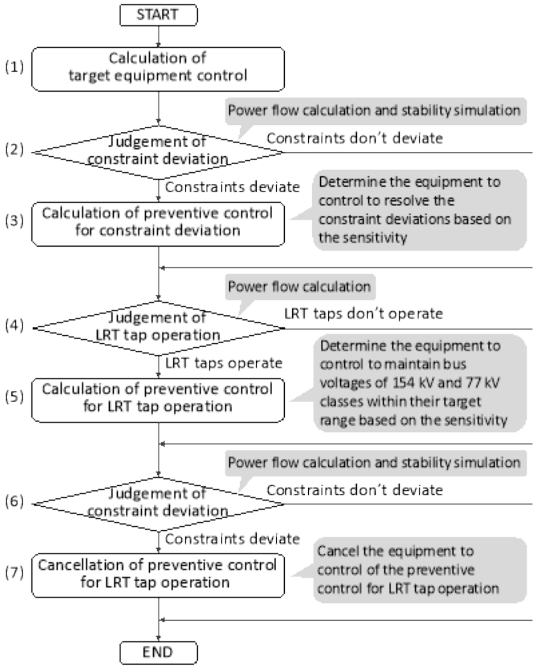

Fig. 4 Flowchart of determination of the equipment to control.

Table II Constraint conditions of the multi-objective optimization problem.

No.	Constraint condition	Objective function (f_i)	Calculation method
1	Prevent over-voltage in a route cut-off fault	Amount of voltage deviation from an over-voltage threshold	Stability simulation
2	Maintain steady-state stability	Time difference between out of step of generators and the end of stability simulation	Stability simulation
3	Maintain operating points of generators within their operational range	Amount of operating point deviation from its operational range	Power flow calculation
4	Maintain bus voltages of 500 kV, 275 kV, 154 kV, and 77 kV classes within their operational range	Amount of voltage deviation from its operational range	Power flow calculation
5	Maintain bus voltages of 154 kV and 77 kV classes within their target range	Amount of voltage deviation from its target range	Power flow Calculation
6	Prevent LRT taps from reaching their operational limit	Amount of voltage deviation from dead band of the LRT tap that reaches its operational limit	Power flow calculation

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continued

<Step (1): Calculation of target equipment control>

- Step (1) determines the equipment to control using the data on the target equipment to control derived by the AI and present equipment data based on on-line measurement data.
- At first, the target equipment state band B is set (Fig. 5).
- Then, when the present equipment state is out of the target equipment state band B, the equipment to control is determined by moving the present equipment state to B_u or B_l (Fig. 5).

Simulation verification

<Simulation conditions>

- Actual past grid data used in off-line learning and verification grid data to evaluate the new VQC method are shown in Table III.
- The condition in winter has heavy power flow to the 500 kV bulk system in the Nagano-region grid.
- The operational ranges and target ranges for bus voltages are shown in Table IV.

<Simulation result>

- The average number of operations of LRT taps of all substations can be reduced by 26%, and that those of SCs and ShRs can be reduced by 17% compared with the existing method while complying with constraint conditions (Table V, Fig. 6, and Fig. 7).

Table III Actual past grid data and verification grid data.

Data kind	Detail
Actual past grid data	• 2/1/2018 ~ 2/5/2018 (every 5 minutes)
Verification grid data	• 2/27/2018 (every 5 minutes)

Table IV Operational ranges and target ranges for bus voltages.

Range kind	Value
Operational range	• 500 kV: 0.95 p.u. ~ 1.04 p.u. • 275 kV, 154 kV, 77 kV: 0.95 p.u. ~ 1.05 p.u.
Target range	• 154 kV, 77 kV: Reference voltage ±1.10%

Table V Comparison of simulation validation results.

Method	Equipment	Number of operations per day		
		Min.^{*1}	Max.^{*1}	Avg.^{*2}
Existing method	LRT taps	17	38	29
	SCs and ShRs	0.7	1.5	0.6
New VQC method	LRT taps	8	35	21 (▲26%)
	SCs and ShRs	0.5	2.3	0.5 (▲17%)

*1 Number for substations where SCs or ShRs operate

*2 Number for all substations in the Nagano-region

Conclusion

- The new VQC method reduced the average number of operations of LRT taps, SCs, and ShRs while complying with operational conditions.
- As a result, maintenance costs of about several million euros can be saved by applying the new VQC method.
- Replacement with the new ISC system using the new VQC method is progressing for its commercial operation, which is planned to start in 2023.
- Implementation of this system will allow stable operation in the Nagano-region grid even with further large-scale introduction of PVs.

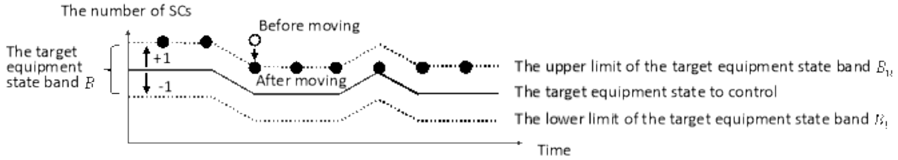

Fig. 5 Image of the target equipment state band and determination of target equipment control.

Fig. 6 Capacity of connected SCs and ShRs^{*3} at substation C.

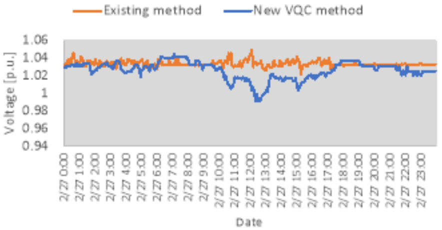

Fig. 7 Bus voltage of 275 kV class at substation A.

*3 Positive value: SC, Negative value: ShR