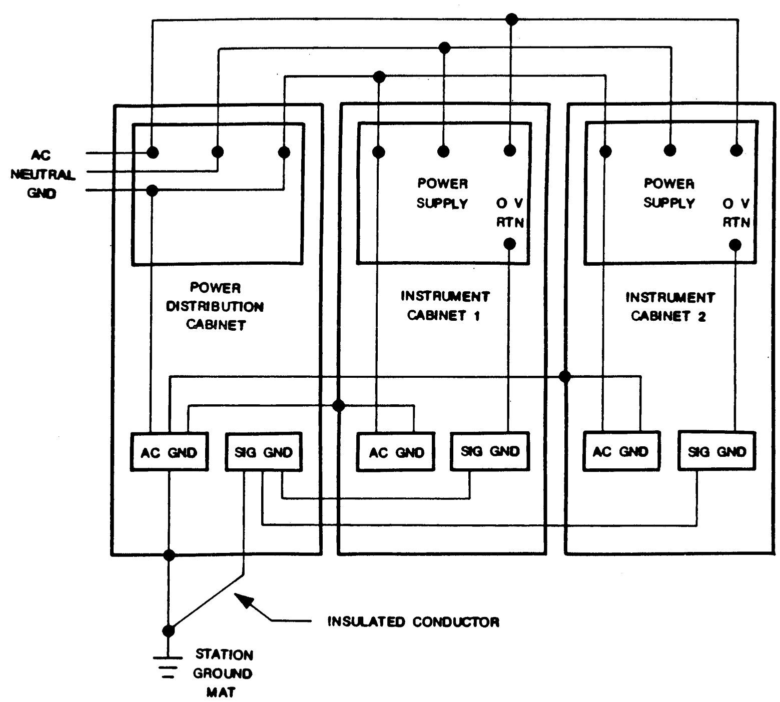

Fig. 1. Single-Point Ground System.

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89 WM 006-8
September 1989

Improving Nuclear Generating Station Response for Electrical Grid Islanding

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Summary

This paper describes problems associated with the performance characteristics of nuclear generating stations which do not have their overall plant control design functions co-ordinated with the other grid controls. Some design changes to typical nuclear plant controls are presented which can result in a significant improvement in both the performance of the grid island and reduce the need to isolate nuclear units during the disturbance.

Four areas of the overall unit controls and turbine governor controls which could be modified to better co-ordinate the control functions of the nuclear units with the electrical grid are discussed.

Some simulation results are presented to show the performance of a typical electrical grid island containing a nuclear unit with and without the changes.

By reviewing data from two islanding events and supplementing that with computer simulation studies, some conclusions are made. The first of these is that overall unit controllers which are not designed with grid disturbances and islanding requirements in mind can cause frequency control problems. On detection of grid islanding the turbine power should be regulated by the speed governor only while the overall unit controls maintain appropriate operation of the reactor and steam bypass system.

As well, turbine auxiliary governors whose settings and time delays are not co-ordinated with the operation of the main governors and underfrequency load shedding relays on the system can cause frequency oscillation and limit cycles. Turbine auxiliary governor design and settings should be co-ordinated with other grid controls, including other unit governors.

Thirdly, allowing some units to run back their turbine load setpoints following load reductions causes unequal sharing of load reductions. Additional simulation studies are needed to determine if unfavourable situations can arise.

Finally, providing automatic turbine load limiter tracking of reactor power during grid islanding operation can provide protection against sudden rapid depressurization of the boilers.

Discusser: J. H. Doudna

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89 WM 011-8
September 1989

Feasibility of Iceland/United Kingdom HVDC Submarine Cable Link

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Summary

This paper addresses the viability of a submarine cable connection from Iceland to the North of Scotland extended by HVDC overhead line to the South of England. Hydro development, submarine cables, HVDC overhead transmission lines, rectifier/invertor stations, investment cost attributable to a power sale, availability of the connection, technical considerations and cost comparisons is discussed.

Hydro Development in Iceland

Economically harnessable hydro and geothermal power in Iceland is estimated to be approximately 30 TWh (30×10^9 kWh) and 20 TWh per annum respectively. This represents continuous electrical power of the order of 3400 MW and 2300 MW respectively. Only 8% of this potential is utilised in Iceland to date.

Table 1 shows different categories of hydro potential in cost per kW at January 1988 prices. Generation in MW for each category is indicated where load factors of 0.9 and 0.6 respectively are assumed.

Cables

Cost of a single 400 kV, 500 MW submarine cable at January 1988 prices is given as approximately £226/m.

The time required to manufacture, lay and test a 950 km, 400 kV, 500 MW cable between Iceland and Scotland is estimated to be in excess of 3 years.

Rectifier and Inverter Stations

The cost of rectifier and inverter stations increases as the voltage is raised. An estimate (at January 1988 prices) for the cost of a pair of convertor stations with associated filters and reactive power compensators, excluding erection, AC → DC → AC is £46 m for a 400 kV, 500 MW monopole arrangement, and £84 m for a ±400 kV, 1000 MW bipole arrangement. Erection costs may be estimated to be 15% of capital cost.

Electrical System Development in Iceland

Development of the Iceland/Scotland Link would be in stages. The first stage would consist of a 400 kV, 500 MW monopole system. Initial capacity, at an annual utilization of 8000 hrs, would be about 4000 GWh/year, i.e., about 500 MW. Subsequent developments would be in 500 MW stages. These would increase the capacity of the connection to 16000 GWh/year (2000 MW) or more. They would entail the development of glacial rivers in Eastern Iceland.

Expected Life

Dams are expected to last at least 80 years, submarine cables up to 60 years, overhead lines of the order of 40-80 years, and rectifier/inverter stations 25-40 years. Transmission line towers would be expected to last 80 years, but the conductors may require restringing after about 40 years. Cost of restringing a line is approximately 50% of current line cost.

Marine Environment

Extensive studies have been made of the seabed between Iceland and the UK.

The seabed between Iceland and the Faeroe Islands is part of a ridge which is up to 250 km wide. The average depth is about 400 m. In places the depth, excluding shore areas, is only 250 m. Thickness of sediment cover varies from 200 m to practically nothing. The northwest parts of the ridge are covered in bedrock.

Between the Faeroe Islands and Scotland are plenty of thick sediments such as clay, sand and mud.

Availability of Submarine Cable

The main precautions for high availability of the cable are to employ strong armour and bury the cable where danger of damage from anchors and fishing equipment is apparent. There are no known failures of double armoured buried cables of type envisaged for the connection to date.

The probable fault frequency of the cable proposed for the link is estimated to be in the region of 0.05 to 0.10 faults per 100 km/year. For a 950 km cable, availability of the cable for a fault rate of 0.05 faults per 100 km/year with a repair time of 28 days and 60 days would be 96.4% and 92.2% respectively. A fault rate of 0.10 faults per 100 km/year would give an availability of 92.7% and 84.4% respectively.

The cable is considered to be the least reliable constituent of the Link.

Link Losses

At rated load, cable losses are estimated to be 3.5 to 5.1%, rectifier/inverter station losses 0.6% to 0.7% per station, and overhead transmission line losses 3% to 6%. Total losses in the Link are therefore between 7.7% and 12.5% of the power supplied.

Cost of Delivered Energy

Table 2 shows average cost of energy supplied to the South of England over 500 MW, 1000 MW and 2000 MW Links for interest at 4.5% p.a., 6% p.a. and 8% p.a. (i) over the first 25 years, and (ii) over the first 40 years respectively. Cost is calculated by means of an equal annuity each year comprising interest payments plus sinking fund. Table 2 shows that for the repayment assumptions of (a), average cost of energy over 40 years for 2000 MW at a load factor of 0.9 and interest at 4.5% p.a. and 6% p.a. is 1.198 p/kWh and 1.373 p/kWh respectively. At a load factor of 0.6 corresponding cost is 1.422 p/kWh and 1.627 p/kWh respectively. After repayment of the initial investment, there would be only operation and maintenance expenses, and cost of energy would be quite low.

The prices with which the Link will have to compete are approximately 2.4-4.1 p/kWh and 2.5-3.5 p/kWh from new nuclear and coal plant respectively, depending on cost of nuclear fuel and coal and assuming a utilization of 6500 hours/year.

Conclusions

[1] Cost of energy delivered would be very competitive with that from new coal-fired or nuclear power plants.
[2] Availability of the connection should at least equal that of electricity from coal and nuclear power stations.
[3] The first 500 MW of Icelandic power could be available at an inverter station in the South of England in 7 to 10 years, 1500 MW could be supplied before the year 2010, and about 2000 MW could be developed by 2010-2015.
[4] Tap-in of surplus power from Scotland in early years could provide 2000 MW at inverter stations in England by the turn of the century.

Discussers: U. Arnaud, G. Bazzi, D. Valenza, and G. Orawski

TABLE 1
Practical Hydro Potential in Iceland

Category	Capacity			Investment cost[ρ]			
	E TWh/yr	N MW	N MW	K/N £/kW	K/N £/kW	K £m	K/E p/kWh/yr
I	18	3425#	2283*	747#	1120*	2558	14.2
II	6	1142#	761*	1052#	1578*	1201	20.0
III	2	381#	254*	1522#	2283*	580	29.0
Developed	4	730	730	873	873	637	15.9
Total	30	5678#	4028*	876#	1235*	4976	16.6

[ρ] Costs in January 1988 prices
Based on load factor of 0.6
* Based on load factor of 0.9
Note: Compensation for land and water rights are on the average valued at 3% of other costs

TABLE 2
Average Cost of Energy Delivered to the South of England at January 1988 Prices—Equal Annuity Analysis

Interest, % p.a.	Load Factor	Average cost, p/kWh					
Repayment assumptions		(a)	(b)	(a)	(b)	(a)	(b)
Ratings, MW		500		1000		2000	
Over 25 years:							
4.5% p.a.	0.6	2.141	1.964	1.981	1.806	1.897	1.722
	0.9	1.722	1.575	1.615	1.470	1.559	1.413
6.0% p.a.	0.6	2.480	2.379	2.292	2.192	2.193	2.093
	0.9	2.002	1.928	1.877	1.794	1.810	1.727
8.0% p.a.	0.6	2.933	2.933	2.706	2.706	2.587	2.587
	0.9	2.377	2.377	2.225	2.225	2.145	2.145
Over 40 years:							
4.5% p.a.	0.6	1.626	1.722	1.493	1.587	1.422	1.516
	0.9	1.334	1.391	1.245	1.302	1.198	1.216
6.0% p.a.	0.6	1.862	2.056	1.708	1.900	1.627	1.818
	0.9	1.531	1.673	1.429	1.570	1.373	1.514
8.0% p.a.	0.6	2.177	2.501	1.996	2.317	1.899	2.220
	0.9	1.794	2.049	1.673	1.927	1.608	1.861

Interest charges during construction ignored. 100% availability assumed.
Repayment assumptions:
(a)—a, d, e = 40 years, b, c = 25 years
(b)—a = 80 years, b, c, d, e = 40 years
a = hydro development
b = submarine cables
c = converter stations
d = DC transmission lines
e = AC system development

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89 WM 017-5
September 1989

Reactive-Power Dispatch by Successive Quadratic Programming

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This paper is concerned with a quadratic model problem formulation and solution for the optimal reactive power dispatch problem. The quadratic reactive-power dispatch problem is stated as the minimization of a quadratic approximation for the nonlinear real-power loss objective function subject to a set of linear inequality constraints on the set of control and dependent variables in the system. All the assumptions considered for the problem decoupling are implied in the formulation of the quadratic problem. The reactive-power problem is formulated in terms of a full set of control variables, namely: generator voltages, transformer turn ratios and switchable shunt susceptances. The calculation of the linear sensitivity relationships for the set of dependent variables is based on the complete fast decoupled load flow reactive power model.

The usual economic objective function utilized in optimal reactive-power dispatch formulations is the real-power loss function. The optimal reactive-power dispatch problem can be formulated as a linearly constrained quadratic programming problem by defining a quadratic model approximation for the loss objective function and linear inequality constraints for the set of dependent variables, that is,

$$\min_{x} \left\{ f(x) = c'x + \frac{1}{2} x'Cx \right\} \quad x \in R^{n_c} \tag{1}$$

subject to

$$x^m \leq x \leq x^M \tag{2}$$

$$y^m \leq y \leq y^M \tag{3}$$

where $f(x)$ is a quadratic approximation of the scalar objective function used in the general nonlinear optimal reactive-power flow problem; x is an n_c-vector of control variables; y is an m-vector of dependent variables and the superindices m and M stand for lower and upper limits, respectively. Equations (2) and (3) describe a set of linear inequality constraints on control and dependent variables. The dependent variables are related to the control variables through sensitivity relations of the form

$$y = Sx \tag{4}$$

where S is a sensitivity matrix of dimension $n \times n_c$, with n being the number of system power-flow nodes and n_c the number of control devices in the system.

The quadratic approximation of the real-power loss function can be obtained from a second-order Taylor series expansion of the original nonlinear real-power loss function. The general structure for the linear and quadratic real-power loss coefficients, assuming an ordered vector of control variables as $x' = [\Delta V_g' \Delta Q_s' \Delta t_r']$, is given as

$$c' = \left[\frac{\partial P_L}{\partial V_i} \quad \frac{\partial P_L}{\partial Q_k} \quad \frac{\partial P_L}{\partial t_p} \right] \tag{5}$$

and

$$C = \begin{bmatrix} \frac{\partial^2 P_L}{\partial V_i \partial V_j} & \frac{\partial^2 P_L}{\partial V_i \partial Q_t} & \frac{\partial^2 P_L}{\partial V_i \partial t_q} \\ \frac{\partial^2 P_L}{\partial Q_k \partial V_j} & \frac{\partial^2 P_L}{\partial Q_k \partial Q_l} & \frac{\partial^2 P_L}{\partial Q_k \partial t_q} \\ \frac{\partial^2 P_L}{\partial t_p \partial V_j} & \frac{\partial^2 P_L}{\partial t_p \partial Q_l} & \frac{\partial^2 P_L}{\partial t_p \partial t_q} \end{bmatrix} \tag{6}$$

where c' is a vector of dimension n_c representing first-order variations of the real-power losses, and C is a matrix of dimension $n_c \times n_c$ representing second-order variations of the real-power loss function. The linear and quadratic loss coefficients required can be obtained from sensitivity computations by the Jacobian method. A detail description of the derivation of these sensitivities is given in the paper.

In general, when compact modeling is used, the set of inequality constraints (2) and (3) can not be computed explicitly. Instead, sensitivity relations based on Taylor series are utilized for the evaluation of such set of constraints. The validity of these models is limited to a small region around a given operating point. Therefore, an iterative procedure is required to update the actual operating point of the system and the sensitivity models used in the problem formulation. A sequence of reactive-power dispatch problem solutions is performed in this paper to determine a suboptimal solution for the original nonlinear programming problem. A power flow solution must be obtained at every iteration to update the current operating system condition.

A constraint relaxation technique has been employed to reduce the number of constraints in the problem and to alleviate the computational burden. The basis idea of the relaxation strategy consist in relaxing all non-violated load-node voltage constraints and all non-violated reactive power generations. A sensitivity graph is used to include, in the quadratic reactive-power dispatch problem, all the generated power constraints up to two nodes apart from the node representing a violated dependent constraint in the sensitivity graph.

An active-set projection method for quadratic programming problems has been selected as the solution algorithm for the quadratic problem stated in Eqs. (1) to (3). In general, solution points for the