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Primary Restoration Path Selection Considering Ferranti Effect and Reactive Power Capability of Black-start Generators

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Abstract – Power system restoration following a massive blackout starts with re-energizing Primary Restorative Transmission (PRT) systems at first. As power systems have been gradually enlarged and become more complex, periodical evaluation and reassignment of PRTs are needed. So far it has been decided by try and error approach by corresponding human experts to analyze and evaluate them. This paper presents an intelligent system that finds optimal primary restoration paths using analytic and heuristic knowledge from PSS/E data, and suggests an optimal PRTs depending on the condition of Ferranti effect or a reactive power capability margin of black-start generator. This system was tested in Korea Electric Power system, and showed a promising result.

Keywords: Intelligent system, Primary restorative system, Ferranti effect, Reactive power capability

1. Introduction

When a massive blackout occurs, fast and reliable power system restoration is very important since the social impact including economic loss is so enormous. Although restoration strategies are slightly different in each country as restoration methods are dependent on faults, voltage levels, structures of transmission grid, and equipment of its own power system, it is clear that during the first stage of restoration, Black-Start Generators (BSGs) that are usually hydro type in Korea, should supply cranking power to Primary Supplied Generators (PSGs) having big capacity through so called primary restorative transmission lines in case of wide area blackout [1-6].

However, as issued by NERC [7], experience has shown that in general remote black-start are difficult and costly to schedule and test.

As to the static analysis of the PRT systems, it can be focused on three major problems. One is the overvoltage of the PRT systems, another is the PRT line charging, and the other is the reactive capability of BSGs.

In the previous researches about these problems, Adibi proposed several methods, which are energizing fewer high voltage lines, operating generators at minimum voltage levels, deactivating switched static capacitors, connecting shunt reactors, and adjusting transformer taps to appropriate positions to prevent generator self-excitation by balancing reactive power [8-11]. Morin [12] and Huang [13] showed voltage profile of PRT lines considering picking-up loads, and Adibi [14] showed quantitative Reactive Capability Limitation (RCL), but did not consider generator pole type.

This paper presents an expert system that finds feasible paths for RB path using analysis of Ferranti effect, reactive power capability of black-start generators. As mentioned before, small hydro generators are used as black-start units in Korea. However, so far the reactive power capability of round rotor type generator is known. The reactive power capability of salient pole generator is presented here including several analytical results [15]. This system consists of three modules that are a data conversion module, an expert system module, and a static analysis module. The data conversion module extracts network topology and system parameters from PSS/E data, and transfers them to the expert system and the static analysis modules. The expert system module finds a feasible path at the transmission grid, and transfers information about the path to the static analysis module. Then, it figures out the terminal voltage, transmission line charging capacity, and reactive capability limitation of black-start generators, and returns the result to the rule base of the expert system.

2. Data Conversion Module

This data conversion module extracts data that are required for this system from PSS/E raw and dynamic data, and transfer them to the expert system and the static analysis modules. Information about power system topology, parameters of transformers and transmission lines are extracted from raw data, and generators' synchronous

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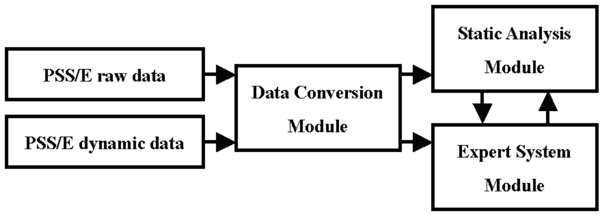

Fig. 1. Modules of the system

reactance value and rotor type that is related to reactive capability limitation of the generator are done from dynamic data. Data flows between the modules are shown in Fig. 1.

3. Intelligent System for Remote Black-start Planning

The Remote Black-start (RB) planning expert system also consists of database, rule base, inference engine, and GUI as usual. The problem representation and knowledgebase is developed as follows.

3.1 Problem representation

To find a feasible and optimal RB path, at first available topological path identification is required. And the several analysis should be considered such as reactive capability limitation to prevent self-excitation and Ferranti effect. For example topologically available paths are 5-2-1, 5-3-2-1, and 5-4-2-1 in the sample network in Fig. 2. The problem is modeled using the state space representation method of

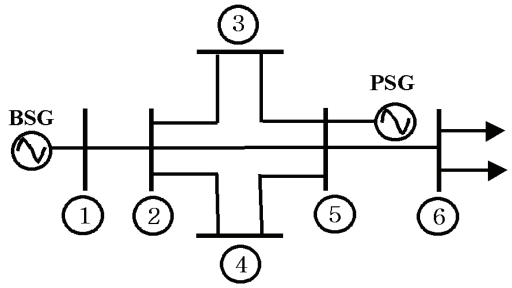

Fig. 2. Sample power system network

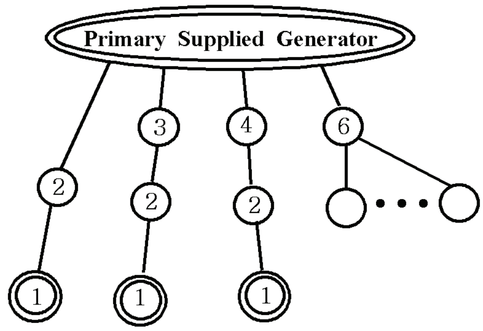

Fig. 3. Problem representation of the state space

AI as shown in Fig. 3.

Transmission line charging capacity is used as cost function of branches between nodes to minimize objective function to decide optimal path. During the searching process if the line charging capacity is larger than reactive capability limitation of the BSG, the corresponding path is discarded. By using this technique the searching space can be dramatically reduced.

Several numerical analysis are introduced at section 4.

3.2 Knowledge base

The rule-base of this expert system module comprises basic rules for searching and inference as well as rules for preventing infinite circulation of path search in loop networks. In fact this is the bottle-neck for practical application of AI techniques to power systems.

4. Static Analysis Module

If overvoltage appears at a receiving end of PRT line by Ferranti effect when the unloaded transmission line is reenergized, this problem can be resolved by compensating lagging reactive power such as picking-up loads at substations. The charging capacity of the PRT line considering the compensation effect by load pick-up, reactance of transformers, and line reactance of the PRT system can be calculated as follows.

4.1 Voltage calculation considering Load pick-up

Single line diagram consisting of two BSGs, step-up transformers, and a PRT line is shown in Fig. 4. At the receiving end point, V_N and I_{SN} are calculated using the desired voltage V_{end} and I_{RN} at first. V_{end} is usually 1.0pu and I_{RN} is zero at the black-start condition.

As the PRT line consists of successive pi networks as shown in the figure, V_1, I_{S1}, I_{Z1} can be calculated by using Eq. (1)~(3) repeatedly. Then V_g, I_{gi} are calculated finally. Although the power flow has been widely used by now, the suggested calculation is definitely very simple and fast. However this method is available only under the support of network topology processor of the expert system. It is clear that future power system operation will utilize the convergence technology together with artificial intelligence and hierarchical cooperation technique.

$$\begin{bmatrix} V_i \\ I_{Si} \end{bmatrix} = \begin{bmatrix} 1+\frac{Zi\cdot Yi}{2} & Zi \\ Yi\left(1+\frac{Zi\cdot Yi}{4}\right) & 1+\frac{Zi\cdot Yi}{2} \end{bmatrix} \begin{bmatrix} V_{i+1} \\ I_{R(i+1)} \end{bmatrix} \tag{1}$$

$$Z_i = \left(\frac{|V_{i-rated}|^2}{S_{Zi}\angle\Phi_{Zi}}\right)^* \tag{2}$$

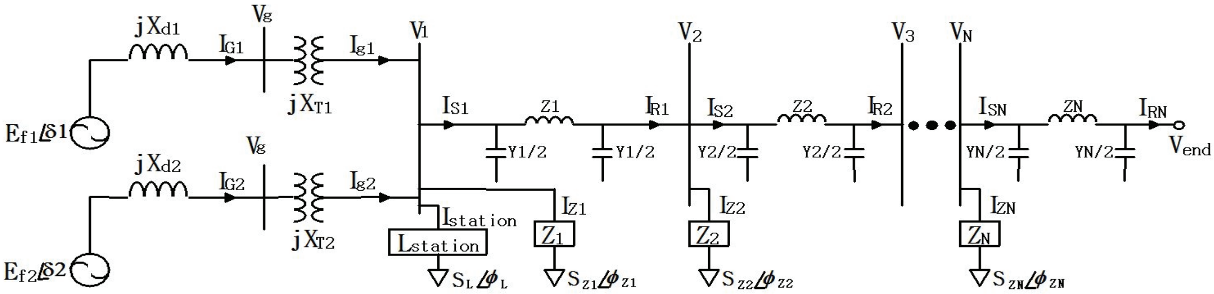

Fig. 4. Single line diagram of a PRT system

$$I_{Zi} = \frac{V_i}{Z_i} \tag{3}$$

where

V_{gi} = Terminal voltage of the i-th BSG
$S_L \angle \Phi_L$ = House load at the Lstation bus
$S_{Zi} \angle \Phi_{Zi}$ = Load picked-up at i-th substation
$V_{i-rated}$ = Rated voltage at the i-th bus

4.2 Terminal voltage of BSGs

Since Korean Power Systems adopt the all-open switching strategy, all CBs should be open for fast restoration except the CBs which are inserted in a PRT line after wide area blackout. When a T/L is reenergized under all-open switching condition, overvoltage may be induced at the receiving end. This overvoltage can cause the dielectric problem of the buses and transformers of each substation and generators of big capacity which are connected to the receiving end of the T/L. Therefore, terminal voltage of the BSGs should be determined to keep voltage of the all components of the PRT system under operating limit.

Terminal voltage of the BSGs can be found from Eqs. (4)~(7) showing relation between some factors, which are sending voltage(V_1), step-up transformer impedance, and current through jX_T . Also, voltage ratio of the transformer should be considered.

$$\text{Let } I_{S1} + I_{Z1} + I_{station} = I_S$$

$$I_{g1} + I_{g2} = I_S \tag{4}$$

$$I_{g1} = \frac{V_g - V_1}{jX_{T1}}, \quad I_{g2} = \frac{V_g - V_1}{jX_{T2}} \tag{5}$$

$$I_{g1} + I_{g2} = \frac{V_g - V_1}{jX_{T1}} + \frac{V_g - V_1}{jX_{T2}} = I_S \tag{6}$$

$$V_g = V_1 + I_S \left(\frac{jX_{T1} \cdot jX_{T2}}{jX_{T1} + jX_{T2}} \right) \tag{7}$$

4.3 Charging capacity of the PRT line

Charging capacity can be found when the lagging reactive components such as picked-up load and inductance of T/Ls and transformers are considered. Therefore, T/L Charging Capacity (TCC) to consider compensating effect is the same as reactive power which BSGs supply. Current from each BSG can be found when V_g of Eq. (7) is substituted for Eq. (5).

4.4 RCL of salient pole generators

The RCL of BSGs should be larger than charging capacity of the PRT line to prevent self-excitation, and this RCL is determined depending on rotor type of the BSG.

As RCL of Non-Salient Pole is already known, only the RCL of salient pole generator is introduced in this paper.

In general, rotors of hydro generators are salient type. The internal voltage of a salient type generator is expressed by Eq. (8). By substituting I_q by Eq. (9) Eq. (11) is obtained. Then Eq. (11) shows that $j(X_d - X_q)I_d$ is on q axis. E_q is the same because angle of E_f is δ from Eq. (10). Eq. (14) is classified into active and reactive power. From Eq. (15), (16), (17), Eq. (18) is derived.

Then finally when $\delta_{\max}$ is 90°, the RCL of a salient pole generator is expressed by Eq. (19).

$$\overline{E_f} = jX_d \overline{I_d} + jX_q \overline{I_q} + \overline{V} \tag{8}$$

where

$\overline{I} = I \angle -\psi$: Generator terminal current
$\overline{I_d} = I_d \angle \delta - 90^\circ$: d axis component of $\overline{I}$
$\overline{I_q} = I_q \angle \delta$ (q axis component of $\overline{I}$)

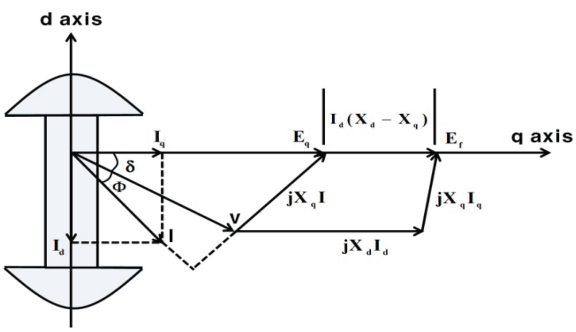

Fig. 5. Phasor diagram for a salient pole

$$\overline{I_q} = \overline{I} - \overline{I_d} \tag{9}$$

$$\begin{aligned}\overline{E_f} &= j\left(X_d - X_q\right)\overline{I_d} + jX_q\overline{I} + \overline{V} \\ &= j\left(X_d - X_q\right)\overline{I_d} + \overline{E_q}\end{aligned} \tag{10}$$

$$\begin{aligned}j\left(X_d - X_q\right)\overline{I_d} &= \left(X_d - X_q\right)I_d\angle\left(90^\circ + \delta - 90^\circ\right) \\ &= \left(X_d - X_q\right)I_d\angle\delta\end{aligned} \tag{11}$$

$$I_d = I\sin\left(\delta + \psi\right) \tag{12}$$

$$E_f = E_q + \left(X_d - X_q\right)I_d \tag{13}$$

$$\begin{aligned}\overline{S} = \overline{V}\overline{I}^* &= \overline{V}[I_q\angle\delta - jI_d\angle\delta]^* = V\angle-\delta[I_q + jI_d] \\ &= \left(V\cos\delta - jV\sin\delta\right)\left(\frac{V\sin\delta}{X_q} + j\frac{E_f - V\cos\delta}{X_d}\right)\end{aligned} \tag{14}$$

$$P = \frac{VE_f}{X_d}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta \tag{15}$$

$$Q = \frac{VE_f}{X_d}\cos\delta - V^2\left(\frac{\cos^2\delta}{X_d} - \frac{\sin^2\delta}{X_q}\right) \tag{16}$$

$$\frac{VE_f}{X_d} = \frac{P}{\sin\delta} + \frac{V^2}{2}\left(\frac{1}{X_d} - \frac{1}{X_q}\right)\frac{\sin 2\delta}{\sin\delta} \tag{17}$$

$$Q = \frac{P}{\tan\delta} - \frac{V^2}{X_q} \tag{18}$$

$$Q_{\max} = -\frac{V^2}{X_q} \tag{19}$$

5. Case Study

The proposed system was applied to Korean power system and a case study for Youngdong local power system – one of the seven predefined subsystem in Korean power grid is introduced.

The structure of Youngdong system is shown in Fig. 6. Gangneung H/P is selected as the BSG and Uljin N/P is done as the PSG, and these selections are identical to Korea

Table 1. PRL candidates list generated by the system

Path	Cadidate of primary restorative lines
1	Gangneung H/P-Gangneung-Donghae-Uljin N/P
2	Gangneung H/P-Gangneung-Youngdong T/P-Donghae-Uljin N/P
3	Gangneung H/P-Gangneung-Youngdong T/P-Ahnin-Bookpyoung-Donghae-Uljin N/P
4	Gangneung H/P-Gangneung-Youngdong T/P-Bookpyoung-Donghae-Uljin
5	Gangneung H/P-Hoenggye-Gangneung-Donghae-Uljin N/P
6	Gangneung H/P-Hoenggye-Gangneung-Youngdong T/P-Donghae-Uljin N/P
7	Gangneung H/P-Hoenggye-Gangneung-Youngdong T/P-Bookpyoung-Donghae-Uljin N/P
8	Gangneung H/P-Hoenggye-Gangneung-Youngdong T/P-Ahnin-Bookpyoung-Donghae-Uljin N/P

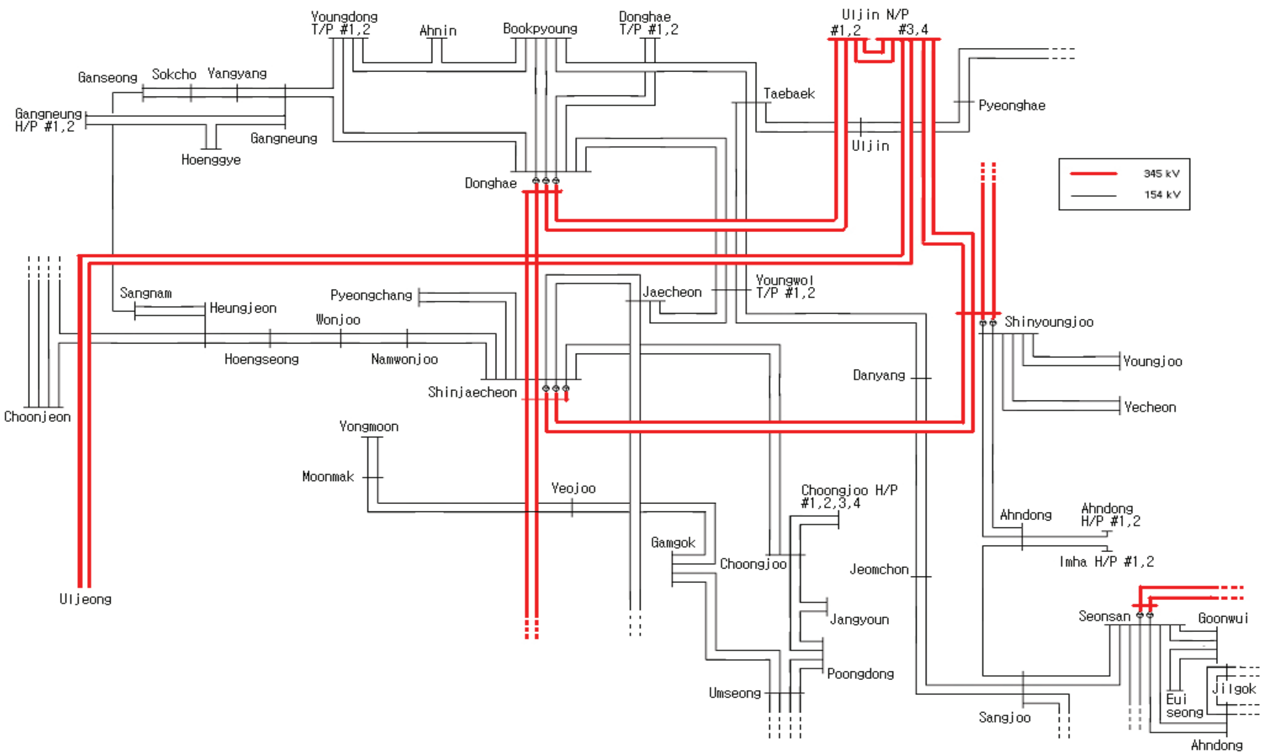

Fig. 6. The structure of Young-dong system

Table 2. Analysis of PRLs for Young-dong area (Receiving end voltage =1.0 p.u)

Path	Terminal vtg. of BSGs[pu]	Line charging capacity[MVAR]	Reactive capability margin[MVAR]
1	0.8120	37.557	18.243
2	0.8093	37.802	17.998
3	0.8004	36.780	19.020
4	0.8004	36.774	19.026
5	0.7838	38.313	17.487
6	0.7809	38.523	17.277
7	0.7725	37.491	18.309
8	0.7724	37.496	18.304

Power Exchange(KPX)'s restoration strategy. Candidates of PRL are shown Table 1 and analytical result is shown in Table 2. Path 1 is the solution if Ferranti effect is the optimal condition, and path 4 is the one for the reactive capability margin. Summation of the line charging capacity and the reactive capability margin is equal to the reactive capability limitation of the BSG, and this limitation by steady state stability is depend on the terminal voltage and the synchronous reactance of the BSG [16]. Despite of different voltages of the BSG, reactive capability limitations of the BSG have same values at table 3 because this limitation is decided by not steady state stability but stator end core heating. In this case, the limitation by stator end core heating is smaller than the one by steady state stability.

6. Conclusion

PRLs are very basic skeleton for restoration when a power system is totally or widely collapsed.

In this paper, an expert system is proposed for the optimal primary restoration planning. This system generates feasible paths using PSS/E data automatically at first. And then the optimal path is suggested by using analysis of Ferranti effect and reactive capability margin. It will be a basic component to the self-healing power system - the final goal of smart grid in 2030. Application to Korean power system showed a promising result.

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