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Development of an Adaptive Overcurrent Relaying Algorithm for Distribution Networks Embedding a Large Scaled Wind Farm

Sung-Il Jang*, Ji-Won Kim and Kwang-Ho Kim****

Abstract - This paper proposes the adaptive relaying of protective devices applied in the neighboring distribution feeders for reliable and efficient operations of a wind farm interconnected with distribution networks by dedicated lines. A wind farm connected to an electric power network is one of the greatest alternative energy sources. However, the wind turbine generators are influenced by abnormal grid conditions such as disturbances occurring in the neighboring distribution feeders as well as the dedicated power. Particularly, in cases of a fault happening in the neighboring distribution feeders, a wind farm might be accelerated until protective devices clear the fault. Therefore, the delayed operation time of protective devices for satisfying the coordination might overly expose the interconnected wind turbine generators to the fault and cause damage to them. This paper describes the proper delayed operation time of protective relay satisfying the coordination of the distribution networks as well as reducing damage on the interconnected wind farm. The simulation results for the Hoenggye substation model composed of five feeders and one dedicated line using PSCAD/EMTDC showed that the proper delayed time of protective devices reflecting the fault condition and the power output of the wind farm could improve the operational reliability, efficiency, and stability of the wind farm.

Keywords: Adaptive Relaying, Wind farm

1. Introduction

In order to solve environmental problems and to cope with rising energy prices and power plant construction costs, small-sized distributed generations (DG) including photovoltaic, wind farms, fuel cells, micro-sized turbines, and internal combustion engine-generators will be connected with power networks in the near future. First of all, the wind farms composed of wind turbine generators have been under construction worldwide because of their ability to harness the power of the wind, which is a clean and inexhaustible energy source. Most of the wind farms like the other distributed generations may be connected in parallel with distribution networks and therefore supply power into power grids as well as local loads. As such, the operational reliability and stability of a wind farm may be influenced by abnormal grid conditions such as a disturbance occurring in the neighboring distribution feeders emanated from the substation to which the wind turbine generator is connected as well as the feeder directly connecting the wind farm. These impacts would be demerits for both the wind farms and the distribution networks [1-5].

When a fault occurs in the neighboring feeders, this indicates that the voltage in the dedicated power line for connecting the wind farm to distribution networks has dropped. Due to the drop in voltage, electro-magnetic torque developed in the wind turbine generator has abruptly decreased, and a wind farm might be accelerated by reasons of the deviation between electro-magnetic torque and mechanical torque applied on the rotor of the associated wind turbine until the fault is cleared by protective devices. The coordination of fuses, reclosers, and protective relays generally causes the operation time of protective devices at the up-stream of a distribution network to be as high as 1.5 seconds [4]. Therefore, it is very important to choose the proper delayed operation time of protective devices for satisfying the coordination as well as reducing damage on the interconnected wind farm.

This paper describes the adaptive relaying of protective devices applied in the neighboring distribution feeders for reliable, efficient, and stable operations of a wind farm interconnected with distribution networks by a dedicated line. In order to reduce the negative influences caused by abnormal grid conditions, we modified the operation time of protective devices in accordance with the deviation between the electro-magnetic torque and mechanical torque characterized by the network voltage and output power of the wind farm, respectively. We propose the advantage of adaptive relaying for maintaining the stability of the wind farm interconnected with 22.9 kV Hoenggye radial distribution networks considering the various fault conditions in

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* BK21 Research Division for Information Technology, Seoul National University, Seoul 151-742, Korea. (sijang@snu.ac.kr)

** Dept. of Electrical and Computer Engineering, Kangwon National University, Chuncheon 200-701, Korea. (kimjiwon@kwnu.kangwon.ac.kr, khokim@kangwon.ac.kr)

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the associated networks and the output power of the wind farm. The result shows that the proper delayed operation time of protective devices considering the fault condition and power output of the wind farm could improve the operational reliability and stability of the wind farm.

2. Modeling of Distribution Networks with the Wind Farm

In this paper, by using PSCAD/EMTDC, we model the Hoenggye distribution networks composed of five feeders and one dedicated line for connecting the wind farm to distribution networks, simulate various operating conditions of the wind farm and disturbances in the distribution networks, and verify the feasibility of the proposed adaptive algorithm.

2.1 Wind Farm Model

In this study, we assume that the wind farm is composed of six Vestas V47-660 kW wound-rotor type induction wind turbine generators [6]. Wound-rotor type induction generators are commonly used in modern wind power systems since they have a rigid and simple structure and are easy to control. Particularly, they can be operated in the broad rotor speed range by controlling the external rotor resistance. The changes in the rotor speed of the induction generator used in the wind power systems must be made to operate within the limit of slip, which is 0% to -10%. Therefore, the rotor speed is maintained by controlling the blades of the wind turbine using pitch and stall control methods. As the wind speed accelerates from zero, the rotor speed and the mechanical input torque also increase to the rated slip [7-9].

In this paper, the wound-rotor type induction wind turbine generators are modeled by using a machine model presented in PSCAD/EMTDC [13]. This machine model is an electromechanical energy conversion device that can be used to simulate the electrical and mechanical components of electrical machines. This model has three nodes: a shaft mechanical speed input node, a mechanical torque input node, and a switch node for determining the mechanical dynamics of the machine according to whether it is operated in speed control mode or torque control mode. The induction generator in this paper is modeled as a constant torque generator, in which the torque input is applied to the mechanical torque terminal with the switch node set to zero. In the torque control mode, the machine computes the rotor dynamic speed based on the inertia, the damping coefficient, and the torque input. Parameters of the wound-rotor type induction generator used in the simulation are provided in the Appendix.

2.2 Distribution Networks Model

We adopt 22.9 kV Hoenggye distribution networks, which consist of five feeders having three-phase laterals connected with R-L network loads and a dedicated line for connecting the wind farm to distribution networks. Fig.1 shows the circuit diagram of the distribution network to which wind farm is connected. In this paper, the wind farm is interconnected with a distribution network using ACSR 160 mm^2 dedicated line because of the large generating capacity. The 690/22900 V step-up transformer with an impedance of 1% is assumed in the wind farm. The 4-step capacitor banks are installed in front of each wind generator to compensate for the reactive power consumed by the induction generators. Capacitor banks are switched-in one by one as the generator's output power increases [10]. The capacity of the first step capacitor in a 4-step capacitor bank is assumed as 100 kvar and the others are assumed as 80 kvar.

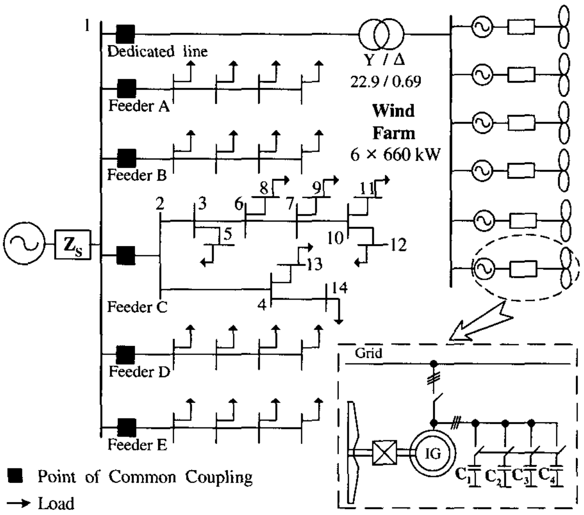

Fig. 1 Hoenggye distribution networks model with wind farm

3. Problem Identification

This section describes several dynamic characteristics of the induction wind turbine generator resulting from the events on distribution networks.

The dynamic operation of the induction generator is governed by the swing equation given below [11],

$$J\frac{dw}{dt} = T_m - T_e \tag{1}$$

where

J moment of inertia of the rotating mass,

T_m mechanical torque applied on the rotor of the associated wind turbine,

w rotor speed

In (1), T_e is electro-magnetic torque developed in the induction generator at the given speed proportional to the square of the terminal voltage as follows [12],

$$T_e = KsV^2 \tag{2}$$

Where K is constant value depending on the parameters of the machine and s is the machine slip. Due to the voltage drop caused by the fault occurring in the power network, the T_e is reduced according to (2), and the rotor continues accelerating until the fault is cleared by (1). Therefore, the delayed operation of protective devices for satisfying the coordination might overly expose the interconnected distributed generations to the fault, causing damage to them. The coordination of fuses, reclosers, and protective relays generally makes the operation time of protective devices at the up-stream of distribution networks to be as high as 1.5 seconds. The previous work in [3] describes the relation between the operation time of protective devices and the stability of distributed generators. Since the operational characteristics of the wind turbine generators depend on their capacity and type, it is difficult to determine the proper operation time of protective relay satisfying the coordination of the distribution systems as well as avoiding damage to the interconnected wind farm. This paper tries to choose the proper delayed operation time of protective devices from the simulation considering the fault condition and the power output of the wind farm and time-current curves of the protective devices applied in the faulted feeder in order to improve the operational reliability, efficiency, and stability of the wind farm.

4. Dynamic Operations of the Wind Farm

This paper describes the proper delayed time of protective devices in the neighboring feeders in order to solve the problems mentioned in Sec. 3. This section provides the delayed time of overcurrent relay applied in Hoenggye distribution networks and the dynamic operation of induction the wind turbine generator according to the fault condition in distribution networks and the power output of the wind farm.

4.1 Time-current characteristics of an overcurrent relay in the Hoenggye distribution feeders

In order to protect the distribution networks, relays provide the intelligence for identifying fault currents, for timing and reclosing, and for controlling the operation of a circuit breaker. There are many different shapes of time-current characteristics available, and the type chosen is dependent upon application. These relays can provide excellent coordination with fuses and reclosers in addition to providing load pick-up capability after an extended outage. Generally, in addition to a time-current characteristic, overcurrent relays also have an instantaneous-trip mechanism, which is operated in a very short time due to serious fault conditions. The time-current characteristics of overcurrent relay used in the Hoenggye distribution feeders are represented in Table 1. In this table, 51 and 51G signify overcurrent relay and overcurrent ground relay, respectively and VI means very inverse, which is a characteristic type for operating time of the protective relay.

Table 1 Time-current characteristics of the overcurrent relay

Feeder Name	Relay	Time Delay Setting (sec)						Instantaneous (sec)	Curve Type
		150%	300%	500%	700%	1000%	2000%		
Feeder A	51	12.15	2.22	1.00	0.68	0.53	-	0.05	VI
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder B	51	12.15	2.22	1.00	0.68	0.53	-		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder C	51	12.15	2.22	1.00	0.68	0.53	0.42		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder D	51	10.42	1.90	0.85	0.60	0.45	-		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder E	51	10.42	1.90	0.85	0.60	0.45	-		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		

4.2 The dynamic operation of wind farm in the fault condition

Many of the faults happening in neighboring distribution feeders may influence the operation of the wind farm. Equation (1) illustrates that the stability of the wind farm may be influenced directly by the capacity and the type of generator, the fault condition, and the power output of the wind farm. In order to observe the dynamic operation of the wind farm in the fault condition, we simulate various kinds of faults including single line to ground, line to line, and a three-phase fault by changing the fault location of distribution networks modeled in Fig. 1 and varying the generating power of the wind farm from zero to the maximum rate. We assume that faults occur in Feeder C at the time 1.0 sec and last for setting values established in Table 1.

Figs. 2 and 3 indicate the simulation results of a single line to ground and line to line fault occurring 2.7 km distance away from the bus 3, in respect to the rotor speed of the wind turbine generator and three phases voltage and the faulted line current at the PCC. In these cases, we operated the wind farm with maximum generating power rate. In both cases, the faulted line voltage at the PCC have decreased due to the fault current during the fault being cleared by protective devices. And the rotor of the wind turbine generator begins to accelerate over the rated speed resulting from the lowered voltage of the distribution network. Even though the fault currents of single line to ground and line to line fault are larger than the rated currents of about 700 % and 500 %, respectively, the rotor speed of the wind turbine can't exceed the 1.1 pu , which is a maximum slip regulation range because of the relatively large voltage magnitude of an unfaulted power line. So, the wind turbine can be operated in a stable condition at its slip regulation interval in the case of the small deviation between electro-magnetic torque and mechanical torque such as single or double line faults.

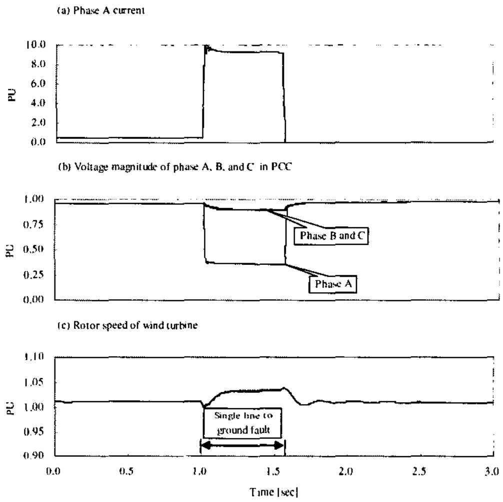

Fig. 2 Simulation results for the single line to ground fault occurred 2.7 km from the bus 3 where the generating power output of the wind farm is 4.5 MVA

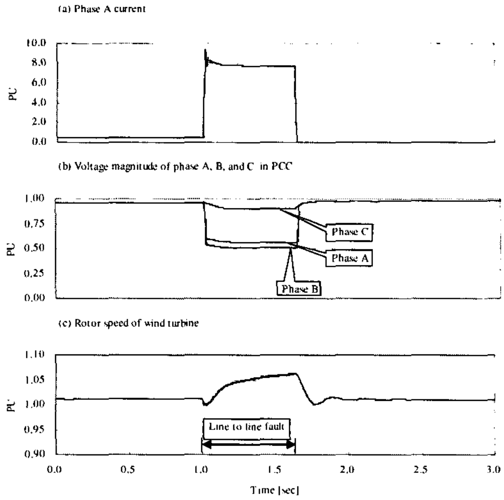

Fig. 3 Simulation results for the line-to-line fault occurred 2.7 km from the bus 3 where the generating power output of the wind farm is 4.5 MVA

With the three-phase fault happening in the same place as the above fault cases, phases A, B, and C in the PCC abruptly decrease at the same time as shown in Figs. 4 and 5, with low magnitude due to the large fault current. These simulations are concerned with the influence of the generating power output of the wind farm on the wind turbine stability itself. Simulation results of 100 % and 50 % generating power of the wind farm are depicted in Figs. 4 and 5, respectively. Despite the same fault position with single line to ground fault and line to line fault, there are some differences beyond the two simulations. The rotor speed of the wind turbine exceeds 1.1 pu at the time of 1.25 sec, due to the large power output of the wind farm as shown in Fig. 4. It is stopped by the mechanical breaker system to prevent the damage to the generator. However, in the case of the simulation for the fault on distribution networks to which the wind farm is connected, the generating power of the wind farm is 50 % and the rotor speed of the wind generator remains stable for 0.55 sec after fault insertion, due to the lower generation of the wind farm. If the delayed time of protective relay is shortened for a few cycles, it will not spoil the coordination of reclosers, fuses, and any other protective devices and the rotor speed of the wind turbine generator may not exceed 1.1 pu. Therefore, we can recognize that the dynamic operation of the wind farm resulting from the fault can be varied according to the types of fault and the generating outputs of the wind farm, and that the stability of the wind farm can be maintained by regulating the delayed operation time of protective relay in the neighboring feeders. Another major factor having an important influence upon the stability of the wind farm is fault position. If the fault occurs far away from the bus, the magnitude of voltage at the PCC cannot decrease enough to accelerate the rotor speed up to maximum slip regulation range during fault duration. However, the fault happening nearby the bus causes a large voltage drop, so that the turbine speed can exceed the maximum slip regulation range faster than the fault cases caused by lower voltage drop. Figs. 6 and 7 are simulation results for the three-phase fault occurring 6 km away from the bus 3 causing lower voltage drop. We assume that the generating power output of the wind farm is 100 % and 50 %, respectively. Compared with the simulation results in Fig. 5, the voltage drop is lower due to the small fault current, so wind turbine generators can be maintained at stable conditions for 0.78 sec after fault insertion as shown in Fig. 6. By shortening the delayed time of protective device for a few cycles, though this case is a three-phase fault with 100 % output power from the wind farm, the wind farm can be operated in a stable and reliable state. Fig. 7 shows that the wind turbine generator whose generating power output is 2.25 MVA cannot be influenced by such three-phase fault, so it is unnecessary to consider the delayed operation time of protective devices for the stability of the wind farm.

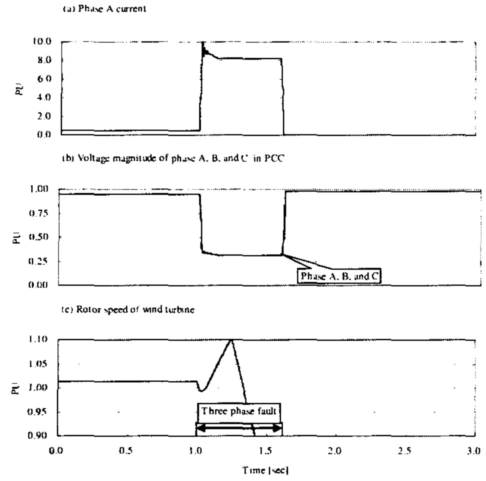

Fig. 4 Simulation results for the three-phase fault occurring 2.7 km from the bus 3 where the generating power of the wind farm is 4.5 MVA

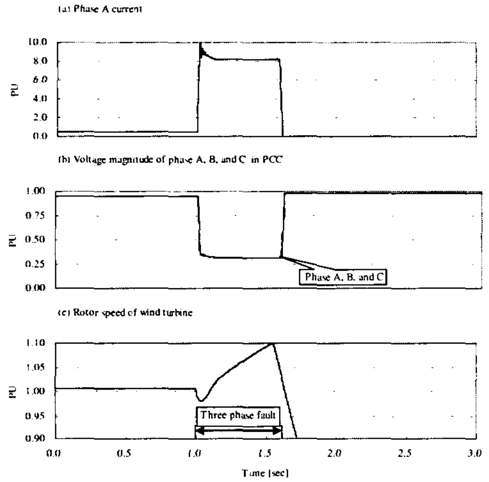

Fig. 5 Simulation results for the three-phase fault occurring 2.7 km from the bus 3 where the generating power of the wind farm is 2.25 MVA.

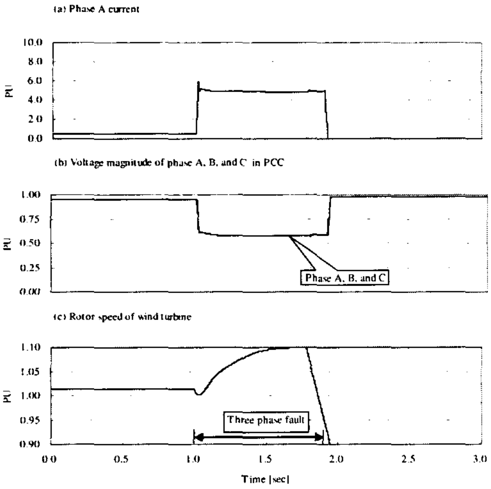

Fig. 6 Simulation results for the three-phase fault occurring 6 km from the bus 3 where the generating power of the wind farm is 4.5 MVA.

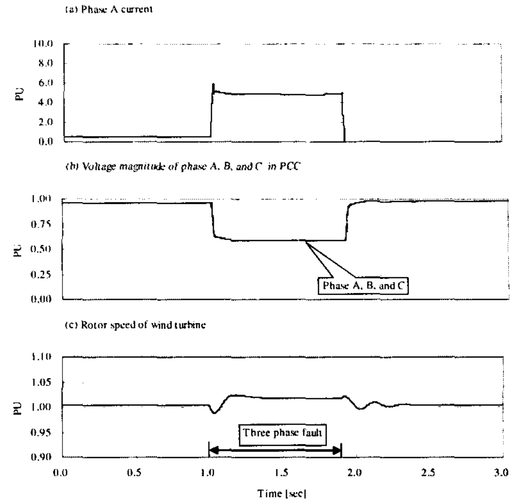

Fig. 7 Simulation results for the three-phase fault occurring 6 km from the bus 3 where the generating power of the wind farm is 2.25 MVA.

5. Adaptive Relaying for Stability of the Wind Farm

In this section, we describe the proper delayed time curves and the adaptive relaying of protective devices in the neighboring feeders in order to maintain the stability of a wind farm. Through simulation results in Sec. 4, the stability of the wind farm may be influenced by the fault type according to whether it is a multi-phase fault or not, the fault position according to whether it occurred in close or far proximity of the bus, and by the generating output of the wind farm.

5.1 Time-current curve of overcurrent relay

Fig. 8 represents the time-current curve (TCC) of an overcurrent relay applied in the Feeder C. The Region 1 and Region 2 in the figure are zones for describing the dynamics of a wind farm under the three-phase fault and the line-to-line fault, respectively. We exclude the zone for dynamics of wind generator under the single line to ground fault that can't have influence on the stability of the wind farm, and whose results aren't changed by the generating power of the wind farm and the fault position except in the case of a very large fault current. The fault with a very large current is isolated swiftly from the distribution network by the instantaneous operation of the relay.

5.2 Proper delayed time curves and adaptive relaying

Figs. 9 and 10 illustrate the proper delayed time curves of protective devices for maintaining the stability of the wind farm according to fault levels and generating outputs of the wind turbine generator under the three-phase fault and the line-to-line fault. In these figures, *WTout* means the output of the wind farm. Let's consider the proper delayed time curve for *WTout* = 1.0 pu in Fig. 9. The crossing point between the TCC of overcurrent relay and the proper delayed time curve is 500 % current magnitude at the time of 1 sec. If the fault current is larger than 500 %, then the wind turbine generator may not be operated in a stable condition under the TCC due to the long fault duration, and it is stopped by the breaker system. However, if the fault current is smaller than 500 %, the fault is isolated by the circuit breaker before the wind generator becomes unstable. We could recognize that the upper area of this crossing point is a stable region and that the other area is an unstable region. Therefore, a fast trip of overcurrent relay lasting a few cycles using the modified TCC of overcurrent relay in Figs. 9 and 10 for a fault having a fault current similar to the value in the crossing point, without spoiling the coordination of reclosers, fuses, and any other protective devices, can prevent the operation of the breaking system for protecting against mechanical damage to the wind generator. In creating the modified TCC of overcurrent relay, we must consider not only the coordination between protective devices, but also the fault types, fault level, and the generating output power of the wind farm. Adaptive relaying of protective devices taking into account the fault condition and the generating output would be an effective and useful method to improve the operational efficiency of the wind farm.

Fig. 11 represents a flow diagram of the proposed adaptive relaying. The available region for regulating protective devices can be changed according to the coordination of reclosers, fuses, and any other protective devices.

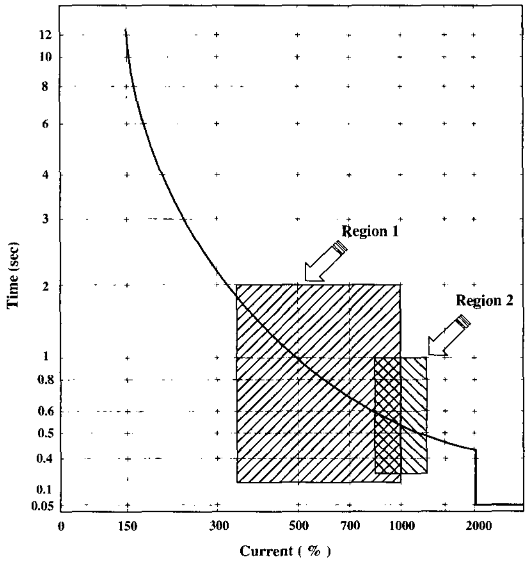

Fig. 8 Time-current curve of the overcurrent relay applied in the Feeder C.

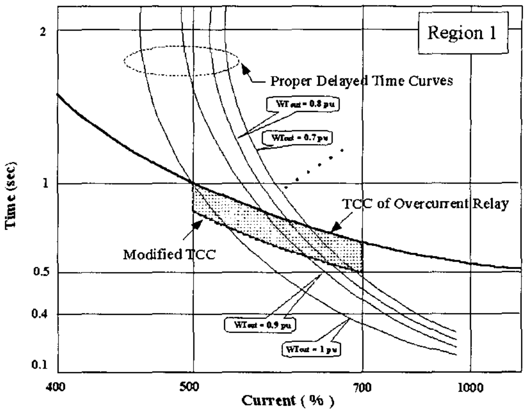

Fig. 9 Proper delayed time curves of region 1 in Fig. 8 for maintaining the stability of the wind turbine generator according to the generating output power of the wind farm in the case of three-phase faults.

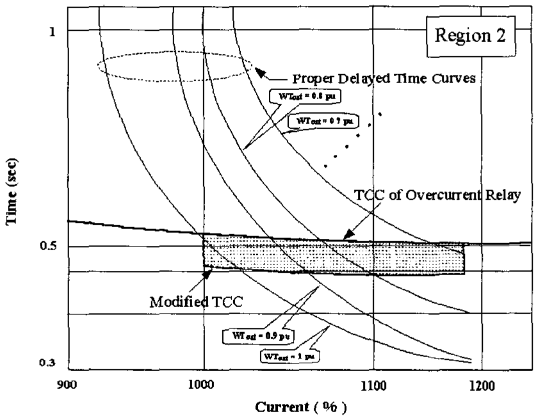

Fig. 10 Proper delayed time curves of region 2 in Fig. 8 for maintaining the stability of the wind turbine generator according to the generating output power of the wind farm in the case of line-to-line faults.

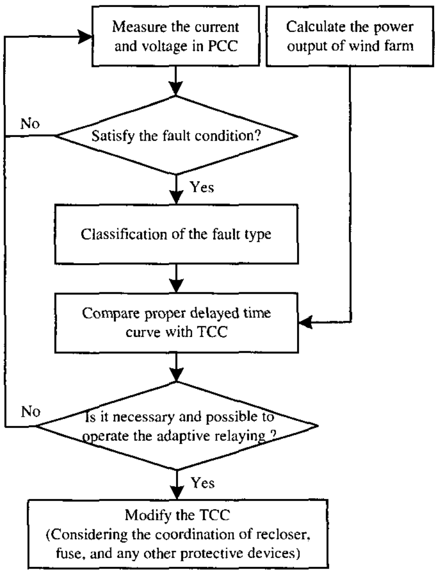

Fig. 11 Flow diagram of the proposed adaptive relaying of protective devices.

6. Conclusion

This paper describes the adaptive relaying of protective devices applied in the neighboring distribution feeders for reliable, efficient, and stable operations of a wind farm interconnected with distribution networks by dedicated lines. The adaptive relaying of protective devices takes into account the fault type, level condition and generating power output of a wind farm. We simulated the dynamics of the wind farm interconnected with the 22.9 kV Hoenggye distribution networks through the various fault conditions in the associated networks and the output power of the wind farm. The proper delayed operation time of protective devices considering the fault condition and power output of the wind farm could improve the operational reliability and stability of the wind farm.

We expect that these results of the adaptive relaying application can be applied to the other distributed generators such as synchronous generators and AC/DC/AC generators.

Appendix

This appendix provides the technical data for the Vestas V47-660 kW wound rotor type induction generator.

Table 2 Parameters of the Vestas V47-660 kW Induction Generator

Details	Wind Turbine
Rating	660 kW
Line to line voltage	690 V
Pole No.	4
Base power	660 kW
Stator connection	Delta
Stator resistance	0.00393 Ω
Stator reactance	0.060 Ω
Rotor resistance, internal	0.00467 Ω
Rotor res. ext. (2% slip)	0.0070 Ω
Rotor res. ext. (10% slip)	0.06233 Ω
Rotor reactance	0.0067 Ω
Iron loss	0.081 Ω
Magnetizing reactance	3.13 Ω

Acknowledgements

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Sung-Il Jang

He received his B.S., M.S., and PhD degrees in electrical engineering from Kangwon National University, Korea, in 1996, 1998 and 2003, respectively. Currently, he is with the BK21 Research Division for Information Technology at Seoul National University. His research interests include distributed generation interface with power system, power quality analysis and adaptive relaying.

Ji-Won Kim

He received his B.S. degree in Electrical Engineering at Kangwon National University. He is currently studying for his M.S. degree in Electrical Engineering at Kangwon National University. His research interests include distributed generation and power quality.

Kwang-Ho Kim

He received his B.S., M.S., and PhD degrees in Electrical Engineering from Seoul National University in 1988, 1990 and 1994, respectively. Since 1995, he has been with the Department of Electrical Engineering, Kangwon National University, and is currently an Associate Professor. He has been also with the Next-Generation Power Technology Center, Korea since 2001. His research interests include distributed generation interface with power systems and power quality analysis.