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Testing and Evaluation of Wind Power Plant Protection System

M. Kezunovic, B. Matic Cuka

Department of Electrical and Computer Engineering
Texas A&M University
College Station, Texas 77840 (USA)
Phone number: 1 979 8457509, e-mail: **kezunov@ece.tamu.edu**, **bmatic@tamu.edu**

Abstract. This paper discusses methodology and test set up which may be used for Wind Power Plant (WPP) planning and protection system evaluation. The test set up consists of a digital simulator, as well as a number of physical relays, recorders, software for system and relay modeling, signal editing, etc. Minimizing economic loss, in terms of using maximum output of wind generated power without interruption and causing minimum equipment damage due to faults, is the main benefit of having protection system that operates correctly. The correctness of operation is crucial during grid disturbances in preventing unwanted power plant disconnection and further system stability violation. Since there are no standardized requirements or methodology for WPP protection system testing, its evaluation is challenging and manly customized to fit a given solution. This paper discusses test requirements and test methodology to perform the evaluation in a comprehensive manner.

Key words

Wind Power Plant, Protection System, Testing, Digital Simulator, Relaying.

1. Introduction

The Department of Energy (DOE) estimated that by 2030 20% of total generation in the US will be from the wind [1]. In such a high penetration scenario the WPP will need to stay connected to the grid during grid disturbances to avoid severe effects on the power system due to lack of generation. This makes technical challenges due to requirements for dependability and security of protection operation. Regulators and system operators in many countries have established grid codes for operation and connection of WPP [2, 3, 4]. The objective is to guarantee WPPs can offer the system support as close as possible to what is expected from the conventional power plants. In the past, it was the common practice to disconnect the WPP during a grid disturbance. However, disconnecting large scale WPPs could cause instability of the power system. For this reason, WPPs are required to remain connected for an extended time period during a grid faults to allow fault clearing and to provide reactive support to the network and voltage restoration. The Federal Energy Regulatory Commission (FERC) in the USA proposed requirements for WPP fault ride-through (FRT) for specific time period and for particular voltage levels. FERC Order No. 661-A [5] specifies requirements that wind generating facility must remain operational during voltage disturbances on the grid. Fast active and reactive power restoration to the pre-fault values after the grid voltage recovery is included into WPP interface requirements. Beside this, the supervisory control and data acquisition (SCADA) needs to ensure appropriate real-time communications and data exchanges between the wind power producer and the grid operator.

The effect of WPP on the grid protection system cannot be ignored. The WPP sort circuit contribution must be taken into account in setting calculation for the grid protection system. The impact of the grid disturbances on WPP protection cannot be neglected either. As regulators are placing rules regarding WPP behavior during and after grid disturbance, correct operation of the WPP protection system is becoming the study focus and it requires comprehensive testing. Furthermore, the new questions arise such as can the same principles used for distribution system be used for WPP protection or should new protection schemes need to be designed.

In the literature there have not been significant work reported in this area. The IEEE 1547 standard [6] for interconnecting distribution resources in electric power systems is an attempt to providing technical specifications for testing of the WPP interconnection. The document is mainly focused on general technical requirements for grid system interconnection with WPP and provides general testing requirements applicable on WPP that will be disconnected during a grid disturbance. Beside this, the only work on testing reported in the literature relates to evaluation of new protection algorithms for WPP systems. So far there has not been standardized procedures or requirements proposed for WPP protection system testing.

2. Background

Due to significant level of wind power penetration into the grid, it is required that wind energy generation has high reliability. The goal of the FRT requirements is to prevent disconnection of an undesirable portion of power generation during an abnormal situation. For wind turbines the FRT requirements are formulated in a voltage versus time curve and the grid support requirement depends on the depth and duration of the voltage dip.

Fig. 1 shows the FRT requirements for the three-phase faults at transmission level for several European countries, USA, New Zealand and Canadian Hydro-Quebec utility. As it can be seen from the figure, there is a lack of standardization among the different countries and the FRT requirements highly depend on the characteristics of the power systems to which WPP is connected.

According to the USA code, WPP remains connected to the transmission system during three phase grid faults as long as the voltage at the point of common coupling is above the 15 % of rated voltage for period less than 625 ms and for voltage up to 80% of the rated voltage for period less than 3 s.

To maintain WPP connected to the grid during disturbance is a real challenge. First, the turbine generators and power electronic converters may be damaged. In the case of the double-fed induction generators (DFIG) the stator terminal voltage dips due to grid faults could induce a large current into the rotor circuit [11]. This may cause severe damage to the power converters, and results in disconnection of wind turbine generators. Second, certain profile of reactive and active power during and after fault condition at the Point of Common Coupling (PCC) with the grid has to be obtained, which means that reactive current injection has to follow certain rules to ensure grid voltage support during voltage sags. Moreover, it has to inject active current immediately after fault clearance, as shown in Fig. 2.

The voltage control must take place within 20 ms after the fault by providing a reactive current on the low voltage side of the generator transformer amounting to at least 2% of the rated current for each percent of the voltage dip [8].

3. Test Requirements

Dependability is a measure of the capability of a protective relay system to operate correctly when there is a fault. On the other head, security is a measure of the ability of protective relay system not to operate when there are no faults. These two factors are used as the criteria for evaluating the effectiveness of the relaying system [9]. In the past, the emphasis was on developing highly dependable protection systems. With new types of generation and line loading condition, relay tripping for no-fault disturbances is unacceptable due to cost reasons and potential deterioration of system stability. Security of relay operation for such reasons is becoming the focus of

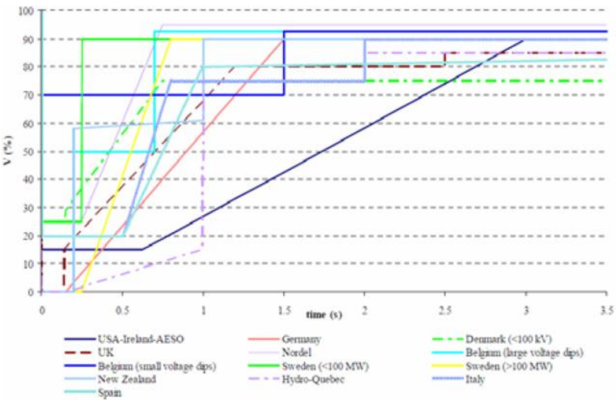

Fig.1. Fault Ride Through requirements [7]

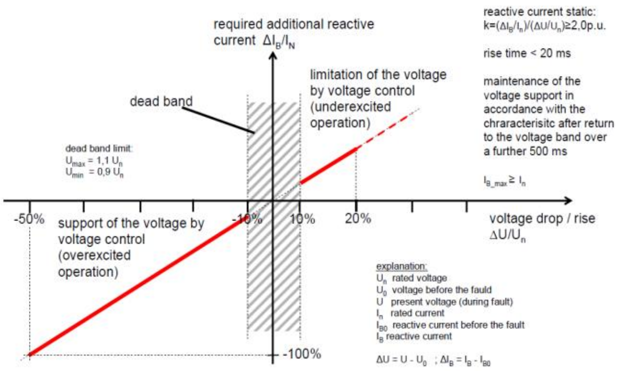

Fig. 2. Voltage support principle [8]

special interest and should be evaluated to the same extent as dependability.

The problems recognized in this paper may be classified as impact of the grid on the WPP protection system and the impact of the WPP dynamic behavior on grid protection system. Besides this, the dependability of the WPP relays may also be jeopardized by Wind Turbine Generators' (WTGs') Short Circuit (SC) current contribution [10].

Generally the grids are passive and they transport electric power unidirectional to the substations or customers. Introducing WPP into the system has a fundamental impact on the operation of the grid. It can lead to bi-directional power flows, change in grid losses, change in fault current levels and operation of the grid protection. The WPP SC current contribution level differs from contribution from conventional generation and depends on WGT type, wind energy penetration level, WPP vs. conventional generation capacity ratio and the WPP interface control. On the other head, the faults in the grid may cause severe under/over voltage, which may lead to relay misoperation.

Appropriate relay testing should validate the design of the relay logic, compare the performance of different relays, verify selection of relay settings, identify vulnerable conditions apt to causing unintended operations, and carry out post-event analysis for the

Table I. – Set of Events

WPP Protection System Testing	Dependability	Fault inside WPP (type, location, inception angle, generation condition, switching operation, FRT,etc.)
	Security	Switching events (transformer, capacitor bank, WTG)
Grid Protection System Testing	Dependability	Fault (type, location, inception angle, generation condition, wind vs. convention generation ratio)
	Security	Generation condition, wind vs. convention generation ratio, switching events, power swing
		Fault out of protection zone

Table II. Test types

Relay	Outcome
Model	Algorithm Sensitivity and Tuning
	Setting Sensitivity and Tuning
Device	Relay Settings Verification (Design test)
	Correctness of Operation (Application test)

understanding of unintended or incorrect relay behavior. The biggest challenge of testing and evaluation lies in defining comprehensive set of events that will cover all system behaviors that may affect protection system operation. Table I. summarizes possible events and parameters that need to be considered. Beside this, testing process requires accurate system and WPP models. Testing study with generalized wind plant models, which do not represent details of control mechanisms and WPP topology may cause misleading results.

According to the test objectives two different types of tests are defined: design test and application test. Design tests may be performed using phasors while application test may be performed using transients. The test waveforms may be generated through modeling and simulation, or in the cases of transients, through replaying recorded waveforms.

The objective of design test is to evaluate relay design functionality and operating characteristic, and to verify relay settings, which is achieved through implementation of comprehensive series of tests. The concern of this test is the response of the relays to phasor inputs that are approximating dynamic changes of signal waveforms during normal and fault conditions [12].

The objective of application test is to verify whether a relay can operate correctly under peculiar application circumstances in power system particularly during abnormal operating conditions. This type of test is to investigate whether the "real" performance of a protective relay complies with its expected performance [13]. The concern of this test is the trip/no trip response and relay operating time performance under specific scenarios. SC current contribution from the wind induction generators have different time decays and peaks compared to the conventional generations.

4. Test Methodology and Tools

The tests can be performed on either a relay model or an actual device. The relay model may be used to evaluate algorithm sensitivity and for tuning of relay settings while the tests with actual relay evaluates relay response and correctness of the operation, Table II.

Concerning the test waveforms, the recorded or/and simulated data may be used to perform relay testing. Intuitively it is preferred to use actual measurement data, as they reflect the real situation. However, the recorded data are often limited; most of the measured transients are captured for events that are not significant, while only a small part of the data contains valuable information. On the other head, the simulated data can be easily generated and made available as needed. Such data has its own disadvantages. It is as accurate as the system model and power system parameters are. The model accuracy can be increased using actual measurement to tune and verify model parameters.

The example of WPP protection system is shown in Fig. 3. In this example the WPP is connected to the transmission network. The grid area is protected by distance relays, the interconnection area by distance, overcurrent, frequency and differential relays. The substation bus, transformer and reactive compensation equipment are protected by differential protection. Overcurrent, under/over-voltage, frequency are used for collector feeders. The step-up transformer has differential protection, and Wind Turbine Generators (WTGs) have under/over voltage, under/over -frequency, over-excitation protection.

To perform protection system dependability validation the fault has to be simulated at different locations along collector system, interconnection and nearby grid as well as on the wind turbine generators, transformer and reactive power compensation device terminals. For each location various fault types have to be simulated at different incident angles and loading conditions to get better evaluation of the protection system behavior. To perform protection system security testing the no fault disturbances, such as transformer and capacitor bank switching, faults outside of protection zone, FRT, different wind energy penetration levels and simultaneous occurrence of those phenomenon have to be simulated. The relay trip outcome has to be compared with a predefined expected relay response.

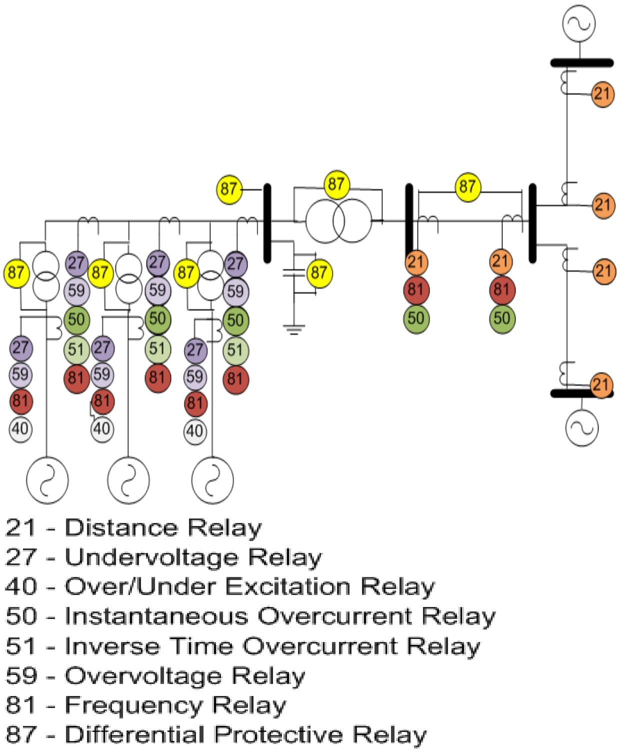

Fig. 3. WPP Protection System

The Fig.4. shows proposed lab set up. The first step is to set up database with the test signals. All signals need to have unique standardized COMTRADE [14] data format. The database is populated with recorded and simulated data obtained using PSCAD/EMTDC [15] simulation software.

The data from the database may be used to test both relay models and actual devices. The relay model testing consists of the following steps: implementing new relay algorithms in MATLAB or selecting existing PSCAD/EMTDC relay models, calculating relay settings for selected system, performing settings validation, running application test using data from the database and evaluating relay outcome based on expected response.

A digital simulator is used to generate "real" voltage and current signals for relay testing. A commercial software program called Relay Assistant [16] that communicates with digital simulator is capable of sending transient voltage and current data and receiving contact status data. The digital simulator applies the voltage and current waveforms to the relay and records the relay trip contact status. Relay Assistant has two distinct features that are useful for performing multiple tests: automated generation of test cases and automated replay of generated test cases. The graphical user interface includes test and signal views for convenient building, displaying and manipulating of the test session, tests and test waveform objects, as shown in Fig. 5. Beside preparing and replaying the test waveforms, Relay Assistant also aids the user in processing and analyzing relay responses. If an expected relay operation is known in advance, Relay Assistant compares it with the actual performance. This is very important for the batch cases where a large number of

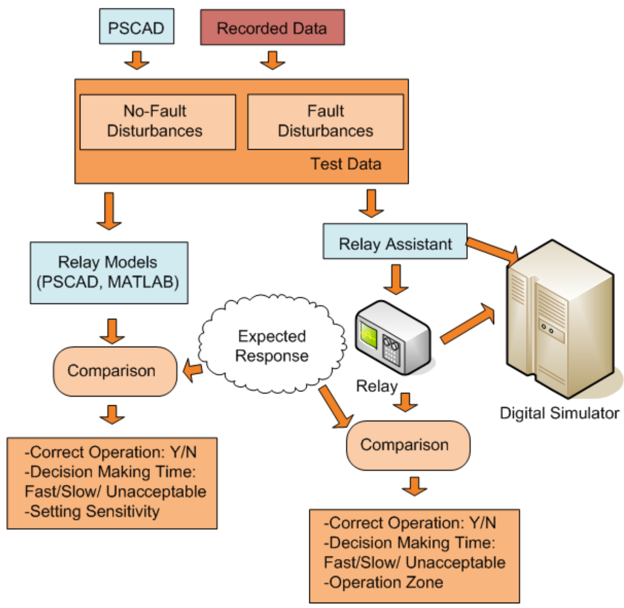

Fig. 4. Test System Set Up

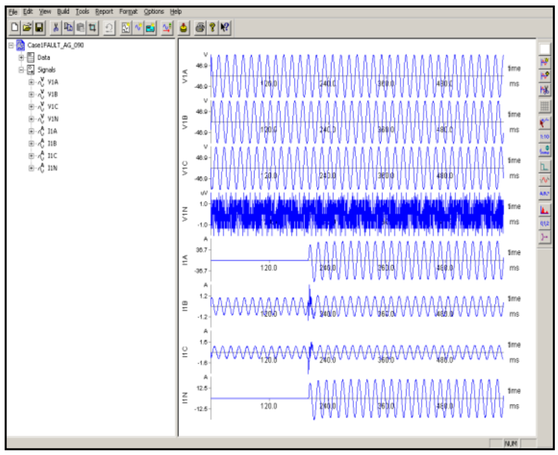

Fig. 4. Relay Assistant Graphical User Interface

test cases are conducted automatically in a single test session.

A. *Example*

This section illustrates short circuit current contribution from the WTG with full convertor for three-line-to ground fault (Fig. 5), double-line-to-ground (Fig 6) and single-line-to-ground (Fig. 7). It may be observed that SC levels are very low, about 10% above the rated current. The relay settings for the grid to which this WPP is connected have to be set lower than the relay settings for the grid to which the conventional power plant is attached. If not considered in setting calculation for grid relays the low level short circuit current contribution may lead to violation of relay dependability.

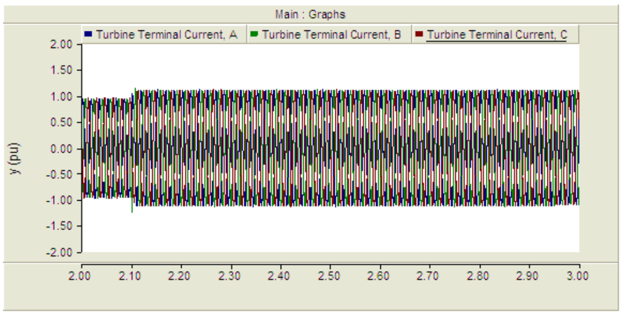

Fig. 5. Three line to ground fault [10]

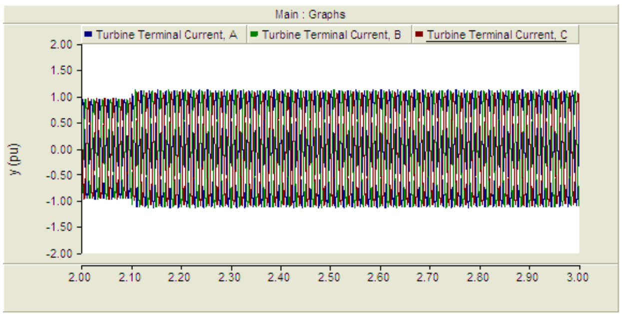

Fig. 6 Line- line to ground fault[10]

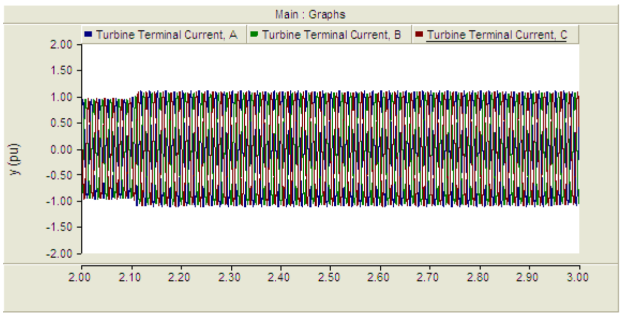

Fig. 7. Single line to ground fault [10]

4. Conclusion

The system for protective relay testing and methodology for WPP protection system performance assessment are described in this paper. The outcome is a test procedure for evaluating impact of the grid disturbances on the WPP protection system and effect of the WPP operation on the grid protection performance. The aim of this test procedure is to find vulnerability in WPP protection system operation and possible operation performance issues. Knowing this system reliability may be enhanced by improving relay settings accuracy and selecting appropriate relay applications. Beside this, the reported procedure may be used in WPP planning. The objective is to guarantee that WPPs can offer the system support as close as possible to what the role of the conventional power plants is.

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