International Journal of
Science and Engineering Investigations vol. 6, issue 60, January 2017
ISSN: 2251-8843

Impact of Variable-Speed Wind Turbines on Stability of Voltage and Current of Short Circuit-Modeled and Simulated in DigSILENT PowerFactory

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Abstract**-**Recently emerged developments in the field of renewable energies disclose that wind turbines and photovoltaic, as modern distributed generation systems in distribution network, are growing in popularity as new energy sources. One of the most prominent criteria relied upon traditional network is that its protection and planning in case of connecting a distributed generation source to power network, is insufficient; therefore, this interconnected electric power system, constantly makes the power system stability confronted with new challenges. This paper investigates the effects of distributed generation, specifically variable-speed wind turbines on distribution network and is particularly focused on the stability of power network during fault conditions and includes voltage dips, transients, and line short circuit fault currents in cases both single-phase and three-phase faults. Furthermore, solutions to overcome miscoordinations resulted from the integration of distributed generators (DGs) into power network have been brought into focus. This paper also investigates how influentially the integration of variable-speed wind turbines into power system enhances the whole system's operation affecting in several ways such as lessening power losses, betterment of voltage, and injecting current. Modeling and simulations have been performed in DigSILENT PowerFactory and the results are analytically presented.

Keywords- *voltage stability, wind turbine, renewable energy integration, microgrids, miscoordination, short circuit, variable-speed, distribution network, DG integration*

I. Introduction

With increase in power demand, and also the need for having a sustainable electric power system, high reliability in power system, better power quality, improvement on voltage profile conditions, and on the other side, lessening air pollution, power systems have been pushing towards using distributed generation resources. Over times, because of high loss of power system and its consequences, numerous damages are applied to power system, which are technically and economically appropriate neither for consumers nor for producers. Distributed generation such wind turbine does diminish these losses injecting current and improving voltage. Some variable-speed wind turbines use voltage source converter (VSC) to control the turbine; the wind turbines are controlled with VSC in simulations of this paper, while on the other hand, some are controlled through doubly-fed induction generator (DFIG). DFIG delivers power to the grid through stator and rotor terminals; the stator is directly connected to power system while rotor is connected to power system via AC/DC/AC power electronic converter at a variable frequency [1]. Having power systems interconnected with distributed resources such as variable-speed wind turbines, newly emerged issues such as voltage dips, over currents, instability of voltage and current, power quality difficulties, and voltage collapse show up. A voltage stability security assessment method was developed that could identify each region that experiences voltage collapse and the equipment outages that cause voltage collapse in each of regions. The method established whether the voltage collapse caused by a contingency is due to clogging voltage instability or loss of control voltage instability [2]. Reference [3] strives to achieve independence of the use of established models for power electrical systems, through artificial intelligence algorithms applied in the evaluation of the voltage profiles of the various system buses under study. It seeks to determine whether the behavior of sets of coherent bars can provide information on the stability of the electric power system. It suggests maintaining the continuity and quality of electricity supply implies the need for models that can represent the dynamics of the electric power systems in order to provide tools for the study of dynamics, both in situations of contingencies and demand changes, as in normal operation.

Reference [4] does a review on the recent research progress in voltage stability and security assessment of power systems of its time. It presents the fundamental concepts of voltage stability, gives a short recall of the classical voltage theory and different criteria currently available for predicting voltage collapse problems in power systems, which have been associated with multiple power flow solutions, bifurcation, dynamics of tap changers, stochastic loads, singular values, etc. Having power systems connected to renewable energy sources such as photovoltaics and wind farms, voltage and current instability problems emerge especially in case of short circuit faults. In order to prevent such issues in electric power systems, various actions should be taken from which one of the vitally important ones is voltage control. Reference [5] suggests that voltage control describes the process with which the voltage is maintained within an acceptable range for the customers connected to electrical power system and for this reason, great wind farms should be equipped with voltage control; in this way, the distributed resources shall not actively regulate the voltage level at the point of common coupling in which the distributed generation is connected to the power system and other local electric power systems.

This paper, having pointed prominent points out above, introduces how modern variable-speed wind turbines impact upon stability of voltage and current of short circuit. By occurring faults in power system, one or some of the feeders and therefore some equipment may get eliminated from the system due to the tripping command of protection system utilities such as over-current and directional relays by circuit breakers. This, undoubtedly, will affect the distribution system and lead to voltage instability and endangering system's security which is of great importance. In order to prevent this tough problem, it should be strived to forecast voltage collapse issues which in case of taking place, contribute in different parts of distribution system such as power flow and magnitude of currents and voltages.

II. Voltage Stability Security

Voltage Stability Security is a vitally prominent and delicate aspect of power system which must be coped with delicately and efficiently. The term – voltage stability – communicates the concept of the ability of power system for maintaining the acceptable steady voltage in all bus bars of the power network in both normal operation conditions and disturbance conditions. Disturbance can be sudden outage of one of the equipment or gradual increase of load. When a disturbance, increase in load demand, or a change in system conditions causes a great uncontrollable drop in voltage control, power system goes to voltage instability conditions. The main reason of instability is power system's failure in providing the requested reactive power. Voltage stability, in fact, is a subset of power system stability; thus, stability definition in this area is similar to stability definition in other dynamic systems. Voltage and current instabilities result in miscoordinations in power network's protection system which consists of circuit breakers and relays. Inverse time over-current relays are utilized in the protection system of the distribution system of this study shown in Figure 5.

Distributed energy (DE) contribution and different load sorts along with the presence of protection-oriented elements such as overcurrent relays create an interconnected power network. The coordination of overcurrent relays is studied in [6]; this reference suggests using an accurate analytical method it is possible to calculate the impedance matrix of the network in fault conditions for determination of the critical fault point precisely correct. One of the focus points of this paper to analyze the stability of voltage and current of short circuit is the trip time of circuit breakers (CBs) of the protection system in distribution system. Circuit breaker's trip time differs depending upon the magnitude of fault current. In case of a three-phase fault, the protection system takes a shorter time for clearing fault since the magnitude of fault current is large. On the other side, in case of a single-phase fault, the protection system takes a longer time for tripping the fault due to lower level of fault current in comparison to three-phase fault case; thus the fault current remains on the system for a longer time and this, seriously, endangers the stability of the voltage in power system. One of the prominent ways to prevent voltage instability in power systems is to assess and calculate the feasible load capacity for a specific power network [7]; there are different methods to calculate this which are not studied in this paper. The determined distinctive limit of voltage stability depends on load trip instruction and stability evaluation.

III. Voltage Stability During DG Integration

Integration of a variable-speed wind turbine into a power network comes up with several consequences. An integrated variable-speed wind turbine as a distributed resource (DR) contributes in short-circuit current and in voltages as well. Integration of DG not only contributes in voltages and short-circuit current, but in other aspects of power system as well. In order to figure these aspects vividly out, [8] can be referred in which standards for interconnecting DR with electric power systems are illustrated; it provides the readers with requirements and specifications of interconnection such as different methods for DR performance and subsequently their impact on the power system, alleviation of power system's area and local limitations, islanding, safety, and power quality. Interconnection test specifications and requirement are also included in IEEE standard 1547.

For achieving optimal operation of microgrid with renewable energy sources, an expert multi-objective AMPSO (Adaptive Modified Particle Swarm Optimization algorithm) is presented in [9] which is accompanied by a back-up Micro-Turbine/Fuel Cell/Battery hybrid power source in order to regulate the power mismatch and to store the excess of energy when necessary. Since distributed generators (DGs) lessen losses through injecting current and improving voltage, one of the prominent matters of microgrids is to determine the most appropriate location for connecting DG to power system in a way that comes with the highest benefits for the system; benefits such as diminishing the power losses and anticipated miscoordinations. One of the appropriate locations for DG installation is where the load quantity is large since a considerable part of losses in power system takes place distant from power source. This is because voltage sag is higher in distant locations. Other suitable locations for distributed generators installation are the busbars which are not close to other power sources. Several criteria are taken into account to opt for the best location for DG in power network; this matter is out of this paper's focus domain. In order to perform precise studies on different short circuit cases, single-phase to ground fault and three-phase to ground fault cases are analyzed in this section of the paper, respectively. A summary of the simulation results then is presented in Table 1.

A. *Single-phase to ground fault occurred at feeder 11*

In a distribution system integrated with variable-speed wind turbine, in case of a single-phase fault in one of the feeders, the fault causes an increase in voltage magnitude in different feeders in comparison to the case where there is no distributed generation unit. As the wind power capacity of the wind turbines goes up, this increase in voltage magnitudes is more giant. Furthermore, it is observed that with the integration of a variable-speed wind turbine the protection system takes a longer time to detect the fault and this time extends by increasing the power of the wind turbine. This is due to the fault currents and is discussed in the next section. The waveforms of voltage magnitudes in case of a single-phase fault at feeder 11 of the simulated distribution system (figure 5) in 3 cases: no DG, 3MW variable-speed wind turbine integrated, and 6MW variable-speed wind turbine integrated are illustrated in Figure 1. As it is depicted, the voltage magnitude at feeder F11 is 0.974 p.u. in case of no turbine, and 0.995 p.u. and 1.019 p.u. in cases with wind turbines 3MW and 6 MW, respectively. This, vividly, proves that in case of a single-phase fault, the higher the wind power capacity is, the smaller the voltage magnitude drop will be. The duration of voltage sag is dependent on the fault clearing time. When a wind turbine is added to the system, the magnitude of voltages drops as it is shown in Figure 1.

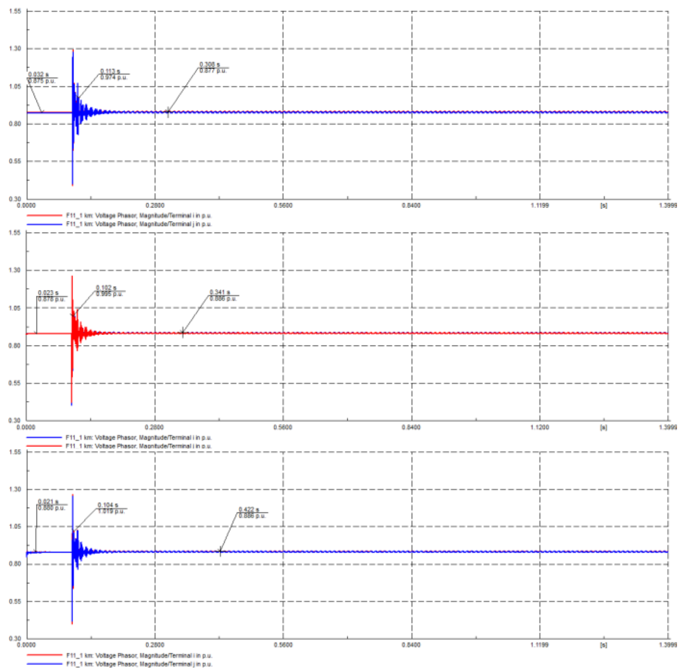

Figure 1. Voltage magnitudes in case of a single-phase fault at feeder F11 in three cases; without DG, with 3MW variable-speed wind turbine, and with 6MW variable-speed wind turbine, respectively

Electric current path is case of a single-phase to ground fault is vividly illustrated in Figure 2.

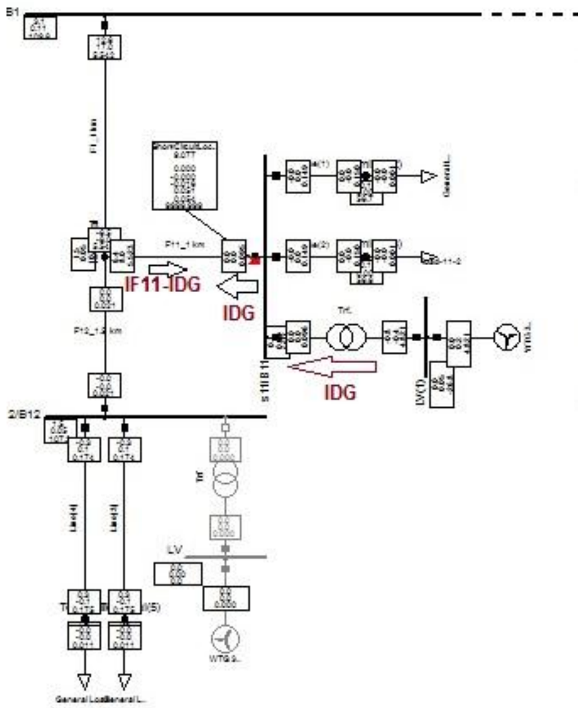

Figure 2. The magnitude of phase to ground fault at feeder 11

B. *Three-phase to ground fault occurred at feeder 11*

In case of a three-phase fault, on the other hand, with contribution of a wind turbine the voltage magnitude descends in comparison with no-DG-connected case; and the higher the wind power capacity is, the larger the voltage magnitude drop will be. In this part of the simulation, a three-phase fault is applied at 0.1 second. The simulation runs for 1.4 s with a time step of 0.0001 s. When a fault is applied to the same studied feeder, it is observed that the magnitude of fault current increases. Tripping time of the circuit breaker is reversely dependent upon the magnitude of fault current.

Pre-fault, during fault, and post-fault voltages and fault detection times of the protection system's circuit breaker in case of single-phase fault detected by the protection system are exhibited in Table 1. In case of a three-phase fault, the magnitude of fault current is greater than its magnitude in case where no wind turbine is attached to the bus bar number 11 with the feeder. This is completely opposite of single-phase to ground fault in which the magnitude of fault current is smaller than its magnitude in case no wind turbine is attached to the bus bar with the feeder; as illustrated in Figure 4. Thus, there circuit breaker of the protection system will trip mistakenly due to great magnitude of fault current; this large fault current magnitude results in faster operation of the circuit breaker. In case of a three-phase fault, on the other side, wind turbine contributes in fault as well and therefore the magnitude of fault current increases and consequently some miscooradinations in the operation of the circuit breakers and the relays of the protection system show up which are no desirable.

TABLE I. THE MAGNITUDE OF VOLTAGE DIPS AND TRIPPING TIME OF THE CIRCUIT BREAKER AT FEEDER 11 FOR 3 CASES: NO WIND TURBINE, 3MW WIND TURBINE, AND 6MW WIND TURBINE IN FAULT CONDITIONS

Fault Location	Wind Power Capacity	Fault Type	Voltage at F11 (p.u.)			Fault Tripping Time (ms)
			Pre-Fault	*During Fault*	*Post-Fault*	
Feeder F11	*No Wind Turbine*	*Phase to Ground*	0.875	0.974	0.877	117.8
		Three-Phase	0.872	0.165	0.054	100.2
	3MW Wind Turbine	*Phase to Ground*	0.878	0.995	0.886	121.5
		Three-Phase	0.878	0.121	0.054	87.2
	6MW Wind Turbine	*Phase to Ground*	0.880	1.019	0.887	123.1
		Three-Phase	0.881	0.119	0.054	58.1

Electric current path is case of a three-phase to ground fault is vividly illustrated in Figure 2.

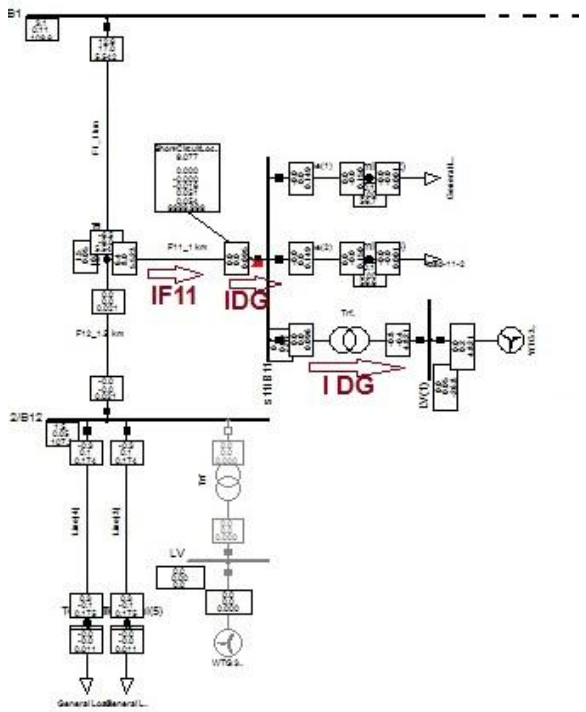

Figure 3. The magnitude of three-phase to ground fault at feeder 11

IV. METHODS TO OVERCOME MISCOORDINATION OF PROTECTION SYSTEM

With the presence of DG in power network and consequently contribution in faults some miscooradinations in the operation of the circuit breakers and the relays of the protection system show up which have to be prevented and therefore a few solutions have been devised for this purpose. The mentioned miscoordinations differ depending on various criteria such as fault type, fault location, DG's type, size, number, and location. Increase in the magnitude of fault current in case of three-phase fault is one the problems leading in wrong coordination of relays and circuit breakers. The very first method which is recommended by this paper is installation of directional over-current relay at the point of common coupling (PCC) where DG unit is connected to power system. The settings of the relay such as CT and current settings can also be adjusted due to the nature of the considered power network and also involved elements. This can work in a successful way sorting the protection-oriented problems out and has been utilized in the simulation of the power network of this study.

The second solution suggests making modifications to the relay setting based on the location and number of the DGs in the network [10]. Reference [10] also comes with introduction and clarification of another method for this purpose which is determination of the capacity of DG at each node in a way that miscoordination does not occur; this method consists of two cases; in the first case just one DG has been taken into consideration at each node, but in the second case presence of 2 or more DGs in separate nodes has been considered. The very first objective of devising and utilizing methods to overcome miscoordination of protection system is standing up to power losses in power system. In this regard, reference [11] comes up with a method in which using a combination of analytical and genetic algorithm methods multiple DG units allocation in distribution network for loss reduction is achieved. As overcurrent relays are used in interconnected distribution network of this study, it is worth to remark that an optimized method for overcurrent relays coordination in interconnected networks is proposed in [12] which reaches this objective using Fuzzy-Based GA Method; it proposes mathematical formulation of directional overcurrent relay (OC) coordination in interconnected networks and uses fuzzy-based Genetic Algorithm (GA) to optimize the proposed objective function (OF) for optimal coordination if OC relays.

V. CURRENT ROLE IN POWER NETWORK STABILITY DURING DG INTEGRATION

In case of single-phase fault, the magnitude of fault current in faulted feeder drops by integration of a wind turbine; as the integrated wind power capacity increases the fault current meets a bigger fall. Hence by addition of a wind turbine to the distribution network, the protection system takes a quite longer time to clear the single-phase fault as it is detected. This time which is called fault clearing time expands as the capacity of wind power rises. Therefore, in case of single-phase fault, the fault remains on the power network for a longer time. Moreover, when a three-phase fault takes place in the distribution system, in case of an integrated variable-speed wind turbine, the magnitude of fault current in faulted feeder goes up comparing to the case with no DG attached on the feeder.

By any increase in wind power capacity, fault current magnitude increase gets larger as well. Thus, it can be proclaimed that by addition of a wind turbine to distribution network, protection system takes a shorter time to clear the three-phase fault as it is detected. This fault clearing time gets shorter as the capacity of wind power rises. In this regard, the performed simulations of this paper disclose that having attached a 6 MW variable-speed wind turbine on the power system, the protection system takes a shorter time to clear the single-phase fault in comparison to the case where a 3 MW wind turbine is attached on the same feeder. Figure 4 exhibits that line's nominal current is 400A when no DG is connected to the network and it decreases to 270A in case of a 3MW variable-speed wind turbine integrated to the distribution network being connected to busbar 11; having connected a 6MW wind turbine to busbar 11, the nominal current of line 11 subsequently drops to 226A. The magnitude of single-phase fault current consequently decreases.

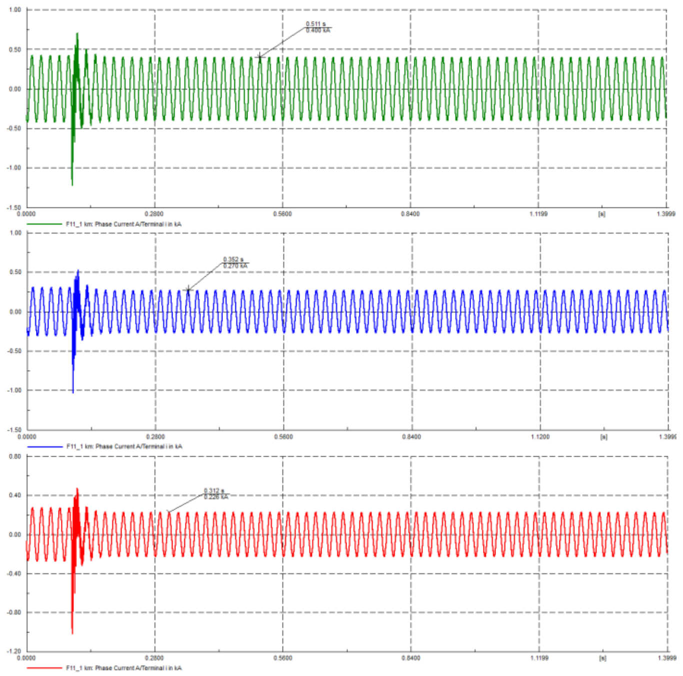

Figure 4. Fault current magnitudes in case of a single-phase fault at feeder F11 in three cases; without DG, with 3MW variable-speed wind turbine, and with 6MW variable-speed wind turbine, respectively

VI. The Modeled and Simulated Distribution Network

The studied system is a distributed 20 KV system connected to an external power grid with a voltage level of 130 KV through a 130/20 KV transformer. The low-voltage side of the transformer is grounded with a 900 Ω resistor in order to make the level of fault current descend. The high-voltage side of the transformer, similarly, is grounded but directly to maintain the transformer protected during lightning and fault conditions. The modeling and simulations have been implemented in DigSILENT PowerFactory. All cables are single-core XLPE cables in ground, with a rated current of 0.58 KA and aluminum material. The cross section of cables in 20 KV and 130 KV parts are 800 mm2 and 2000 mm2 respectively.

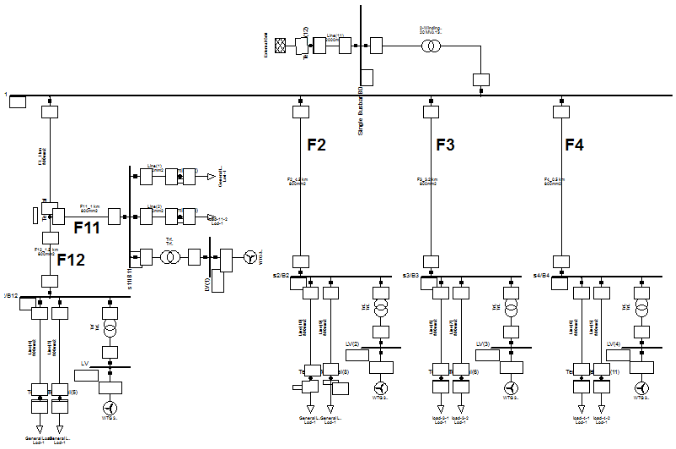

Figure 5. The single-line schematic of the modeled distribution network

VII. Conclusion

Renewable energy integration into electric power system, along with all its pros and enhancement, comes with several issues for the power system. In this paper, the impacts of integration of renewable energy – particularly variable-speed wind turbines – into power network is studied. One the most vitally important issues to be pointed out is instability in voltage and current of the short circuit in case of faults which causes miscoordination in protection system of the power network. The studied 20KV distribution network is analytically investigated. The operation of protection system's circuit breakers and over-current relays in case of faults, in particular, single-phase to ground and three-phase to ground faults, is taken into consideration.

In addition, due to the emerged miscoordinations in the operation of protection system in the presence of DG, a few solutions are reviewed and presented. The presented and recommended method of this paper to utilize in order to overcome miscoordinations of protection system of power network is installation of directional over-current relay at the point of common coupling (PCC) where DG is connected to the power system; this can work in a thriving way sorting the remarked protection-oriented problems out. A couple of more solutions are reviewed which are making modifications to the relay setting based on the location and number of DGs and determination of the capacity of DG at each node in a way that miscoordination does not take place. The latter method consists of two cases. Finally, the 20KV radial distribution network modeled and simulated in DigSILENT PowerFactory software is introduced analytically investigated.

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