Impacts of Short Circuits on Wind Turbine Generator Interfaced Radial Distribution Feeder Sequence Impedance.

Kemei P. Kirui [1], David K. Murage[2], and Peter K Kihato[3]

***Abstract*—** With the global increase in wind turbine distributed generators penetration, the need for a detailed assessment of the impacts of the wind turbine generators (WTGs) on a power systems distribution network operations has become critical. This assessment is normally done to allow for the simulation of the dynamic response of the distribution network to major disturbances like the short circuits once wind turbine generators (WTGs) are connected. Penetration of the wind turbine generators into a distribution network has great impacts on the sequence impedance of the network with some factors contributing to this impacts being: The size of the WTG penetrating the distribution network, the location at which the WTG is connected and the Type of the WTG interfacing technology used.

An important aspect of the WTGs studies is to evaluate their impacts on the distribution power system network positive, negative and zero sequence impedances under differing operating conditions. The magnitudes of the sequence impedances are important for analyzing the short circuit handling capacity of the distribution network. Due to the topological and operational differences between the different types of WTGs interfacing technologies , the electrical generators design industry have divided wind turbine generators into four different types labeled as Type I, Type II, Type III and Type IV.

The main concern of this paper was to investigate the effects of integrating each of the four types of WTG configurations on the power systems distribution network's positive, negative and zero sequence reactance/impedances. The radial distribution feeder studied was the IEEE 13 nodes radial test feeder and it was modeled and simulated for the sequence reactances/impedances analysis

***Keywords*—** Distributed Generators, Type I-IV WTG, Positive, Negative and Zero Sequence Reactances.

Kemei P. Kirui, Msc Student, Department of Electrical and Electronic Engineering, JKUAT, (phone:+254723479169; e-mail: kemei.kirui@gmail.com)

David K. Murage, Department of Electrical and Electronic Engineering, JKUAT, (e-mail: dkmurage25@yahoo.com).

Peter K. Kihato, Department of Electrical and Electronic Engineering, JKUAT, (e-mail: pkihato@jkuat.ac.ke),

I. Introduction

A. Distributed Generation Interfacing Technologies into a Distribution Power Systems Network

All of the DGs utilizing various types of renewable energy resources fall into two major categories regarding their modes of interfacing with the main grid. Normally inverters are used in DG systems after the generation process, since the generated voltage may be in DC or AC form but it is required to be changed to the nominal voltage and frequency of the distribution network. Therefore, this voltage has to be converted to the nominal requirements of the distribution network by use of inverters [1]. DG interfacing technologies provides the protection that allows a DG unit to operate in parallel with the main utility grid. Protection requirements for connecting DG units into the distribution network are generally established by each utility and should adhere to the required standards. The interfacing requirements established at the point of common coupling between the utility and the DG address the concerns of both the DG owner and the utility and it should satisfy the main utility requirements before the DG is connected to the main grid[2][3]. The two major categories of DG interfacing technologies into the main grid are: [2].

i. Directly Interfaced Distributed Generators (DIDG)
ii. Inverter Interfaced Distributed Generators (IIDG)

The interfacing schemes used in IIDG maintains a constant output voltage, active and reactive power that matches the desired predetermined set points of the main utility grid [4][5]. Fault currents in critical conditions with an IIDG connected into the power grid are limited by the inverters having current limiting ranges, hence the fault current share injected by IIDGs is not as much as DIDGs which shares most of their fault currents with the main utility grid [5][6]. The DIDG type has the ability to easily synchronize with the grid and produce active and reactive power simultaneously [5]. Complexity is added to the network when different types of DGs in terms of their fault current responses are interconnected together in a distribution network since they all play a major role in the distribution network's response during fault condition.

There are three basic interfacing technologies for DGs namely the synchronous generators, the induction generators and the power electronics devices [7]

II. Wind Turbine Generator Technologies

A. Type I Wind Turbine Generator

Generic models have been developed for four major WTG topologies the first topology being referred to as a Type I WTG. This machine is pitch-regulated and drives a squirrel cage induction generator which is directly coupled to the grid. Fig 1 shows the layout of a Type I Wind Turbine Generator (WTG) [8]. Due to the poor power factor present during induction machine operation, compensating capacitor banks are used near the terminals of the Type I WTG [9].

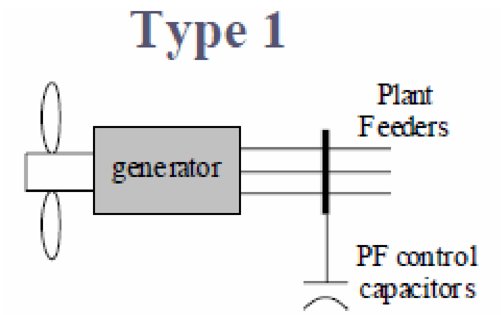

Fig 1: Type I Wind Turbine Generator

B. Type II Wind Turbine Generator.

Type II WTG is a variation on the Type I WTG. It is an induction generator operating at variable slip. It utilizes a wound rotor induction generator whose rotor windings are brought out via slip rings and brushes and then coupled to a resistive bank [9]. Fig 2 shows the layout of a Type II WTG. A disadvantage of using the Type I WTG is the large torque swings that occur with turbulence in the wind speed. By varying the resistance of the rotor windings of the type II WTG, a more dynamic response to wind turbulence can be achieved by allowing a change in speed in the generator rotor reducing the large torque swings hence prolonging the life of its mechanical components [8]. Type II WTG still requires compensating capacitor banks to achieve its operations within the required typical power factor limits.

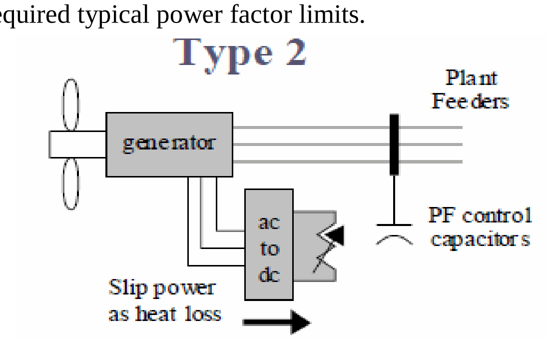

Fig 2: Type II Wind Turbine Generator

C. Type III Wind Turbine Generator.

Type III wind turbine generator is pitch-regulated and features a wound rotor induction generator with an AC/DC/AC power converter connected between the rotor terminals and the main grid. The generator stator winding is directly coupled to the grid [8]. Fig 3 shows the layout of a Type III WTG. The Type III wind turbine generator is known as a doubly-fed induction generator (DFIG). Rather than its rotor windings being connected to dynamically controlled resistors, there is a power converter between the rotor windings and the grid. The addition of the power converter between the rotor windings and the grid allows the same benefits of the Type II design without the resistive losses and the ability to provide reactive power support without external capacitor banks hence a variable speed operation that allows for a more efficient energy capture below rated wind speeds [8]. In order to protect the power converter from high short-circuit currents, protective devices such as a “crowbar” or a “chopper” circuit are used. The type of protective device used to protect the rotor converter has a significant impact on the short-circuit behavior of the Type III machine [9].

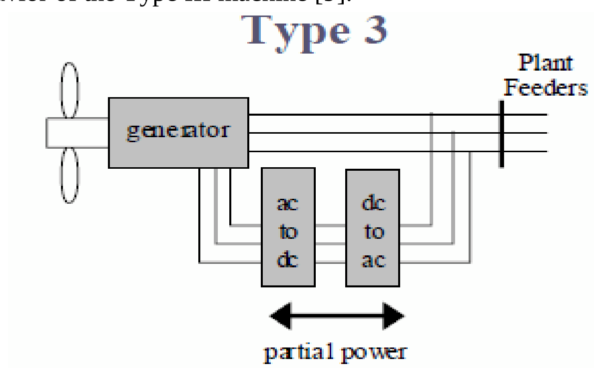

Fig 3: Type III Wind Turbine Generator

D. Type IV Wind Turbine Generator.

Type IV WTG is pitch-regulated and features an AC/DC/AC power converter through which the entire power of the generator is processed as shown in Fig 4 [8]. The power converter allows for independent control of the quadrature and the direct axis output currents at the grid interface, providing fast active and reactive power control over a wide range of generator speeds [8]. Type IV WTG is decoupled from the grid through a power converter which is rated to the full output of the turbine. It has the same advantages of the Type III design with variable speed operation and reactive power support. Since the generator is decoupled from the grid, the stator windings can operate at variable frequencies hence expanding the types of the machines that can be used with the most common being the synchronous machines and the squirrel cage induction machines [9].

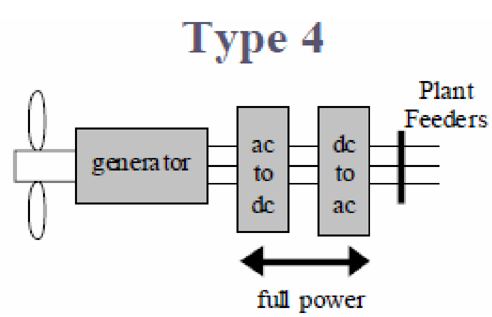

Fig 4: Type IV Wind Turbine Generator

III. IEEE 13 Node Radial Test Feeder Configuration

The IEEE 13 node radial test feeder is a short, unbalanced and relatively highly loaded 4.16kV feeder. The features of the IEEE 13 node radial test feeder is basically the presence of: A 5000kVA 115kV/4.16kV Delta/Star substation transformer connected to the swing/grid node; One substation voltage regulator consisting of three single phase units connected in star; Eight overhead distribution lines and two underground cables with variety of lengths and phasing; Unbalanced delta and star connected distributed and spot loads; Two shunt capacitor banks one having a single phase connection at node 611 and the other a three phase connection at node 675; and a 500kVA 4.16kV/0.48kV star/star solidly grounded in-line transformer connected between node 633 and node 634. Fig 10 shows the schematic layout of the IEEE 13 node radial test feeder used as the model which was simulated without showing the different connected loads or the nature and configuration of the distribution components of the network [10]. The effect of the voltage regulator located at node 650 is not taken into consideration in the simulations, calculations and analysis and the short circuit currents contribution by the motoring loads was considered minimal at 1% of their Locked-Rotor Current (LRC). The short circuit contribution by the WTGs is set at 600% of their Locked-Rotor Current (LRC)

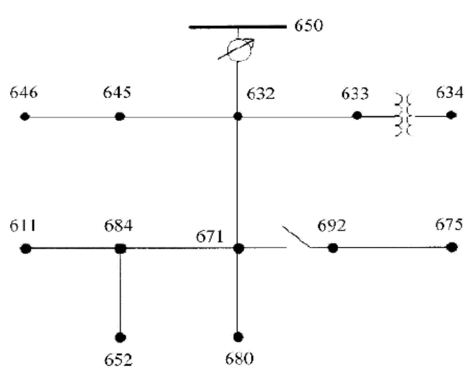

Fig5: The IEEE 13 Node Radial Test Feeder Schematic Diagram

IV. Impacts of WTG Interfacing Technology on IEEE 13 Node Radial Test FEEDER SEQUENCE REACTANCE

Table I: Positive/Negative Sequence Reactance with 1MW and 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 634

NODE ID	Positive/Negative Sequence Reactances in Ohms				
	NO WTG	1MW Type I/II/III WTG	1MW Type IV WTG	3MW Type I/II/III WTG	3MW Type IV WTG
NODE650	3.68607	1.78175	2.96611	1.21979	1.7483
NODE632	3.90891	1.765	3.0783	1.13086	1.70289
NODE633	3.98072	1.75698	3.1003	1.09784	1.66951
NODE634	0.06219	0.02154	0.0435	0.0093	0.01678
NODE645	3.98114	1.83727	3.1506	1.20315	1.77517
NODE646	4.02868	1.88481	3.1981	1.25068	1.82271
NODE671	4.13252	1.9899	3.3025	1.35615	1.92793
NODE692	4.13252	1.9899	3.3025	1.35615	1.92793
NODE675	4.15143	2.00886	3.3215	1.37513	1.94695
NODE684	4.18005	2.03743	3.35	1.40368	1.97546
NODE611	4.26642	2.1238	3.4364	1.49005	2.06183
NODE680	4.24553	2.10291	3.4155	1.46916	2.04094
NODE652	4.23085	2.08823	3.4008	1.45448	2.02626

From table I it can be seen that there is a reduction in both the positive and negative sequence reactances once WTGs are connected at node 634. Type I/II/III WTGs cause the highest reduction on both the positive and negative sequence reactances as compared to Type IV WTGs. Type I, Type II and Type III WTGs causes equivalent reduction of the positive and negative sequence reactances hence they exhibit similar characteristics on both the positive and negative sequence reactances reduction rate. As the WTG capacity increases from 1MW to 3MW, there is a further reduction on the feeder positive and negative sequence reactances.

Table II: Positive Sequence Reactance with 1MW and 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650

NODE ID	Positive Sequence Reactances in Ohms				
	NO WTG	1MW Type I/II/III WTG	1MW Type IV WTG	3MW Type I/II/III WTG	3MW Type IV WTG
NODE650	3.68607	1.47508	2.978	0.67	1.432
NODE632	3.90891	1.69977	3.201	0.895	1.657
NODE633	3.98072	1.77167	3.273	0.967	1.729
NODE634	0.06219	0.03279	0.053	0.022	0.0322
NODE645	3.98114	1.77204	3.274	0.968	1.729
NODE646	4.02868	1.81958	3.321	1.015	1.776
NODE671	4.13252	1.9247	3.426	1.121	1.882
NODE692	4.13252	1.9247	3.426	1.121	1.882
NODE675	4.15143	1.94366	3.445	1.14	1.901
NODE684	4.18005	1.97223	3.473	1.168	1.929
NODE611	4.26642	2.0586	3.559	1.255	2.016
NODE680	4.24553	2.03771	3.539	1.234	1.995
NODE652	4.23085	2.02303	3.524	1.219	1.98

Table III: Negative Sequence Reactance with 1MW and 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650

NODE ID	Negative Sequence Reactances in Ohms				
	NO WTG	1MW Type I/II/III WTG	1MW Type IV WTG	3MW Type I/II/III WTG	3MW Type IV WTG
NODE650	3.68607	1.40456	2.978	0.62698	1.43181
NODE632	3.90891	1.6293	3.201	0.85237	1.65666
NODE633	3.98072	1.70121	3.273	0.92432	1.72858
NODE634	0.06219	0.03186	0.053	0.02152	0.03222
NODE645	3.98114	1.70158	3.274	0.92467	1.72895
NODE646	4.02868	1.74911	3.321	0.9722	1.77649
NODE671	4.13252	1.85427	3.426	1.07782	1.88175
NODE692	4.13252	1.85427	3.426	1.07782	1.88175
NODE675	4.15143	1.87323	3.445	1.0968	1.90079
NODE684	4.18005	1.90181	3.473	1.12535	1.92929
NODE611	4.26642	1.98818	3.559	1.21172	2.01566
NODE680	4.24553	1.96729	3.539	1.19083	1.99476
NODE652	4.23085	1.95261	3.524	1.17615	1.98009

From table II and table III, it can be seen that there is a reduction in both the positive and negative sequence reactances once WTGs are connected at node 650. Type I/II/III WTGs cause the highest reduction on both the positive and negative sequence reactances as compared to Type IV WTGs. When WTGs are connected at node 650, type I/II/III WTGs do not exhibit similar characteristics on the rate of reduction of both the positive and the negative sequence reactances like when they are connected at node 634. There is a higher reduction on the positive sequence reactance as compared to the negative sequence reactance for Type I/II/III WTGs at node 650.

Table IV: Zero Sequence Reactance with1MW and 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 634

NODE ID	Zero Sequence Reactances in Ohms				
	NO WTG	1MW Type I/II/III WTG	1MW Type IV WTG	3MW Type I/II/III WTG	3MW Type IV WTG
NODE650	0.2768	0.2768	0.2738	0.2768	0.26557
NODE632	0.97988	0.97988	0.9212	0.97988	0.79443
NODE633	1.17125	1.17125	1.0811	1.17125	0.89315
NODE634	0.0248	0.0248	0.0209	0.0248	0.01378
NODE645	1.18825	1.18825	1.1296	1.18825	1.00281
NODE646	1.31746	1.31746	1.2588	1.31746	1.13202
NODE671	1.68289	1.68289	1.6243	1.68289	1.49761
NODE692	1.68289	1.68289	1.6243	1.68289	1.49761
NODE675	1.73127	1.73127	1.6727	1.73127	1.546
NODE684	1.8121	1.8121	1.7535	1.8121	1.62681
NODE611	1.89837	1.89837	1.8398	1.89837	1.71308
NODE680	2.03491	2.03491	1.9763	2.03491	1.84963
NODE652	1.93707	1.93707	1.8785	1.93707	1.75178

Table V: Zero Sequence Reactance with 1MW and 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650

NODE ID	Zero Sequence Reactances in Ohms				
	NO WTG	1MW Type I/II/III WTG	1MW Type IV WTG	3MW Type I/II/III WTG	3MW Type IV WTG
NODE650	0.2768	0.2768	0.27464	0.2768	0.26914
NODE632	0.97988	0.97988	0.97772	0.97988	0.97224
NODE633	1.17125	1.17125	1.16909	1.17125	1.16361
NODE634	0.0248	0.0248	0.02477	0.0248	0.0247
NODE645	1.18825	1.18825	1.1861	1.18825	1.18061
NODE646	1.31746	1.31746	1.3153	1.31746	1.30981
NODE671	1.68289	1.68289	1.68074	1.68289	1.67526
NODE692	1.68289	1.68289	1.68074	1.68289	1.67526
NODE675	1.73127	1.73127	1.72912	1.73127	1.72364
NODE684	1.8121	1.8121	1.80994	1.8121	1.80446
NODE611	1.89837	1.89837	1.89621	1.89837	1.89073
NODE680	2.03491	2.03491	2.03276	2.03491	2.02728
NODE652	1.93707	1.93707	1.93491	1.93707	1.92943

From table IV and table V, it can be seen that there is no change on the zero sequence reactance for Type I/II/III WTGs connected at node 650 and node 634 irrespective of the capacity of the WTG. Type IV WTGs cause a gradual reduction on the zero sequence reactance. The amount of reduction increases also as the Type IV WTG capacity increase from 1MW to 3MW.

V. Impacts of Location of WTGs on IEEE 13 Node Radial Test FEEDER SEQUENCE REACTANCES

Table VI: Positive Sequence Reactance with 1MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

NODE ID	Positive Sequence Reactances in Ohms				
	NO WTG	Type I/II/III WTGs		Type IV WTGs	
		634	650	634	650
NODE650	3.68607	1.78175	1.47508	2.96611	2.97795
NODE632	3.90891	1.765	1.69977	3.0783	3.20146
NODE633	3.98072	1.75698	1.77167	3.10028	3.27331
NODE634	0.06219	0.02154	0.03279	0.04351	0.05278
NODE645	3.98114	1.83727	1.77204	3.15056	3.27372
NODE646	4.02868	1.88481	1.81958	3.1981	3.32126
NODE671	4.13252	1.9899	1.9247	3.3025	3.42559
NODE692	4.13252	1.9899	1.9247	3.3025	3.42559
NODE675	4.15143	2.00886	1.94366	3.32148	3.44457
NODE684	4.18005	2.03743	1.97223	3.35003	3.47312
NODE611	4.26642	2.1238	2.0586	3.4364	3.55949
NODE680	4.24553	2.10291	2.03771	3.41551	3.5386
NODE652	4.23085	2.08823	2.02303	3.40083	3.52392

Table VII: Negative Sequence Reactance with 1MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

NODE ID	Negative Sequence Reactances in Ohms				
	NO WTG	Type I/II/III WTGs		Type IV WTGs	
		634	650	634	650
NODE650	3.68607	1.78175	1.4046	2.96611	2.97795
NODE632	3.90891	1.765	1.6293	3.0783	3.20146
NODE633	3.98072	1.75698	1.7012	3.10028	3.27331
NODE634	0.06219	0.02154	0.0319	0.04351	0.05278
NODE645	3.98114	1.83727	1.7016	3.15056	3.27372
NODE646	4.02868	1.88481	1.7491	3.1981	3.32126
NODE671	4.13252	1.9899	1.8543	3.3025	3.42559
NODE692	4.13252	1.9899	1.8543	3.3025	3.42559
NODE675	4.15143	2.00886	1.8732	3.32148	3.44457
NODE684	4.18005	2.03743	1.9018	3.35003	3.47312
NODE611	4.26642	2.1238	1.9882	3.4364	3.55949
NODE680	4.24553	2.10291	1.9673	3.41551	3.5386
NODE652	4.23085	2.08823	1.9526	3.40083	3.52392

Table VIII: Positive Sequence Reactance with 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

NODE ID	Positive Sequence Reactances in Ohms				
	NO WTG	Type I/II/III WTG NODE 634	TYPE I/II/III WTG NODE 650	Type IV WTG NODE 634	TYPE IV WTG NODE 650
NODE650	3.68607	1.21979	0.66984	1.7483	1.43181
NODE632	3.90891	1.13086	0.8952	1.70289	1.65666
NODE633	3.98072	1.09784	0.96715	1.66951	1.72858
NODE634	0.06219	0.0093	0.02209	0.01678	0.03222
NODE645	3.98114	1.20315	0.9675	1.77517	1.72895
NODE646	4.02868	1.25068	1.01503	1.82271	1.77649
NODE671	4.13252	1.35615	1.12062	1.92793	1.88175
NODE692	4.13252	1.35615	1.12062	1.92793	1.88175
NODE675	4.15143	1.37513	1.1396	1.94695	1.90079
NODE684	4.18005	1.40368	1.16815	1.97546	1.92929
NODE611	4.26642	1.49005	1.25453	2.06183	2.01566
NODE680	4.24553	1.46916	1.23363	2.04094	1.99476
NODE652	4.23085	1.45448	1.21895	2.02626	1.98009

Table IX: Negative Sequence Reactance with 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

NODE ID	Negative Sequence Reactances in Ohms				
	NO WTG	Type I/II/III WTGs		Type IV WTGs	
		634	650	634	650
NODE650	3.68607	1.21979	0.62698	1.7483	1.43181
NODE632	3.90891	1.13086	0.85237	1.70289	1.65666
NODE633	3.98072	1.09784	0.92432	1.66951	1.72858
NODE634	0.06219	0.0093	0.02152	0.01678	0.03222
NODE645	3.98114	1.20315	0.92467	1.77517	1.72895
NODE646	4.02868	1.25068	0.9722	1.82271	1.77649
NODE671	4.13252	1.35615	1.07782	1.92793	1.88175
NODE692	4.13252	1.35615	1.07782	1.92793	1.88175
NODE675	4.15143	1.37513	1.0968	1.94695	1.90079
NODE684	4.18005	1.40368	1.12535	1.97546	1.92929
NODE611	4.26642	1.49005	1.21172	2.06183	2.01566
NODE680	4.24553	1.46916	1.19083	2.04094	1.99476
NODE652	4.23085	1.45448	1.17615	2.02626	1.98009

From table VI, VII, VIII and IX it can be seen that the positive and the negative sequence reactances reduces once WTGs are connected on a radial feeder with the highest reduction occurring once Type I/II/III WTGs are connected at node 650 as compared to the reduction when Type I/II/III WTGs are connected at node 634. Type IV WTGs cause a minimal reduction on both the positive and the negative sequence reactance as compared to the reduction in the sequence reactance for Type I/II/III WTGs.

Table X: Zero Sequence Reactance with 1MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

NODE ID	Zero Sequence Reactances in Ohms				
	NO WTG	Type I/II/III WTGs		Type IV WTGs	
		634	650	634	650
NODE650	0.2768	0.2768	0.2768	0.2738	0.27464
NODE632	0.97988	0.97988	0.97988	0.9212	0.97772
NODE633	1.17125	1.17125	1.17125	1.0811	1.16909
NODE634	0.0248	0.0248	0.0248	0.0209	0.02477
NODE645	1.18825	1.18825	1.18825	1.1296	1.1861
NODE646	1.31746	1.31746	1.31746	1.2588	1.3153
NODE671	1.68289	1.68289	1.68289	1.6243	1.68074
NODE692	1.68289	1.68289	1.68289	1.6243	1.68074
NODE675	1.73127	1.73127	1.73127	1.6727	1.72912
NODE684	1.8121	1.8121	1.8121	1.7535	1.80994
NODE611	1.89837	1.89837	1.89837	1.8398	1.89621
NODE680	2.03491	2.03491	2.03491	1.9763	2.03276
NODE652	1.93707	1.93707	1.93707	1.8785	1.93491

Table XI: Zero Sequence Reactance with 3MW Type I/II/III WTGs and Type IV WTGs Connected at Node 650 and Node634

ID	Zero Sequence Reactances in Ohms				
	Without WTG	Type I/II/III WTG NODE 634	Type I/II/III WTG NODE 650	Type IV WTG NODE 634	Type IV WTG NODE 650
NODE650	0.2768	0.2768	0.2768	0.2656	0.2691
NODE632	0.97988	0.97988	0.97988	0.7944	0.9722
NODE633	1.17125	1.17125	1.17125	0.8932	1.1636
NODE634	0.0248	0.0248	0.0248	0.0138	0.0247
NODE645	1.18825	1.18825	1.18825	1.0028	1.1806
NODE646	1.31746	1.31746	1.31746	1.132	1.3098
NODE671	1.68289	1.68289	1.68289	1.4976	1.6753
NODE692	1.68289	1.68289	1.68289	1.4976	1.6753
NODE675	1.73127	1.73127	1.73127	1.546	1.7236
NODE684	1.8121	1.8121	1.8121	1.6268	1.8045
NODE611	1.89837	1.89837	1.89837	1.7131	1.8907
NODE680	2.03491	2.03491	2.03491	1.8496	2.0273
NODE652	1.93707	1.93707	1.93707	1.7518	1.9294

From table X and XI it can be seen that the zero sequence reactances do not reduce/change once Type I/II/III WTGs are connected on a radial feeder. Type IV WTGs cause a minimal reduction on the zero sequence reactance. Type IV WTGs connected at node 634 cause the highest reduction on the zero sequence reactances as compared to the reduction when Type IV WTGs are connected at node 650

VI. Conclusion

Wind turbine generators interfacing technology has great impacts on the distribution network's positive, negative and zero sequence reactances. Connection of type I/II/III WTGs does not alter or change the magnitudes of the distribution network's zero sequence reactances. Irrespective of the location and the capacity of the WTGs, type I/II/III WTGs does not cause any change or a reduction on the distribution network's zero sequence reactances hence eventually no reduction on the zero sequence impedance.

The connection of type IV WTGs causes a reduction on the distribution feeder zero sequence reactances from the original values of the zero sequences reactance when there was no WTG connection. As the capacity of the WTGs increases, there a further reduction on the zero sequence reactances.

The positive and the negative sequence reactances also reduce as the capacity of the WTGs increases. Type I/II/III WTGs causes the highest reduction on the positive and negative sequence reactances as compared to the effects of the Type IV WTGs on both the network's positive and negative sequence reactances and ultimately on the impedances.

The location for placement of the WTGs onto the distribution network also has great impacts on the magnitudes and the rate of reduction of the network's sequence reactances.

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