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Impacts of DFIG and Type IV WTG' Capacity and the Location of Placement on IEEE 13 Node Radial Test Feeder Positive, Negative and Zero Sequence Reactance in Short Circuits

[1]**Kemei Peter Kirui**, [2]**David K Murage**, [3]**Peter K Kihato**

[1,2,3]Department of Electrical and Electronic Engineering, Jomo Kenyatta University of Agriculture and Technology, Kenya

Abstract **- With the ever increasing number and capacities of the distributed generations (DGs)penetrating the conventional radial electrical power distribution networks, there is need for a detailed assessment on the impacts the DGs have on the distribution network's sequence impedances during fault conditions. The conventional distribution networks are designed to extract power from the transmission network and distribute it to the loads. The distribution networks were not designed to have DGs directly connected into them hence their power flow is unidirectional from the main utility grid to the loads. When balanced, un-faulted and in normal operating state, the power system's voltages and currents can be evaluated and determined with utmost simplicity. When the power systems is balanced and un-faulted, the line and phase for both the voltages and the currents are of equal magnitudes and displaced by 120° from each other, however, when the power system network is unbalanced and faulted, the magnitudes of the phase voltages and currents are not equal and are displaced by angles more or less than 120°, hence evaluating and determining the network quantities can be difficult under the unbalanced and faulted operating conditions.**

During a fault, a simplified approach to the evaluation of the network voltages and currents can be achieved by use of symmetrical components theory which proposes that for any set of unbalanced currents occurring in an electrical network, a set of three balanced currents namely the positive sequence currents, the negative sequence currents and the zero sequence currents can be developed and used to simplify the solution to the unbalanced phase voltages and currents. The flow of the three set of symmetrical currents gives rise to a set of three symmetrical voltages namely the positive, negative and zero sequence voltages. The impedance offered by each power system equipment to the flow of the symmetrical sequence currents are respectively referred to as the positive sequence impedances, the negative sequence impedances and the zero sequence impedances.

Wind turbine generators (WTGs) are one of the most common renewable energy dependent DG technologies largely integrated into the distribution networks. These WTGs are interfaced into the distribution networks either through induction or synchronous machines with the two generator technologies broadly classified as the doubly fed induction generator (DFIG) and the Type IV WTG technologies. An important aspect of the DFIG and the Type IV WTG studies is to evaluate their impacts on the positive, negative and zero sequence impedances of a distribution network under different short circuit conditions. For purposes of this paper, the IEEE 13 node radial test feeder was modelled for the short circuit study in electrical transient analysis program (ETAP) software. The short circuit study was then performed on the radial test feeder firstly without WTGs connected and secondly with DFIGs and Type IV WTGs interchangeably connected at NODE650, NODE632, NODE671 and NODE680 of the radial test feeder. This paper presents a detailed investigation on the impacts the DFIG and the Type IV WTG with their capacities being increased from 1MW to 3MW have on the positive, the negative and the zero sequence reactance of NODE650, NODE632, NODE671 and NODE652 of the IEEE 13 node radial test feeder during a short circuit.

Keywords: DFIG, Type IV WTG, Positive Sequence Reactance, Negative Sequence Reactance, Zero Sequence Reactance.

I. SEQUENCE IMPEDANCES OF A POWER SYSTEM NETWORK

i) Introduction

The entire performance of a power system can be easily determined once the impedances offered by the different elements/equipment of the power system to the flow of the different sequence component of the currents have been evaluated. These sequence impedances are generally used to simplify the asymmetrical fault calculations in power system power load flow studies, stability studies and short circuit studies.

The basic theory of symmetrical components stipulates that the phase currents and the phase voltages in a three phase electrical system can be represented by a set of symmetrical three components. During the normal and balanced operations of a power system network, the synchronous generator's phase currents are equal in magnitudes and are displaced by exactly 120° from each other, hence only the positive sequence currents flows through the network. During a fault, the generator currents become unbalanced and of unequal magnitudes with their phase displacement being more or less than 120º[1]. The imbalances in the magnitudes and the phase angles on the network phase voltages and currents gives rise to the negative and the zero sequence components of currents and consequently the negative and the zero sequence voltages. The presence of the negative and the zero sequence currents in a power system network describes the presences of an unbalanced condition commonly caused by short circuit faults.

Each element of the power system network offer impedance to the different sequence components of currents hence, in unbalanced fault calculations, each piece of equipment will have three values of impedances: the positive sequence impedance, the negative sequence impedance and the zero sequence impedance each corresponding to the sequence currents flowing through them[2].The corresponding sequence impedances are:

A) Positive Sequence Impedance

The impedance offered by an equipment or circuit to flow of positive sequence current is called the positive sequence impedance represented by (Z_1). The positive sequence has all its electrical quantities numerically equal and displaced from each other by 120º.

B) Negative Sequence Impedance

The negative sequence impedance is the impedance offered by the network to the flow of negative sequence currents and is represented by (Z_2). Generators and motors are supposed to operate with balanced three phase loading, but exposure to unbalanced loading is inevitable. Unbalances could arise from many different sources like unbalanced loads, un-transposed transmission lines, short circuit faults and open phases, etc. These unbalances appear as negative sequence currents in the generator leads. The negative sequence currents have a rotation opposite that of the power system's positive sequence currents.

C) Zero Sequence Impedance

The impedances offered by any circuit or equipment to zero sequence currents are called the zero sequence impedance (Z_0).

ii) Sequence Impedances of Power System Elements

The concept of impedances of various elements/equipment of a power system network both stationary and rotating to the flow of the positive, negative and zero sequence currents is of considerable importance in determining the fault currents in a three phase unbalanced system. These sequence impedances, the positive sequence, the negative sequence and the zero sequence are generally used to simplify the asymmetrical fault evaluation for power system fault analysis. The positive and negative sequence impedances of linear, symmetrical and static circuits like transmission lines, cables, transformers and static loads are equal and are the same as those used in the analysis of balanced conditions. This is due to the fact that impedance of such circuits is independent of the phase order, provided the applied voltages are balanced. The zero sequence impedance depends upon the path taken by the zero sequence currents. As this path is generally different from the path taken by the positive and negative sequence currents, the zero sequence impedance is usually different from both the positive and the negative sequence impedance.

A) Synchronous Generators

The positive, negative and zero sequence impedances of rotating machines are generally different. The positive sequence impedance of a synchronous generator is equal to the synchronous impedance of the machine with the negative sequence impedance being much less than the positive sequence impedance [3][4].

B) Transformers

Since transformers have the same impedance with reversed phase rotation, their positive and negative sequence impedances are equal; this value being equal to the impedance of the transformer. However, the zero sequence impedance depends upon earth connection. If there is a through circuit for the earth currents, zero sequence impedance will be equal to positive sequence impedance otherwise it will be infinite.

C) Transmission Lines

The positive sequence and the negative sequence impedances of a transmission line are the same; this value being equal to the impedance of the line. This is expected because the phase rotation of currents does not make any difference in the constants of the line. However, the zero sequence impedance is usually much greater than the positive or negative sequence impedance of lines [1][2].

II. THE DFIG AND TYPE IV WTG TECHNOLOGIESSHORT CIRCUIT BEHAVIORS

i) Synchronous Machine Short Circuit Model

A synchronous machine for short circuit modelling, can be represented with a Thevenin equivalent circuit where the voltage and impedance represent the worst case condition which is the highest short-circuit current contribution immediately following a fault. Figure 1 shows the Thevenin’s equivalent of a synchronous machine having a sub-transient reactance equivalent of X_d’’.

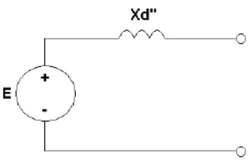

Figure 1: Synchronous Machine Short Circuit Equivalent

Wind power plants on the other hand do not employ these types of machines for energy production. Wind power plants either employ an induction machine with a direct connection to the main electrical grid, or they decouple the wind turbine generator from the main grid through power electronic devices.

ii) Induction Machines Short Circuit Model

The major difference between an induction machine and a synchronous machine in regards to their behavior during a fault is their method/mode of excitation. For a synchronous machine the excitation is provided from an independent DC source that is unaffected by a fault on the AC system. Due to this separate excitation, a synchronous machine continues to supply high transient currents throughout the duration of a fault event [5]. In contrast to this, the drop in line voltage caused by a fault will cause the induction machine to lose excitation hence it only supplies transient currents to the fault for one or two cycles. Most induction machines on the electric power grid are small enough such that their contribution to the fault current can be neglected, however the induction machines used in WTG’s power plants are large enough that they are taken into account for determining the total fault current. The equivalent machine impedance for fault calculations for an induction machine is the sum of the stator and rotor reactance as shown in Figure 2.

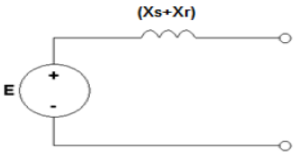

Figure 2: Sub-Transient Induction Machine Equivalent Circuit

A) DFIG Short-Circuit Model

The DFIG is pitch-regulated wound rotor induction generator with an AC/DC/AC power converter connected between the rotor terminals and the main grid with its stator winding directly coupled to the grid hence the name 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 as shown in Figure 3. The addition of the power converter between the rotor windings and the grid is 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 [6]. In order to protect the power converter from high short-circuit currents, protective devices such as a “crowbar” or a “chopper” circuit are used.

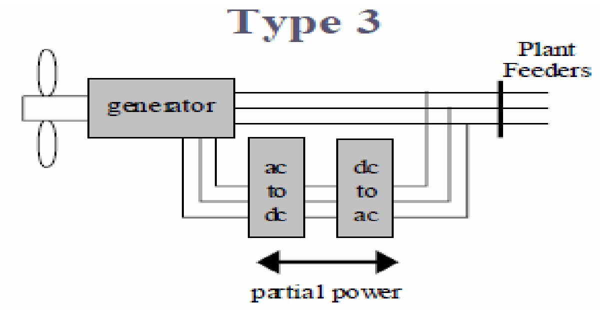

Figure 3: Doubly Fed Induction Generator

The short-circuit behavior of DFIG is modelled differently depending on the method used in protecting its rotor power converter. Figure 4 and Figure 5 shows the two methods used to protect the power converter on the rotor circuit of the DFIG. Early designs of the DFIG used a crowbar circuit that/which is activated during the initial phase of a fault [7]. The crowbar circuit diverts the short-circuit currents away from the power converter, essentially shorting out the rotor windings.

The removal of the power converter during a fault makes the DFIG behave similar to the synchronous generator design, where worst case short-circuit current is based on the internal impedance of the induction machine as shown in Figure 4. The other method of protecting the rotor converter is done with a chopper circuit. With a chopper circuit, better grid support such as low voltage ride through, is achieved during a fault by keeping the rotor converter active, but still limiting the currents to protect the sensitive power electronics devices within the power converters. When this method is used the short-circuit contribution from a DFIG is similar to that of a Type IV WTG and the equivalent circuit is shown in Figure 5.

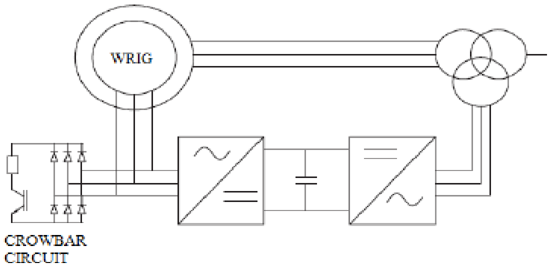

Figure 4: DFIG Crowbar Protection of the Power Converter

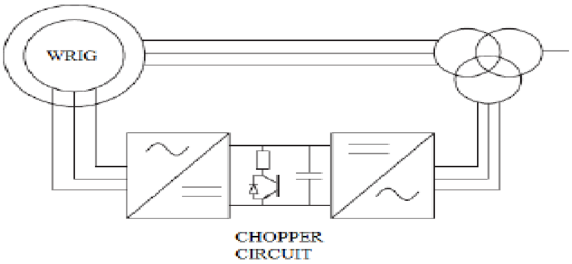

Figure 5: DFIG Chopper Protection of the Power Converter

B) Type IV WTG Short-Circuit Model

Type IV WTG features an AC/DC/AC power converter through which the entire power of the generator is processed. The generator may be either an induction or a synchronous type machine as shown in Figure 6. In the Type IV design the wind turbine generator is decoupled from the grid through a power converter which is rated to the full output of the turbine. 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 permanent magnet synchronous machine and the squirrel cage induction machines.

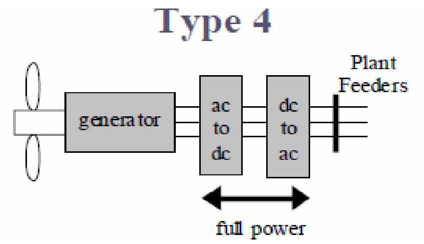

Figure 6: Type IV Wind Turbine Generator

Unlike the DFIG design where the short-circuit behavior was dominated by the generator characteristics, it is the design of the power converter that drives the electrical behavior of the Type IV WTG. The power converter in the DFIG design with the chopper circuit protection is sensitive to excessive currents, so too is the converter in a Type IV WTG design [8]. So in-order to protect the power electronics devices a current limit of $1.1pu$ is designed into the power converter. Rather than the common voltage source behind an impedance short-circuit equivalent used to model most generators, the Type IV WTG is a current source designed for maximum short circuit contribution as shown in Figure 7.

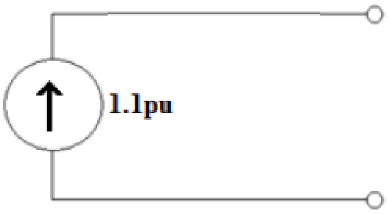

Figure 7: Type IV WTG Short-Circuit Equivalent

III. IMPACTS OF DFIGs AND TYPE IV WTGs' CAPACITY AND THE LOCATION OF PLACEMENT ON IEEE 13 NODE FEEDER POSITIVE, NEGATIVE AND ZERO SEQUENCE REACTANCE

i) 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 IEEE 13 node radial test feeder has: A 5000kVA 115kV/4.16kV Delta/Star substation transformer connected at NODE650 as the main grid supply; 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 NODE611 and the other a three phase connection at NODE675; and a 500kVA 4.16kV/0.48kV star/star solidly grounded in-line transformer connected between NODE633 and NODE634. Figure 8 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 feeder [9]. The short circuit currents contribution by the motoring loads was considered minimal at 1% of their Locked-Rotor Current (LRC) while the short circuit contribution by the WTGs was set at 600% of their LRC. The WTGs were both solidly grounded.

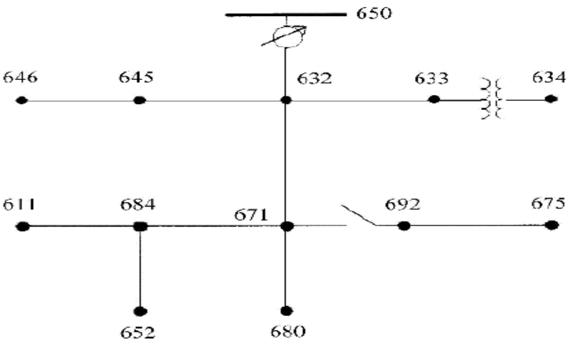

Figure 8: The IEEE 13 Node Radial Test Feeder Schematic Diagram

Four nodes were then chosen for the placement of the WTGs. The choice of the nodes was based on the distance the nodes were located from the main grid substation. The nodes were: NODE650 zero feet away, NODE632 2000 feet away, NODE671 4000 feet away and finally NODE680 5000 feet away from the main grid substation.

NODE652, though being the farthest node from the main grid substation at 5100 feet, had a single phase connection with an underground cable hence the reason for the choice of NODE680 for WTGs placement as the farthest node at 5000 feet because it has a three phase overhead line interconnecting it with the rest of the test feeder nodes.

All the chosen nodes for WTG placement are/were three phase nodes with three phase overhead lines interconnecting them with the rest of the test feeder node.

Four nodes were again chosen to study the impacts the DFIG and Type IV WTGs have on the variations on the radial test feeder positive, negative and zero sequence reactance. The four nodes chosen for the study were: NODE650 zero feet away from the main grid; NODE632 2000 feet away from the main grid; NODE671 4000 feet away from the main grid and finally NODE652 which was the farthest node at 5100 feet away from the main grid.

The DFIG and the Type IV WTG were interchangeably connected at nodes: NODE650, NODE632, NODE671 and NODE680 with their capacities being increased from 1MW to 3MW to analyze the impacts the increase in their capacities have on the positive, negative and zero sequence reactance of NODE650, NODE632, NODE671 and NODE652.

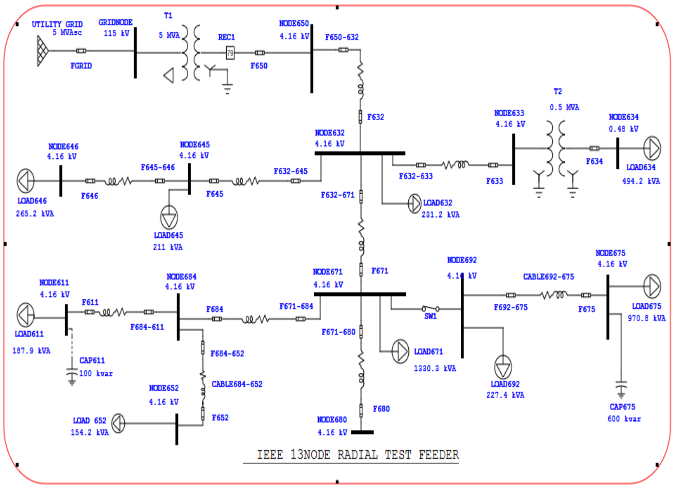

Figure 9: IEEE 13 Node Radial Test Feeder ETAP Model One-Line Diagram

ii) Impacts of DFIG and Type IV WTG' Capacity and the Location of Placement on NODE650Sequence Reactance in a Short Circuit

A) Positive Sequence Reactance at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Table 1: Positive, Negative and Zero Sequence Reactance in Ohms without WTG

NODE ID	Positive Sequence	Negative Sequence	Zero Sequence
NODE650	3.68607	3.68607	0.2768
NODE632	3.90891	3.90891	0.97988
NODE671	4.13252	4.13252	1.68289
NODE652	4.23085	4.23085	1.93707

Table 2: Positive Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE650	1.4751	0.66984	2.97795	1.57667
NODE632	1.55344	0.81834	2.96981	1.54857
NODE671	1.62645	0.94501	2.9625	1.49067
NODE680	1.66095	1.0062	2.95893	1.43181

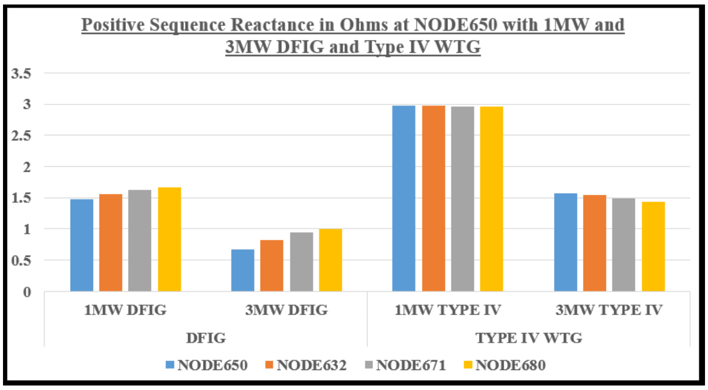

Chart 1: Positive Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the positive sequence reactance at the faulted NODE650 was 3.68607Ω during as seen from Table 1. This value of 3.68607Ω would reduce in magnitude to 1.4751Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE650. As the 1MW DFIGs were placed farther away from the faulted NODE650, the positive sequence reactance increased in magnitude from 1.4751Ω to: 1.55344Ω when the 1MW DFIG was connected at NODE632; 1.62645Ω when the 1MW DFIG was connected at NODE671; and finally to 1.66095Ω when the 1MW DFIG was connected at NODE680 as seen from Table 2 and Chart 1.

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When the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE650 reduced from 1.4751Ω to 0.66984Ω. This value of 0.66984Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE650 at nodes 632,671 and 680 respectively. The value of the positive sequence reactance at the faulted NODE650 reduced: From 1.55344Ω to 0.81834Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; from 1.62645Ω to 0.94501Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; and finally from 1.66095Ω to 1.0062Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW as seen from Table 2 and Chart 1.

The positive sequence reactance at the faulted NODE650 was 2.95893Ω when a 1MW Type IV WTG was connected at NODE680. This value of 2.95893Ω gradually increased to: 2.9625Ω when the 1MW Type IV WTG was connected at NODE671; 2.96981Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 2.97795Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 2 and Chart 1.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE650 reduced from 2.95893Ω to 1.43181Ω. This value of 1.43181Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the positive sequence reactance at the faulted NODE650 was: 1.49067Ω when the 3MW Type IV WTG was connected at NODE671; 1.54857Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.57667Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 2 and Chart 1.

B) Negative Sequence Reactance at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Table 3: Negative Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

WTG Location	DFIG		Type IV WTG	
	1MW DFIG	3MW DFIG	1MW Type IV	3MW Type IV
NODE650	1.40456	0.62698	2.97795	1.57667
NODE632	1.48791	0.77503	2.96981	1.54857
NODE671	1.56543	0.90974	2.9625	1.49067
NODE680	1.60203	0.97252	2.95893	1.43181

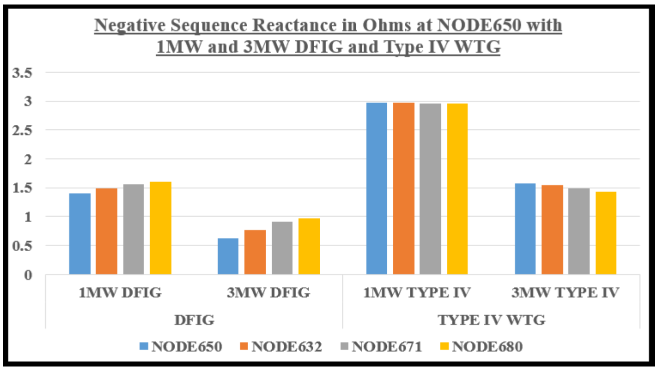

Chart 2: Negative Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the negative sequence reactance at the faulted NODE650 was 3.68607Ω during as seen from Table 1. This value of 3.68607Ω would reduce in magnitude to 1.40456Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE650. As the 1MW DFIGs were placed farther away from the faulted NODE650, the negative sequence reactance increased in magnitude from 1.40456Ω to: 1.48791Ω when the 1MW DFIG was connected at NODE632; 1.56543Ω when the 1MW DFIG was connected at NODE671; and finally to 1.60203Ω when the 1MW DFIG was connected at NODE680 as seen from Table 3 and Chart 2.

When the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW, the negative sequence reactance at the faulted NODE650 reduced from 1.40456Ω to 0.62698Ω. This value of 0.62698Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE650 at nodes 632,671 and 680 respectively. The value of the negative sequence reactance at the faulted NODE650 reduced: From 1.48791Ω to 0.77503Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; from 1.56543Ω to 0.90974Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; and finally from 1.60203Ω to 0.97252Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW as seen from Table 3 and Chart 2.

C) Zero Sequence Reactance at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Table 4: Zero Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		Type IV WTG	
	1MW DFIG	3MW DFIG	1MW Type IV	3MW Type IV
NODE650	0.2468	0.20285	0.27464	0.26914
NODE632	0.25322	0.23272	0.27419	0.2662

NODE671	0.25743	0.24558	0.27381	0.26494
NODE680	0.25902	0.24957	0.27365	0.26475

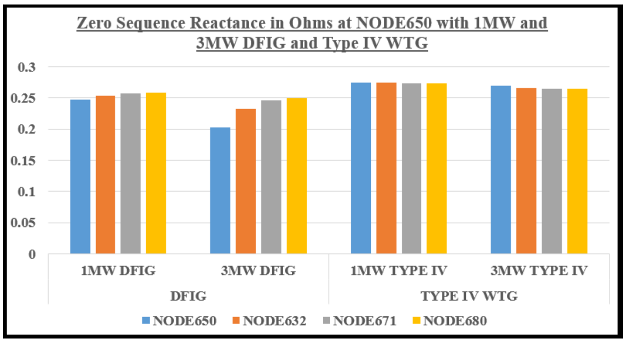

Chart 3: Zero Sequence Reactance in Ohms at NODE650 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the zero sequence reactance at the faulted NODE650 was 0.2768Ω during as seen from Table 1. This value of 0.2768Ω would reduce in magnitude to 0.2468Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE650. As the 1MW DFIGs were placed farther away from the faulted NODE650, the zero sequence reactance increased in magnitude from 0.2468Ω to: 0.25322Ω when the 1MW DFIG was connected at NODE632; 0.25743Ω when the 1MW DFIG was connected at NODE671; and finally to 0.25902Ω when the 1MW DFIG was connected at NODE680 as seen from Table 4 and Chart 3.

When the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE650 reduced from 0.2468Ω to 0.20285Ω. This value of 0.20285Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE650 at nodes 632,671 and 680 respectively. The value of the zero sequence reactance at the faulted NODE650 reduced: From 0.25322Ω to 0.23272Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; from 0.25743Ω to 0.24558Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; and finally from 0.25902Ω to 0.24957Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW as seen from Table 4 and Chart 3.

The zero sequence reactance at the faulted NODE650 was 0.27365Ω when a 1MW Type IV WTG was connected at NODE680. This value of 0.27365Ω gradually increased to: 0.27381Ω when the 1MW Type IV WTG was connected at NODE671; 0.27419Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 0.27464Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 4 and Chart 3.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE650 reduced from 0.27365Ω to 0.26475Ω. This value of 0.26475Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the zero sequence reactance at the faulted NODE650 was: 0.26494Ω when the 3MW Type IV WTG was connected at NODE671; 0.2662Ω when the 3MW Type IV WTG was connected at NODE632; and finally 0.26914Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 4 and Chart 3.

iii) Impacts of DFIG and Type IV WTG' Capacity and the Location of Placement on NODE632 Sequence Reactance in a Short Circuit

A) Positive Sequence Reactance at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Table 5: Positive Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE632	1.51002	0.67698	3.08062	1.5071
NODE671	1.59188	0.82416	3.07288	1.47452
NODE650	1.69978	0.89519	3.20146	1.65666
NODE680	1.63058	0.89284	3.0691	1.40753

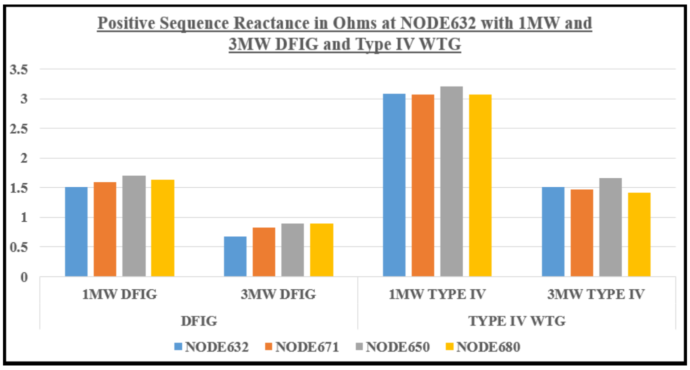

Chart 4: Positive Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the positive sequence reactance at the faulted NODE632 was 3.90891Ω during a fault as seen from Table 1. This value of 3.90891Ω would reduce in magnitude to 1.51002Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE632. As the 1MW DFIGs were placed farther away from the faulted NODE632, the positive sequence reactance increased in magnitude from 1.51002Ω to: 1.59188Ω when the 1MW DFIG was connected at NODE671; 1.63058Ω when the 1MW DFIG was connected at NODE680; and finally to 1.69978Ω when the 1MW DFIG was connected at NODE650 as seen from Table 5 and Chart 4.When the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE632 reduced from 1.51002Ω to 0.67698Ω. This value of 0.67698Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE632 at nodes 671,650 and 680 respectively. The value of the positive sequence reactance at the faulted NODE632 reduced: From 1.59188Ω to 0.82416Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; from 1.63058Ω to 0.89284Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; and finally from 1.69978Ω to 0.89519Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 5 and Chart 4.

The positive sequence reactance at the faulted NODE632 was 3.0691Ω when a 1MW Type IV WTG was connected at NODE680. This value of 3.0691Ω gradually increased to: 3.07288Ω when the 1MW Type IV WTG was connected at NODE671; 3.08062Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 3.20146Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 5 and Chart 4.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE632 reduced from 3.0691Ω to 1.40753Ω. This value of 1.40753Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the positive sequence reactance at the faulted NODE632 was: 1.47452Ω when the 3MW Type IV WTG was connected at NODE671; 1.5071Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.65666Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 5 and Chart 4.

B) Negative Sequence Reactance at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Table 6: Negative Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE632	1.43618	0.63322	3.08062	1.5071
NODE671	1.52312	0.78438	3.07288	1.47452
NODE650	1.6293	0.85237	3.2016	1.65666
NODE680	1.56416	0.81485	3.0691	1.40753

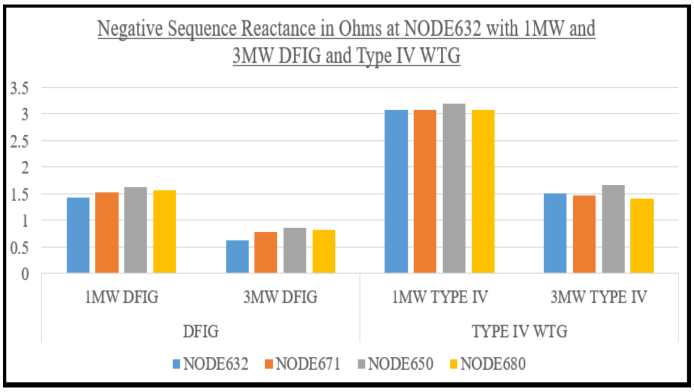

Chart 5: Negative Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the negative sequence reactance at the faulted NODE632 was 3.90891Ω during a fault as seen from Table 1. This value of 3.9 0891Ω would reduce in magnitude to 1.43618Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE632.

As the 1MW DFIGs were placed farther away from the faulted NODE632, the negative sequence reactance increased in magnitude from 1.43618Ω to: 1.52312Ω when the 1MW DFIG was connected at NODE671; 1.6293Ω when the 1MW DFIG was connected at NODE650; and finally to 1.63608Ω when the 1MW DFIG was connected at NODE680 as seen from Table 6 and Chart 5.

When the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW, the negative sequence reactance at the faulted NODE632 reduced from 1.43618Ω to 0.63322Ω. This value of 0.63322Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE632 at nodes 671,650 and 680 respectively.

The value of the negative sequence reactance at the faulted NODE632 reduced: From 1.52312Ω to 0.78438Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; from 1.63608Ω to 0.81485Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; and finally from 1.6293Ω to 0.85237Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 6 and Chart 5.

C) Zero Sequence Reactance at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Table 7: Zero Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE632	0.68996	0.43104	0.92428	0.78766
NODE671	0.73965	0.5873	0.9207	0.7853
NODE650	0.94993	0.90604	0.97773	0.97224
NODE680	0.75873	0.63645	0.91925	0.78283

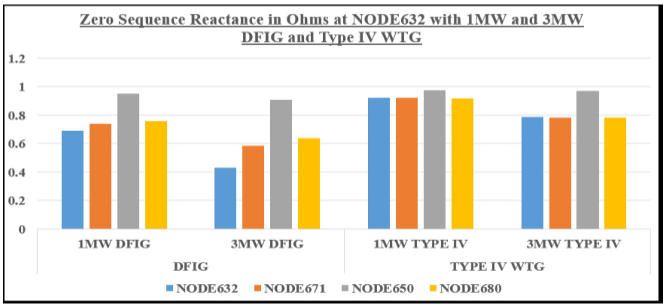

Chart 6: Zero Sequence Reactance in Ohms at NODE632 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the zero sequence reactance at the faulted NODE632 was 0.97988Ω during as seen from Table 1. This value of 0.97988Ω would reduce in magnitude to 0.68996Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE632. As the 1MW DFIGs were placed farther away from the faulted NODE632, the zero sequence reactance increased in magnitude from 0.68996Ω to: 0.73965Ω when the 1MW DFIG was connected at NODE671; 0.75873Ω when the 1MW DFIG was connected at NODE650; and finally to 0.94993Ω when the 1MW DFIG was connected at NODE650 as seen from Table 7 and Chart 6.

When the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE632 reduced from 0.68996Ω to 0.43104Ω. This value of 0.43104Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE632 at nodes 671,650 and 680 respectively. The value of the zero sequence reactance at the faulted NODE632 reduced: From 0.73965Ω to 0.5873Ω when the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW; from 0.75873Ω to 0.63645Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; and finally from 0.94993Ω to 0.90604Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 7 and Chart 6.

The zero sequence reactance at the faulted NODE632 was 0.91925Ω when a 1MW Type IV WTG was connected at NODE680. This value of 0.91925Ω gradually increased to: 0.9207Ω when the 1MW Type IV WTG was connected at NODE671; 0.92428Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 0.97773Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 7 and Chart 6.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE632 reduced from 0.91925Ω to 0.78283Ω. This value of 0.78283Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the zero sequence reactance at the faulted NODE632 was: 0.7853Ω when the 3MW Type IV WTG was connected at NODE671; 0.78766Ω when the 3MW Type IV WTG was connected at NODE632; and finally 0.97224Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 7 and Chart 6.

iv) Impacts of DFIG and Type IV WTG' Capacity and the Location of Placement on NODE671 Sequence Reactance in a Short Circuit

A) Positive Sequence Reactance at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Table 8: Positive Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	1.54271	0.6835	3.17605	1.41918
NODE680	1.58584	0.76009	3.17206	1.38187
NODE632	1.73507	0.90253	3.30482	1.63278
N0DE650	1.92472	1.12062	3.42559	1.88175

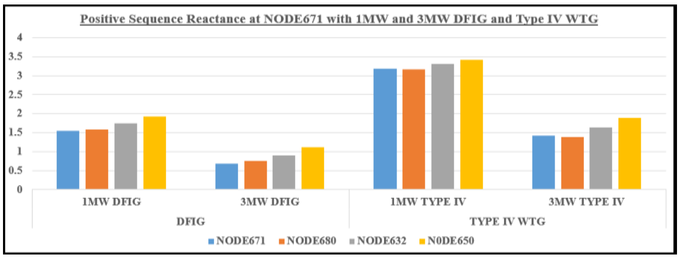

Chart 7: Positive Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the positive sequence reactance at the faulted NODE671 was 4.13252Ω during a fault as seen from Table 1. This value of 4.13252Ω would reduce in magnitude to 1.54271Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE671, the positive sequence reactance increased in magnitude from 1.54271Ω to: 1.58584Ω when the 1MW DFIG was connected at NODE680; 1.73507Ω when the 1MW DFIG was connected at NODE632; and finally to 1.92472Ω when the 1MW DFIG was connected at NODE650 as seen from Table 8 and Chart 7.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE671 reduced from 1.54271Ω to 0.6835Ω. This value of 0.6835Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE671 at nodes 680,632 and 650 respectively. The value of the positive sequence reactance at the faulted NODE671 reduced: From 1.58584Ω to 0.76009Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.73507Ω to 0.90253Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 1.92472Ω to 1.12062Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 8 and Chart 7.

The positive sequence reactance at the faulted NODE671 was 3.17206Ω when a 1MW Type IV WTG was connected at NODE680. This value of 3.17206Ω gradually increased to: 3.17605Ω when the 1MW Type IV WTG was connected at NODE671; 3.30482Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 3.42559Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 8 and Chart 7.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE671 reduced from 3.17206Ω to 1.38187Ω. This value of 1.38187Ω would again increase in magnitude as the 3MW Type IV WTG was connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the positive sequence reactance at the faulted NODE671 was: 1.41918Ω when the 3MW Type IV WTG was connected at NODE671; 1.63278Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.88175Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 8 and Chart 7.

B) Negative Sequence Reactance at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Table 9: Negative Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	1.46572	0.63892	3.17605	1.41918
NODE680	1.51147	0.71752	3.17206	1.38187
NODE632	1.66127	0.8588	3.30482	1.63278
N0DE650	1.85427	1.07782	3.42559	1.88175

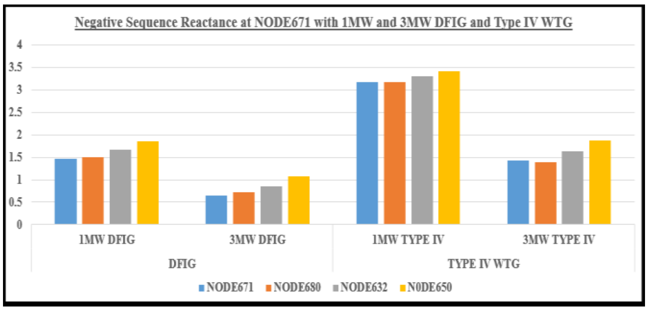

Chart 8: Negative Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the positive sequence reactance at the faulted NODE671 was 4.13252Ω during a fault as seen from Table 1. This value of 4.13252Ω would reduce in magnitude to 1.46572Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE671, the positive sequence reactance increased in magnitude from 1.46572Ω to: 1.51147Ω when the 1MW DFIG was connected at NODE680; 1.66127Ω when the 1MW DFIG was connected at NODE632; and finally to 1.85427Ω when the 1MW DFIG was connected at NODE650 as seen from Table 9 and Chart 8.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE671 reduced from 1.46572Ω to 0.63892Ω. This value of 0.63892Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE671 at nodes 680,632 and 650 respectively. The value of the positive sequence reactance at the faulted NODE671 reduced: From 1.51147Ω to 0.71752Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.66127Ω to 0.8588Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 1.85427Ω to 1.07782Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 9 and Chart 8.

C) Zero Sequence Reactance at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Table 10: Zero Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	0.97719	0.5269	1.49779	1.08839
NODE680	1.03287	0.6711	1.49381	1.07866
NODE632	1.39319	1.13448	1.62736	1.49085
N0DE650	1.65297	1.60912	1.68075	1.67527

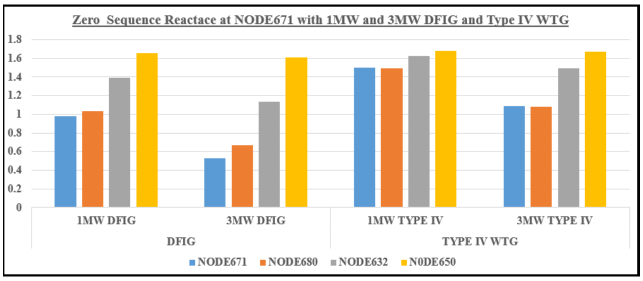

Chart 9: Zero Sequence Reactance in Ohms at NODE671 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the zero sequence reactance at the faulted NODE671 was 1.68289Ω during as seen from Table 1. This value of 1.68289Ω would reduce in magnitude to 0.97719Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE671, the zero sequence reactance increased in magnitude from 0.97719Ω to: 1.03287Ω when the 1MW DFIG was connected at NODE680; 1.39319Ω when the 1MW DFIG was connected at NODE632; and finally to 1.65297Ω when the 1MW DFIG was connected at NODE650 as seen from Table 10 and Chart 9.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE671 reduced from 0.97719Ω to 0.5269Ω. This value of 0.5269Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE671 at nodes 680,632 and 650 respectively. The value of the zero sequence reactance at the faulted NODE671 reduced: From 1.03287Ω to 0.6711Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.39319Ω to 1.13448Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 1.65297Ω to 1.60912Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 10 and Chart 9.

The zero sequence reactance at the faulted NODE671 was 1.49381Ω when a 1MW Type IV WTG was connected at NODE680. This value of 1.49381Ω gradually increased to: 1.49779Ω when the 1MW Type IV WTG was connected at NODE671; 1.62736Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 1.68075Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 10 and Chart 9.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE671 reduced from 1.49381Ω to 1.07866Ω. This value of 1.07866Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the zero sequence reactance at the faulted NODE671 was: 1.08839Ω when the 3MW Type IV WTG was connected at NODE671; 1.49085Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.67527Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 10 and Chart 9.

v) Impacts of DFIG and Type IV WTG' Capacity and the Location of Placement on NODE652 Sequence Reactance in a Short Circuit

A) Positive Sequence Reactance at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Table 11: Positive Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	1.64104	0.78183	3.27438	1.51751
NODE680	1.68417	0.85842	3.27039	1.4802
NODE632	1.83338	1.00085	3.40315	1.73111
NODE650	2.02305	1.21895	3.52392	1.98009

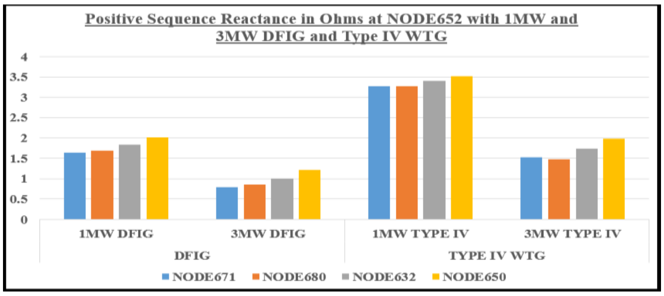

Chart 10: Positive Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the positive sequence reactance at the faulted NODE652 was 4.23085Ω during a fault as seen from Table 1. This value of 4.23085Ω would reduce in magnitude to 1.64104Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE671, the positive sequence reactance increased in magnitude from 1.64104Ω to: 1.68417Ω when the 1MW DFIG was connected at NODE680; 1.83338Ω when the 1MW DFIG was connected at NODE632; and finally to 2.02305Ω when the 1MW DFIG was connected at NODE650 as seen from Table 11 and Chart 10.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE652 reduced from 1.64104Ω to 0.78183Ω. This value of 0.78183Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE652 at nodes 680,632 and 650 respectively. The value of the positive sequence reactance at the faulted NODE652 reduced: From 1.68417Ω to 0.85842Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.83338Ω to 1.00085Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 2.02305Ω to 1.21895Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 11 and Chart 10.

The positive sequence reactance at the faulted NODE652 was 3.27039Ω when a 1MW Type IV WTG was connected at NODE680. This value of 3.27039Ω gradually increased to: 3.27438Ω when the 1MW Type IV WTG was connected at NODE671; 3.40315Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 3.52392Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 11 and Chart 10.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the positive sequence reactance at the faulted NODE652 reduced from 3.27039Ω to 1.4802Ω. This value of 1.4802Ω would again increase in magnitude as the 3MW Type IV WTG was connected at nodes 671, 632 and the highest value was when the Type IV WTG was connected at NODE650. The value of the positive sequence reactance at the faulted NODE652 was: 1.51751Ω when the 3MW Type IV WTG was connected at NODE671; 1.73111Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.98009Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 11 and Chart 10.

B) Negative Sequence Reactance at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Table 12: Negative Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	1.56405	0.73725	3.27438	1.51751
NODE680	1.60981	0.81585	3.27039	1.4802
NODE632	1.7596	0.95713	3.40315	1.73111
NODE650	1.95261	1.17615	3.52392	1.98009

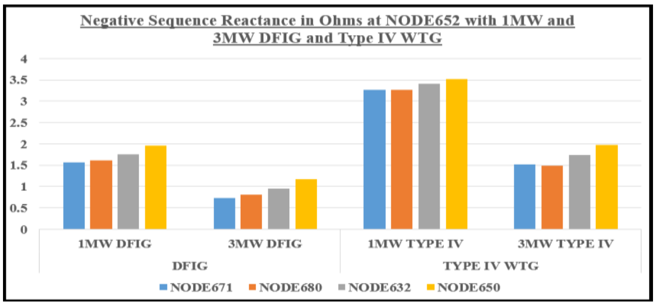

Chart 11: Negative Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the negative sequence reactance at the faulted NODE652 was 4.23085Ω during a fault as seen from Table 1. This value of 4.23085Ω would reduce in magnitude to 1.56405Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE671, the negative sequence reactance increased in magnitude from 1.56405Ω to: 1.60981Ω when the 1MW DFIG was connected at NODE680; 1.7596Ω when the 1MW DFIG was connected at NODE632; and finally to 1.95261Ω when the 1MW DFIG was connected at NODE650 as seen from Table 12 and Chart 11.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the negative sequence reactance at the faulted NODE652 reduced from 1.56405Ω to 0.73725Ω. This value of 0.73725Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE652 at nodes 680,632 and 650 respectively. The value of the negative sequence reactance at the faulted NODE652 reduced: From 1.60981Ω to 0.81585Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.7596Ω to 0.95713Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 1.95261Ω to 1.17615Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 12 and Chart 11.

C) Zero Sequence Reactance at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Table 13: Zero Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

WTG LOCATION	DFIG		TYPE IV WTG	
	1MW DFIG	3MW DFIG	1MW TYPE IV	3MW TYPE IV
NODE671	1.23136	0.78108	1.75196	1.34256
NODE680	1.28704	0.92527	1.74798	1.33283
NODE632	1.64736	1.38865	1.88153	1.74502
NODE650	1.90715	1.86329	1.93492	1.92944

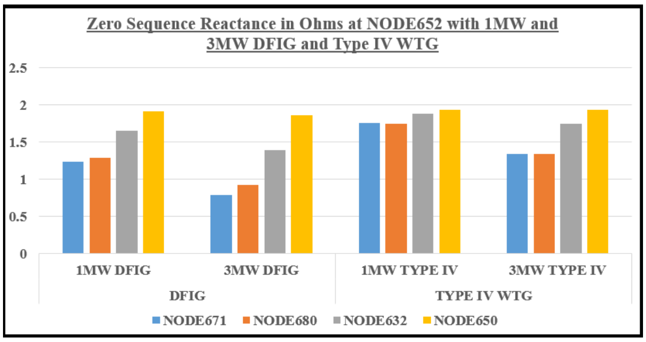

Chart 12: Zero Sequence Reactance in Ohms at NODE652 with 1MW and 3MW DFIG and Type IV WTG

Without WTGs connected, the zero sequence reactance at the faulted NODE652 was 1.93707Ω during as seen from Table 1. This value of 1.93707Ω would reduce in magnitude to 1.23136Ω when the radial test feeder was again short circuited but now with a 1MW DFIG connected at NODE671. As the 1MW DFIGs were placed farther away from the faulted NODE652, the zero sequence reactance increased in magnitude from 1.23136Ω to: 1.28704Ω when the 1MW DFIG was connected at NODE680; 1.64736Ω when the 1MW DFIG was connected at NODE632; and finally to 1.90715Ω when the 1MW DFIG was connected at NODE650 as seen from Table 13 and Chart 12.

When the capacity of the DFIG connected at NODE671 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE652 reduced from 1.23136Ω to 0.78108Ω. This value of 0.78108Ω would again increase in magnitude as the 3MW DFIG were placed farther away from the faulted NODE652 at nodes 680,632 and 650 respectively. The value of the zero sequence reactance at the faulted NODE652 reduced: From 1.28704Ω to 0.92527Ω when the capacity of the DFIG connected at NODE680 was increased from 1MW to 3MW; from 1.64736Ω to 1.38865Ω when the capacity of the DFIG connected at NODE632 was increased from 1MW to 3MW; and finally from 1.90715Ω to 1.86329Ω when the capacity of the DFIG connected at NODE650 was increased from 1MW to 3MW as seen from Table 13 and Chart 12.

The zero sequence reactance at the faulted NODE652 was 1.74798Ω when a 1MW Type IV WTG was connected at NODE680. This value of 1.74798Ω gradually increased to: 1.75196Ω when the 1MW Type IV WTG was connected at NODE671; 1.88153Ω when the 1MW Type IV WTG was connected at NODE632; and finally to 1.93492Ω when the 1MW Type IV WTG was connected at NODE650 as can be seen from Table 13 and Chart 12.

When the capacity of the Type IV WTG connected at NODE680 was increased from 1MW to 3MW, the zero sequence reactance at the faulted NODE652 reduced from 1.74798Ω to 1.33283Ω. This value of 1.33283Ω would again increase in magnitude as the 3MW Type IV WTGs were connected at nodes 671, 632 and the highest value was when the WTG was connected at NODE650. The value of the zero sequence reactance at the faulted NODE652 was: 1.34256Ω when the 3MW Type IV WTG was connected at NODE671; 1.74502Ω when the 3MW Type IV WTG was connected at NODE632; and finally 1.92944Ω when the 3MW Type IV WTG was connected at NODE650 as seen from Table 13 and Chart 12.

V. CONCLUSION

Wind turbine generators interfacing technology, increase in capacity and location for placement has great impacts on a distribution feeder's positive, negative and zero sequence reactance. The DFIG generator impacted on the positive sequence reactance, the negative sequence reactance and the zero sequence reactance just like a synchronous generator. The positive and negative sequence reactance were both of equal magnitudes when the Type IV WTGs were connected in to the test feeder hence the effect of a Type IV WTG on the networks sequence reactance were not similar to the effects caused by a synchronous generators.

A) Positive Sequence Reactance

- The positive sequence reactance reduced once the DFIG machines were connected into the radial test feeder.
- As the DFIG machines were placed farther away from the faulted node, the positive sequence reactance gradually increased at the faulted node.
- The magnitudes of the positive sequence reactance further reduced in magnitudes as the capacity of the DFIG machines was increase from 1MW to 3MW
- Type IV WTG machine caused a minimal reduction on the NODE's positive sequence reactance as compared to the reduction experienced for DFIG machines.

- The lowest magnitudes for positive sequence reactance for Type IV WTG machines was experienced for Type IV WTG machines connected at NODE680. These magnitudes would progressively increase as the Type IV WTG machines were connected at NODE671, NODE632 and finally the highest magnitudes were experienced when Type IV WTG machines were connected placed at NODE650.

B) Negative sequence Reactance

- The negative sequence reactance reduced once the DFIG machines were connected into the radial test feeder.
- As the DFIG machines were placed away from the faulted node, the negative sequence reactance gradually increased at the faulted nodes.
- The magnitudes of the negative sequence reactance further reduced in magnitudes as the capacity of the DFIG machines was increase from 1MW to 3MW
- The reduction on the negative sequence reactance for Type IV WTG machines were the same with the reduction onthe positive sequence reactance for the Type IV WTG.
- Type IV WTG machine caused a minimal reduction on the test feeder negative sequence reactance as compared to the reduction experienced for DFIG machines.
- The lowest magnitudes for negative sequence reactance for Type IV WTG machines was experienced for Type IV WTG machines placed/connected at NODE680. These magnitudes would progressively increase as the Type IV WTG machines were connected at NODE671, NODE632 and finally the highest magnitudes were experienced when Type IV WTG machines were connected at NODE650.

C) Zero Sequence Reactance

- The zero sequence reactance reduced once the DFIG machines were connected into the radial test feeder.
- As the DFIG machines were placed farther away from the faulted node, the zero sequence reactance gradually increased at the faulted node.
- The magnitudes of the zero sequence reactance further reduced in magnitudes as the capacity of the DFIG machines was increase from 1MW to 3MW
- Type IV WTG machine caused a minimal reduction on the NODE's zero sequence reactance as compared to the reduction experienced for DFIG machines.
- The lowest magnitudes for zero sequence reactance for Type IV WTG machines was experienced for Type IV WTG machines placed/connected at NODE680. These magnitudes would progressively increase as the Type IV WTG machines were connected at NODE671, NODE632 and finally the highest magnitudes were experienced when Type IV WTG machines were connected placed at NODE650.

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AUTHOR'S BIOGRAPHY

Mr. Kemei Peter Kirui is a Kenyan born at Kiptere Location, Kericho County on 14th May 1983. He trained as anElectrical Engineer and graduated with a Bachelor's degree in Electrical and Communication Engineering from Moi University, Kenya and an Msc in Electrical Engineering from JKUAT Kenya. He also trained in Technology Education and graduated with a PGDE in Technology Education from Moi University, Kenya. Mr Kemei is a registered graduate engineer by the Kenya Engineers Registration Board (ERB) and a trained Energy Auditor by Kenya Association of Manufacturers (KAM). His areas of interest in research are: Power Systems Protection; Power Systems Distribution Network Planning; and Renewable Energy Technologies.

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