New Protection Scheme for Type 4 Wind Turbines

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***Abstract*—The short circuit behavior of the early generation wind turbines depends solely on the physical characteristics of the machine. Conventional protection schemes can be applied to provide protection to those wind farms. But full converter based Type 4 wind turbine generators have complex fault current characteristics governed by the converter controls, with fault current responses very different from synchronous generators. The use of relays with conventional protection and supervision schemes may cause misoperation. This paper presents preliminary concepts for a new protection scheme based on converter control system behavior and tested with simulation of a Type 4 wind turbine in RTDS.**

Keywords—Type 4 Wind turbines, Protection, WTG, Converter based generation.

I. Introduction

The rapid increase of energy demand globally and the impending threat of extinction of fossil fuel reserves is forcing the world to switch to other sources of energy. Switching to renewable energy sources provides substantial benefits for climate, health and economy. Keeping this in view many governments changed policies with the intention to expand the use of rapidly growing renewable energy technologies. The growth of renewable energy technologies has led to the increase in penetration of wind turbine generators (WTG) in power system. The development of the WTG technologies led to online grid connections of wind turbines. Almost all new megawatt scale wind power plants that are being deployed off shore use either variable speed doubly fed induction generators (Type 3) or full converter based (Type 4) WTGs [1].

Generally short circuit studies are done to determine the settings for protection schemes specific for the part of the power system under study. Type 1 WTGs use fixed speed squirrel cage induction machines and Type 2 WTGs employ variable slip wound rotor induction machines. The short circuit behavior of Type 1 and Type 2 WTG are dependent on physical characteristics of the WTGs [2] which are dominated by transient and sub-transient responses of the machines, and are well understood. The fault current contributions for such WTGs are determined by the physics (construction) of the machines. The fault current can be several times the rated current for a fault near the WTG terminals. The fault current is limited by the system and WTG impedances.

On the other hand, Type 3 and Type 4 WTGs have much more complex fault current characteristics. The fault current characteristics are governed by the proprietary controls of the power converters used in the generators. Since the Type 4 WTG is fully converter based, the fault current is generally limited to 1.1 to 1.2 times the rated load current depending on the rating of the power converter. The short circuit characteristics of Type 3 WTGs are similar to those of Type 4 WTGs, the only difference being the crow bar operation during severe faults. During crow bar operation, the fault characteristics transition from a controlled current source to that of a Type 2 induction generator. The burgeoning use of Type 3 and Type 4 WTGs makes design of protection schemes difficult because the existing tools do not accurately model the dynamics of these WTG control systems and existing protective relays can misoperate.

An accurate model of fault behavior of the system is required to design a reliable protection scheme. The converter manufacturers control schemes are confidential and proprietary so protection engineers have limited knowledge of how the WTGs will respond. The Type 4 WTG modifies the voltage waveforms synthesized by the converter to limit and control the current magnitude, and depending on the manufacturer, produces balanced, unity power factor currents during in response to unbalanced faults. This unconventional behavior of the Type 4 WTG presents a host of challenges for designing reliable protection schemes. Over many years, the power industry has developed methods for modeling various for WTGs and their associated control systems. Initiatives have been organized by working groups within the Western Electricity Coordinating Council (WECC), the Institute of Electrical and Electronics Engineers (IEEE), the Electric Power Research Institute (EPRI) and the International Electrotechnical Commission (IEC)to develop generic dynamic models for various WTG types for power flow studies. However, the generic models developed are identified by these groups as not being suitable for fault studies [3].

In this paper, a detailed switching model of the grid side converter of a Type 4 WTG is developed in order to simulate the fault response of the wind turbine. These results are examined to evaluate which aspects of present protection schemes can be used and where their limitations are. Some of the limitations employing those schemes are identified and briefly discussed. Preliminary concepts for new protection scheme are proposed based on the WT system operation and verified for different types of faults**.** It is important to understand the basic concepts of the grid side converter control in order to develop a protection scheme for the Type 4 WTG utilizing measurable quantities that convey information.

II. CONVERTOR CONTROL DESIGN AND ASPECTS

The WTG converter controller generates modulating functions to control the switching of the power electronic devices in the three phase legs of a three-phase converter based on power injected by the wind turbine and a reactive power set point. These controllers often utilize current regulators to limit currents to within the ratings of the power electronic devices. There are several factors that need to be considered when designing a controller for generating these modulating waves. The major factors are the frequency phase voltage magnitude at which the power needs to be exported, which is determined by measuring the voltages at the point of interconnect with the external power system. The frequency synchronization is implemented using a phase locked. The control architecture is typically divided into two control loops, an outer control loop and an inner control loop. The outer control loop determines reference currents based on the required real and reactive power commands and the inner current controller generates the modulating functions by comparing the reference current values with the actual measured current values [4]. The inner current control loops are implemented in a two-axis synchronous rotating reference frame by applying the Park's transformation. Doing so allows the controller to decouple real and reactive power and improves dynamic performance of the control scheme.

The representation of transformation of voltage or currents to the synchronous reference frame can be explained as follows. The zero-axis value is non-zero only when there is a ground imbalance in a three-phase set. Since the converter is ungrounded the zero component of the current is zero. The d (direct) axis value is obtained by sampling the reference phase quantity at its own frequency. The q (quadrature) axis value is sampled at the same frequency, but with a 90-degree phase difference in sampling with respect to the direct axis quantity. If the sampling frequency is synchronized with the signal frequency, it is sampled at the same point on wave in each cycle, generating constant values as illustrated in Figure 1.

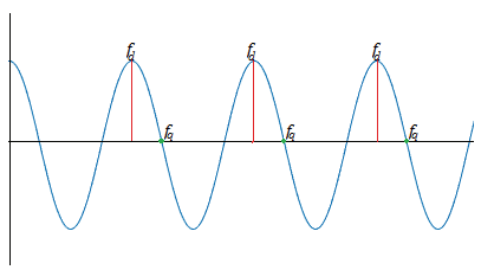

Figure 1: Time domain representation of dq0 transformation

The complex 3 phase power in terms of voltage and current phasors is given by (1) and (2).

$$P_{3\phi} - j.Q_{3\phi} = V_a.I_a^* + V_b.I_b^* + V_c.I_c^* \tag{1}$$

$$P_{3\phi} - j.Q_{3\phi} = [V_a \quad V_b \quad V_c].\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* \tag{2}$$

When transformed into dq0 reference frame using the Park's transformation, equation (1) transforms into (3) and (4). As noted above, since the converter is ungrounded on the ac side, the zero axis terms do not contribute to the real power.

$$P_{3\phi} = \frac{3}{2}\left[V_d.I_d + V_q I_q + V_0 I_0\right] \tag{3}$$

$$Q_{3\phi} = \frac{3}{2}\left[-V_d.I_q + V_q I_d\right] \tag{4}$$

If the synchronization reference is taken such that the voltage q axis value is zero then $V_q = 0$ which further simplifies the equation. Setting $V_q = 0$ in (3) and (4) and ruling out the zero axis quantities results in (5) and (6).

$$P_{3\phi} = \frac{3}{2}[V_d.I_d] \tag{5}$$

$$Q_{3\phi} = \frac{3}{2}\left[-V_d.I_q\right] \tag{6}$$

Using equations (5) and (6) in balanced steady state conditions, the real power and reactive power are directly dependent on the d axis and q axis currents respectively. Real can be regulated directly by controlling the d-axis component of the current and reactive power by controlling the q-axis component of the current, making the control loop design simpler and easier.

Outer Control Loop

A relatively slow outer control loop is created for determining I_d and I_q reference values from the set point values for real and reactive power. In the case of a wind turbine generator, the output power from the wind is hard to forecast accurately. The wind will also be continuously varying, so it is difficult to determine the I_d current reference value directly. The inverter I_d reference needs to follow the wind turbine generator output injected to the dc bus, otherwise either energy gets dumped in the capacitor and the dc bus voltage level increases and could possibly damage the power electronic devices, or if the power input falls, and the inverter supplies more ac power than coming from the dc link voltage will as the capacitors get drained and the system will not be able to maintain the voltage at the inverter terminals. Therefore, to vary the exported ac power with the change in wind generation, the input to the power control loop is based on regulating the dc link voltage. The generic energy flow is shown in Figure 2. The control scheme is based on keeping the DC link voltage constant. When the controller senses the increase in voltage level increases the I_d reference value to increase ac output power, P_{out}. This control scheme is commonly used in many applications with dc links.

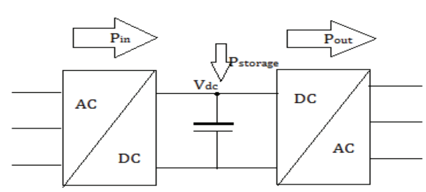

Figure 2: Generic power flow diagram of AC/DC/AC converter.

When it comes to the reactive power control, there is no compensation provided to the wind farm owner if they supply reactive power to the grid. Therefore, the reactive power supplied to the grid is typically zero under normal steady state conditions. However, the WTG designer may export reactive power under lower ac system voltage conditions. In order to meet LVRT codes [5][6], the converter might supply reactive power during a fault. Under normal operating conditions the reactive power supplied is zero which means the value of the I_q reference is zero.

Inner Control Loop

The inner control loops generate modulating waves for each phase to use in switching functions. These modulating waves will be a scaled replica of the commanded converter terminal voltages. The controller determines the voltage that has to be supplied at the terminal to drive the current corresponding to the reference values. Since the control is done in dq frame the output values m_d and m_q are transformed to the ABC reference to get modulating waves m_a, m_b and m_c.

A closed loop control is preferred due to the sensitivity of the output and to protect the power electronic devices from excessive currents. The I_d and I_q reference values are compared with the processed measured values. Different types of compensators may be used depending on the type of the reference signal and desired performance. The inner control loops are often implemented using proportional-integral (PI) compensators. The integral term of the compensator ensures that the reference values are closely tracked and to guarantee zero steady-state error [4].

A simple control flow diagram for the I_d and I_q current regulators is shown in Figure 3. The measured values of current at the point of interconnect with the external system (IAP, IBP and ICP) are processed through a high pass filter to reduce the switching harmonics and are scaled to per unit. The resultant current is fed to an ABC-DQ transformation block. The block introduces a phase shift which will be subsequently corrected (not shown in diagram). After the phase correction, the actual values are compared with reference values, and the error signal generated is fed through a PI compensator. To improve response to large changes in operating points, the transformed voltages at the point of interconnect (Vd and Vq) are added in through a feed forward loop [4]. As the control loop is in per unit the resultant outputs are the modulating waves in the synchronous dq reference frame. The measured voltages at the point of interconnection are used as the synchronizing reference, with V_d aligned with the positive peak of $V_a(t)$. These quantities are transformed back to the abc reference frame using the DQ-ABC transformation block for simulation. The output abc modulating waves are used for the generating the firing commands for the switches. The firing pulses for each simulated switch are generated separately with the functions generated by comparing the modulating wave with a unipolar triangular carrier signal. A similar control diagram is also shown in [7]

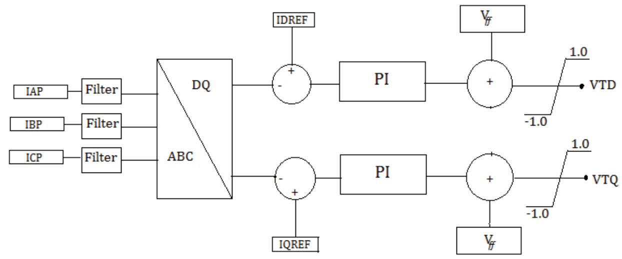

Figure 3: Simulation model - I_D and I_Q current regulator

The schematic diagram of the system modeled in this research is shown in Figure 4. The point of interconnection is at the high voltage side of the transformer.

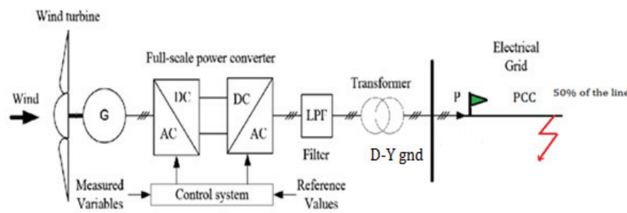

Figure 4: Type 4 WTG simulation test system with fault

When a fault occurs on the power system, the voltages at the point of interconnection fall. The current from the converter is determined by the voltage difference between the voltage at the point of interconnect the voltage at the terminal of the converter separated by the resistance and inductance of the low pass filter and of the transformer. The converter controller will control the magnitude and angle of voltage synthesized by the converter to meet the current commands. So unlike the back emf in a rotating machine, the converter voltage will rapidly change in response to a change in external voltage due to the fault, as a result, the voltage at the point of interconnection will not be elevated by the generator response. This change in voltage at the converter terminals and at the relay location conveys information that can be the starting point for a protection scheme. References [8], [9], [10] give more information on modeling wind turbines.

III. SIMULATION OF FAULTS

The faults are simulated at 50 percent of the transmission line connected to the wind turbine. Two classes of faults are simulated.

Case 1 – Unbalanced faults
· Single Line to Ground Faults (A–G Fault)
· Line to Line Faults (B–C Fault)
· Double Line to Ground Faults (B–C–G Fault)

Case 2 – Balanced faults
· 3 Phase Faults (3ϕ Fault)

As noted above, the magnitude of converter current is limited by the converter controls to stay within the switch current ratings i.e., the maximum amount of current the converter switches can withstand. Sustained over current can destroy the switches. As a result, the key measurement feature for developing a new protection scheme is that the magnitude of voltage at the terminals of the converter. The voltage is reduced at the onset of the fault to keep the current constant and to keep the reactive power at the set point. Effectively, the exported real power is reduced.

The power produced by the wind turbine generator does not change, the difference in power gets stored in the DC link. This action results in a rise in the DC link voltage which might damage the converter switches. There are two ways to overcome this problem to protect the devices. The first is the use of a crowbar circuit which is a set of resistors connected across the DC link through a thyristor switch or an IGBT; dumping the energy to the resistor. Another solution is to add an energy storage scheme to the DC link effectively connecting a set of batteries or larger capacitor backs through a bidirectional dc/dc converter. This dc/dc converter operates when the voltage rises above a threshold, and the energy gets transferred to the energy storage system. The stored energy can be utilized when extra power output is required from the WTG during normal operation. The energy storage could also be used to create synthetic inertia on the power system. In this analysis, a second capacitor bank is connected through back-to-back thyristors and used to model energy storage.

Faults are simulated at 50% of the length of the transmission line. The measured voltage and current at the point of interconnect are plotted in each of the fault cases. In each fault case, the fault occurs at t=0.4s and lasts for a period of 2.5 cycles before the circuit breaker opens. Note that in reality the circuit protection may not respond so quickly. The time window was chosen to challenge the performance of the protection algorithm.

Event 1A: Single Line to Ground Fault (SLG)

Figure 5 shows the voltages at the relay location (P) in the Figure 3. Figure 6 shows the measured current. Note that there is a slight increase in current amplitude, and in ripple, but both are too small to easily distinguish the fault location or fault type. The change voltage due to the fault is more pronounced, and is limited to the faulted phase. In cases where the transformer has a Y-grounded winding facing the power system, the zero-sequence current will be the most significant response. There is a slight increase in the voltage amplitude on the upfaulted phases.

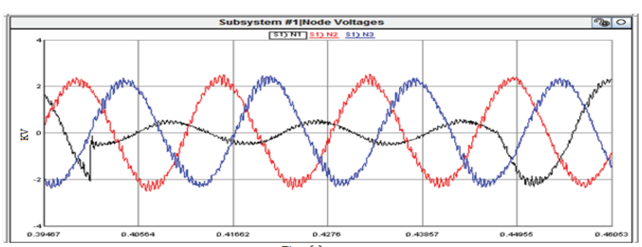

Figure 5: Line to ground voltages at relay location - Event 1A

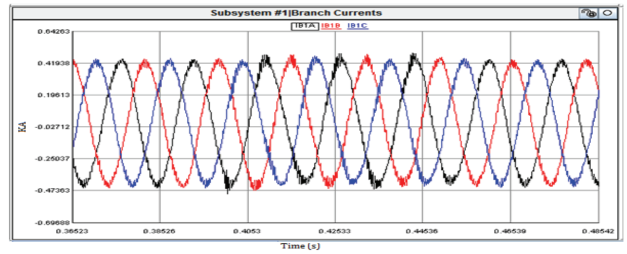

Figure 6: Phase currents at relay location – Event 1A

Event 1B: Line to Line Fault (LL)

The second case looks at the response to a LL fault. Figure 7 shows the voltages at the relay location. Figure 8 shows the measured current. Note that there is a slight increase in current amplitude, and in ripple, but too small to easily distinguish the fault location or fault type. There is little to visually distinguish Figure 8 from the results in Figure 6. The change in voltage due to the fault is more pronounced, and is limited to the faulted phases. Evaluation of the sequence currents shows that the response is primarily positive sequence current.

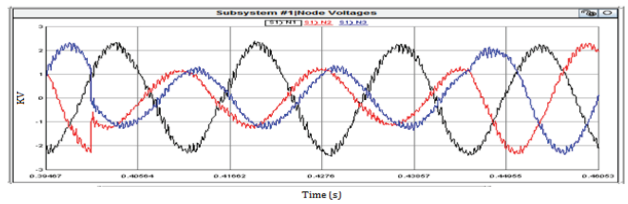

Figure 7: Line to ground voltages at relay location– Event 1B

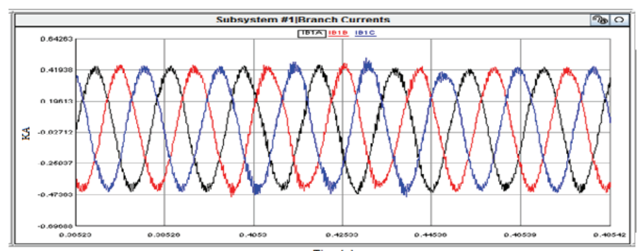

Figure 8: Phase currents at relay location – Event 1B

5.2c Event 1C: Double Line to Ground fault (DLG)

The third case looks at the response to a DLG fault. Figure 9 shows the voltages at the relay location. Figure 10 shows the measured current. Note that there is a slight increase in current amplitude, and in ripple, but too small to easily distinguish the fault location or fault type. Again, there is little to visually distinguish Figure 10 from the results in Figure 6 or 8. Nor would there be much difference if the symmetrical components were calculated and compared. The change the voltages due to the fault are more pronounced, and are again limited to the faulted phases. Note that there is some difference between the DLG and LL fault response.

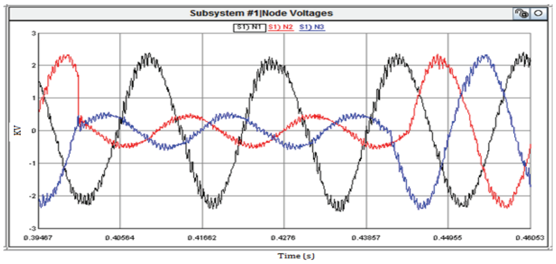

Figure 9: Line to ground voltages at relay location – Event 1C

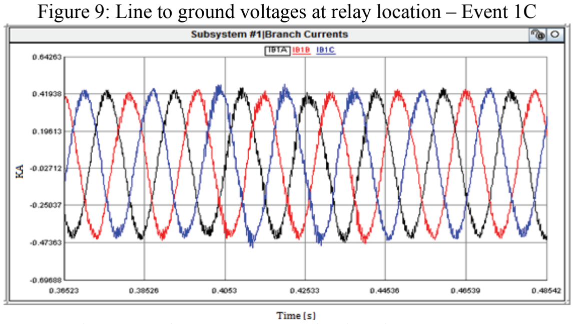

Figure 10: Phase currents at relay location – Event 1C

Event 2: Three phase fault at 50% of the line

The fourth case looks at the response to a three-phase fault. Figure 11 shows the voltages at the relay location. Figure 12 shows the measured current. Note that there is a slight increase in current amplitude, and in ripple, but too small to easily distinguish the fault location or fault type. There is little to visually distinguish Figure 12 from the results in unbalanced fault cases. The change the voltages due to the fault are more pronounced, and are again limited to the faulted phases.

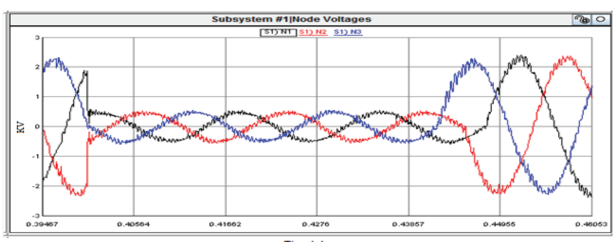

Figure 11: Line to ground voltages at relay location – Event 2

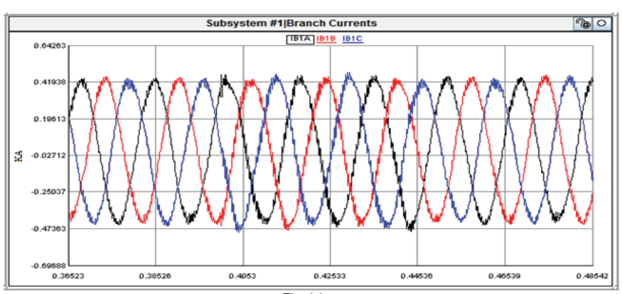

Figure 12: Phase currents at relay location – Event 2

The voltage waveforms demonstrate the indirect impact of the controller reacting to the fault by varying the magnitude of converter terminal voltages to keep the current within limits when there is a fault in the system. The current supplied by the wind turbine is almost constant and has little negative sequence current. There is only slight change in the current in response to the fault since the controller is reacting fast to bring the current within the set limits. The reaction time of the controller is measured in switching periods. The disturbance can also be sensed through the dc link voltage, although that is not readily available to the transmission relay. Note that there is a change in dc link voltage for any kind of disturbance, but there isn't a clear signature differentiating different fault types or faulted phases.

IV. NEED FOR NEW PROTECTION SCHEME

In case of fault supplied by a Type 4 WTG converter, the converter is designed such that the current output typically doesn't exceed 1.1-1.2 per unit due to design choices and the current rating of the switches. When a fault occurs beyond the PCC, the controller adjusts amplitude and phase of the converter modulating wave reducing the voltage at the converter terminal in order to keep the current magnitude within the limit and maintain power factor. As a result, an overcurrent element cannot be applied to provide reliable protection for a wind farm with Type 4 WTGs. If it is employed, such elements are unlikely to generate a trip command and the relay will misoperate.

WTGs connected to a system with a weak source at the other end of the transmission line, there is potential for significant voltage variations with wind speed and the resulting WTG power output. In such cases, alternative reactive power sources are operated or load shedding is done which requires a certain time interval for operation. So a relay is used for protection at the point of interconnect might misoperate, disconnecting the source from the system.

A line current differential scheme is a good option for protecting lines connected to wind farms with 4 WTG systems. But as previously stated, the system up to the point of interconnect is owned by the wind farm owner and from that point onwards, it may be in the hands of the transmission owner. Hence a dedicated communication line might not be possible. Line current differential protection cannot be applied in situations where communication is not available. In addition, the fault current at the wind farm end of the line may fall below the minimum pick up level for the differential element in cases where a small number of WTGs in a large farm are operating.

For distance protection in the case of a wind farm with Type 4 WTGs, the currents are limited and are balanced even for unbalanced faulted conditions. Negligible negative sequence or zero sequence current flows from the converter. The WTG cannot be modeled as a source behind impedance in the positive sequence. It can be considered as a variable source keeping the current constant maintaining a constant power factor. For such a situation, the directional supervising element fails to qualify the fault as forward and the relay could fail to operate. In addition, the voltage at the relay location could be lower than expected for the current measured due to the limited current. The conventional schemes are explained clearly in [11]

V. Proposed Scheme

Based on the fault response of the system, the following schemes could be considered to provide protection, but they are not adequate.

- DC link voltage: It is clearly observed that the dc link voltage varies for different types of faults. This response can be used for fault detection, but the type of fault, distance to fault or the faulted phases cannot be determined using the change in dc link voltage. Measuring the dc link voltage requires access wind turbine vendors providing the relays with access to that voltage from each turbine.
- Transients induced by the fault: There are transients induced in the transmission line due to the sudden change in the voltage based on the characteristics of the transmission line. Transients can be detected when the fault occurs at a nonzero voltage. It will be difficult to sense transients if the fault occurs at a point on the voltage waveform near a voltage zero. Therefore, an additional scheme that works under all conditions is needed.

The voltage at the PCC varies as the converter controller varies the converter output voltage to keep the current constant at the point of interconnect. Before the fault, the effective impedance looking into the system is high and the current supplied is at unity power factor. Once a fault occurs in the system, the magnitude and phase of the modulating wave changes to keep the current less than current threshold, which is typically around 1.2 pu. Since the fundamental component of the terminal voltage is a scaled version of the modulating wave, the change is seen in the terminal voltage. In addition, a change in the voltage at the PCC will also be seen, although less clearly. This change in voltage can be used to identify the fault and protective measures can be taken (issuing the trip signal to the breaker).

Generally, in case of a microprocessor relay, the output of the potential transformer is fed to a loop with an anti-aliasing filter, an A/D converter, and a Fourier filter. The gain of a Fourier filter or a cosine is unity at fundamental frequency and is zero for all the harmonics of the fundamental quantity (provided it is a one cycle cosine filter). The anti-aliasing filter attenuates the higher frequency components. The final output values will then be used for processing. The simulation responses for this thesis are dealt in a similar fashion. The simulated sampled ac voltages are processed through down sampler with linear interpolation then fed to a band pass filter of range 59 – 61 Hz and then the RMS values of the output waveforms are calculated and scaled to per unit.

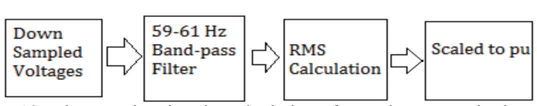

Figure 13: Diagram showing the calculation of pu voltage magnitudes

Simulation Results

Event 1A: SLG fault at 50% of the line

When the fault occurs in phase A, the effective impedance of the faulted phase seen by the relay will be the impedance of the transmission line up to the fault point. The converter controller varies effective line to ground voltage of the faulted phase in such a way that the fault current is kept down to 1.1 pu, nearly equal to the other phases. As shown in Figure 14, only the faulted phase sees a change in voltage.

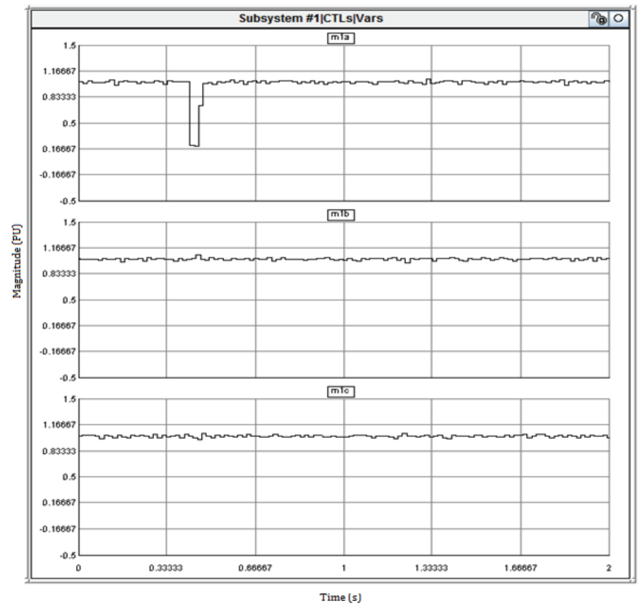

Figure 14: Calculated voltage magnitude at the relay location – Event 1A

Event 1B: LL fault at 50% of the line

In the case of the LL fault in Figure 15, the instantaneous magnitude of the line to ground voltages on phases are reduced for a BC line to line fault. The phase A voltage is almost unaffected

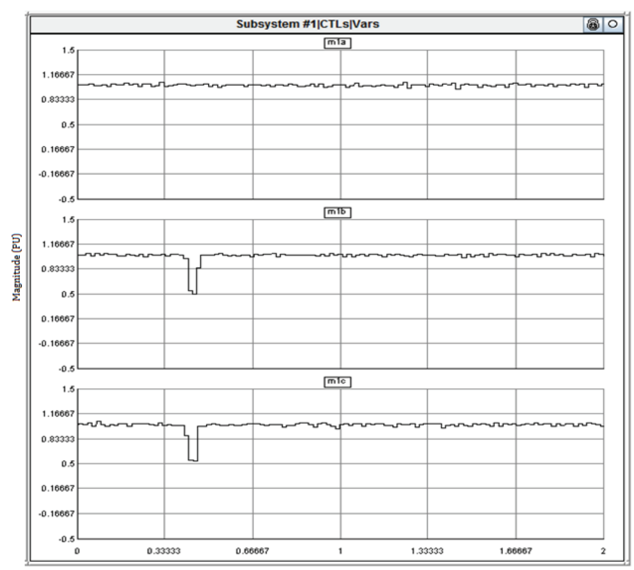

Figure 15: Calculated voltage magnitude at the relay location – Event 1B

Event 1C: DLG fault at 50% of the line

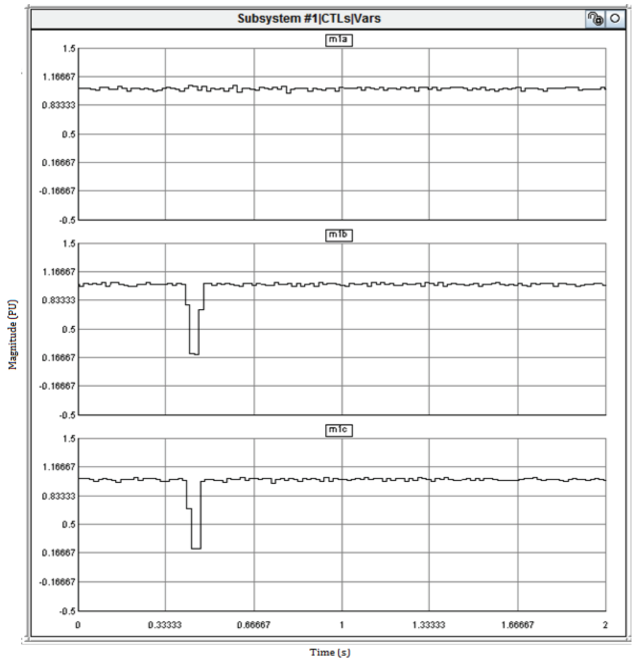

Figure 16: Calculated voltage magnitude at the relay location – Event 1C

Figure 16 shows that the magnitudes of the line to ground voltages on the faulted phases are again reduced for DLG fault and look similar to the LL fault case, but there is a larger change in magnitude. This voltage dip is same as the SLG fault in each phase when there is no fault resistance

Event 2: Three phase fault

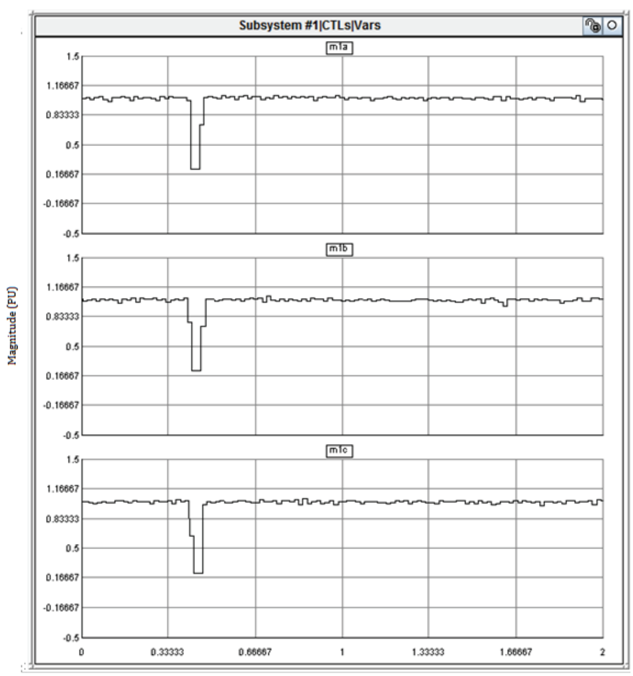

Figure 17: Calculated voltage magnitude at the relay location – Event 2

For a 3-phase fault, all the three phases experienced the dip in the magnitude. This dip is same as the previous ground faults at the same fault but for all the three phases.

The partial trip logic is shown in the Figure 18. The modulating wave is calculated from voltage measured at the point of interconnect, compensating for the number of wind turbines active, the transformer connections and nominal voltage. The Delta(I) is the once cycle difference value (delta quantity) of the converter current phasor. The current supervision is to differentiate between drop in voltage due to faults or due a decrease in wind output causing a voltage change. Since the current is driven by converter operation and change for faults is small, a supervisory could be more reliable when the protection operation is based on modulating waves.

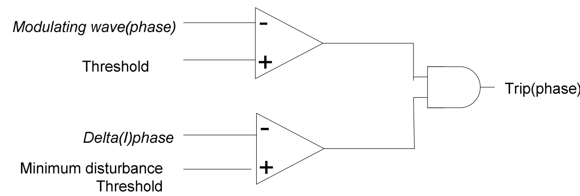

Figure 18: Partial trip logic (per phase)

Many additional cases were also simulated, including faults at different locations on the transmission line and faults with varying fault resistance. These are described in more detail in [12]. It is observed that the dip in voltage magnitude is proportional to the percent length of the line to the fault point. Figure 19 shows effective voltage magnitude the plotted for different fault locations. The straight line shifts up along Y axis if the remote end system is a strong source but the linear dependence will be more or less the same.

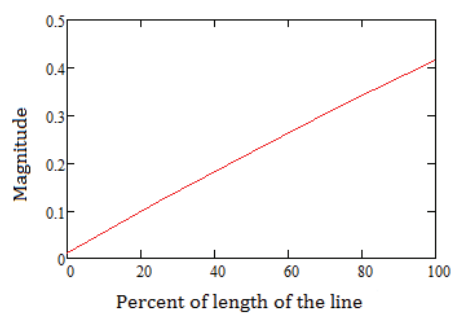

Figure 19: Length of line to the fault point Vs. Modulating wave magnitude

The results of Figure 19 show that for solid faults with no fault resistance, the dip in voltage magnitude is nearly proportional to the distance to the fault point. The slight magnitude at 0% of the transmission line is the on-state voltage drop across the circuit breaker. So, an additional advantage of this approach is that the approximate fault location can be determined using the dip in magnitude.

Fault location calculation might not give accurate fault location if there is a fault resistance involved; the dip in voltage gets reduced due to the potential at the fault point on the transmission line. If the fault resistance is high the change in voltage magnitude is small.

VI. CONCLUSION

This paper presented a preliminary development of a protection scheme for protective systems for systems fed by Type 4 wind turbines. The faults simulated at different points of the transmission line gave a good insight into the effects on WTG response. The proposed scheme based on the reduction in magnitude of the point of interconnect voltage, thus back tracing the modulation wave magnitude works for all wind conditions and different wind farm operating conditions. More information is provided in the Master's thesis in [12]. The fault current contribution changes a little for different wind speeds but in almost all cases the fault current will be almost equal to the pre-fault current.

REFERENCES

[1] Antonio Luque, Olimpo Anaya-Lara, William Leithead and Grain P. Adam, "Coordinated control for wind turbine and VSC-HVDC transmission to enhance FRT capability." *10th Deep Sea Offshore Wind R&D Conference*, Deep Wind'2013.

[2] Reigh Walling, Ekrem Gursoy and Bruce English, "Current Contributions from Type 3 and Type 4 Wind Turbine Generators during Faults." *Transmission and Distribution Conference and Exposition (T&D)*, 2012 IEEE PES, 7-10 May, 2012.

[3] Bing Chen, Arun Shrestha, Fred A. Ituzaro, and Normann Fischer, "Addressing Protection Challenges Associated With Type3 and Type4 Wind Turbine Generators." presented at the *40th Annual Western Protective Relay Conference*, October 2013.

[4] Amirnaser Yazdani and Reza Iravani, *Voltage-Sourced Converters in Power Systems – Modeling, Control, and Applications*. Wiley, March 2010.

[5] G. Joós, "Wind Turbine Generator Low Voltage Ride through Requirements and Solutions." *IEEE Power and Energy Society General Meeting*, 20 – 24 July, 2008.

[6] Rajveer Mittal, K. S. Sandhu and D. K. Jain, "Low Voltage Ride-Through of grid interfaced wind driven PMSG." *Asian research publishing network* Vol. 4, No. 5 July 2009.

[7] Mohit Singh and Surya Santaso, *Dynamic Models for Wind Turbines and Wind Power Plants.* NREL and The University of Texas at Austin, October 2011

[8] RTDS technologies. *Real time digital simulator controls library manual*, July 2013.

[9] J. R. Williams and B. Karlson, *Wind power plant short-circuit modeling guide*. Sandia National Laboratories, New Mexico & California, SAND2012-6664, 2012

[10] Pouyan Pourbeik, *Proposed Changes to the WECC WT4 Generic Model for Type 4 Wind Turbine Generators*. NREL, December 2011.

[11] J.L. Blackburn and T.J. Domin, *Protective Relaying: Principles and Applications, Fourth Edition*. CRC Press, 2014

[12] Shashidhar Reddy Sathu, *Design, Modeling and Analysis of a New Protection Scheme for Type 4 Wind Turbine.* Master's Thesis, University of Idaho, December 2016