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Grid Connected Wind Farm: Short Circuit Analysis and Relay Coordination Using ETAP

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***Abstract* - The integration of wind farms with the grid is of paramount importance in the quest for harnessing renewable energy sources. This study delves into the grid integration of a wind farm comprising six Wind Turbine Generators (WTGs) and places a specific emphasis on load flow analysis to assess voltage profiles across various buses, as well as Active and Reactive Power flow characteristics. Furthermore, the research investigates the intricacies of short circuit analysis, encompassing both three-phase and single-line-to-ground fault scenarios at various bus locations. Relay coordination schemes are explored to optimize fault isolation strategies within the system. One of the prominent challenges addressed in this study is the integration of wind farms at voltage levels such as 33 kV or 66 kV, often situated at locations remote from the grid's central infrastructure, where the grid's strength is relatively weaker. This scenario can pose a significant threat to power system protection since inverter-based generators have lower inertia, potentially affecting their ability to provide fault currents detectable by conventional protection systems. The paper concludes by discussing the encountered challenges and proposing areas for future research and innovation. The comprehensive model used in this study is developed within the ETAP environment.**

Keywords: WTG, Short Circuit Analysis, Load Flow, 3 Phase & Line to Ground fault, Power grid, Protection Relay setting & Coordination.

I. Introduction

The integration of wind farms into the power grid is a vital component of modern power systems, driven by the growing emphasis on harnessing renewable energy resources. Wind farms, equipped with Wind Turbine Generators (WTGs), represent a substantial share of the renewable energy portfolio. As such, understanding the intricate dynamics of grid integration and ensuring the reliability and stability of power systems when wind farms are connected are of paramount importance.

This study centers its focus on a wind farm configuration comprising six WTGs and explores the challenges and strategies associated with its integration into the grid. In particular, this study conducts an analysis of load flow to evaluate voltage profiles across various bus locations. Active and Reactive Power flow characteristics are also scrutinized to ensure the effective utilization of wind energy resources as well as grid compliance.

Furthermore, the study explores the power system protection, examining the implications of short circuit events, including both three-phase and single-line-to-ground faults, which can occur at multiple bus locations within the wind farm. The coordination of protective relays is investigated as a means to enhance the ability to detect and isolate faults swiftly and effectively.

One significant challenge addressed in this research is the integration of wind farms at voltage levels, such as 33 kV or 66 kV, situated in locations distanced from the main grid infrastructure. This spatial separation introduces complexities in maintaining grid stability, as inverter-based generators within the wind farm may exhibit lower inertia and fault current contributions that can potentially challenge the conventional protection mechanisms.

The ensuing sections of this paper present a comprehensive analysis of the wind farm configuration, the methodologies employed, key findings, and discussions on addressing challenges and future research directions. The study leverages the ETAP platform to construct a detailed model consisting of six 4.5 MW WTGs, a network of two 33 kV main buses connecting two wind farm clusters, and a double-circuit Panther line facilitating the wind farm's connection to the power grid through a step-up 33/66 kV, 50 MVA power transformer.

In summary, this research strives to contribute to the understanding of grid integration challenges for wind farms and provides valuable insights into ensuring a reliable and stable power supply while advancing the utilization of renewable energy sources within present-day power grids.

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II. Load Flow Analysis

The power flow problem is the computation of voltage magnitude and phase angle at each bus in a power system under balanced three-phase steady-state conditions. As a by-product of this calculation, real and reactive power flows in equipment such as transmission lines and transformers, as well as equipment losses can be computed. The following four variables are associated with each bus k: voltage magnitude Vk, phase angle δk, net real power Pk, and reactive power Qk supplied to the bus. At each bus, two of these variables are specified as input data, and the other two are unknowns to be computed by the power flow program [12], [13].

A) Network Topology

In the figure 1, there are total 22 Nos of Buses (1 Swing Bus, 6 Voltage Bus & 15 Load Bus).

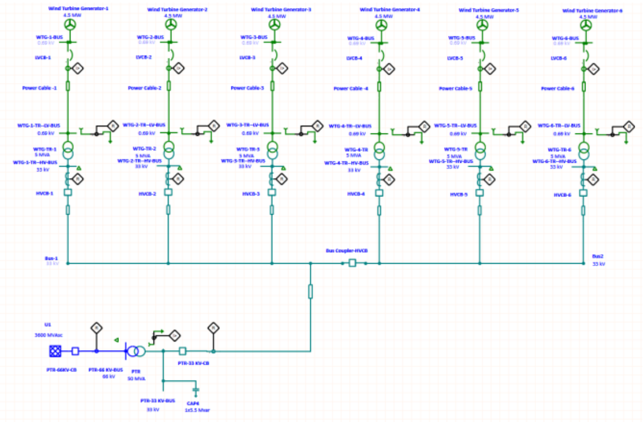


Figure 1: Wind farm

Table 1: Bus Details

Sl. No	Bus ID	Type of Bus	No
1	PTR-66 KV-BUS	Swing	01
2	WTG-1-BUS	Voltage Control	01
3	WTG-2-BUS	Voltage Control	01
4	WTG-3-BUS	Voltage Control	01
5	WTG-4-BUS	Voltage Control	01
6	WTG-5-BUS	Voltage Control	01
7	WTG-6-BUS	Voltage Control	01
8	Others	Load Bus	15
9	Total	All	22

B) Simulation Result

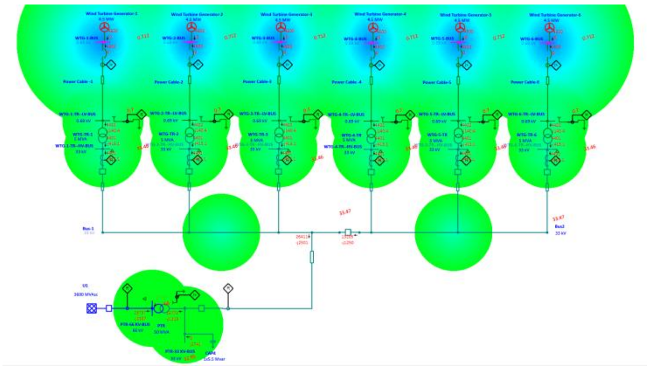
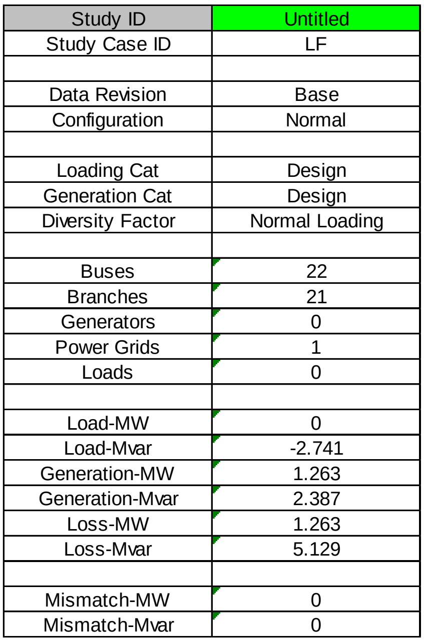


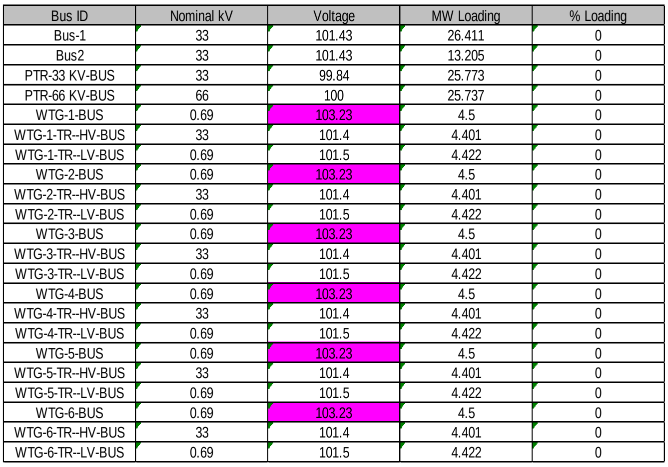
Figure 2: Load Flow

1. General



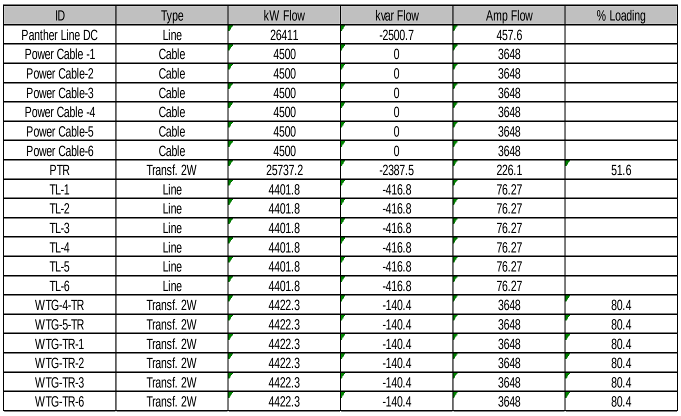
Study ID	Untitled
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	22
Branches	21
Generators	0
Power Grids	1
Loads	0
Load-MW	0
Load-Mvar	-2.741
Generation-MW	1.263
Generation-Mvar	2.387
Loss-MW	1.263
Loss-Mvar	5.129
Mismatch-MW	0
Mismatch-Mvar	0

2. Bus



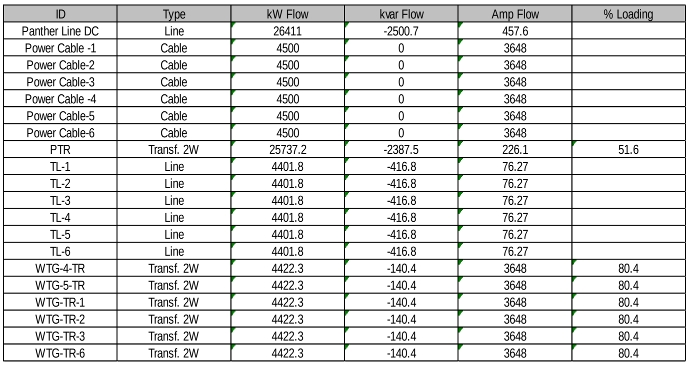
Bus ID	Nominal kV	Voltage	MW Loading	% Loading
Bus-1	33	101.43	26.411	0
Bus2	33	101.43	13.205	0
PTR-33 KV-BUS	33	99.84	25.773	0
PTR-66 KV-BUS	66	100	25.737	0
WTG-1-BUS	0.69	103.23	4.5	0
WTG-1-TR--HV-BUS	33	101.4	4.401	0
WTG-1-TR--LV-BUS	0.69	101.5	4.422	0
WTG-2-BUS	0.69	103.23	4.5	0
WTG-2-TR--HV-BUS	33	101.4	4.401	0
WTG-2-TR--LV-BUS	0.69	101.5	4.422	0
WTG-3-BUS	0.69	103.23	4.5	0
WTG-3-TR--HV-BUS	33	101.4	4.401	0
WTG-3-TR--LV-BUS	0.69	101.5	4.422	0
WTG-4-BUS	0.69	103.23	4.5	0
WTG-4-TR--HV-BUS	33	101.4	4.401	0
WTG-4-TR--LV-BUS	0.69	101.5	4.422	0
WTG-5-BUS	0.69	103.23	4.5	0
WTG-5-TR--HV-BUS	33	101.4	4.401	0
WTG-5-TR--LV-BUS	0.69	101.5	4.422	0
WTG-6-BUS	0.69	103.23	4.5	0
WTG-6-TR--HV-BUS	33	101.4	4.401	0
WTG-6-TR--LV-BUS	0.69	101.5	4.422	0

3. Branch



ID	Type	kW Flow	kvar Flow	Amp Flow	% Loading
Panther Line DC	Line	26411	-2500.7	457.6	
Power Cable -1	Cable	4500	0	3648	
Power Cable-2	Cable	4500	0	3648	
Power Cable-3	Cable	4500	0	3648	
Power Cable -4	Cable	4500	0	3648	
Power Cable-5	Cable	4500	0	3648	
Power Cable-6	Cable	4500	0	3648	
PTR	Transf. 2W	25737.2	-2387.5	226.1	51.6
TL-1	Line	4401.8	-416.8	76.27	
TL-2	Line	4401.8	-416.8	76.27	
TL-3	Line	4401.8	-416.8	76.27	
TL-4	Line	4401.8	-416.8	76.27	
TL-5	Line	4401.8	-416.8	76.27	
TL-6	Line	4401.8	-416.8	76.27	
WTG-4-TR	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-5-TR	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-1	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-2	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-3	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-6	Transf. 2W	4422.3	-140.4	3648	80.4

4. Load



ID	Type	kW Flow	kvar Flow	Amp Flow	% Loading
Panther Line DC	Line	26411	-2500.7	457.6	
Power Cable -1	Cable	4500	0	3648	
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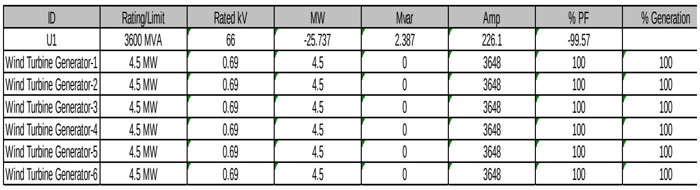
Power Cable-3	Cable	4500	0	3648	
Power Cable -4	Cable	4500	0	3648	
Power Cable-5	Cable	4500	0	3648	
Power Cable-6	Cable	4500	0	3648	
PTR	Transf. 2W	25737.2	-2387.5	226.1	51.6
TL-1	Line	4401.8	-416.8	76.27	
TL-2	Line	4401.8	-416.8	76.27	
TL-3	Line	4401.8	-416.8	76.27	
TL-4	Line	4401.8	-416.8	76.27	
TL-5	Line	4401.8	-416.8	76.27	
TL-6	Line	4401.8	-416.8	76.27	
WTG-4-TR	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-5-TR	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-1	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-2	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-3	Transf. 2W	4422.3	-140.4	3648	80.4
WTG-TR-6	Transf. 2W	4422.3	-140.4	3648	80.4

5. Source



ID	Rating/Limit	Rated kV	MW	Mvar	Amp	% PF	% Generation
U1	3600 MVA	66	-25.737	2.387	226.1	-99.57	
Wind Turbine Generator-1	4.5 MW	0.69	4.5	0	3648	100	100
Wind Turbine Generator-2	4.5 MW	0.69	4.5	0	3648	100	100
Wind Turbine Generator-3	4.5 MW	0.69	4.5	0	3648	100	100
Wind Turbine Generator-4	4.5 MW	0.69	4.5	0	3648	100	100
Wind Turbine Generator-5	4.5 MW	0.69	4.5	0	3648	100	100
Wind Turbine Generator-6	4.5 MW	0.69	4.5	0	3648	100	100

III. Short Circuit Analysis

Short circuits occur in power systems when equipment insulation fails due to system over voltages caused by lightning or switching surges, to insulation contamination (salt spray or pollution), or to other mechanical causes. The resulting short circuit or "fault" current is determined by the internal voltages of the synchronous machines and by the system impedances between the machine voltages and the fault. Short-circuit currents may be several orders of magnitude larger than normal operating currents and, if allowed to persist, may cause thermal damage to equipment. Windings and bus bars may also suffer mechanical damage due to high magnetic forces during faults. It is therefore necessary to remove faulted sections of a power system from service as soon as possible. Standard EHV protective equipment is designed to clear faults within 2.5 cycles (50 ms at 50 Hz). Lower voltage protective equipment operates more slowly (for example, 5 to 20 cycles) [14].

The short circuit analysis is performed as per IEC 60909 and maximum fault current both for 3 Phase & Line to Ground cases on various buses have been simulated using ETAP [15].

A) System Description

There are 6 Nos of WTG (Type-3) each having 4.5 MW capacity have been used in this study. The power from WTG is evacuated through a Power Transformer (0.69/33 kV, 5 MVA) which connect 0.69 side to WTG and 33 kV side to Transmission line & further to Grid (Sc MVA 3600) at 66 KV Voltage level through a Step up Power Transformer (33/66 KV).

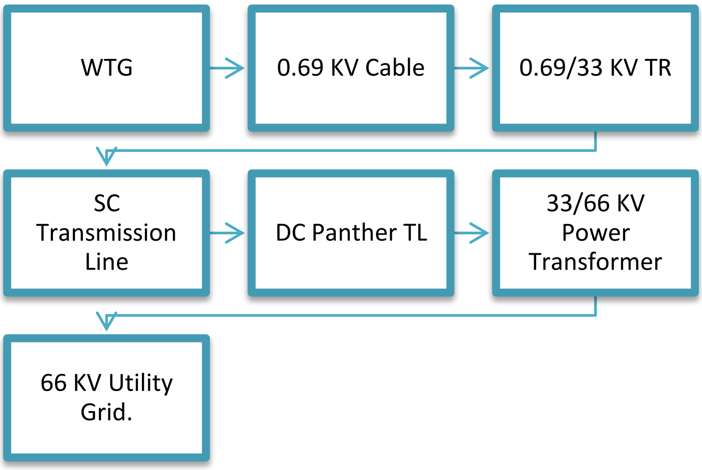


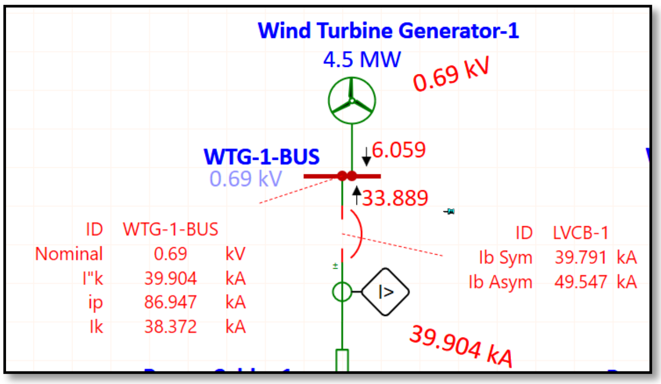
Figure 3: WTG-Grid Interconnection Block Diagram

B) Equipment Input data

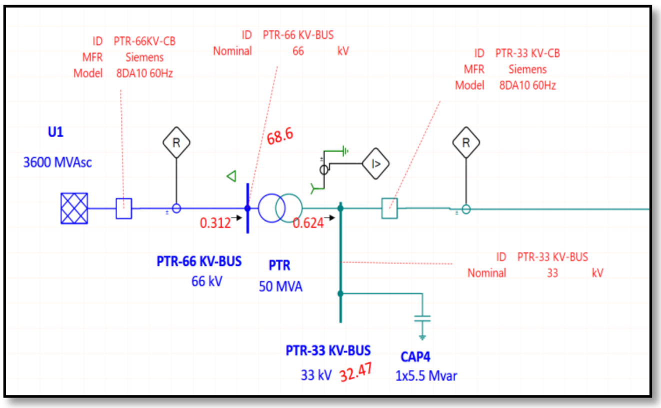
Sl. No	ID	Description	No
1	WTG	0.69 kV, 4.5 MW, Type-3	06
2	Power Cable	5 R X 500mm2 (cu) Re : 0.051 Ω/1000 m X : 0.088 Ω/1000 m	200 Mtr
3	WTG TR	0.69/33 kV, 5 MVA, %Z 7.15, R/X 0.078	06
4	TL-1	Single Ckt	1 Km
5	TL-2	Double Ckt	20 Km
6	PTR	33/66 kV, 50 MVA, %Z 8, R/X 0.034	01
7	Power Grid	Short Circuit MVA – 3600 @ 66 kV.	

C) 3 Phase Fault Analysis@ WTG-1 Bus

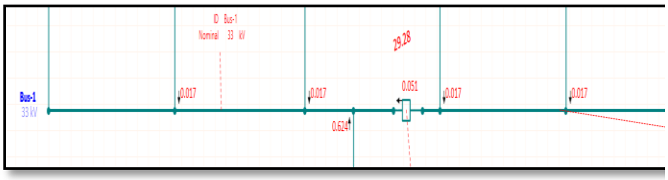
a) Creation of 3 Phase fault @ WTG-1 Bus



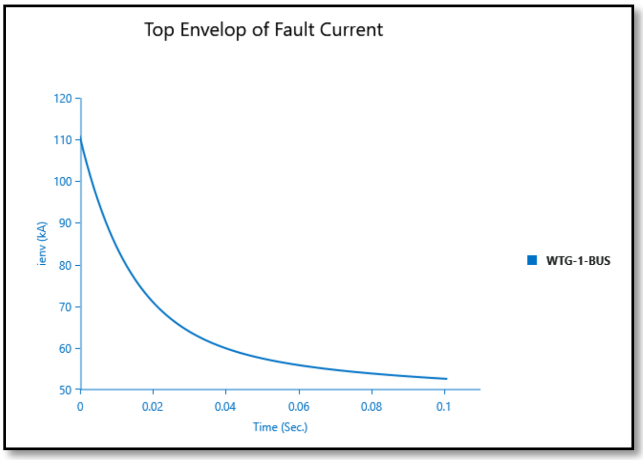
b) Fault Contribution by Grid

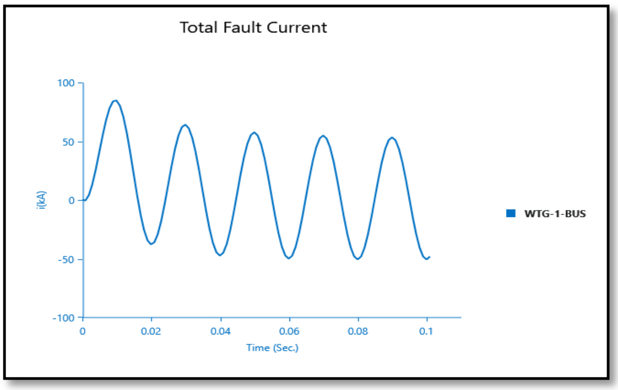


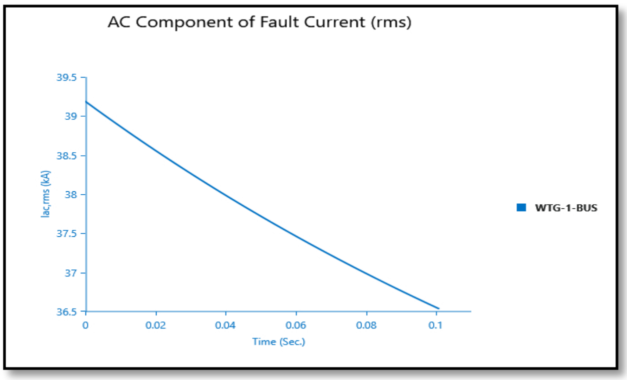
c) Fault Contribution by WTGs

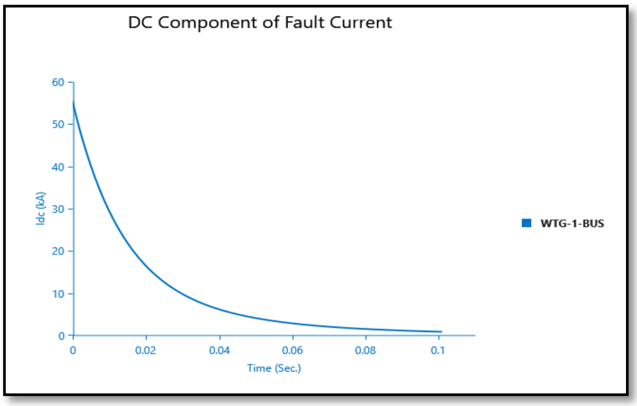


d) IEC 61363 Short Circuit Plots (Transient)



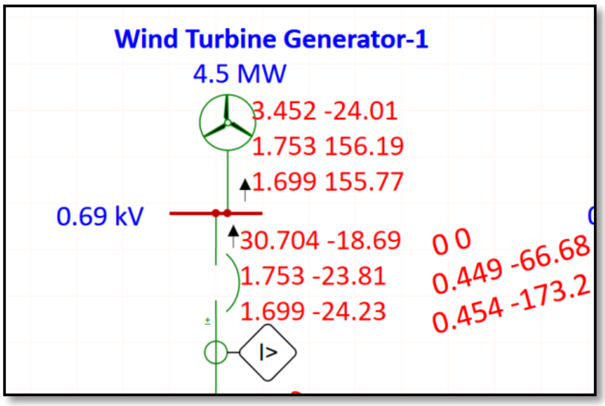






D) L-G Phase Fault Analysis @ WTG-1 Bus

a) Creation of 1 Phase fault @ WTG-1 Bus



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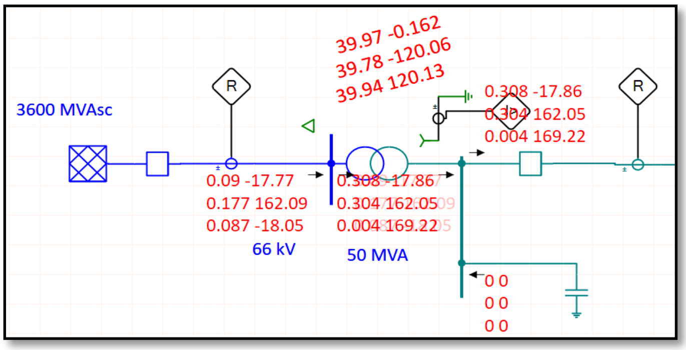
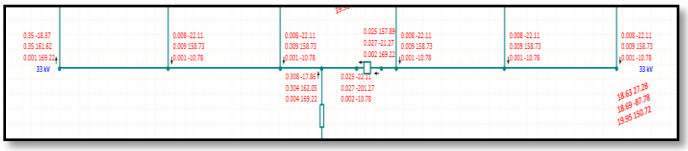
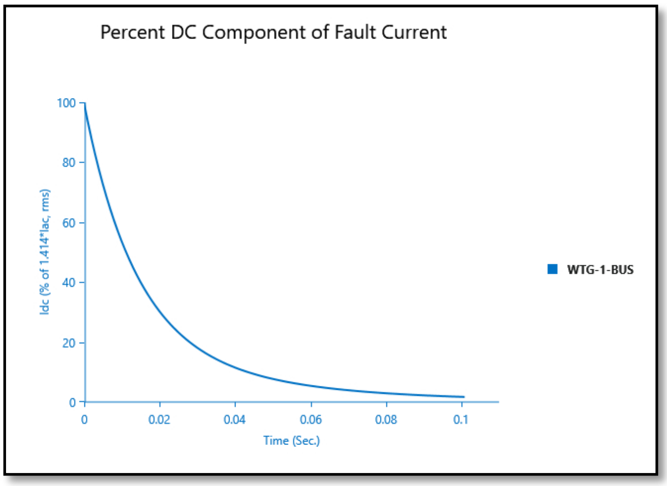
b) Fault Contribution by Grid

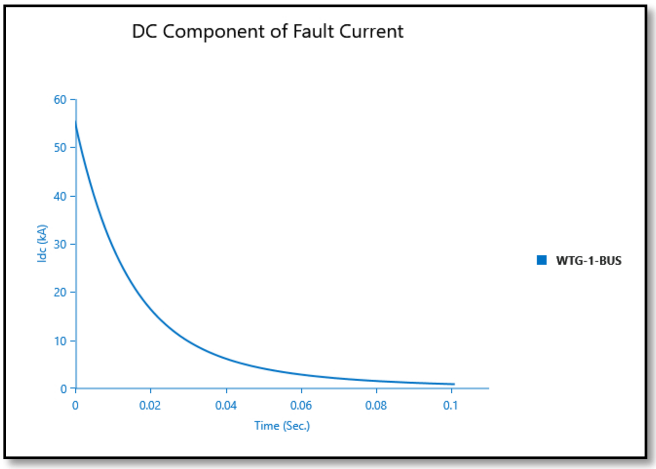


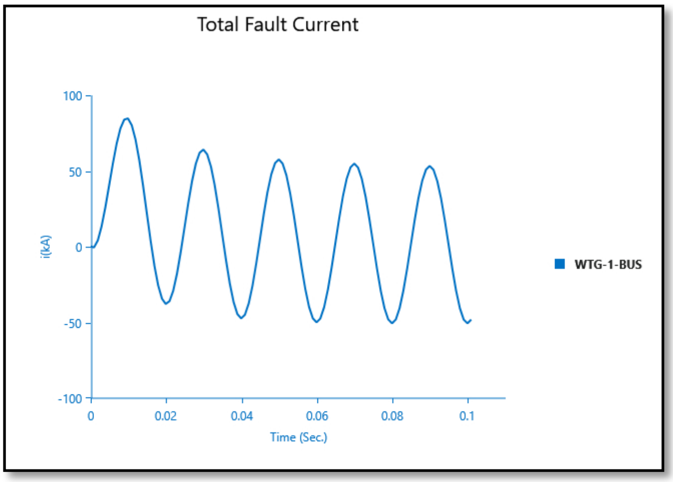
c) Fault Contribution by WTGs

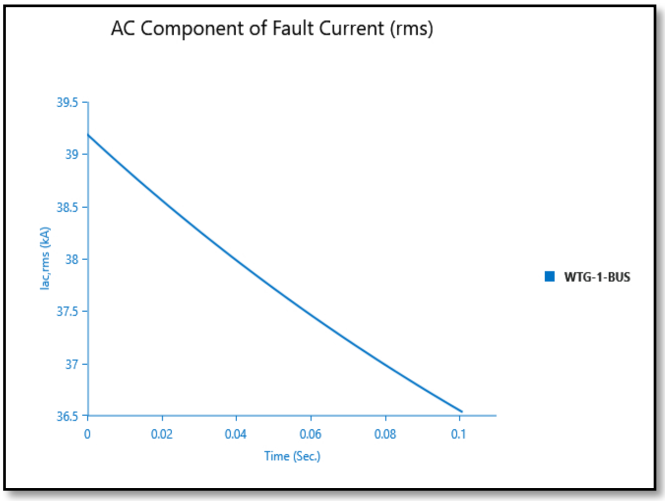


d) IEC 61363 Short Circuit Plots (Transient)









IV. Protection Coordination Study

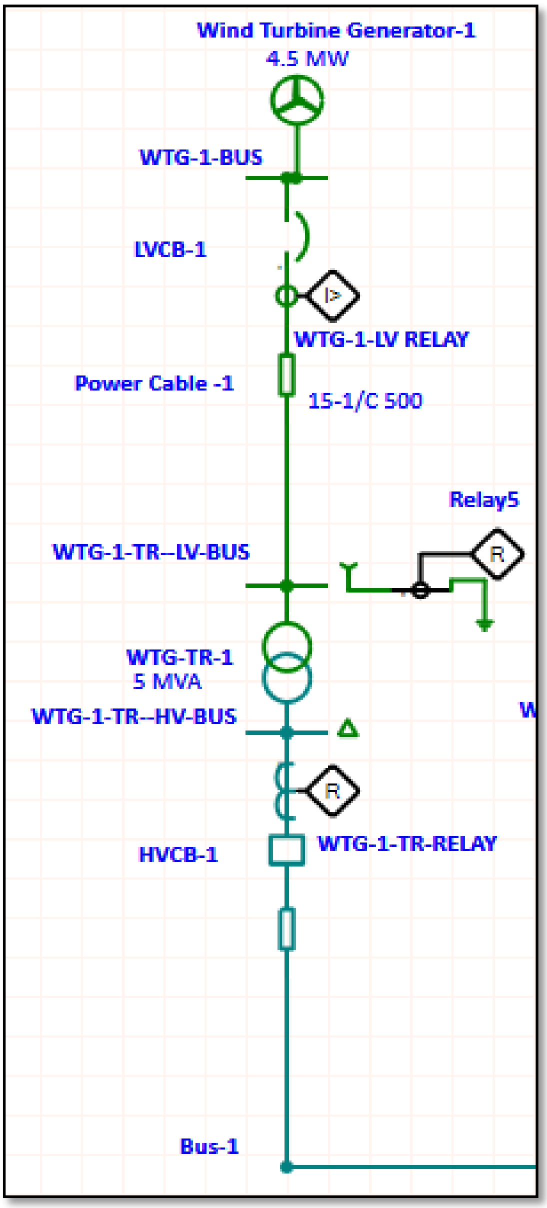
Protection systems have three basic components:

1. Instrument transformers
2. Relays
3. Circuit breakers

An effective protection system is vital for grid reliability. Coordination ensures swift fault detection and isolation while maintaining generation continuity. Advanced relay technology and communication networks are employed to safeguard equipment and optimize the performance of the system, minimizing downtime and grid disturbances [16].

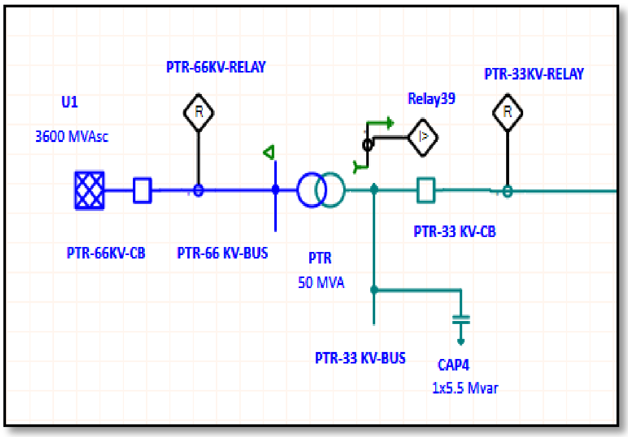
A) Protection & Relaying diagram (WTG)

For (WTGs) and transformers in wind farm applications, a dual circuit breaker setup comprising Low Voltage Circuit Breakers (LVCBs) and High Voltage Circuit Breakers (HVCBs) is employed. These circuit breakers are equipped with Current Transformers (CTs) and relays designed to protect against faults using both Time-Over current and Instantaneous characteristic features.



This comprehensive protection scheme ensures the safe and efficient operation of the entire system.

B) Protection & Relaying diagram (Grid Side- Upstream)



The power transformer is employed with two circuit breakers on 33 KV & 66 KV Side with CTs & relays, protection against over current and earth fault.

C) Technical Particulars of components

Sl. No	ID	Description	No
1	LVCB -1	0.69 kV, 6300A, 75 kA SCR	01
2	HVCB -1	36 kV, 1250A, 31.5 kA SCR	01
3	LVCT	CTR 5000/1	03
4	Relay-1	Phase & Ground OCR	01
5	HVCT	CTR 150/1	01
6	Relay-2	Phase & Ground OCR	01
7	TR-NCT	CTR 1000/1	01
8	Relay-3	Ground fault	01
9	PTR-33KV-CB	36 kV, 1250A, 40 kA SCR	01
10	PTR-66KV-CB	72 kV, 1250A, 40 kA SCR	01
11	PTR-33KV-CT	CTR 600/1	01
12	PTR-66KV-CT	CTR 500/1	01
13	PTR-33KV-Relay	Phase & Ground OCR	01
14	PTR-66 KV-Relay	Phase & Ground OCR	01
15	PTR-NCT	CTR 1000/1	01
16	NCT-Relay	Ground Fault	01

D. Relay Coordination (Operational Sequence)

Effective coordination among relays is essential for reliable power system and protection. To achieve this, in this paper faults on WTG Bus, & Tie Bus and Grid Side are created and relay operational sequence and their operation time are recorded. Each relay characteristic has been shown in the TCC.

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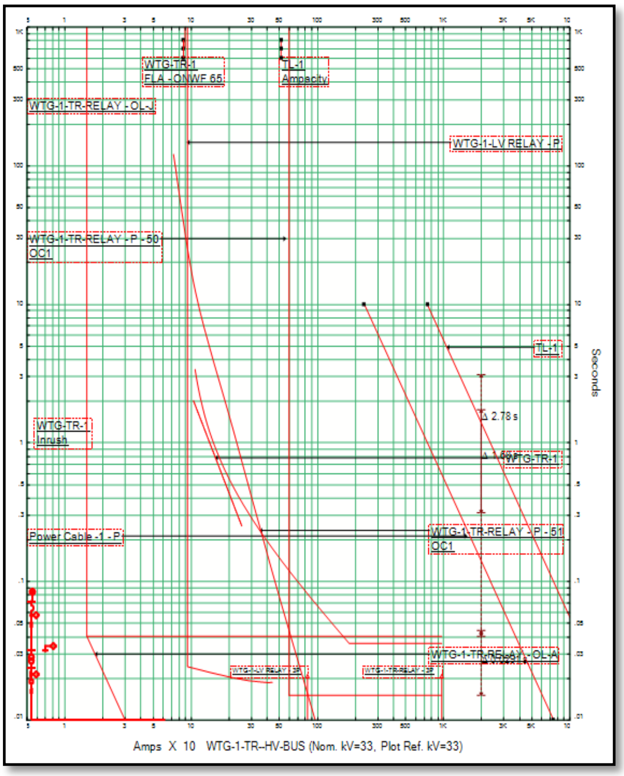
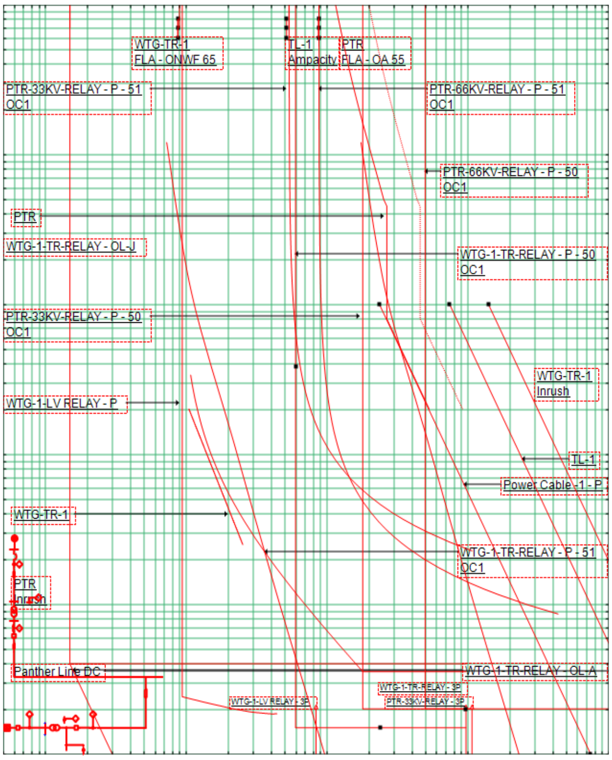
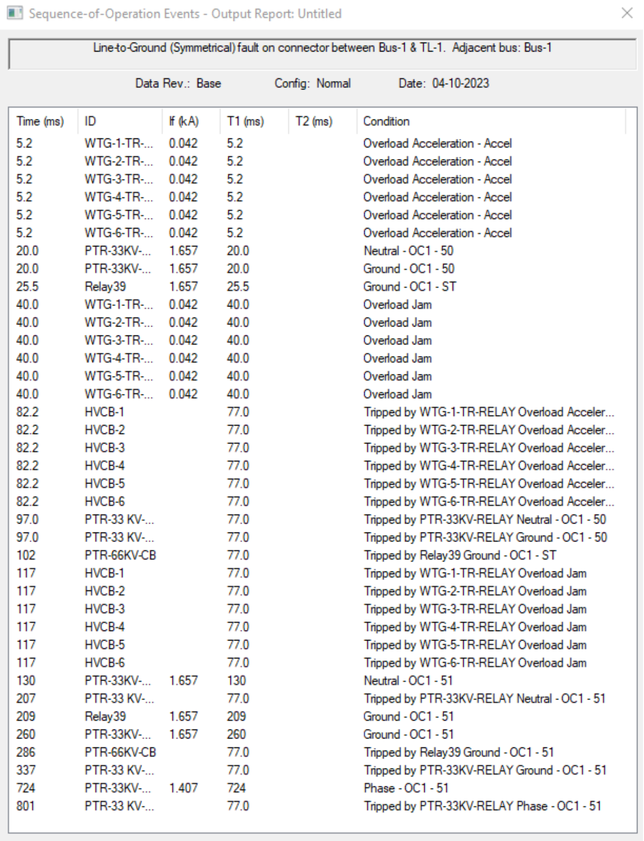
a) Relay Coordination between LVCB & HVCB



b) Relay Coordination among WTG LVCB to PTR 66 KV



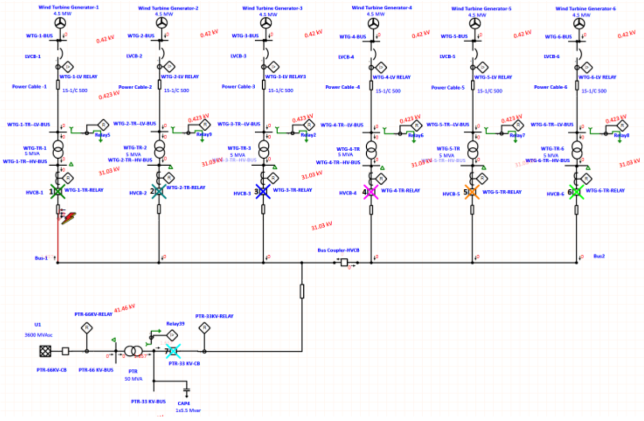
A fault was created on 33 KV Line of WTG-1 and sequence of operation of relays and tripping of breakers captured.



Line-to-Ground (Symmetrical) fault on connector between Bus-1 & TL-1. Adjacent bus: Bus-1

Data Rev.: Base Config: Normal Date: 04-10-2023

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
5.2	WTG-1-TR-...	0.042	5.2		Overload Acceleration - Accel
5.2	WTG-2-TR-...	0.042	5.2		Overload Acceleration - Accel
5.2	WTG-3-TR-...	0.042	5.2		Overload Acceleration - Accel
5.2	WTG-4-TR-...	0.042	5.2		Overload Acceleration - Accel
5.2	WTG-5-TR-...	0.042	5.2		Overload Acceleration - Accel
5.2	WTG-6-TR-...	0.042	5.2		Overload Acceleration - Accel
20.0	PTR-33KV-...	1.657	20.0		Neutral - OC1 - 50
20.0	PTR-33KV-...	1.657	20.0		Ground - OC1 - 50
25.5	Relay39	1.657	25.5		Ground - OC1 - ST
40.0	WTG-1-TR-...	0.042	40.0		Overload Jam
40.0	WTG-2-TR-...	0.042	40.0		Overload Jam
40.0	WTG-3-TR-...	0.042	40.0		Overload Jam
40.0	WTG-4-TR-...	0.042	40.0		Overload Jam
40.0	WTG-5-TR-...	0.042	40.0		Overload Jam
40.0	WTG-6-TR-...	0.042	40.0		Overload Jam
82.2	HVCB-1		77.0		Tripped by WTG-1-TR-RELAY Overload Acceler...
82.2	HVCB-2		77.0		Tripped by WTG-2-TR-RELAY Overload Acceler...
82.2	HVCB-3		77.0		Tripped by WTG-3-TR-RELAY Overload Acceler...
82.2	HVCB-4		77.0		Tripped by WTG-4-TR-RELAY Overload Acceler...
82.2	HVCB-5		77.0		Tripped by WTG-5-TR-RELAY Overload Acceler...
82.2	HVCB-6		77.0		Tripped by WTG-6-TR-RELAY Overload Acceler...
97.0	PTR-33 KV-...		77.0		Tripped by PTR-33KV-RELAY Neutral - OC1 - 50
97.0	PTR-33 KV-...		77.0		Tripped by PTR-33KV-RELAY Ground - OC1 - 50
102	PTR-66KV-CB		77.0		Tripped by Relay39 Ground - OC1 - ST
117	HVCB-1		77.0		Tripped by WTG-1-TR-RELAY Overload Jam
117	HVCB-2		77.0		Tripped by WTG-2-TR-RELAY Overload Jam
117	HVCB-3		77.0		Tripped by WTG-3-TR-RELAY Overload Jam
117	HVCB-4		77.0		Tripped by WTG-4-TR-RELAY Overload Jam
117	HVCB-5		77.0		Tripped by WTG-5-TR-RELAY Overload Jam
117	HVCB-6		77.0		Tripped by WTG-6-TR-RELAY Overload Jam
130	PTR-33KV-...	1.657	130		Neutral - OC1 - 51
207	PTR-33 KV-...		77.0		Tripped by PTR-33KV-RELAY Neutral - OC1 - 51
209	Relay39	1.657	209		Ground - OC1 - 51
260	PTR-33KV-...	1.657	260		Ground - OC1 - 51
286	PTR-66KV-CB		77.0		Tripped by Relay39 Ground - OC1 - 51
337	PTR-33 KV-...		77.0		Tripped by PTR-33KV-RELAY Ground - OC1 - 51
724	PTR-33KV-...	1.407	724		Phase - OC1 - 51
801	PTR-33 KV-...		77.0		Tripped by PTR-33KV-RELAY Phase - OC1 - 51



V. Conclusion

In conclusion, this paper has presented a comprehensive case study of a wind farm and its interconnection with the grid. The study encompassed various critical aspects, including load flow analysis, short-circuit analysis, and protection and coordination study, to ensure the reliable and efficient operation of the interconnected power system.

The load flow analysis provided valuable insights into the network's capability to transfer power while maintaining acceptable voltage limits, a crucial factor in grid stability. Additionally, the short-circuit analysis assessed the equipment's capacity to withstand fault conditions, including

3-phase and L-G faults, aiding in the proper sizing of circuit breakers.

Furthermore, the protection and coordination study addressed the essential aspect of relay settings and their sequence of operation to swiftly isolate faults when they occur, thus enhancing the overall system's reliability.

The findings and methodologies presented in this paper are of great significance to power utilities, project consultants, and operators. They serve as a valuable reference for designing and operating WTG wind farms and their integration with the grid, ensuring the safe and efficient generation of renewable energy. As the world continues to transition towards sustainable energy sources, the insights provided in this study will contribute to the successful development and operation of wind energy projects, ultimately aiding in the global pursuit of a cleaner and more sustainable energy future.

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