Chapter

An Algorithm for Default Detection of Wind Turbine Generators

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Abstract

The protection of the wind turbine generator (WTG) required discrimination between internal and parallel WTG faults. Furthermore, it must discriminate the fault of its feeder line and parallel feeder line. This chapter describes the protection of wind turbine generators based on fault current and voltage analysis, which can identify the instantaneous operation, delay operation, or immune operation. A proposed Algorithm based digital relay is presented to provide all the different fault detection in a single unit suitable for internal and external fault protection of wind turbine generator. The main challenge to this scheme is that fault resistance may wrongly operate the scheme in some rare conditions. The phase angle of negative sequence current components determines the type of fault. The algorithm used negative sequence current and voltage to positive sequence current and voltage ratio, which is less than the set value in case of external fault. The fault seniors have been explained using simulation results on the wind turbine generator system modeled in a software environment.

Keywords: internal fault, feeder, positive sequence current, relay, wind turbine generator

1. Introduction

The parts of the wind turbine generator are shown in **Figure 1**. Blades are connected to this rotor hub. By rotating the motor shaft angle, one can turn the blade's direction, resulting in a change in mechanical power. This rotational mechanical energy rotates the rotor, and by using a gearbox, speed can be changed. By changing the speed, torque will be changed. The frequency of the generated voltage depends on the speed and number of poles. The variable frequency is converted into the constant frequency using a power converter. At this stage, two converters are used. One is an AC-DC converter, and the second is a DC-AC converter called a back-to-back converter. This is often called a gear-less wind turbine generator [2]. As electrical technology is very advanced, mechanical energy to electrical energy can be converted with different machines. Based on this machine used, the wind turbine generators are classified. The most common challenges for the wind turbine are as follows: (1) highly variable wind power injection into the grid, (2) increased penetration of wind energy, (3) Electrically weak distribution network, and (4) heavy reactive power burden by Induction generator (IG).

The classification of wind energy conversion system (WECS) is shown in **Figure 2**. Squirrel cage induction generators (SCIG) are a traditional method, but one cannot

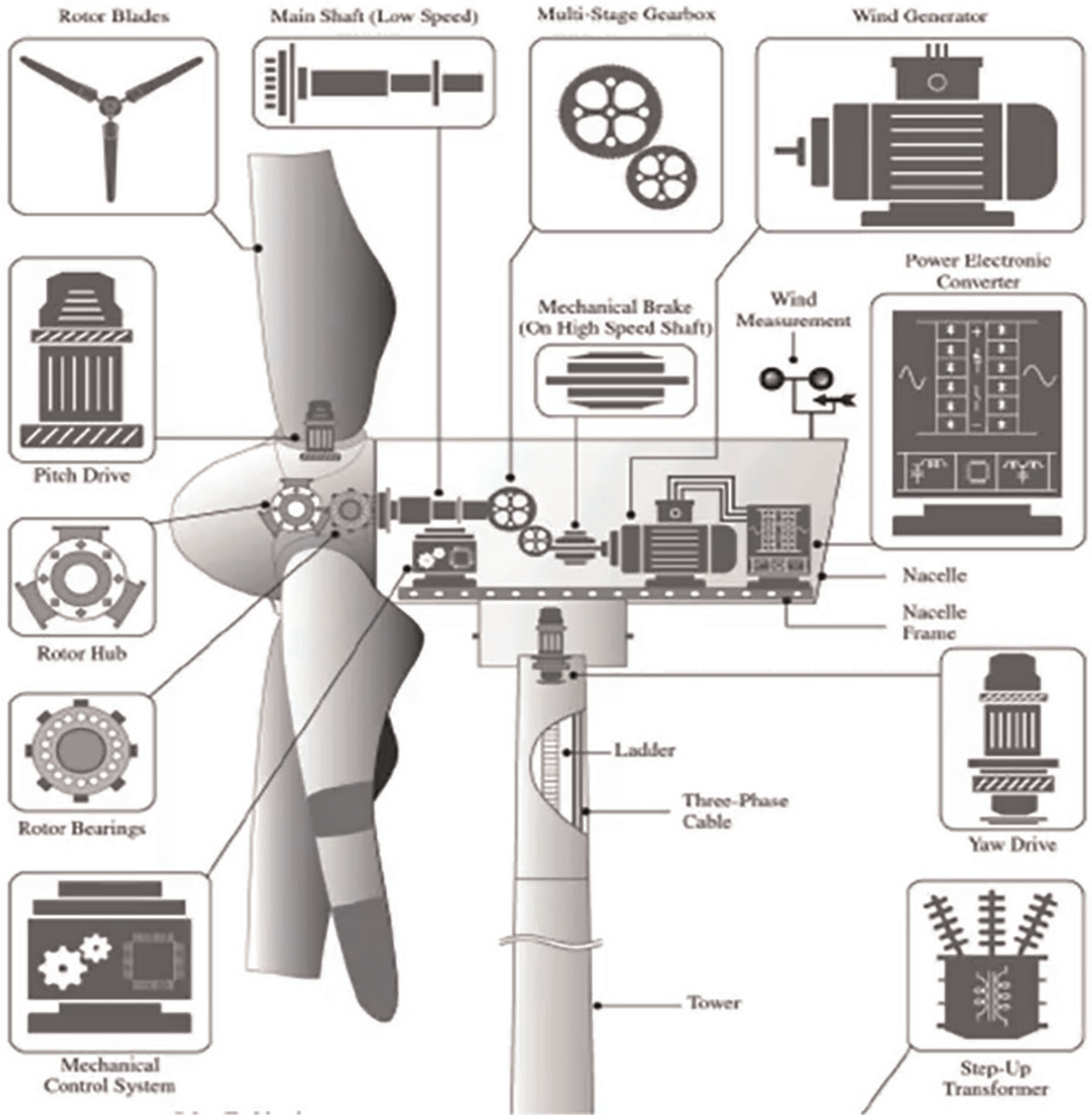

Figure 1.
Parts of wind turbine generator adapted from [1].

get maximum power at different wind speeds. The SCIG is generally known as a fixed-speed wind turbine. At variable rates, wind turbine generators are two types which are gear-less and with gear. Gear-less wind turbine generators may be running at a slower speed, but one can change the number of poles. The wound rotor synchronous generator (WRSG) and permanent magnet synchronous generator (PMSG) is the gear-less wind turbine. The wound rotor synchronous generator (WRSG) and permanent magnet synchronous generator (PMSG) maybe with gear also [3]. Doubly fed induction generator (DFIG), SCIG, wound rotor induction generator (WRIG) with variable rotor resistance also come under the gear category.

2. Grid connected operation of SCIG

The SCIG has the following main parts: (1) Gear Box, (2) cage induction generator, (3) soft starter, and (4) Capacitor for power factor compensation.

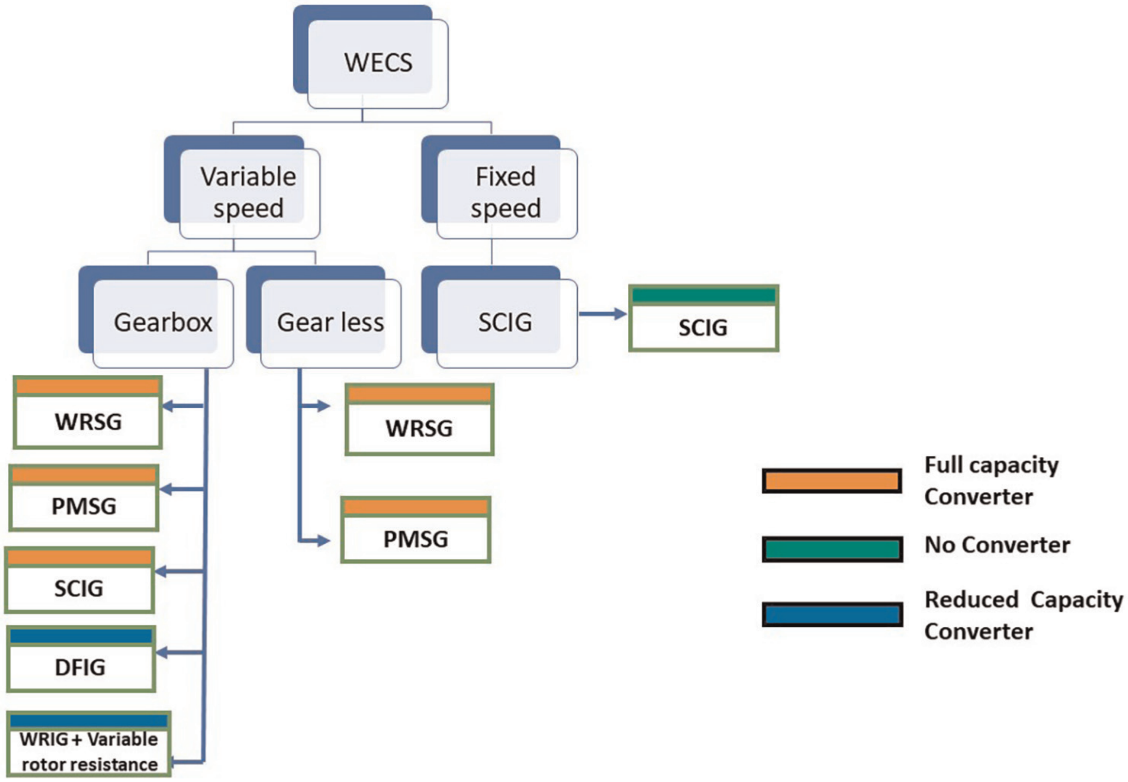

Figure 2.
Classification of wind turbine generator.

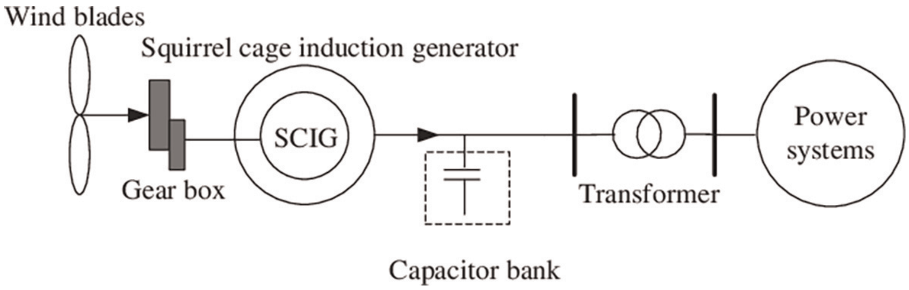

Figure 3.
Fixed speed SCIG wind turbines from [4].

The SCIG is a very simple structure of WTG used in the system. SCIG is directly connected to the grid using a starter and transformer. A soft starter is available in starting only to limit high inrush current. This is the most widely used structure worldwide due to less maintenance and simple design. The main disadvantage is that full power cannot be extracted from the grid. The SCIG needs high reactive power, which the capacitor bank locally supplies, as shown in **Figure 3**. The machine is run above synchronous speed using pitch control.

3. Configuration of wind farm

A wind farm composed of six 1.5 MW wind turbines is connected to a 25 kV distribution system that exports electricity to a 120 kV network via a 25 km long feeder from a 25 kV bus 4. Three 1.5 MW wind turbines pairs simulate the 9-MW wind farm. Wind turbines use squirrel cage induction generators (SCIG) [5].

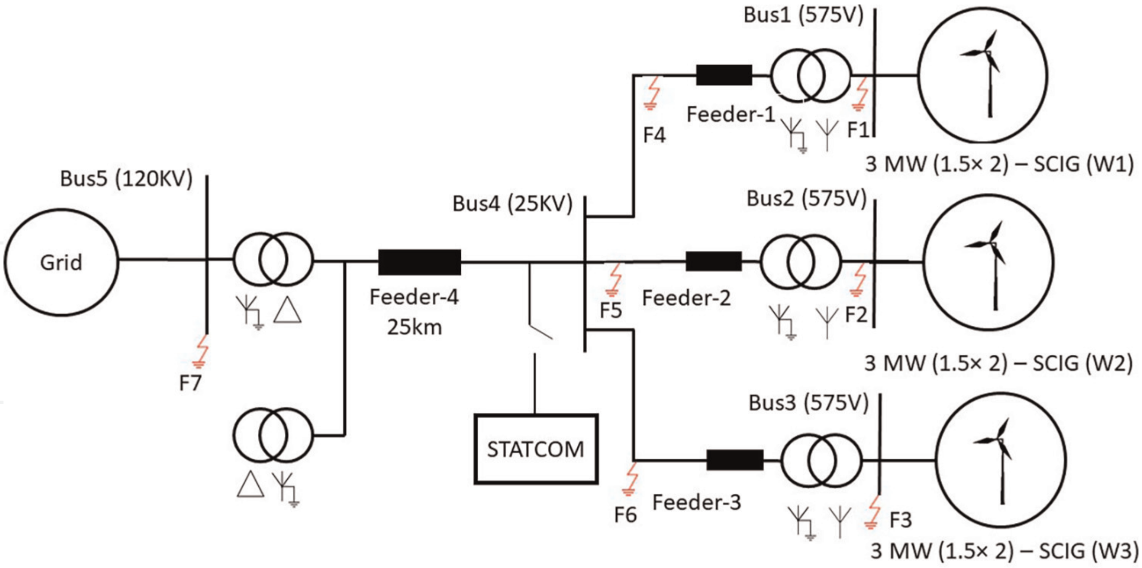

Figure 4.
9 MW—Wind farm connected to the grid.

Figure 4 shows the system considered for protection in which three wind turbine generators are connected to the grid.

The stator winding is connected directly to the 60 Hz grid, and a controllable-pitch windmill drives the rotor [6, 7]. The pitch angle is controlled to limit the generator's output power to its nominal value for winds exceeding the little velocity (9 m/s). A protection system is installed at each wind generator from W1 to W3, which measures voltage, current, and speed. Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus [8–10]. The rest of the reactive power required to maintain the 25-kV voltage at bus B4 close to 1 pu is provided by a 3-Mvar STATCOM with a 3% droop setting. Modeling of Wind Turbine Generator is carried in MATLAB Software [11]. The data of wind turbine generator modeling is shown in Appendix A.

4. Protection of wind turbine generator

The digital protection system installed on W1 to W3 consist of following protections covers in single digital relay for wind turbine generator [12].

1. Instantaneous AC overcurrent

2. Positive-sequence AC overcurrent

3. Unbalance AC current

4. Positive-sequence under voltage

5. Positive-sequence under voltage

6. Negative-sequence unbalanced voltage

7. Zero-sequence unbalanced voltage

Fault position	Relay 1 operation	Relay 2 operation	Relay 3 operation
F1	Instantaneous	Non-operation	Non-operation
F2	Non-operation	Instantaneous	Non-operation
F3	Non-operation	Non-operation	Instantaneous
F4	Instantaneous	Instantaneous	Instantaneous
F5	Instantaneous	Instantaneous	Instantaneous
F6	Instantaneous	Instantaneous	Instantaneous
F7	Delayed	Delayed	Delayed

Table 1.
Desired operation of digital relay R1, R2, and R3 at W1, W2, and W3 respectively.

The desired protection for relay 1 at W1, relay 2 at W2, and relay 3 at W3 are shown in **Table 1** for different fault locations.

4.1 Protection algorithm

The relay R1, R2, and R3 are located at Bus 1, Bus 2, and Bus 3. The algorithm is explained in this section by considering Relay R1 to protect W1 against internal faults F1. For faults F4, F5 and F6 at POC at Bus 4, R1 reacts instantaneously as both these three faults impact the W1 directly. On the other hand, the relay R1 remains stable for F2, F3 and F7 and maybe operate as a backup to the primary relay addressing these faults. Here, F2 and F3 are parallel feeder faults considered external faults for F1. F7 is a external fault in the grid system. The protection algorithm for such desired operation as per **Table 1** is shown in **Figure 5**. As per the Algorithm, relay R1 measured three-phase voltage and current V_{abc} and I_{abc} with the help of PT and CT in the beginning [13]. Using the symmetrical component method, Positive sequence, negative

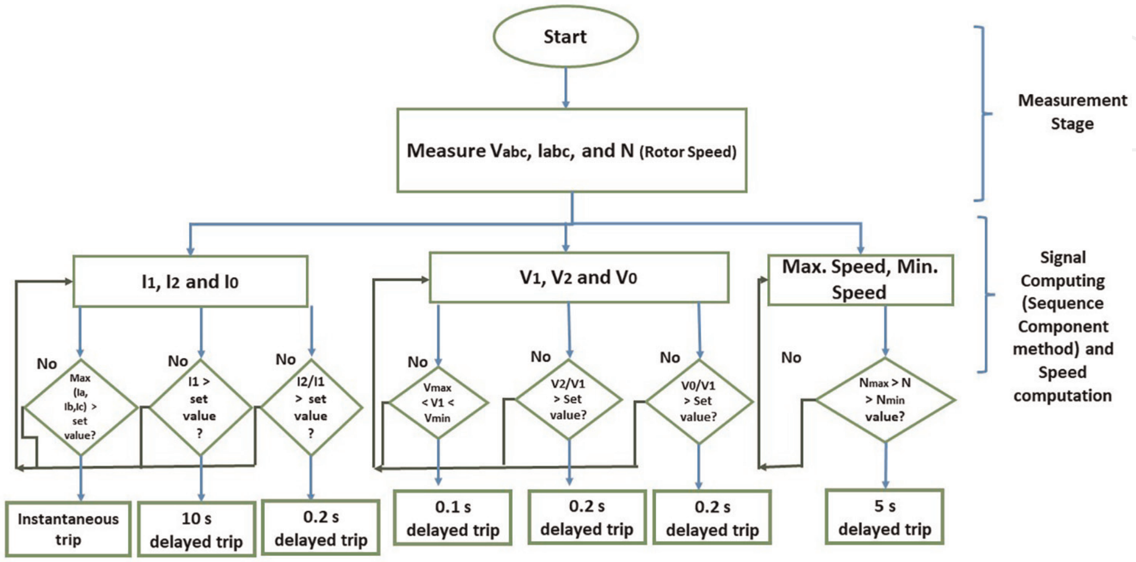

Figure 5.
Protection algorithm for WTG.

sequence, and zero sequence voltage and current are V_1, V_2, V_0 and I_1, I_2, I_0 respectively have been calculated. Based on the different conditions as shown in **Figure 5**, the tripping commands have been sent to the circuit breaker of W1. The next section will describe how the Algorithm detects LG, LL, LLL, LLLG faults for internal and external fault conditions.

5. Different internal and external fault detection by digital relay

5.1 LG faults

LG faults have been applied at F1 to F7 locations as internal and external faults. Considered F1 fault as LG fault and used at 15 s of simulation time for 0.3 s duration which is an internal fault for W1. in this case-1, the voltages are unbalanced significantly which has V0/V1 ratio found 0.985pu which is greater than a set value and as per algorithm the relay issue tripping after 0.001 s which instantaneous. It is important to note that in this case, relay R2 at W2 and R3 at W3 are not affected and remain immune. The tripping coordination of R1 to R3 for this case-1 is shown in **Figure 6**. **Figure 7** shows that positive sequence and zero sequences are present significantly during the fault, and the ratio of V0/V1 exceeds the set value. Similarly, LG fault has been applied at the F6 location. In this case, the fault is at POC, which required the operation of all the relays operated at 0.2 s. **Table 2** shows the other faults and measurement of current and voltage sequence components during the faults at bus 1.

5.2 LL faults

As internal and external faults, LL faults have been applied at F1 to F7 locations. Considered F2 fault as LL fault and used at 15 s of simulation time for 0.3 s duration which is an internal fault for W2. In this case-2, the positive sequence voltages less than set value and as per the algorithm the relay issue tripping after 0.001 s. It is important to note that in this case, relay R1 at W1 and R3 at W3 are not affected

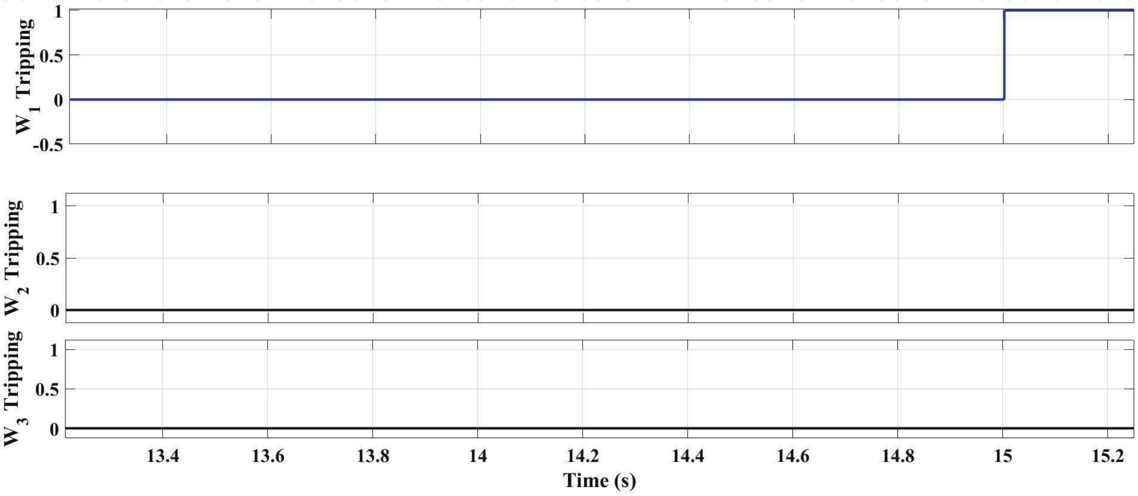

Figure 6.
Tripping of at W1, W2, and W3 while LG fault near bus 1.

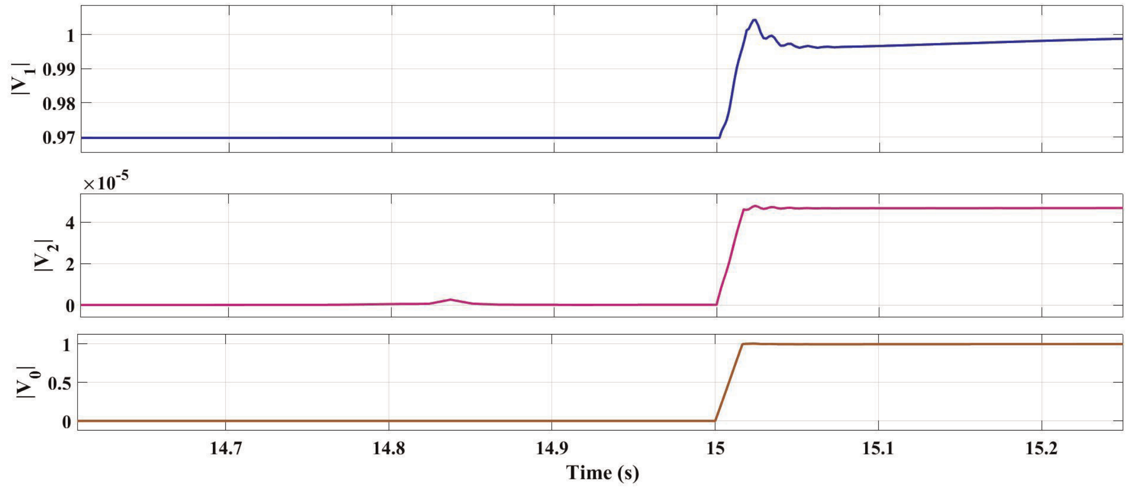

Figure 7.
Positive, negative, and zero sequence voltage variation during internal fault at W1.

Internal fault type	Fault location	Max (Ia,Ib,Ic) (p.u)	I1 (p.u)	I2/I1 (p.u)	V1 (p.u)	V2/V1 (p.u)	V0/V1 (p.u)
LG	Bus 1	R1:0 R2: 0.977 R3:0.979	R1:0 R2:0.983 R3:0.9846	R1:0 R2:0 R3:0	R1:0.998 R2:0.979 R3:0.979	R1:0 R2:0 R3:0	R1:0.985 R2:0.0001 R3:0.0001
LL	Bus 1	R1: 0 R2:0 R3:0	R1: 0 R2:0 R3:0	R1:0.037 R2:0.022 R3:0.022	R1:0.821 R2:0.9015 R3:0.9015	R1:0.458 R2:0.2568 R3:0.2568	R1:0 R2:0 R3:0
LLG	Bus 1	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.037 R2:0.022 R3:0.022	R1:0.0821 R2:0.9015 R3:0.09015	R1:0.458 R2:0.2568 R3:0.2568	R1:0.662 R2:0 R3:0
LLL	Bus 1	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0 R2:0 R3:	R1:0.738 R2:0.738 R3:0.738	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0
LLLG	Bus 1	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.665 R2:0.738 R3:0.738	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0

Table 2.
Internal fault on feeder 1, 2, and 3 near SCIG.

and remain immune. Additionally, It provides backup protection after 0.15 s and 0.14 s by R1 and R3 to R2. The V1 and V2/V1 variations are shown in **Table 2** during the LL fault at bus 2.

5.3 LLG faults

As internal and external faults, LLG faults have been applied at F1 to F7 locations. Considered F3 fault as LLG fault and used at 15 s of simulation time for 0.3 s duration which is an internal fault for W3. in this case-3, the positive sequence voltages less than set value and as per algorithm the relay issue tripping after 0.001 s. It is important to note that in this case, relay R1 at W1 and R3 at W3 are not affected and remain immune. Additionally, It provides backup protection after 0.15 s and 0.14 s by R1 and R2 to R3.

5.4 LLLG faults

LLLG faults have been applied at F1 to F7 locations as internal and external faults. Considered F4 fault as LLLG fault and used at 15 s of simulation time for 0.3 s duration which is the internal fault for W1. in this case-4, the positive sequence voltages less than set value and as per algorithm the relay issue tripping after 0.001 s. In this case, relay R2 at W2 and R3 at W3 is also instantaneous as the fault is on the point of Common Coupling (POC). **Table 3** shows that I2/I1 and V1 change significantly during fault at bus 4.

5.5 LLL faults

LLL faults have been applied at F1 to F7 locations as internal and external faults. Considered F5 fault as LLL fault and used at 15 s of simulation time for 0.3 s duration which is the internal fault for W2. In this case-5, the positive sequence voltages less than set value and as per algorithm the relay issue tripping after 0.001 s. It is important to note that in this case, relay R1 at W1 and R3 at W3 is also instantaneous as the fault is on the point of Common Coupling (POC).

5.6 External fault

When LG fault is applied on the F7 location, which is in the grid and considered an external fault to the wind farm, the ratio of negative sequence voltage to positive sequence voltage and negative sequence current to positive sequence current is less than the set value [14]. So, as per the algorithm, relays R1 to R3 issued delayed tripping at 0.21 s after the fault instant. For all the other external faults, the variation of V1, V2/V1, and I2/I1 are shown in **Table 4**.

Fault type	Fault location	Max (Ia,Ib,Ic) (p.u)	I1 (p.u)	I2/I1 (p.u)	V1 (p.u)	V2/V1 (p.u)	V0/V1 (p.u)
LG	Bus 4	R1:0	R1:0	R1:0.02	R1:0.88	R1:0.24	R1:0.76
		R2:0	R2:0	R2:0.02	R2:0.88	R2:0.24	R2:0.76
		R3:0	R3:0	R3:0.02	R3:0.88	R3:0.24	R3:0.76
LL	Bus 4	R1:0	R1:0	R1:0.05	R1:0.545	R1:1.0	R1:0
		R2:0	R2:0	R2:0.05	R2:0.545	R2:1.0	R2:0
		R3:0	R3:0	R3:0.05	R3:0.545	R3:1.0	R3:0
LLG	Bus 4	R1:0	R1:0	R1:0.046	R1:0.473	R1:1.0	R1:0.994
		R2:0	R2:0	R2:0.046	R2:0.473	R2:1.0	R2:0.994
		R3:0	R3:0	R3:0.046	R3:0.473	R3:1.0	R3:0.994
LLL	Bus 4	R1:0	R1:0	R1:0	R1:0.0007	R1:0	R1:0
		R2:0	R2:0	R2:0	R2:0.0007	R2:0	R2:0
		R3:0	R3:0	R3:0	R3:0.0007	R3:0	R3:0
LLLG	Bus 4	R1:0	R1:0	R1:0	R1:0.0007	R1:0	R1:0
		R2:0	R2:0	R2:0	R2:0.0007	R2:0	R2:0
		R3:0	R3:0	R3:0	R3:0.0007	R3:0	R3:0

Table 3.
Internal fault on feeder 1, 2, and 3 near POC.

Fault type	Fault location	Max (Ia,Ib,Ic) (p.u)	I1 (p.u)	I2/I1 (p.u)	V1 (p.u)	V2/V1 (p.u)	V0/V1 (p.u)
LG	Bus 5	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.024 R2:0.024 R3:0.024	R1:0.845 R2:0.845 R3:0.845	R1:0.289 R2:0.289 R3:0.289	R1:0 R2:0 R3:0
LL	Bus 5	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.051 R2:0.051 R3:0.051	R1:0.574 R2:0.574 R3:0.574	R1:0.897 R2:0.897 R3:0.897	R1:0 R2:0 R3:0
LLG	Bus 5	R1:0 R2: R3:	R1:0 R2: R3:	R1:0.042 R2: R3:	R1:0.479 R2: R3:	R1:0.877 R2: R3:	R1:0 R2: R3:
LLL	Bus 5	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.001 R2:0.001 R3:0.001	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0
LLLG	Bus 5	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0	R1:0.001 R2:0.001 R3:0.001	R1:0 R2:0 R3:0	R1:0 R2:0 R3:0

Table 4.
External fault of W1, W2, and W3 at grid side.

6. Challenges and possibilities

The main challenge in this protection scheme is that the relays R1 to R3 are affected by fault resistance while power swing occurs near them, and they cannot detect it. It is important to note that power swing blocking and out-of-step tripping functions are available to handle these challenges in the existing system [15].

7. Results and discussions

The results of **Tables 2–4** clearly show the quantity such as instantaneous overload current (Ia, Ib, Ic), I1, I2/I1, V1, V2/V1, and V0/V1 changes during different faults differently. This variation is used in the digital relay to identify internal and external feeder faults. The relays at W1 to W3 remain immune due to correct settings during grid faults. In this protection scheme, instantaneous overload current (Ia, Ib, Ic) provides instantaneous AC Over current, I1 provides AC Overcurrent (positive-sequence), I2/I1 provides Ac Current unbalance, V1 provides AC over and under-voltage (positive sequence), V2/V1 provides AC unbalance voltage (negative sequence), V0/V1 provides C unbalance voltage (zero sequences) protection to W1 to W3 against internal and external feeder faults correctly.

8. Conclusions

F1 from F2 and F3 can be detected using positive sequence voltage because the fault current of F2 and F3 can be seen at W1 via step-up transformer and feeder, due to which current is reduced compared to F1 in case of LG fault. While W2 sees F2 directly and W3 sees F3 directly, that is not affected F1, which is a parallel feeder fault. In the case of external fault, zero sequences cannot be used as they are trapped in the winding. So algorithm used negative sequence current and voltage to positive sequence current and voltage ratio, which is less than the set value in case of external fault. So, R1 to R3 does not operate. The proposed Algorithm based digital relay provides all the different fault detection in a single unit suitable for internal and external fault protection of WTG. The main challenge to this scheme is that fault resistance may mal-operate the scheme in some rare events.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

WTG	wind turbine generator
IG	Induction generator
WECS	wind energy conversion system
SCIG	squirrel cage induction generators
WRSG	wound rotor synchronous generator
PMSG	permanent magnet synchronous generator
WRSG	wound rotor synchronous generator
WRIG	wound rotor induction generator
KV	Kilo Volt
STATCOM	Static Var Compensator
W1	Wind turbine 1
F1	Fault 1
POC	Point of Common Coupling
R1	Relay 1
LG	Line to ground
LL	Line to line
LLL	Line to line to line
LLG	Line to line to ground
LLLG	Line to line to line to ground
I1	Positive sequence Current
V1	Positive sequence Voltage
I2	Negative sequence Current
V2	Negative sequence Voltage
I0	Zero Sequence Current
V0	Zero Sequence Voltage
pu	Per unit

Appendix A: wind turbine generator modeling

SCIG data

Parameter	Symbol	Unit	Value
Nominal power	Pn	VA	3.33 MVA
Line-to-line voltage	Vn	Volt	575
frequency	fn	Hz	60
Stator	Rs	pu	0.004843
Stator	Lls	pu	0.1248
Rotor	Rr’	pu	0.004377
Rotor	Llr’	pu	0.1791
Magnetizing inductance	Lm	pu	6.77
Inertia constant	H	s	5.04
Friction factor	F	pu	0.001
Pairs of poles	P		3
Nominal wind turbine mechanical output Power (W)	Pm	W	3 MW
Base wind speed	Nw	m/s	9
Base rotational speed	N	pu	1
Maximum power at base wind speed	Pm(max)	pu	1
Pitch angle controller gain	Kp and Ki	pu	5 and 25
Maximum pitch angle	β_{max}	deg	45
Maximum rate of change of pitch angle	$d\beta/dt$	deg/s	2

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