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Fault Ride Through Constrained Protection Scheme for Distribution Networks with DFIG-Based Wind Parks

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Abstract

The main protection of distribution networks is based on overcurrent relays (OCRs). Due to the slow operation of these relays, some distributed generations (DGs), e.g. wind parks, may be unable to meet the fault ride through (FRT) requirements, which leads to unnecessary generation loss during faults. This paper proposes a new protection scheme for distribution networks that considers the FRT requirements of DFIG-Based wind parks. This is achieved by considering both the protection coordination constraints and FRT requirements in a single protection scheme. Considering the FRT requirements, the new method determines whether each overcurrent relay operates fast enough. If not, the proposed scheme determines a suitable solution for each relay to facilitate a faster operation. The proposed method is tested on the IEEE 33 bus test network and compared with conventional methods. Its superior impact on improving the FRT requirements and hence preventing unnecessary disconnection of DFIG-Based wind parks during short circuit faults is demonstrated through simulation results, proving by this its applicability and efficacy.

Keywords: Communication link, coordination, fault ride through (FRT), overcurrent

relay, wind turbine.

1. Introduction

The increasing influence of wind parks on the network stability during/after short circuit faults has urged Transmission System Operators to stipulate the fault ride through (FRT) requirements. According to the FRT requirements, *during short circuit faults, wind farms must remain connected to the grid for certain time duration depending on the voltage level at the point of common coupling (PCC)* [1]. This time, also called *the allowed FRT time*, can be determined using the FRT characteristic. In Fig. 1, the allowed FRT time for a fault leading to e.g. 30% voltage sag at the PCC is shown.

In order to enhance the FRT capability of wind parks, various solutions have been proposed and discussed in the past. Most of these methods focus either on external devices, or modifications of power electronic converter control systems. Recently, it has been recognized that the FRT related aspects have to be considered when designing protection systems/solutions. As an effective hardware solution, during faults the crowbar circuit is proposed to isolate the rotor side converter (RSC) of a doubly fed induction generator (DFIG) [2]. This method may lead to absorbing reactive power by the DFIG as the crowbar turns it into an induction machine. Another common approach to enhance the FRT capability of wind parks is based on using the fault current limiters (FCLs) [3]. The resistive type FCL (RFCL) is proposed in [4]. However, the RFCL may bring on extreme heat because it shows unbalanced heating features. In [5] an inductive FCL is implemented which acts as a filter during normal conditions and as a FCL during faults. It should be noted that this kind of FCLs has a much bigger size compared to the RFCL (around four times). A switch-type fault current limiter is proposed in [6].

By limiting the fault current, this method improves voltage at the PCC. However, it needs a complicated structure as well as a non-linear controller. Active BFCL with a new topology is proposed in [7] which increases the efficiency by limiting the power losses. Implementing the static synchronous compensator (STATCOM) is another approach to enhance the FRT [8]. The STATCOM is a device able to inject reactive power to the network during faults. However, it has some drawbacks, e.g. limitation in injecting current, as well as high costs.

As a software solution, in [9] a *damping flux control method* is proposed. This method enhances the FRT capabilities of DFIG based wind turbine by reducing the oscillations of electromagnetic torque. Other methods like model predictive control (MPC) [10] are also studied, but they can be considered as both complex and costly. Protection based methods try to clear faults within the permitted time by the FRT capabilities. In [11] a protection scheme is proposed. It is based on dual setting schemes of the overcurrent relays. It clears faults in a very short time which is less than the allowed FRT time. But since in this method there is not any feedbacks from the FRT capabilities during coordinating relays, it cannot guarantee that there will not be any FRT violations in different networks and situations. In [12] a new objective function for coordinating the OCRs and considering the FRT requirements is proposed. However, this method is both complex and not reliable and secure to guarantee a full prevention from FRT violations. In [13] a method is proposed to coordinate protection devices based on the transients of fault current and adding the FRT requirements into sizing of FCL formulations to enhance the FRT requirements of wind parks.

This paper presents a new protection scheme that takes into account the FRT requirements of wind parks. The novelties and contributions of this paper are as follows:

- A new constraint is proposed and added to the conventional overcurrent relay coordination methods. This constraint makes it possible to find the relays that during faults at their primary zone, the disconnection of wind turbines might occur as a result of violation from the FRT requirements.
- After specifying the relays that are responsible for FRT violations in conventional methods, the proposed method adopts a suitable solution for those relays, ensuring that they will operate faster enough and meet the FRT requirements. This solution is either based on a) adopting, or readjusting the definite time (DT) stage of OCRs respecting the FRT requirements, or b) using a communication link between the relay that is responsible for FRT violation and its downstream relay. After determining the solution (a or b), the required formulations and considerations to find the settings of the DT stages or the communication links are provided. This is done in a way not even to guarantee the FRT requirements, but also to determine the least number of communication links, which makes this method economically justified. The result is prevention of disconnection of DFIGs during faults.
- The proposed method is independent of the DG control (for converters), the method can be applied to different control modes adopted during faults.
- This method can be used not only for the wind parks but also for different types of DGs that are supposed to meet the FRT requirements.

The paper is organized as follows: In section 2, the conventional protection coordination problem is described. The FRT requirements and their constraints, added to the protection coordination problem, are described in section 3. The proposed new scheme to enhance FRT requirements is presented in section 4. The simulation results are described in section 5. Finally, section 6 presents the conclusion drawn from this

research, supporting next generation of networks with a high penetration of DGs, particularly wind farms, through a novel approach for protection coordination respecting FRT requirements.

2. Overcurrent relay coordination formulation

The objective function to minimize the operating time of overcurrent relays can be formulated as follows [14]:

$$\text{Minimize } T = \sum_{i=1}^N \sum_{j=1}^M (t_{bij} + t_{pij}) \quad (1)$$

where M and N represent the total number of fault locations and relays, respectively. Also, i and j are the identifiers of relays and fault location, respectively. Here t_b is the operating time of the backup relay and t_p is the operating time of the main Inverse Definite Minimum Time (IDMT) type overcurrent relay which can be calculated as follows:

$$t_i = TDS_i \frac{n}{\left(\frac{I_{SCi}}{I_{Pi}}\right)^k - 1} \quad (2)$$

where I_{SCi} is the short circuit current measured by the relay and I_{Pi} is the pickup current. Parameters n and k define the relay IDMT characteristic. Finally, TDS is the Time Dial Setting. The main constraints of this problem are as follows:

$$t_b - t_p \geq CTI \quad \forall (i, j) \in \lambda \quad (3)$$

$$TDS_{\min} \leq TDS_i \leq TDS_{\max} \quad (4)$$

$$I_{P \min} \leq I_{Pi} \leq I_{P \max} \quad (5)$$

where λ is the collection of primary and backup relays pairs. The Coordination Time Interval (CTI) is set to 0.2 s and the minimum and maximum values of the TDS are set to 0.05 and 1, respectively.

As it can be seen, it is clear that the conventional overcurrent relays coordination problems do not take the FRT requirements into consideration. However, in the next sections it will be shown that by considering the FRT requirements, the disconnection of wind parks during faults can be prevented and at the same time the proposed method does not have the costs or complexity of other FRT enhancement methods that were discussed earlier.

3. Problem statement

In this paper the grid code of Germany, depicted in Fig. 1, is considered and used in simulations which follows later. As it can be seen, the time that wind parks must abide the situation and stay online during faults depends on the voltage amplitude at the PCC.

As discussed in the last section, conventional relay coordination methods do not consider the FRT requirements. Because of the long operating times of some relays, it is likely that some faults be cleared in a time longer than the allowed FRT span. Consequently, a huge power loss may happen, especially in a network with high penetration of wind parks. To be clearer, a simple distribution network equipped with DFIGs is depicted in Fig. 2. Given a fault F_n , if the relay R_n operates at an instant which is longer than the FRT time, then the DFIGs may be disconnected from the network. However, if the tripping signal is sent by the relay before the allowed FRT time, the DFIG will stay connected and continue its operation. Therefore, in addition to the CTI in (3), it is necessary to consider a new constraint related to FRT requirements in the protection coordination problem. This new proposed constraint guarantees that the summation of the relay tripping time and the circuit breaker's operating time is less than the allowed FRT time during faults. The proposed FRT constraint to be added to the conventional relay coordination methods is as follows:

$$t_{F_n}^{R_n} + t_{CB} \leq t_{F_n}^{FRT} \quad (6)$$

where the left hand side of this constraint is the sum of operating times of the relay R_n and its circuit breaker, for the fault F_n , shown as $t_{F_n}^{R_n}$ and t_{CB} , respectively. Here $t_{F_n}^{FRT}$ is the allowed FRT time during the same fault which can be calculated easily as discussed earlier using Fig. 1, when the voltage at the PCC is known. However, it should be noted that calculating this time may need some considerations. For more details, according to Fig. 2, the FRT of one DFIG should be chosen as a reference. Hence, by considering the critical situation, continuous operation of other DFIGs will be guaranteed. In this paper the minimum allowed FRT time of the wind generators is taken as a reference, as follows:

$$t_{F_n}^{FRT} = \min((t_{DFIG1}^{FRT}, t_{DFIG2}^{FRT}, \dots, t_{DFIGi}^{FRT}, t_{DFIGi+1}^{FRT}, \dots, t_{DFIGj}^{FRT}) | F_n) \quad (7)$$

where j is the total number of upstream wind generators to the fault location.

4. Proposed protection scheme considering fault ride through requirements

As discussed earlier, since the conventional relay coordination methods do not take the FRT requirements into account, disconnection of wind parks during faults is likely. This section presents a new protection scheme based on relay characteristic adjustment and availability of communication link.

By changing the location of faults the voltage amplitude at the PCC will be affected and the new voltage imposes a new FRT time according to Fig. 1. Hence, it is possible to find the FRT curve as a function of time and fault current. Since the overcurrent relay curve is also a function of time and fault current, both the FRT and relay curve can be mapped together as depicted in Fig. 3. While considering the resistance for the faults,

the fault current decreases, and the operating time of the relay increases. At the same time, the voltage at the PCC increases and the allowed FRT time increases. In other words, the operating time of the relay and the allowed FRT time change in the same direction. The worst case is when faults are without resistance but it is still correct during faults with resistance. A similar argument can be expressed for different fault types and worst case is during three-phase faults.

It should be noted that the FRT requirement is satisfied when there is not any convergence between the two curves and the wind park will be able to ride through the fault which is shown in Fig. 3.

However, there are cases in which the two curves have an intersection point. It means that the conventional protection scheme cannot meet the FRT requirements, since the constraint presented in (6) is not satisfied. In this case, depending on the position of the intersection point, there are two solutions that are discussed in the following.

4.1. Readjusting relay characteristic regarding the FRT requirements

In cases in which only faults close to relay lead to violation from (6), the DT OCR stage might be a proper solution. This case is depicted in Fig. 4. As it can be seen, using the DT stage properly, the relay curve lies below the FRT curve, which means that the FRT requirement is satisfied. However, in the literature, there is not any information to set the DT stage considering the FRT requirements. This section provides all the required formulations to find the settings of the DT stage in a way to guarantee both accurate coordination with other relays and fulfilling the FRT requirements.

Fig. 5 shows the DT stage and its main settings that are the pickup current and its operating time. In order to obtain the pickup current of the DT stage, the FRT constraint presented in (6) should be considered again. There is a fault current that the two sides of

(6) would be equal which is called the critical current in this paper as shown in (8). This critical current can be set as the pickup current of the DT stage as presented in (9).

$$t_{I_F}^{relay} + t_{CB} = t_{I_F}^{FRT} \Rightarrow I_{Cr} = I_F \quad (8)$$

$$I_P^{DT} < \alpha \cdot I_{Cr} \quad (9)$$

where $t_{I_F}^{relay}$ is the operating time of relay for fault current I_F and $t_{I_F}^{FRT}$ is the FRT time for the same fault current. Also, I_P^{DT} is the pickup current of the DT stage and α is a coefficient between 0.75 to 0.95 in order to make sure that the DT stage starts at a proper time and prevent any errors impacting the method. In this paper 20% is considered 20% between the DT stage pickup current and the maximum fault current of its downstream relay as follows:

$$I_P^{DT} \geq 1.2 \times I_{Fmax}^{R1} \quad (10)$$

Where I_{Fmax}^{R1} is the maximum fault current seen by relay R1. The last setting of the DT stage to be discussed is its tripping time which is determined by (11) where $\min(t_{FRT})$ is obtained from Fig.2.

$$\begin{aligned} t^{DT} &= \min(t_{FRT}) - t_{CB} \\ \begin{cases} \min(t_{FRT}) = 150 \text{ ms} \\ t_{CB} = 100 \text{ ms} \end{cases} &\Rightarrow t^{DT} = 50 \text{ ms} \end{aligned} \quad (11)$$

4.2. Applying communication channels for enhancing the FRT requirements

As earlier discussed, in some cases it is possible to ensure that relays will meet the FRT requirements by adjusting their characteristics according to (9) and (10). However, there are some conditions that this solution is not reliable enough and the FRT violation might still happen. As shown in Fig. 6, in this case it is vital that the relay operates faster for almost all parts of its primary zone to make sure that the FRT constraint in (6)

is satisfied. For such cases, this part proposes to use a communication channel between the relays to prevent from any FRT violations from (6). In the following, the communication channel and its required equations to prevent from FRT violations is presented.

As shown in Fig. 7, it is required that relay R2 operates as a DT stage for all parts of its primary zone to avoid FRT violations. Hence, the default characteristic of R2 should be set as DT except for cases that it is a backup relay. In other words, when a fault occurs in the primary zone of relay R1, relay R2 is not allowed to operate fast and should follow the inverse curve. This is achieved by a communication link between relays R2 and R1. When a fault occurs on relay R1 primary zone like F1, a signal will be sent to relay R2 that blocks its DT stage. Otherwise, relay R2 is allowed to trip by the DT stage because when there is not any received signal, it means the fault is on the primary zone of relay R2.

Considering the FRT requirements, constraints of the proposed relay coordination method are now as follows:

$$t_{channel} + t^{R1_min} < t^{R2_DT} \leq t_{F2}^{FRT} - t_{CB} \quad (12)$$

$$t_{F1}^{R2_inverse} - t_{F1}^{R1} \geq CTI \quad (13)$$

where t^{R2_DT} is the tripping time of relay R2 DT stage, t^{R1_min} is the minimum time that R1 can detect a fault and $t_{channel}$ is the time delay of the communication channel which is around 15-40 ms for a 10 km 100 Mb/s fiber optic cable. Left hand side of (12) guarantees that R2 will not operate as a DT stage for faults on primary zone of R1 and its right hand side fulfils the FRT requirements. It should be noted that the communication channel between R1 and R2 allows R3 and all upstream relays operate faster according to the following equations.

$$t_{F2}^{R3} - t_{F2}^{R2-DT} \geq CTI \quad (14)$$

$$t_{F1}^{R3} - t_{F1}^{R2-inverse} \geq CTI \quad (15)$$

The flowchart of the proposed method is depicted in Fig. 8. As it can be seen, the method starts by optimal coordination of relays using conventional methods as discussed in section 2. Then, it checks the FRT violation using (6) starting from downstream relay. If the FRT constraint is satisfied, it goes to the next relay. Otherwise, it finds a suitable solution according to parts A and B of this section and finds the settings of the solution. Then, it updates the settings of all upstream relays and checks the same relay again. In this flowchart, N is the total number of relays and K is relay counter. The process ends when the counter reaches the number of relays and all the relays are checked from the FRT prospect. It should be noted that since applying communication links might add more costs, the proposed method is able to find the minimum number of required communication links in the network as it always checks the relay characteristic modification solution first. The outcome of this flowchart is assuring the FRT requirements are satisfied and prevent any unnecessary wind power lost during faults. When applying the new protection scheme, secondary consequences of faults to power systems, e.g. cascading events, or even blackouts can be avoided.

5. Simulation results

The proposed protection coordination method considering the FRT requirements of DFIG-Based wind parks is tested using the IEEE 33 bus test network. This case study is taken and modified from [15]. As depicted in Fig. 9, this test system is equipped with four 1.5 MVA DFIGs and 21 overcurrent relays. In order to prevent from sympathetic tripping caused by DGs, Relays R5, R8, R19, R20 and R21 are equipped with directional elements. The base voltage is 12.66 kV and the base power is 20 MVA. The

proposed protection coordination problem is solved using genetic algorithm (GA) in MATLAB. Also, the short circuit and load flow analyses are executed by the same platform. The short circuit current contribution from type 3 wind turbines (DFIG) is relatively small compared to conventional sources like synchronous generators [16, 17]. To reflect this issue, the current contribution of the DFIG during fault is assumed similar to a synchronous generator by the transient reactance considering a maximum value for the current [16]. The objective function discussed in section 2 without considering the FRT requirements is solved using GA and the results are presented in Table 1 which presents optimal values of TDS and pickup current of relays while the FRT constraints are ignored.

Table 2 shows the risk of FRT violation and disconnection of DFIG-Based wind parks during faults in conventional relay coordination methods. Various three-phase faults at different locations in the studied network are considered. Then the tripping time of the main relays and the FRT time obtained from the FRT curve in Fig. 1 using the voltage amplitude of PCC during faults are obtained and compared in Table 2. As it can be seen, there are many cases in which the tripping time of relays and their respective circuit breakers is more than the allowed FRT time, shown in red colors. In other words, in conventional methods, since the FRT is not considered, the FRT constraint in (6) may be breached. For example, the voltage at PCC will be 0.32 pu. for a fault at location B9 that its FRT time according to Fig. 2 becomes 630 ms. Since relay R14 clears this fault in 650 ms, it is clear that the FRT constraint in (6) will be violated and the result may be disconnection of the wind turbine at B8. All parts of the under studied network that may cause FRT violation and disconnection of wind turbine during faults are highlighted with red arrows shown in Fig. 9.

In Table 3 the simulation results of the proposed method considering FRT requirements of the IEEE 33 bus test network are presented. The optimal settings of the overcurrent relays as well as the settings of the DT stages and communication links are presented. The second column of this table determines whether the FRT requirements are satisfied for each relay or not. If it is stated as *satisfied* it means a fault in primary zone of that relay will be cleared before the allowed FRT time of the wind turbines. While *not satisfied* means during a fault in the primary zone of that relay, the FRT constraint at (6) will be breached. In cases in which the FRT is not satisfied for a relay, the third and fourth columns of Table 3 determine the best solution to make the relay able to meet the FRT requirements. In this case, if the DT stage of the relay is sufficiently enough, the third column is stated by *YES*. If not, it means that a communication link is necessary and the fourth column is stated by *YES*. Finally, the settings of the inverse curve and DT stage relays are presented in the fifth and sixth columns of the same Table.

As it can be seen, the settings of relays R18 and R17 are unchanged compared to conventional methods. It is because these relays are able to meet the FRT constraint in (6). However, relay R16 is not able to satisfy (6) and a communication link between this relay and relay R17 is needed to make it able to operate faster. The tripping time of this relay for faults in its main protection zone is set to 70 ms thanks to the communication link. This time is suitable considering the time delay of the communication channel and circuit breaker operating time. It should be noted that as shown in Table 3, relay R16 trips the faults outside its main protection zone by the inverse curve and its settings are unchanged compared to the conventional methods, too. Also, even though relay R15 satisfied the FRT requirements, applying the communication channel between its

downstream relays, leads to a reduction in the operating time of relay R15. Relay R14 has the same situation as relay R16 and a communication link with relay R15 is required to meet the FRT requirements. The FRT status for relay R13 is different. Although this relay cannot meet the FRT requirements, it does not require a communication link. In order to meet the FRT requirements, it is enough for this relay to operate as a DT stage with a 50 ms tripping time for fault currents more than 957 A as depicted in the same table. Relay R12 satisfies (6) and its settings are unchanged. With the same descriptions, relays R11 and R9 need a communication link with relays R12 and R10, respectively. Relay R7 also satisfies the FRT with a DT stage for fault currents more than 1380 A.

It should be noted in cases in which a communication link is required, the operating time of the relays is set to 70 ms according to the left hand side of (12). However, this time can be different as it is a function of the delay of the communication link and the minimum time that its downstream relay can detect the fault depicted in Fig. 10. For 150 ms as the least allowed FRT time according to Fig. 1 and 80 ms for the CB operating time, the right hand side of (12) will also be satisfied.

The performance of the proposed method has also been examined on the IEEE 69-Bus test system equipped with four 1.5 MVA DFIGs as depicted in Fig. 11. In this figure, the locations that violation from FRT requirements happens in conventional methods have been determined by red arrows. The base voltage of this network is 12.66 kV and the base power is 100 MVA. More details can be found in [18]. The settings of the relays and the location and settings of the required communication links considering the FRT requirements have been provided in Table 4. According to this table, it is shown that by implementing 4 communication links it is possible to make the DFIGs

able to ride through the faults and prevent from any unnecessary power loss during faults.

It should be noted that In the event of a change in the topology of the system, the short circuit calculations should be updated. Hence, the method should be repeated considering the new short circuit currents. In this case the settings of the relays and the number or location of communication links might be changed.

6. Conclusion

A highly effective protection coordination method, considering the FRT requirements of DFIG-based wind parks, has been proposed in this paper. The simulation results showed that in conventional relay coordination schemes a fault even far from a wind turbine might lead to FRT violation and an unnecessary power loss might happen. The proposed protection method is not only easy to implement but also very reliable and can guarantee stable operation of wind parks during voltage sags. The required constraints related to the FRT requirements as well as the proper solutions are presented. After determining the FRT status of each relay, the proposed method by either modification of relay characteristic using DT stage or communication links was able to clear the faults in the permitted time from FRT requirements. The simulation results showed the proposed method can properly consider FRT requirements and prevent any power loss during faults. Also, the proposed method is not dependent on the DG control which makes the method very versatile.

Appendix

The parameters of DFIGs and transformers are as follows:

DFIGs: Rated apparent power: 1.5 MVA, Rated voltage: 690 V, Stator resistance: 0.0048 pu, Stator leakage inductance: 0.09321 pu, Magnetizing inductance: 3.95279 pu, Wound rotor resistance: 0.0055 pu, Wound rotor leakage inductance: 0.09955 pu.

Transformers: Rated apparent power: 1.5 MVA, 0.69 kV/12.66 kV $uk=6\%$

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Figure Caption

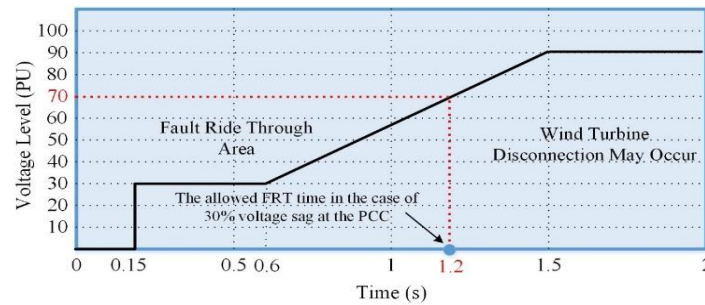


Fig.1 Germany's Fault Ride Through (FRT) Curve.

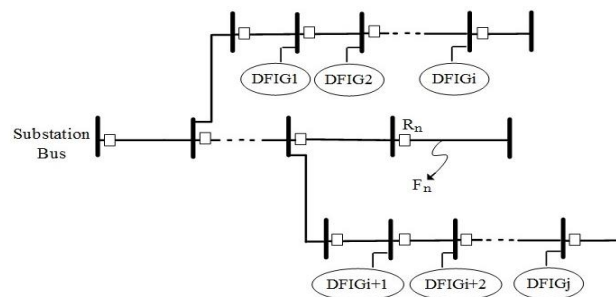


Fig. 2. Simple distribution network with DFIG.

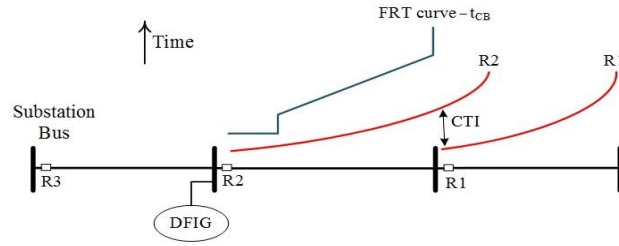


Fig. 3. FRT and relay curves without any intersection (the FRT is satisfied).

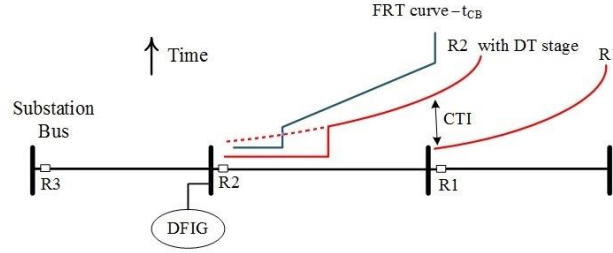


Fig. 4. Definite time stage for FRT violations originated from faults close to relay location.

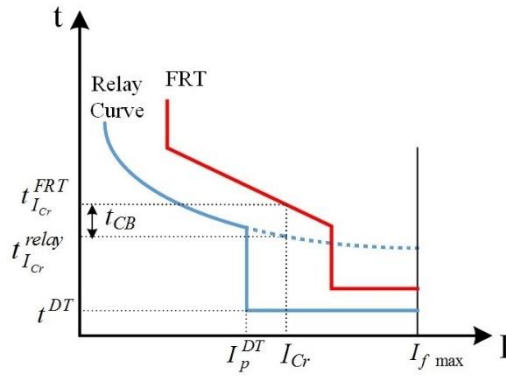


Fig. 5. Setting the definite time stage considering the FRT requirements.

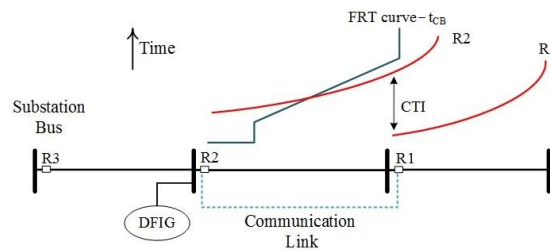


Fig.6 . Cases that there is not any achievable relay settings to meet the FRT.

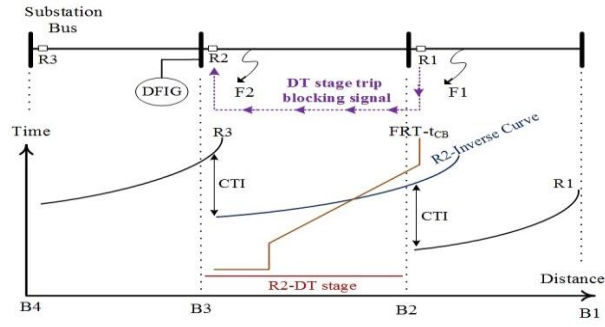


Fig.7 . Communication channel FRT constraint protection coordination.

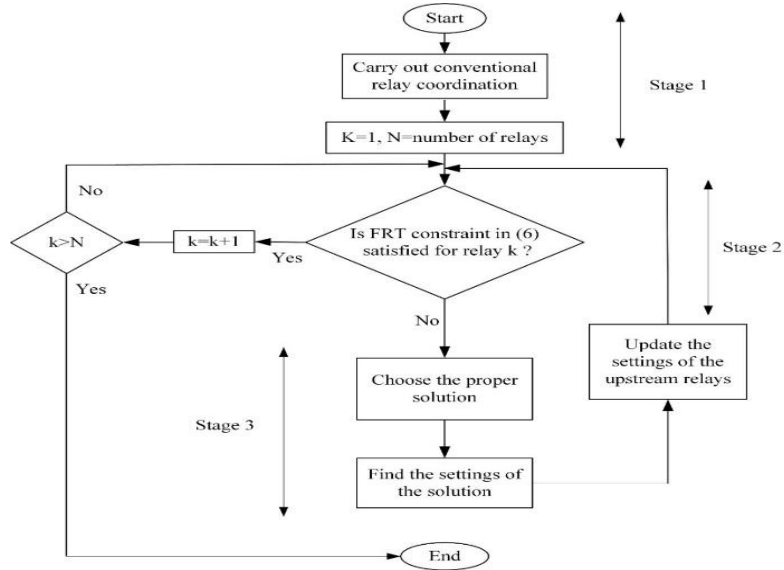


Fig. 8. Flowchart of the proposed protection method considering the FRT requirement

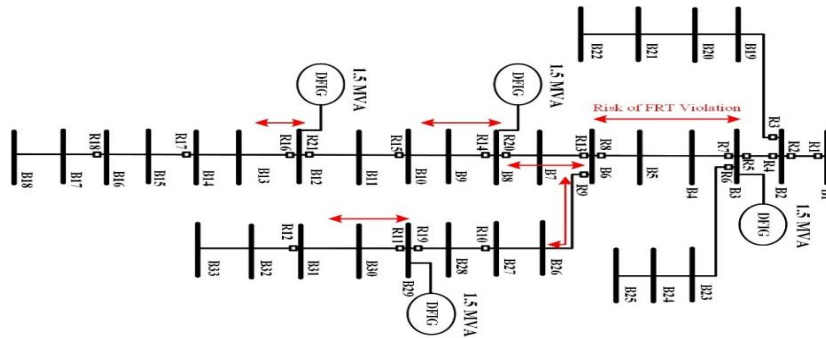


Fig. 9. IEEE 33-bus network with integrated DFIG wind turbines.

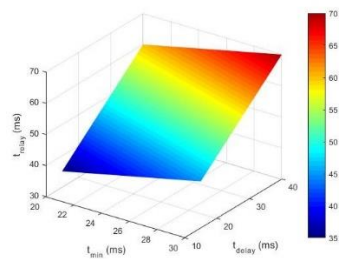


Fig. 10. Influence of communication link delay and minimum fault detecting time by the downstream relay on the operating time of relay.

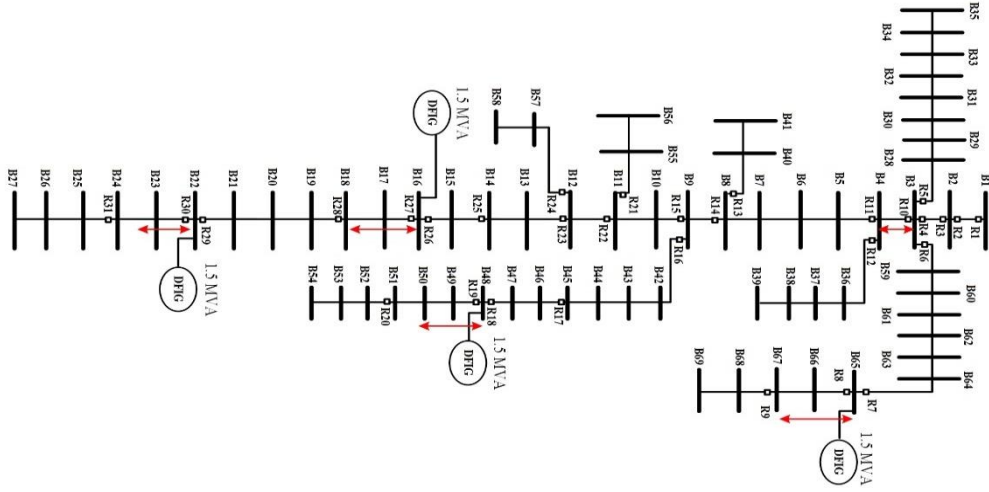


Fig. 11. IEEE 69-bus network with integrated DFIG wind turbines.

Table Caption

Table 1. Optimal OCRs settings with standard reverse curve from conventional methods

Relay Number	$TDS(s)$	$I_p(A)$	Relay Number	$TDS(s)$	$I_p(A)$
R4	0.56	78	R13	0.42	61
R7	0.48	72	R14	0.31	125
R9	0.33	58	R15	0.26	68
R10	0.27	27	R16	0.24	34
R11	0.16	31	R17	0.15	29
R12	0.05	25	R18	0.05	26

Table 2. The allowed FRT time and relay tripping time comparison during faults in different location

Fault Location	OCR Tripping Time (ms)	FRT Allowed Time (ms)	Fault Location	OCR Tripping Time (ms)	FRT Allowed Time (ms)
B4	879	150	B14	451	855
B5	907	150	B15	276	960
B7	798	803	B26	596	603
B9	650	630	B27	617	753
B10	744	901	B30	248	150
B13	429	720	B31	269	650

Table 3. Optimal OCR settings considering FRT requirements for the IEEE 33 bus distribution network.

Relay Number	FRT Status	DT Stage	Communication Link	Inverse Curve		DT	
				$TDS(s)$	$I_p(A)$	$I_p (A)$	$t(ms)$
R4	-	-	-	0.49	74	-	-
R7	Not Satisfied	YES	NO	0.37	69	$I > 1380$	50
R9	Not Satisfied	NO	YES (R9 and R10)	0.30	57	$I > 57$	70
R10	Satisfied	-	-	0.27	28	-	-
R11	Not Satisfied	NO	YES (R12 and R11)	0.16	31	$I > 31$	70
R12	Satisfied	-	-	0.05	25	-	-
R13	Not Satisfied	YES	NO	0.34	59	$I > 957$	50
R14	Not Satisfied	NO	YES (R14 and R15)	0.29	107	$I > 107$	70
R15	Satisfied	-	-	0.25	62	-	-
R16	Not Satisfied	NO	YES (R16 and R17)	0.24	34	$I > 34$	70
R17	Satisfied	-	-	0.15	29	-	-
R18	Satisfied	-	-	0.05	26	-	-

Table 4. Optimal OCR settings considering FRT requirements for the IEEE 69 bus distribution network.

Relay Number	FRT Status	DT Stage	Communication Link	Inverse Curve		DT	
				$TDS(s)$	$I_p(A)$	$I_p (A)$	$t(ms)$
R31	Satisfied	-	-	0.05	12	-	-
R30	Not Satisfied	NO	YES (R31 and R30)	0.24	23	$I > 1867$	70
R28	Satisfied	-	-	0.37	29	-	-
R27	Not Satisfied	NO	YES (R28 and R27)	0.52	34	$I > 1675$	-
R25	Satisfied	-	-	0.58	38	-	-
R23	Satisfied	-	-	0.72	40.5	-	-
R22	Satisfied	-	-	0.82	57.5	-	-
R15	Satisfied	-	-	0.91	77	-	-
R14	Satisfied	-	-	1.06	81	-	-
R11	Satisfied	-	-	1.19	96	-	-
R10	Not Satisfied	NO	YES (R11 and R10)	1.43	98	$I > 9802$	70
R9	Satisfied	-	-	0.05	10.5	-	-
R8	Not Satisfied	NO	YES (R8 and R9)	0.31	12	$I > 3889$	70
R6	Satisfied	-	-	0.49	20.5	-	-
R20	Satisfied	-	-	0.05	32	-	-
R19	Not Satisfied	NO	YES (R19 and R20)	0.12	181	$I > 1548$	70
R17	Satisfied	-	-	0.18	193	-	-
R16	Satisfied	-	-	0.29	199	-	-