Coordinated protection and control strategy with wind power integration for distribution network

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Abstract: In this study, an optimal protection and control coordination strategy is proposed, which pursues to prevent unwanted protection and control operations caused by wind power integration, as well as adjust the emergency states of the power system to stable operation conditions. Moreover, in order to implement the proposed strategies, a hardware in-the-loop real-time simulation and testing platform is built up to demonstrate those unexpected protective control operations and testify the related solutions in a test distribution network. The related case studies and simulation results can demonstrate the effectiveness of the proposed methods.

1 Introduction

In Denmark, 40% of the total electrical power is transformed from wind in 2015 [1]; and more than 83 other countries of the world have started to adopt wind power as one kind of their power generations [2]. In whole Europe, 11.4% of the total electrical power usage comes from wind in 2014, and this rate is growing rapidly every year. At the same time, the technology of distribution generation (DG) has been highly developed and implemented, which greatly help the integration and utilisation of wind power [3].

When DG has been integrated to power grids, many advantages can be obtained on distribution system operation and control, e.g. local balance of power generation and consumption [4] etc. Moreover, with the applications of various modern distribution automation schemes, the normal distribution power networks are gradually evolving into micro-grids with more observability and controllability [5].

However, with more DG integration and smart technology application in the distribution level, the operation conditions of the power network become more variable and unpredictable; especially with wind power generation. On the other side, the protection system is normally conservative and standalone [6, 7]. It is vulnerable to those unpredictable operation conditions which are not considered in advance. Also, the normal emergency control actions, e.g. load shedding (LS) and generation rescheduling/islanding, are based on local measurement. These actions between protection and emergency control have not been coordinated sufficiently to keep the modern power systems secure and stable in the post disturbance stage. Thus, when a power network easily and frequently changes due to the DG integration or other events, the related protection and control system is prone to lose its coordination and operate in an unwanted way, which may be a trigger of the blackout of the whole system.

To inhibit the negative influences of DG integration and upgrade the protection and control system performance in the post disturbance stage, an optimal protection and control coordination strategy is proposed for the distribution network with wind power integration. The cooperation strategy between relays and controllers is defined to prevent those unexpected relay and control operations. Moreover, a hardware in the loop (HIL) real-time simulation platform is developed to provide a practical method to implement and demonstrate the proposed strategy.

The rest of this paper is organised as follows: Section 2 will briefly give the introduction of the studied test system and related problem analysis; the proposed strategy and HIL real-time simulation platform-based implementation will be presented in Section 3; case simulation and method verification will be given in Section 4; finally, the conclusions are drawn in Section 5.

2 Problem analysis

2.1 Simple model of active distribution network

In this study, a simple test distribution network is adopted, as shown in Fig. 1. This system contains five buses, two DGs [one gas turbine generator (GTG) and one wind turbine generator (WTG)] and three loads. The nominal system voltage is 12.66 kV and total load capacity is 2.5 MW.

In this test active distribution network, the detailed model of a 1.5 MW full scale converter based wind turbine synchronous generator is adopted for the WTG, while a 2 MVA general GTG with a governor and an exciter is utilised for the GTG [8]. The wind speed model, the aerodynamic model, the mechanical models, the electrical models and the controller models have been concretely built in the WTG system model. The penetration level of the DG units, i.e. WTG and GTG, is sufficient to support all local loads (L1, L2, and L3) in islanded operation mode.

The relays applied on the distribution feeders are distance relays, which are implemented with the general quadrilateral impedance characteristics [9]. These relays are represented by symbols ‘R\(_i\)’, e.g. R1-R5 in Fig. 1. The forward ones and backward ones are shown in red and black, respectively. R5 and R5r are installed with normally open circuit breakers, which can be closed to make a loop topology. R\(_{GTG}\) and R\(_{WTG}\) are the relays for protecting DGs, R\(_{L1}\), R\(_{L2}\), and R\(_{L3}\) are the relays for three dispersed loads. The related basic data can be found in the Appendix of [10].

2.2 Problem analysis

2.2.1 Unwanted protection operation: Based on this small test system, the main influences of DG integration on the protection system of the distribution network can be investigated. Compared with current relay algorithms, the impedance relay algorithms are regarded as a better solution with a higher selectivity in the protection system of the distribution network. However, the main unexpected protection operation issues can be still encountered due to the DG integration.

(i) Protection blinding. The case shown in Fig. 2 has been adopted to describe this kind of unexpected protection operation. When the test system is operating in the islanded and radial mode, i.e. CB,
R5, and R5r are open. A three-phase bolted short circuit F1 occurs at the end of zone 2 of R1 (20% of the length of line 12 to bus 1). The related impedance loci seen by R1 are focused, and the variations of them in the system with/without WTG can be seen from Fig. 2b. Since zone 1 is not easy to be influenced by the infeed current of DG, the issues with the backup zones (zone 2 and zone 3) are more serious. With the contribution due to WTG integration, the fault current seen by R2 is increased from 511 to 567 A, while the fault current seen by R1 is decreased from 511 to 480 A. In Fig. 2, the black impedance locus is related to the faulty situation in islanded operation mode without WTG, while the pink impedance locus is the situation in islanded operation mode with WTG connected. Thus, after WTG is connected into the grid, if the settings of the distance protection system are still set as the situation without WTG, the infeed current from the WTG will make backup zones of distance relay R1 become less sensitive or blind to F1 in the situation with WTG, when R2 fails. Especially, zone 2 cannot locate the F1 clearly in the new operation condition. The backup cooperation between R1 and R2 will be jeopardised.

(ii) Sympathetic tripping. If the former fault occurs in the grid-connected condition, the impact of infeed current from the WTG is smaller than the situation in the islanded condition. When the relay setting of R1 has already considered the WTG integration in islanded condition as new zone 2, the distance relay will locate the fault in a closer place (brown locus in Fig. 2b). If the inverse time overcurrent relay is applied, a faster tripping will be initiated, which is the classic case of sympathetic tripping. As for the impedance relay, wrong fault location-induced tripping could also be regarded as sympathetic tripping. The related relay characteristics and operation loci can be seen in Fig. 2b.

(iii) Unwanted DG islanding to cascading blackout. If we continually consider the former fault case in the islanded condition, during longer time delay of zone 2 of R1 when R2 does not work, the low voltage at bus 0 may induce an unexpected tripping of GTG. At almost the same time, the WTG at bus 1 could be tripped unexpectedly due to an even worse voltage situation. Then this islanded distribution network will be out of power and a local cascaded blackout occurs. The related impedance loci, breaker status, current and voltage waveforms can be observed in Fig. 3.

It can be seen that all these situations caused by DG integration and network changing induce mal-operation and non-cooperation of the original protection system, which are very harmful to the required reliability of the protection system [11].

2.2.2 Unwanted protective control operation: If a three-phase bolted short circuit F2 is applied on the external grid side, the test distribution network will be islanded by opening the main CB, which can be seen from Fig. 4. The network islanding induces a temporary power imbalance of ∼500 kW inside. The original local generation rescheduling is very slow, while the local LS is not activated. Thus, the generation under frequency relay strategies on both GTG and WTG will be tripped since the related disturbance are big enough to violate the related criteria (f<48 Hz, 1 s delay for WTG and 2 s delay for GTG). The related data can be found in Fig. 4 as well.

Then the cascaded blackout of this small test system will be triggered, which can be observed from Fig. 5. The frequencies, voltages, currents and breaker status from the critical points are shown in the figure, it can be clearly seen that the progress of this blackout occurred in this small islanded system network due to the lack of generation is made by unexpected cascading trips. The voltage on the WTG side increases to above 2 p.u., which will be
dealt with by the WTG control system to discharge the surplus energy and stall the wind turbine.

3 Proposed strategy and implementation

To prevent these unexpected protection and control operation, the related protection and control strategies need to be improved to better consider the situations and give more efficient time and room to each other. Thus, the voltage and frequency of the test distribution network in the post disturbance stage can be regulated to a secure and stable level. Based on the problem analysis and case studies discussed above, the cooperation between different protections, and the cooperation between protection and emergency controls will be predesigned offline and executed online, based on the centralised control centre and IEC 61850 communication network. In this study, the emergency control will focus on protective relay blocking (RB), generator rescheduling (GR) and LS.

To obtain a reliable protection and control cooperation strategy for new system operation conditions, the prevailing breaker status and controller status are adopted to identify the updated operation condition, and then the new suitable protection setting groups (SGi) and control modes (Ci) will be chosen and applied to all related relays and controllers. The brief progress of the proposed strategy can be seen in Fig. 6.

3.1 Problem statement and optimisation algorithm

With the aim to efficiently coordinate the distributed protective relays and controllers, the related control centre will be conducted to choose an optimal coordination protective control strategy, which can minimise the total power loss in the post disturbance stage. The protective control strategies will include relay setting regulation (SGR), RB, GR, and LS. Thus, the objective function of the problem can be expressed as follows:

\[
\min P_l = \min (k_1 P_{SGR} + k_2 P_{RB} + P_{GR} + P_{LS}).
\]  

where \( P_l \) is the total power loss in the post disturbance stage; \( P_{SGR} \) and \( P_{RB} \) are protection strategies SGR and RB induced power loss, respectively; \( P_{GR} \) and \( P_{LS} \) are the control strategies GR and LS induced power loss, respectively. Also, this optimisation problem will be still constrained by protection operation requirements and limits, power flow equations, generation dispatch capability etc. [9, 12].

The relationships between control strategy GR/LS and power loss can be easily deduced [13], while the relationships between SGR/RB and power loss is not that directly connected. Consider the risk of failures of SGR and RB, the related power loss can be calculated based on the possible power loss induced by those failures or those unexpected relay operations during cascading trips [10]. Two weight factors \( k_1 \) and \( k_2 \) are chosen in (1). In this study, \( k_1 = 1.2 \) and \( k_2 = 1.5 \) are adopted, which means the RB has higher priority than SGR, and protection strategies have higher priority than control strategies.

3.2 Implementation of the proposed strategies

To provide a practical method to implement and demonstrate the proposed strategy, a HIL real-time simulation platform is developed, which can be seen in Fig. 7. This HIL real-time simulation platform has been built based on Opal-RT’s eMEGAsim simulator, OMICRON test devices and ABB Relion 670 relays [14, 15]. Firstly, test power systems are modelled based on Matlab/Simpower systems and eMEGAsim/Artemis tool boxes, especially the primary power components. Secondly, virtual secondary power components are developed in a Matlab/Opal programming environment, e.g. relays and controllers are modelled based on the standard library models or user defined models. Thirdly, a communication network is built based on the relevant communication protocols, e.g. GOOSE (IEC 61850- 8-1).

Fig. 5 Islanding operation-induced system disturbance
(a) Frequencies and criteria, (b) Breaker status of DGs, (c) Voltages at critical points, (d) Currents during blackout

Fig. 6 Solution of coordinated protection and control

Fig. 7 Hardware-in-the-loop real-time simulation platform

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and sampled values (SV/IEC 61850-9-2LE), in an Opal simulation system. Fourthly, the connection interface is built between the practical ABB Relion 670 relays and Opal simulator based on both the IEC 61850 communication network and wired analogue/digital signal channels. In the end, the related control algorithms are developed in the control centre in OPAL to realise the protection and control optimal coordination strategy and testify it in this HIL real-time simulation platform.

4 Case study and simulation results

Based on the optimal cooperation strategy described above, the former two cascaded blackout cases are used here to validate the effectiveness of those strategies.

4.1 Case 1 on the cascading trips described in Fig. 4

The reason for this cascaded blackout is the mis-cooperation of the protection system, i.e. Zone 2 of R1, as a backup protective function, is slower than the operation of RWTG and RG TG. The defined solutions based on the proposed optimal strategy can be seen in Table 1. The minimised power loss is 0.4 MW.

After the related solutions have been implemented, the fault has been cleared timely and the trend of cascading trips has been stopped. Thus, parts of the distribution network survive the faulty transition with new solutions, and voltages at remaining buses recover to a secure level. The impedance seen by R1 has been moved out of the operation areas. The related results can be observed in Fig. 8

![Image](image_url)

**Fig. 8 Case 1 cascaded blackout prevention with coordination solution**

(a) Impedance loci seen by R1, (b) Breakers under solution

| Case 1 | Loss   |
|--------|--------|
| protection mis-cooperation solutions | zone 2 of R1 is slower than RWTG and RG TG |
| | 2.5 MW |
| | 1. new zone 2 with delay 0.4 → 0.6 s |
| | 0.4 MW |
| | 2. blocking under voltage relay of RG TG for 1 s |
| | 3. unblocking RWTG, free to operation |

**Table 1 Protection and control coordination strategy**

| Case 2 | Loss   |
|--------|--------|
| islanding-induced power unbalance solutions | −500 kW |
| | 2.5 MW |
| | 1. blocking R1 and R3 for 1 s |
| | 0 MW |
| | 2. blocking under frequency relay of RG TG and RW TG for 1 s |
| | GTG: 1.16 MW → 1.26 MW with delay 0.4 s |
| | L3: 0.5 MW → 0.1 MW with delay 0.8 s |

**Table 2 Protection and control coordination strategy**

4.2 Case 2 on the cascading trips described in Fig. 5

The reason for this cascaded blackout is the big power unbalance induced by islanding of the distribution network. The defined solutions based on the proposed optimal strategy can be seen in Table 2. In this case, the power load loss can be totally prevented by the optimal solution.
After the related solutions are implemented, the unexpected relay operations and emergency voltage/frequency conditions have been efficiently inhibited, and the trend of cascading trips has been stopped. Thus, the islanded distribution network survives the big power unbalance with new solutions, and voltages at remaining buses recover to a secure level. The impedance seen by R1 has been moved out of the operation areas. The related results can be observed in Fig. 9.

5 Conclusion

In this study, an optimal coordinated protection and control strategy is proposed to prevent an unexpected controller and relay operations due to the WTG integration, such as protection blinding, sympathetic tripping, unwanted DG islanding etc. The proposed strategy can efficiently coordinate the distributed relays and controllers, quickly define the effective protective control strategies to adjust the emergency operation conditions and prevent the cascading events. Moreover, a HIL real-time simulation platform is developed in this study to provide a practical method to implement and demonstrate the proposed strategy. Based on the case studies, the feasibility and necessity of the proposed optimal coordinated protection and control strategy against cascading events in the distribution power network have been verified.

6 References

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Fig. 9 Case 2 cascaded blackout prevention with coordination solution
(a) Breaker status under new solution, (b) Frequency waveforms under new solution, (c) Currents by critical relays, (d) Voltages of critical points

After the related solutions are implemented, the unexpected relay operations and emergency voltage/frequency conditions have been efficiently inhibited, and the trend of cascading trips has been stopped. Thus, the islanded distribution network survives the big power unbalance with new solutions, and voltages at remaining buses recover to a secure level. The impedance seen by R1 has been moved out of the operation areas. The related results can be observed in Fig. 9.