A COMMUNICATION BASED PROTECTION SYSTEM FOR SOLVING DG RELATED PROTECTION CHALLENGES

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ABSTRACT

This paper presents a communication based protection automation system which is designed for solving DG related protection problems. The system is able to tackle problems related protection blinding, nuisance tripping of feeders and generators and problems related to unintentional islanding. Moreover, the system can be configured to allow low voltage ride-through without compromising loss of mains protection. However, the system also has the potential of enhancing the reliability of electricity distribution service to DG units by automatically switching an alternative feeding path if the original feeding route is faulted.

INTRODUCTION

The amount of distributed generation (DG) connected to distribution network level is growing strongly. DG has many potential benefits on the usage of distribution systems such as reducing distribution losses, improving voltage profiles, levelling demand peaks and increasing reliability of distribution service to consumers. However, DG also raises a number of new challenges. The main challenges related to distribution system protection raised by the addition of DG are protection blinding, nuisance tripping of intelligent electric devices (IEDs), failed reclosing and unintentional islanding [1].

Establishing a reliable loss of mains (LOM) protection is particularly challenging if fast automatic reclosing (AR) utilized. AR is meant for removing temporary faults automatically without causing an extended interruption in the supply of electricity. This is achieved by opening a circuit breaker (CB) connecting the faulted feeder to the supplying grid for a short period of time and then reclosing the CB. AR has a great significance for the reliability of electricity supply since, e.g., in Finland the majority of faults on overhead lines are temporary in nature (e.g. due to lighting strikes or storms) and thus also clearable by AR. LOM protection has to be able to detect islanding and disconnect islanded DG units rapidly enough for the fault arc to extinguish during fast automatic reclosing. For instance, in Finland the circuit breaker open time used in fast automatic reclosing is typically 300 ms, which in practice means that DG units should be disconnected approximately within 200 ms in order to ensure a dead time of 100 ms for the ionized gasses created by the fault arc to disperse. Moreover, LOM protection has to be able to detect islanding even though the load in the islanded part of network would match the power produced by the islanded DG units. Certain active LOM protection methods are able to meet these requirements but this comes at the cost of degraded power quality because active methods are based on detecting islanding by deliberately injecting perturbations to the network. However, these methods may not function properly if the islanded network contains both inverter coupled and directly coupled synchronous generators [2]. Moreover, even though there would be only inverter based DG units in the islanded circuit, the active LOM protection methods have to be synchronized with each other in order to ensure reliable LOM protection. However, this usually means that the power quality problems caused by the active LOM protection method become even more severe.

Despite the high number of publications dealing with these problems, protection concepts being capable of taking all the protection problems related to DG into account are scarce. This paper presents a protection concept for distribution networks which aims to solve all the DG related protection challenges. The studied system is largely based on the ideas presented in [3]. However, the studied protection automation system was also designed to increase the reliability of distribution service to DG units. This kind of service may be attractive to the owners of large DG units that are connected to remote locations, since even short outages may be harmful to them. The idea behind the proposed protection automation configuration is that distribution networks are often built meshed but operated in radial mode. In many cases a customer may have two or more line routes through which the supply is provided. This potential can be harnessed with a proper intelligence.

THE PROTECTION AUTOMATION SYSTEM

The idea of the proposed protection system is explained with the help of Fig. 1. In this example figure, there are two medium voltage feeders fed by the transmission grid via a HV/MV transformer. The first feeder, i.e. feeder A, is protected by two line differential protection IEDs. There is also a DG unit connected to the tail part of the feeder which is protected by a LOM IED. The other feeder is protected by an overcurrent protection IED. All the IEDs which are situated near to each other are communicating with each other using the generic object oriented substation event (GOOSE) defined in the IEC 61850 standard. The protection communication link between the differential protection IEDs A1 and A2 is established using an optical wire and digital signals. The bandwidth of the optical link is high enough to enable the sending of user definable information in addition to the differential protection related communication. This sending of additional binary signals between the differential IEDs is referred to as the binary signal transfer (BST) [3]. GOOSE messages can also be used for establishing the vertical communication instead of BST if line differential protection is not used in the network. However, suitable communication channel such as optical cable or 4G/LTE wireless communication link is needed in such case.

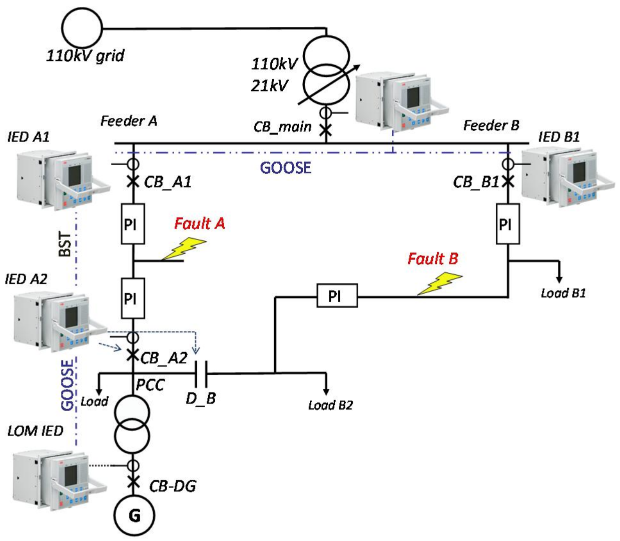

Figure 1. The examined network model

The proposed protection concept is able to tackle DG related protection problems. Nuisance tripping problems can be reliably avoided by sending blocking signals between IEDs. For instance, if a fault occurred on feeder B at such a distance that IED B1 tripped on its low stage, i.e. time delayed overcurrent stage, it could still cause a voltage dip at the DG terminals deep enough to cause an unwanted tripping of the DG unit. This can be avoided if IED B1 sends a block command to the LOM IED once IED B1 detects a fault on the feeder which it is protecting. Protection blinding problems caused by fault current contribution from DG can, on the other hand, be tackled by the use of differential protection. If desired, the system can also be made fully fault ride through (FRT) compatible by setting the LOM IED undervoltage protection (UVP) function to allow the low voltage ride-through (LVRT). Moreover, this does not compromise LOM protection because the transfer trip issued by IEDs A1 and A2 will always rapidly and reliably trip the DG unit whenever the DG unit becomes islanded, irrespective of the power imbalance in the islanded circuit. The communication delays in the system are of minor scale. Sending a block signal from IED B1 first via GOOSE to IED A1, then via BST to IED A2 and finally from IED A2 to LOM IED would take less than 30 ms according to [3]. If there should be any abnormalities in the communication, the LOM IED automatically switches stricter settings for providing better LOM protection.

The system is also designed to be able to enhance the reliability of distribution service to DG units in networks which are operated in an open ring configuration. The idea behind this is that IEDs can be made to control the disconnector separating the two feeders. This can be explained again with the example shown in Fig. 1. When a fault occurs at fault location A, the differential protection isolates this fault by opening circuit breakers CB_{A1} and CB_{A2}. IED A2 then immediately sends a trip command to the LOM IED since unintentional islanding is prohibited. After this, IED A2 sends a close command to the normally open disconnector D_B, and after a chosen delay, a close permit to the LOM IED. However, the actual closing time of the DG unit circuit breaker is decided by the synchronism check function.

The switching sequence has to be accomplished in a short period of time since the generator accelerates when it is unable to feed power to the grid while the mechanical power given by the prime mover remains constant. If the generator accelerates excessively, the reconnection back to the network is not possible. The proposed switching sequence is more likely to be successful if the generator is connected to the network via frequency converter. This is firstly because the synchronization rules are not as strict for inverter connected DG units as for directly connected synchronous generators. Secondly, the speed of the generator behind the frequency converter is decoupled from the frequency of the main grid and reconnection to the grid may still be possible even if the generator would have accelerated considerably. In fact, it is advisable to let the generator accelerate instead of feeding all the available power from the generator to the DC-link in order to limit the DC link voltage during LVRT [4]. However, countermeasures may be needed to avoid overspeed problems. The DC-link voltage rise can also be mitigated by activating a breaking chopper in the DC link [4].

LABORATORY SETUP

The studies were done with the help of the RTDS (real time digital simulator). RTDS was chosen for these studies because it performs the electromagnetic transient simulations needed for simulating the functioning of a power system in real time, and enables the connection of real external devices to function as a part of the simulation. Two ABB RED615 differential protection IEDs, one REF615 overcurrent protection IED and one REF615 which was configured to function as a LOM IED were connected to the RTDS. The voltage and current measurements from the IED locations shown in Fig. 1 were amplified to a realistic scale for the IEDs with the help of three Omicron CMS156 amplifiers. The IEDs then sent their protection and control commands back to the RTDS via digital signals for controlling the circuit breakers and the diconnector D_B as illustrated in Fig. 1.

The protection settings used in the IEDs are shown in Table I. For more information concerning the differential protection parameters, refer to [5]. In addition to these, a simple synchronism check function was implemented with the help of the components available in RSCAD component library. This synchronism check function, which is activated by a digital signal sent from IED_A2 (see Fig. 1), checks that the voltage magnitude- and frequency are within the allowed limits (ΔV and Δf). The function also checks that the phase difference (Δ angle) between the voltages on both sides of the DG unit circuit breaker is within the allowed range. The settings for this function are also displayed in table I.

Table I. The utilized protection settings

Line differential prot.		**Synchronism check settings**		
function	threshold	function	threshold	
High op. val.	4000 %In	Δ V	0.08 xUn	
Low op. val.	200 %In	Δ f	0.5 Hz	
End sect. 1	100 %In	Δ angle	10 deg	
Slope sect. 2	50%			
End sect. 2	500 %In			
Slope sect. 3	150%			
Operate delay	45 ms			
I_nominal	100 A			
Overcurrent prot. (B1)		**Loss of mains protection**		
function	threshold	function	threshold	delay
I> Start value	250 A	UVP	0.8 p.u.	200 ms
I> delay	220 ms	OVP	1.15 p.u.	200 ms
I>> Start value	1000 A	OFP	51 Hz	200 ms
I>> delay	80 ms	UFP	48 Hz	200 ms

SIMULATION MODELS

The network model which is shown in Fig. 1 was used for these simulations. The parameters of the PI line models and the loads are shown in table II. The DG unit used in the studies was a 1600kVA rated hydro power driven synchronous generator connected via a 0.66kV/21kV step-up transformer. The inertia constant of the machine was 2s. The reactive power control of the generator was realized using a cascade control, where a control loop determined the set point of the automatic voltage regulator with the aim of maintaining the reactive power output at a target value. Certain simplifications, namely the omission of the turbine controller modelling and the assumption of constant torque were made in the studies. These measures are justified since hydro power plants have relatively high inertial mass which makes them respond to changes slowly, whereas protection studies are dealing with short timeframes only. Moreover, the omission of turbine controller is justified because DG units are typically not attending to frequency control.

Table II. The parameters of the utilized network model

From	**To**	**R+ [Ω]**	**X+ [Ω]**
Substation	Fault point A	6.00	5.56
Fault point A	Feeder A end	2.64	1.19
Substation	Fault point B	8.13	6.23
Fault point B	Feeder B end	5.42	4.15
110kV voltage source impedance		39.60	88.20
Loads		**P [kW]**	**Q [kVAr]**
Load at feeder A		833.65	274.01
Load B1		220.50	72.50
Load B2		220.50	72.50

SIMULATION RESULTS

This chapter presents a selection of the simulation results that were done using the presented laboratory setup and simulation models. The first case presents how the proposed system can be used to avoid unwanted tripping of DG. An unwanted tripping of the DG unit may take place if the connection point voltage of the DG unit drops below the utilized UVP limit due to a fault on the adjacent feeder. A case, where a three phase fault was inflicted on fault point B (see Fig. 1) was simulated and the results from this case are shown in Fig. 2. The top most graph represents currents flowing through CB_{B1} and the graph below this respectively represents the MV side currents fed by the DG unit. The statuses of all the circuit breakers marked in Fig. 1 are displayed at the third graph. This graph also shows when the fault pulse is inflicted. It can be seen from the top most graph, that the rms value of the current flowing through CB_{B1} is below the high stage overcurrent protection setting (I>>) and IED B1 thus trips with its low stage overcurrent protection (I>) approximately 220 ms from the starting of the fault (see table I). Note that the mechanical opening time of the circuit breaker causes an additional delay of 50 ms. The current flowing through CB_{B1} thus drops to zero approximately after 270 ms from the beginning of the fault. The synchronous generator based DG unit begins to swing slightly at the time when CB_{B1} opens as it can be seen from the currents fed by the DG unit. However, the DG unit stabilizes after a while.

The lower most graph represents the connection point voltage of the DG unit. It can be seen from this graph that the voltage drops below the utilized UVP threshold 0.8p.u. This would cause the LOM IED to trip unwantedly. However, the unwanted tripping of the DG unit is avoided because as IED B1 detects the fault on its feeder, it sends a block command via IEDs A1 and A2 to the LOM IED. Unwanted tripping of the DG unit could, in certain circumstances, also be caused by the tripping of rate of change of frequency protection due to adjacent feeder faults [1]. However, such unwanted tripping of DG can be similarly blocked as the UVP function.

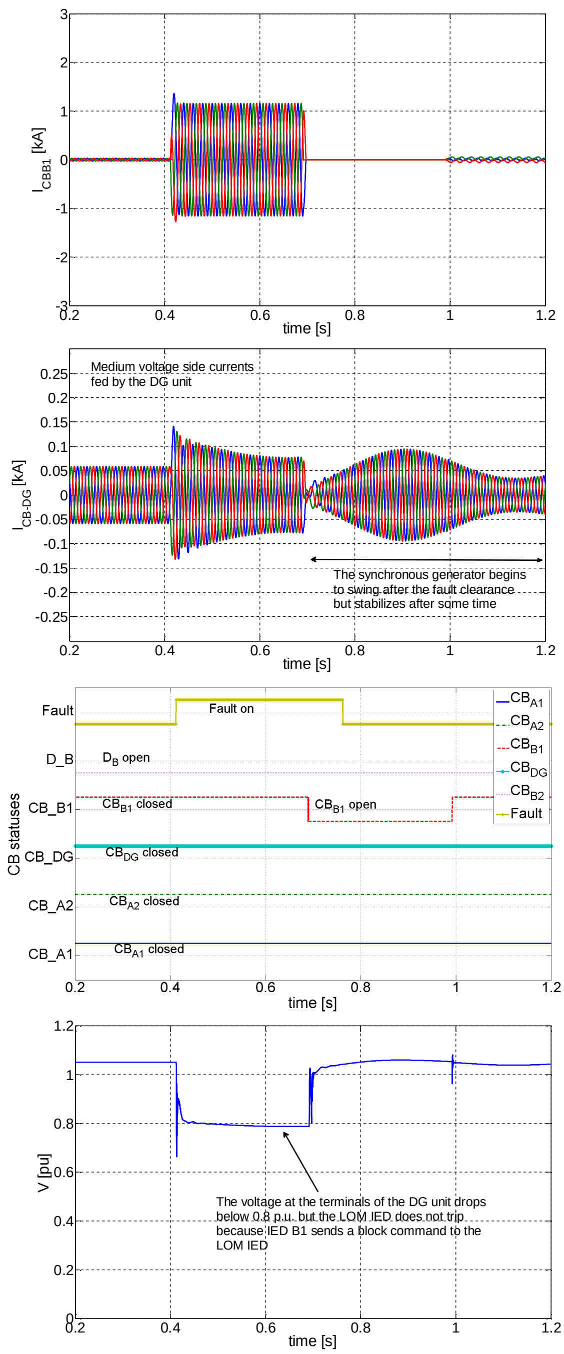

Figure 2. The unwanted tripping of the DG unit is avoided due to the block command sent by IED_{B1}

The following case presents a case where a three phase permanent fault occurs at fault point A. This causes the differential protection IEDs A1 and A2 to trip and open their circuit breakers in approximately 95ms (45ms IED operate delay + 50 ms circuit breaker mechanical opening delay). The graphs related to this case are shown in Fig. 3. IED A2 then sends a trip command to the LOM IED. In this laboratory setup the LOM IED trips approximately 4ms after IEDs A1 and A2 (the optical cable between the IEDs A1 and A2 is fairly short). This simulation shows that the examined protection system can tackle the unintentional islanding problem very rapidly and reliably.

Starting from the top, the graphs in Fig. 3 represent the MV side current fed by the DG unit, circuit breaker statuses, voltage magnitudes from both sides of the CB_{DG}, voltage frequency from the DG side of the circuit breaker and the phase difference between the voltages on both sides of CB_{DG}. It can be seen from the graphs that CB_{DG} is closed again when voltage magnitude-, frequency and the phase difference are within the tolerated limits. The delay between the closing of disconnector D_B and closing of CB_{DG} is caused by the synchronism check function and the mechanical closing delay of circuit breaker CB_{DG} (closing delay for the switches is assumed to be 60 ms). Note that voltage at the grid side of the circuit breaker drops to zero when both the DG unit circuit breaker as well as disconnector D_B are open. During this time the angle difference naturally fluctuates strongly because the voltage at the grid side of CB_{DG} is zero. A negative angle difference in Fig. 3 signifies that angle of the generator voltage is leading the voltage of the grid.

CB_{A1} tries to clear the fault by performing automatic reclosing as it can be seen from the "CB statuses" graph. Note that CB_{A2} is kept open during the automatic reclosing sequence so that the tail part of the feeder can be safely switched to feeder B already before the automatic reclosing. There is a voltage dip at the DG terminals when CB_{B1} recloses to the faulted line. However, there is no risk of nuisance tripping of the DG unit since the differential IEDs operate much faster in comparison to the UVP function of the LOM IED. If there should be a fault outside of the area protected by the differential protection IEDs on feeder A, for instance, in the DG unit transformer, the overcurrent function which is used as back up protection in IED A1 trips feeder A and sends a transfer trip command to the LOM IED.

In this simulation, the mechanical torque of the generator was set to 0.36p.u. If the value of the mechanical torque is increased from this, the angle difference drifts away from the tolerated limits. This is because the generator accelerates when it is unable to feed the power given by the prime mover. In this case, the electrical output power of the DG unit falls to zero once the DG unit is disconnected and thus the generator will accelerate. The successfulness of the feeding path change depends on many factors such as the inertia constant of the machine, nominal power of the generator and network structure.

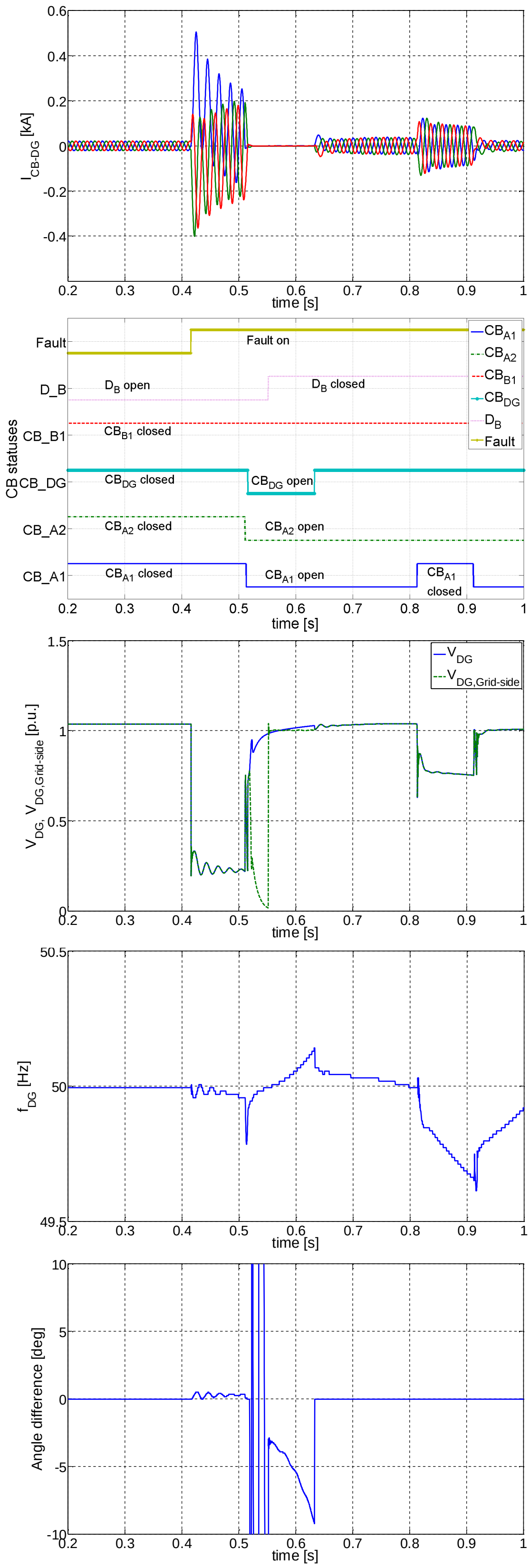

Figure 3. Feeding path of the DG unit changed

CONCLUSIONS

This paper presented a protection automation concept based on inter-IED communication. The horizontal communication between IEDs is established using the GOOSE messages defined in the IEC-61850 standard, whereas, the vertical communication is done by using the optical link between differential protection IEDs. The vertical communication can also be established using GOOSE messages but suitable communication link such as an optical cable or 4G/LTE communication link is needed in this case. The proposed concept is able to tackle typical DG related protection challenges such as protection blinding, nuisance tripping of feeders and DG units as well as non-detected islanding. Moreover, the rapid operation of the LOM protection provided by the concept ensures that fast automatic reclosing can be used on feeders that contain DG. The proposed concept can also be configured to allow DG units to be FRT compatible without compromising the performance of LOM protection. The system can also automatically switch the feeding path of DG units in open ring network configurations in case if the original feeding path becomes faulted. A simulation case demonstrating this feature is presented in this paper. This simulation case was done using a directly coupled synchronous generator based DG unit which is the most difficult type of DG from the feeding path change option point of view.

REFERENCES

[1] K. Mäki, A. Kulmala, S. Repo and P. Järventausta, 2007, "Studies on grid impacts of distributed generation in a combined real-time simulation environment", *Proceedings CIRED conference*

[2] O. Raipala, A. Mäkinen, S. Repo and P. Järventausta, 2012, "The effect of different control modes and mixed types of DG on the non-detection zones of islanding detection", *Proceedings of CIRED workshop*

[3] O. Rintamäki and K. Kauhaniemi, 2009, "Applying modern communication technology to loss-of-mains protection", *Proceedings CIRED conference*

[4] A. Mäkinen, O. Raipala, K. Mäki, S. Repo and H. Tuusa, 2009, "Fault ride through studies of full power converter wind turbine in a real time simulation environment", *Proceedings Nordic wind power conference*

[5] O. Rintamäki and J. Ylinen, 2008, "Communicating line differential protection for urban distribution networks", *Proceedings CICED conference*