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Method to Prevent the Malfunction Caused by the Transformer Magnetizing Inrush Current using IEC 61850-based IEDs and Dynamic Performance Test using RTDS Test-bed

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Abstract – The digital substations are being built based on the IEC 61850 network. The cooperation and protection of power system are becoming more intelligent and reliable in the environment of digital substation. This paper proposes a novel method to prevent the malfunction caused by the Transformer Magnetizing Inrush Current(TMIC) using the IEC 61850 based data sharing between the IEDs. To protect a main transformer, the current differential protection(87T) and over-current protection(50/51) are used generally. The 87T IED applies to the second harmonic blocking method to prevent the malfunction caused by the TMIC. However, the 50/51 IED may malfunction caused by the TMIC. To solve that problem, the proposed method uses a GOOSE inter-lock signal between two IEDs. The 87T IED transmits a blocking GOOSE signal to the 50/51 IED, when the TMIC is detected. The proposed method can make a cooperation of digital substation protection system more intelligent. To verify the performance of proposed method, this paper performs the real time test using the RTDS (Real Time Digital Simulator) test-bed. Using the RTDS, the power system transients are simulated, and the TMIC is generated. The performance of proposed method is verified in real-time using that actual current signals. The reaction of simulated power system responding to the operation of IEDs can be also confirmed.

Keywords: IED, IEC 61850, GOOSE, Real Time Digital Simulator(RTDS), Transformer Magnetizing Inrush Current(TMIC), Current differential protection(87T), Over current protection(50/51)

1. Introduction

The digital substation system is an important element for building a smart power grid. The smart grid is expected that every piece of equipments will possess some type of setting, monitoring and/or control. In order to be able to manage the large number of devices and to enable the various devices to communicate with one another, the IEC 61850 communication networks and systems in substations was needed [2, 3]. The cooperation and protection of power system are becoming more intelligent and reliable in the environment of digital substation. Therefore, data sharing among IEDs, and between host system and IED is available through the IEC 61850 network.

This paper proposes a novel method to prevent the malfunction caused by the Transformer Magnetizing Inrush Current(TMIC) using the IEC 61850 based data sharing between the IEDs. The TMIC is an inrush current caused by a nonlinearity of transformer core. Intensity of the inrush current depends on the instance of the sinusoidal voltage in which it is switched on as well as on characteristics of the ferromagnetic core such as its residual magnetism and its magnetization curve [4]. Therefore, it is not classified as a fault of power system. To protect a main transformer of large scale power plant, the current differential protection(87T) IED and over-current protection (50/51) IED are used. Commonly, to prevent the malfunction caused by the TMIC, only the 87T IED applies to the second harmonic blocking method [5]. On the other hand, the 50/51 IED has the risk of malfunction due to the TMIC, when that IED is applied to the primary winding side of transformer protection system.

The instant over-current block(50B) relay is conventionally used to prevent the malfunction caused by inrush current. That inrush current occurs when circuit breaker closes at the initial stages. That inrush current does not have sufficient second harmonic to detect. The holding time of transient state caused by inrush current is different from the TMIC. Therefore, the 50B relay is unsuitable for the detection of TMIC.

To solve that malfunction of the 50/51 IED, the proposed method uses the GOOSE inter-lock between the 87T IED and the 50/51 IED based on the IEC 61850 network. The transformer protection 87T IED transmits a blocking GOOSE signal to the 50/51 IED, when the TMIC is detected. Thus, the 50/51 IED can prevent the malfunction caused by the TMIC. The proposed method can make a

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cooperation of digital substation protection system more intelligent.

To verify the performance of proposed method, this paper performs the dynamic performance test using the RTDS (Real Time Digital Simulator) test-bed. A power system including the transformer is modeled, and the TMIC is simulated by the RTDS. Using that actual current signals, the performance of IEC 61850 based IEDs is verified in real-time. We can also confirm the reaction of simulated power system responding to the operation of IEDs.

2. Proposed Method

Fig. 1 represents the protection scheme of a main transformer used in the digital substation and the large scale power plant. The components of a main transformer protection system consist of the main protection 87T IED and the back-up protection 51 IED.

The magnetizing inrush current mostly occurs when the voltage is pressurized to the transformer. The magnitude of inrush current is affected by the phase of voltage at the moment of pressurization, and the residual flux of transformer core. The inrush current is generated more in case that the residual flux is larger and the phase of voltage at the moment of pressurization is in the proximity of 0˚ or 180˚. The sympathetic inrush and recovery inrush are also needed to considered. The sympathetic inrush is an influx phenomenon to the normal operating transformer from the other abnormal operating transformer, when those two transformers are working in parallel. The recovery inrush occurs when the circuit breaker which is used in an adjacent outside feeder is open.

The TMIC flows only in the primary of transformer, because a magnetization branch is only included in the primary of transformer. Therefore, as shown in Fig. 1, the 87T and 50/51 may operate abnormally. To prevent the malfunction caused by the TMIC, the 87T IED applies to the second harmonic blocking method however, the 50/51 IED needs any method to prevent that malfunction.

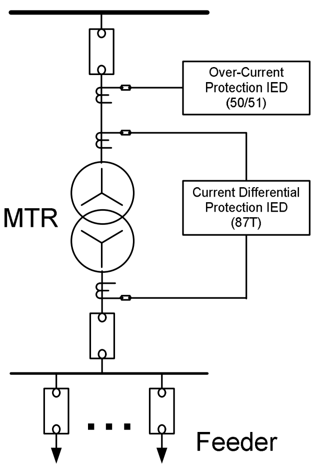


Fig. 1. Protection scheme of a main transformer

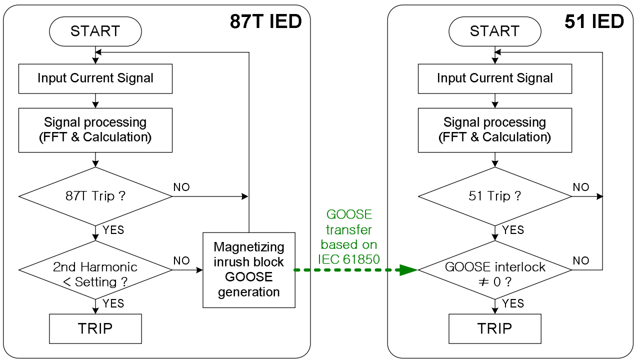


Fig. 2. Flow chart of proposed method

This paper proposes a method to solve the malfunction of 50/51 IED caused by the TMIC. The proposed method uses the GOOSE inter-lock between the 87T IED and the 50/51 IED based on the IEC 61850 network. Fig. 2 represents a flow chart of proposed method. The 87T IED and the 50/51 IED perform FFT signal process and calculation for internal functions using the acquired current signals. After then each protection algorithms are operated. When the calculated second harmonic values of three phase primary currents exceed the setting value, the 87T IED transmits a magnetizing inrush block GOOSE inter-lock signal to the 50/51 IED through IEC 61850 based network. The 50/51 IED prevents the malfunction caused by the TMIC using that received GOOSE inter-lock signal.

3. RTDS Test-bed Composition

To verify the performance of proposed method, the dynamic performance test is performed using the RTDS test-bed. The test-bed consists of the RTDS, the current AMPs (Amplifiers), the PCs, and the IEDs which have the proposed algorithm. Using the RTDS, the transient of power system are simulated, and the TMIC signals are generated. The Current AMPs connected to the RTDS amplify the simulated TMIC signals in real scale [6, 7]. Using that actual current signals, the performance of IEC 61850 based IEDs which have the proposed algorithm is verified in real-time. The connection of communication between the IEDs is also necessary for the GOOSE transmissions based on the IEC 61850 network.

The reactions of simulated power system responding to the operation of IEDs can be confirmed, because that components of the test-bed are composed of the closed-loop system. When the 50/51 IED operates caused by the TMIC generated by the RTDS, the 50/51 IED sent out a digital output signal to the RTDS. The digital signal can decide to the operation of primary circuit breaker in the simulated power system using the RTDS.

Fig. 3 represents the RTDS test-bed composition. The detailed explanation of each parts in Fig. 3 is as follows.

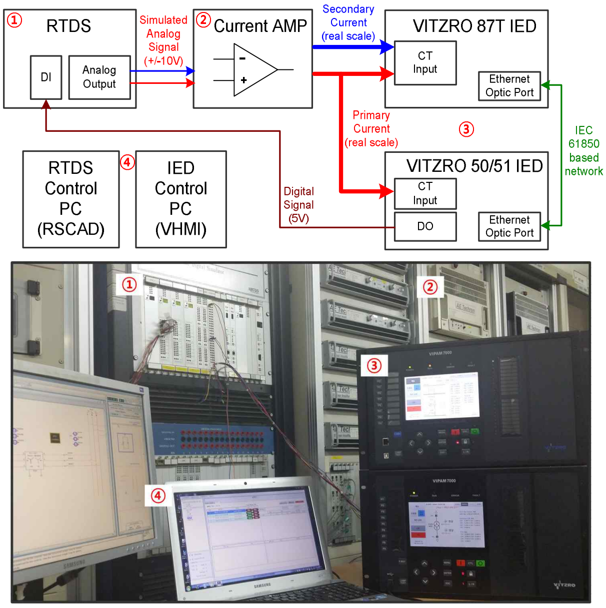


Fig. 3. RTDS test composition

3.1 RTDS (REAL TIME DIGITAL SIMULATOR)

The RTDS is a power system simulator that solves electromagnetic transient simulations in real time. To simulate the transient characteristic (that is, transformer magnetizing inrush current) using the RTDS, a power system has to be modeled by the PC software, RSCAD. The simulated inrush current analog signals out through the analog output channels of the RTDS with a range of ±10 volts. To confirm the reactions of simulated power system responding to the operation of IEDs, a digital input channel of the RTDS is connected to a digital output port of the 50/51 IED with hard-wiring. The digital signal with a range of 5V can decide to the operation of primary circuit breaker in the simulated power system using the RTDS.

3.2 Current AMP(Amplifier)

The current AMPs represented in Fig. 3 are connected to the RTDS analog output channels. The current AMPs amplify the simulated analog signals (a range of ±10 volts) into a maximum range of ±100 Amperes. Therefore, the RTDS generates the transformer magnetizing inrush currents in real scale through the Current AMPs.

3.3 IEC 61850 based VITZROTECH IEDs

Two IEC 61850 based VITZROTECH IEDs are used to verify the proposed method. The 87T IED is VIPAM7000 Transformer protection type which is used for 154kV MTR protection. The 50/51 IED is VIPAM7000 Bay control type which is used for 170kV GIS bay control and protection. Each ethernet optic ports of the IEDs are connected to the IEC 61850 based network, respectively. And the CT terminals of each IEDs are connected to the current AMPs with hard-wiring connection for the real magnetizing inrush current input.

In the case of 87T IED, the CT terminals are connected to the current AMPs with six channels that is, primary currents and secondary currents. Because, the 87T IED performs current differential protection. When the magnetizing inrush current occurs, the 87T IED blocks the trip of current differential protection, and sends out an inrush current blocking GOOSE signal.

On the other hand, the CT terminals of 50/51 IED are connected to the current AMPs with three channels that is, only primary currents. Using the proposed method, the 50/51 IED blocks the over-current protection when the GOOSE interlock signal is received from the 87T IED. A digital output port of the 50/51 IED is connected to a digital input channel of the RTDS for the circuit breaker in the simulated power system.

To confirm the results of tests, each IEDs can print out the fault waves saved as comtrade file format.

3.4 PCs for the control RTDS and IEDs

The PC for RTDS control is used to running the RSCAD software tool. The RSCAD provides a user-friendly interface with the RTDS hardware, and is designed to allow the user to perform all of the necessary steps to prepare and run simulations, and to analyze simulation results. That is, the PC for RTDS control performs such as, modeling of the power system, control and monitoring of the RTDS, and data acquisition.

The PC for IED control is used to running the VHMI software tool. The VHMI is the exclusive software tool to provide a user-friendly interface with the VITZROTECH IEDs. The functions such as, control, monitor, and data handling of the IEDs can be perform using the VHMI.

4. Case Study

The case studies are performed using the RTDS test-bed. To verify the proposed method and confirm the reaction of simulated power system responding to the operation of IEDs, this paper performs two case studies. The first case is a malfunction case of the 50/51 IED which does not use the proposed method. The second case is a normal operation case of the 50/51 IED which uses the proposed method.

Fig. 4 is represents the model system for the simulation of magnetizing inrush current using the RTDS/RSCAD. The model system in Fig. 4 is a simple 154kV power

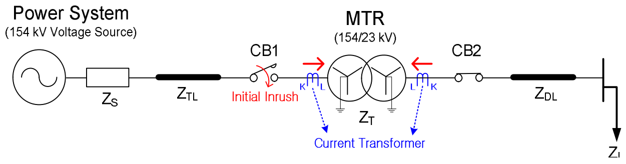


Fig. 4. Model system

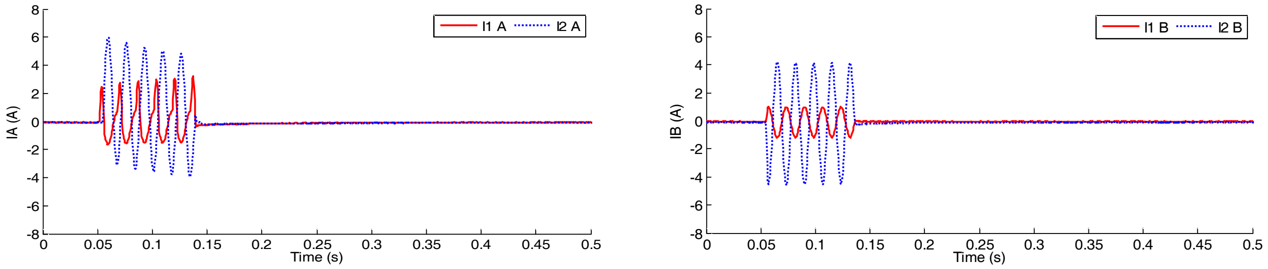
system. The 154kV ideal voltage source supplies power to the 23kV load, through the 154/23kV transformer that the winding connection is Y-Y. In that modeling, the transformer module considers the feature of magnetizing saturation for the generation of inrush current.

Table 1 is represents the specific data of simulated model system. The load current of that model system is about 0.7A(154kV side) and 2.52A(23kV side). Those results are calculated by the Eq. (1) which does not include the impedances of source, transformer, and lines.

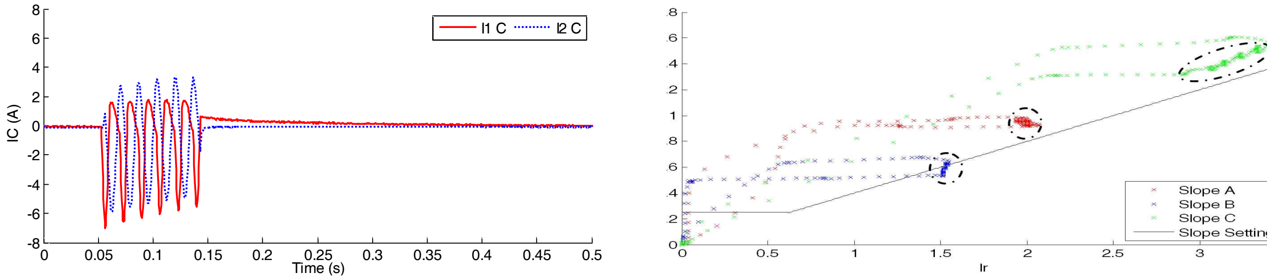
$$I_{load} = \frac{S_{3\phi\, load}}{\sqrt{3\times V_{ll}\times PF}}\times\frac{CT_{2nd}}{CT_{1st}} \qquad (1)$$

Table 1. Specific data of the model system

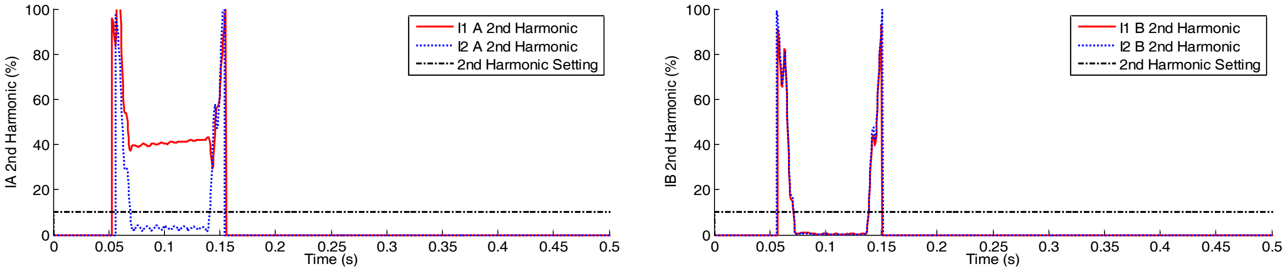
Item	Data		Note
Source (154kV)	$R1_S+jX1_S$	0.043%+j0.268%	%Z 100MVA Base
	$R0_S+jX0_S$	0.077%+j0.078%	
Transmission Line(154kV)	$R1_{TL}+jX1_{TL}$	0.23%+j1.818%	
	$R0_{TL}+jX0_{TL}$	1.257 %+j5.509 %	
Transformer (154/23kV)	Z_T	j32.43%	
Current Transformer	Primary	1200/5 A	-
	Secondary	2000/5 A	
Distribution Line(23kV)	$R1_{DL}+jX1_{DL}$	10.41%+j22.38%	%Z 100MVA Base
	$R0_{DL}+jX0_{DL}$	35.97 %+j87.78 %	
Load(23kV)	Z_L	40MVA, P.F=0.9	-



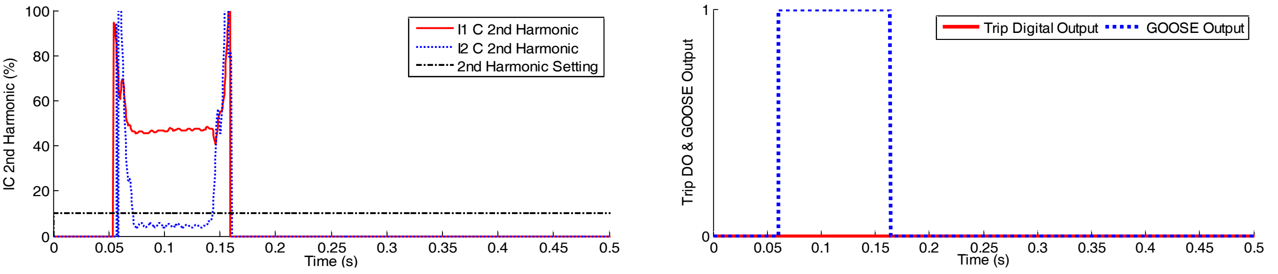
(a) Primary and secondary A-phase currents (b) Primary and secondary B-phase currents



(c) Primary and secondary C-phase currents (d) Calculated ratios of the differential protection



(e) 2nd harmonics of the A-phase currents (f) 2nd harmonics of the B-phase currents



(g) 2nd harmonics of the C-phase currents (h) Trip DO & GOOSE output

Fig. 5. Case 1 result of 87T IED

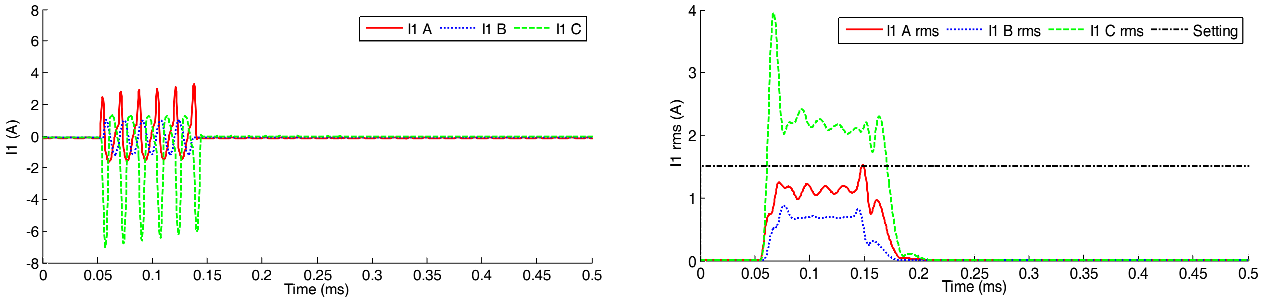
where, $\boldsymbol{S}_{3\varphi load}$ is a three phase complex power, $\boldsymbol{V}_{ll}$ is a line voltage, $\boldsymbol{PF}$ is a power factor, and $\boldsymbol{CT}_{1st}$ and $\boldsymbol{CT}_{2nd}$ are the current transformer ratios of primary and secondary, respectively.

4.1 Case 1: Malfunction case

Case 1 is the results of malfunction case, because the 50/51 IED does not use the proposed method. The initial transformer magnetizing inrush currents at the moment of transformer pressurization are simulated by the RTDS model system. Using the actual currents generated by current AMPs, the performance of conventional IED which does not use the proposed algorithm is verified in real-time. The reactions of simulated power system responding to the operation of IEDs are also confirmed. Figs. 5 and 6 are the test results of 87T IED operation and 51 IED operation, respectively. Also, Fig. 6 includes the result that reaction of RTDS responding to the operation of IEDs.

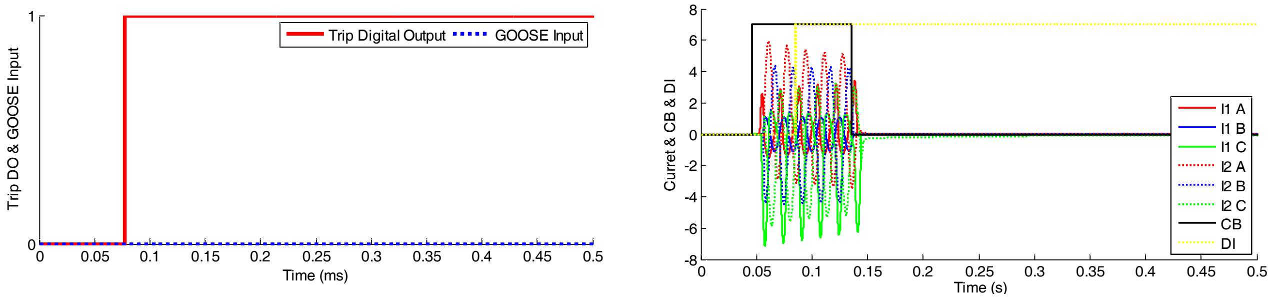
Figs. 5(a)-(c) are the current waves of case 1 which printed out from the 87T IED. In Fig. 5, (a) is A-phase current, (b) is B-phase current, and (c) is C-phase current. Also, the red solid line represents primary current and the blue dotted line represents secondary current, respectively. The magnetizing inrush currents flow to the A-phase and C-phase primary current. Fig. 5(d) represents the calculated slope of differential current protection using the waves which are printed out from 87T IED. In Fig. 5(d), the points are represent the calculated ratios which are the differential currents(Id) over the restriction currents(Ir) using all samples. The red point is A-phase, the blue point is B-phase, and the green point is C-phase, respectively. The black line represents the setting value of 87T slope. The black short dash circle lines indicate the pseudo steady states of each currents after the transient states. The ratios of A-phase and C-phase exceed the setting value exactly caused by the inrush current. Figs. 5(e)-(g) are the second harmonic component of each phase currents. In Fig. 5, (e) is A-phase current, (f) is B-phase current, and (g) is C-phase current. Also, the red solid line represents primary current, the blue dotted line represents secondary current, and the black short dash line represents the setting value of inrush blocking, respectively. The primary second harmonic components of A-phase and C-phase exceed the setting value exactly. Fig. 5(h) represents the trip and the GOOSE output bit of 87T IED. The red solid line is trip digital output, and the blue dotted line is GOOSE output bit. In case 1, the result of 87T IED performance test is as follow. The ratios of A-phase and C-phase exceed the setting value exactly caused by the TMIC. However, the trip of all phase is blocked by the second harmonic detection, and the 87T IED sent out an inrush current blocking GOOSE signal.

Fig. 6(a) is current waves of case 1 which printed out from the conventional 50/51 IED, and Fig. 6(b) is calculated RMS values of three phase current using the waves data. In Figs. 6(a) and (b), the red solid line is A-phase, the blue dotted line is B-phase, the green broken line is C-phase, respectively. The black short dash line in Fig. 6(b) represents the setting value of over-current protection. The over-current of C-phase exceeds the setting value caused by the magnetizing inrush current. Fig. 6(c)



(a) 3-phase currents of 50/51 IED

(b) 3-phase RMS currents of 50/51 IED



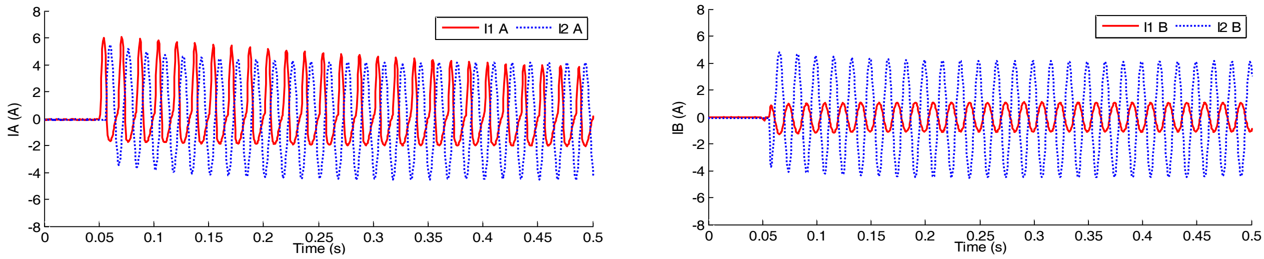
(c) Trip DO & GOOSE input of 50/51 IED

(d) Data of RTDS

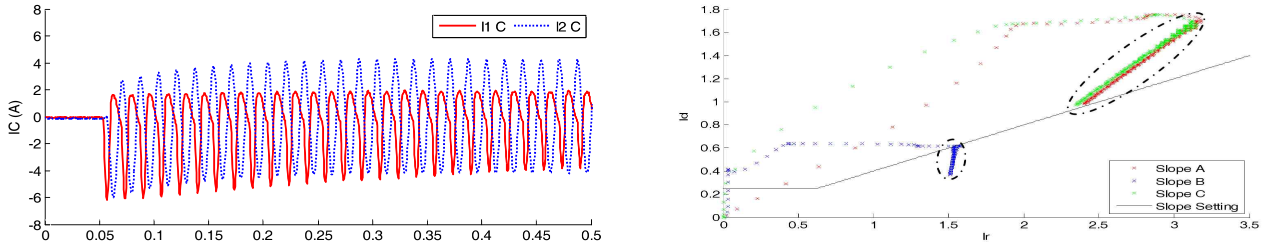
Fig. 6. Case 1 result of 51 IED and RTDS reaction

represents a malfunction test result of the conventional 50/51 IED. In Fig. 6(c), the red solid line is a trip digital output, and the blue dotted line is a GOOSE input signal. In case of the case 1, the result of conventional 50/51 IED performance test is as follow. The over-current of C-phase exceeds the setting value caused by TMIC. The inrush current blocking GOOSE signal is not detected, because the conventional 50/51 IED does not use the proposed method. Therefore, the trip digital output is sent out, even though the transient TMIC is not a fault of power system.

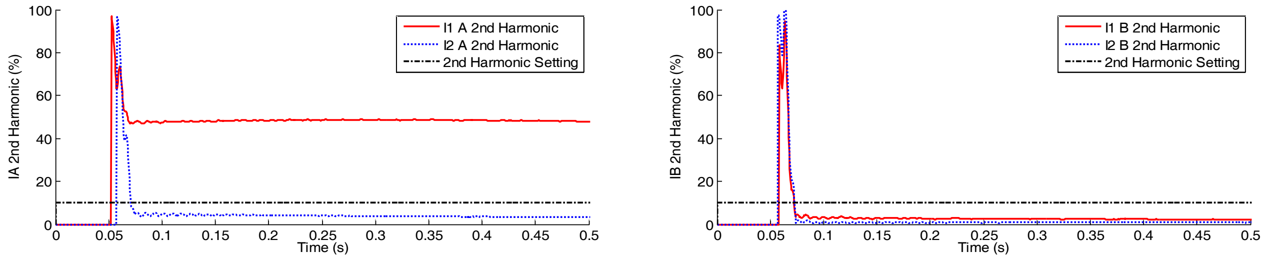
Fig. 6(d) is waves of case 1 which printed out from the RTDS. In Fig. 6(d), the sine waves represented by solid lines are the primary currents, and the sine waves represented by dotted lines are the secondary currents. Also, the red line is A-phase, the blue line is B-phase, the green line is C-phase, respectively. The black solid line is the status of circuit breaker modeled by the RTDS, and the yellow dotted line is a digital input signal transmitted from the 50/51 IED. Using the data of Fig. 6(d), the reactions of simulated power system responding to the operation of conventional IED can be confirmed. In case of the case 1, the result of power system reaction is as follow. The circuit breaker was closed at about 0.05s, so that the TMICs were occurred. After then, the circuit breaker was opened, cause of the digital input signal transmitted from the 50/51 IED, even though the transient TMIC is not a fault of power system. The circuit breaker reaction time of power system was modeled to 0.05s.



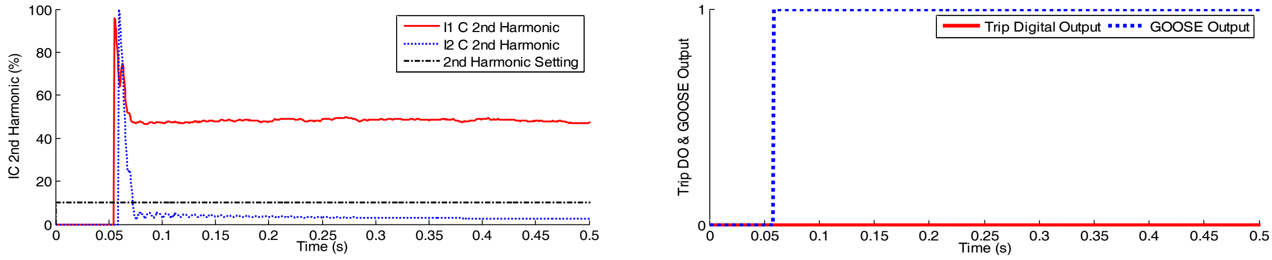
(a) Primary and secondary A-phase currents (b) Primary and secondary B-phase currents



(c) Primary and secondary C-phase currents (d) Calculated ratios of the differential protection



(e) 2nd harmonics of the A-phase currents (f) 2nd harmonics of the B-phase currents



(g) 2nd harmonics of the C-phase currents (h) Trip DO & GOOSE output

Fig. 7. Case 2 result of 87T IED

4.2 Case 2: Normal operation case

Case 2 is the results of normal operation case using the proposed method. The 50/51 IED and 87T IED are connected by the IEC 61850 based network, and the magnitudes of TMIC may be different from case 1 slightly. Other conditions of test-bed equal to the case 1. Figs. 7 and Fig. 8 are the test results of 87T IED operation and 51 IED operation, respectively. Also, Fig. 8 includes the result that reaction of RTDS responding to the operation of IEDs.

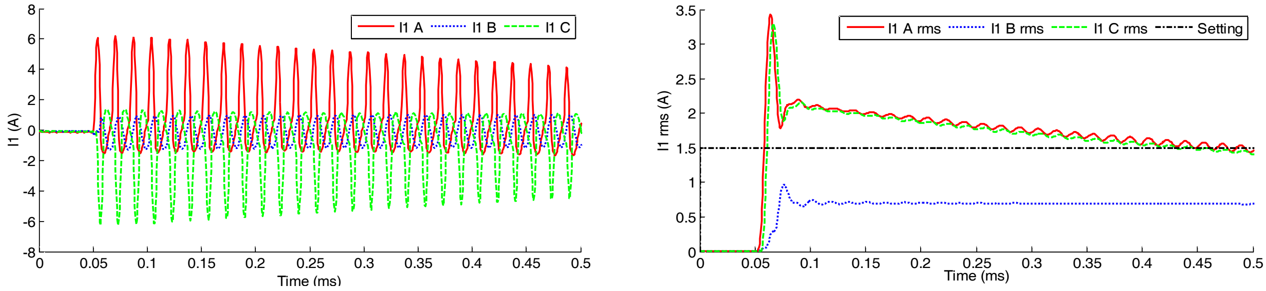
Figs. 7(a)-(c) are the current waves of case 2 which printed out from the 87T IED. The magnetizing inrush currents flow to the A-phase and C-phase primary current. Fig. 7(d) represents the calculated slope of differential current protection. The yellow dotted circle lines indicate the pseudo steady states of each currents after the transient states. The ratios of A-phase and C-phase exceed the setting value exactly caused by the inrush current. The ratios of all phase have been smaller under the setting value as time passes. Figs. 7(e)-(g) are the second harmonic component of each phase currents. The primary second harmonic components of A-phase and C-phase exceed the setting value exactly. Fig. 7(h) represents the trip and the GOOSE output bit of 87T IED. The red solid line is trip digital output, and the blue dotted line is GOOSE output bit. In case 2, the result of 87T IED performance test is same as case 1. The ratios of A-phase and C-phase exceed the setting value exactly caused by the TMIC. However, the trip of all phase is blocked by the second harmonic detection, and the 87T IED sent out an inrush current blocking GOOSE signal.

Fig. 8(a) is current waves of case 2 which printed out from the 50/51 IED using the proposed method, and Fig. 8(b) is calculated RMS values of three phase current. The over-currents of A-phase and C-phase exceed the setting value caused by the magnetizing inrush current. The currents of all phase have been smaller under the setting value as time passes. Fig. 8(c) represents a normal operation test result of the 50/51 IED using the proposed method. The over-currents of A-phase and C-phase exceed the setting value caused by TMIC. However, the trip of 50/51 IED was blocked by the inrush current blocking GOOSE signal received from 87T IED at about 0.07s. Therefore, the trip digital output does not generated.

Fig. 8(d) is waves of case 2 which printed out from the RTDS. Using the data of RTDS, the reactions of simulated power system responding to the operation of proposed method can be confirmed. In case of the case 2, the result of power system reaction is as follow. The circuit breaker was closed at about 0.05s, so that the TMICs were occurred. The circuit breaker dose not be opened normally, because the transient TMIC is not a fault of power system. After just a few seconds, the power system has been recovered into the steady state.

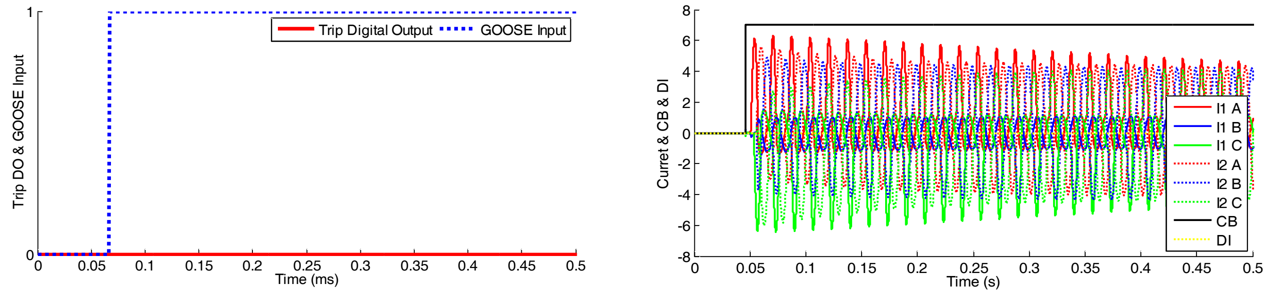
5. Conclusion

This paper proposes a novel method to prevent the malfunction caused by the transformer magnetizing inrush current using the data sharing between the IEDs. Also, the real time test using the RTDS test-bed is performed to



(a) 3-phase currents of 50/51 IED

(b) 3-phase RMS currents of 50/51 IED



(c) Trip DO & GOOSE input of 50/51 IED

(d) Data of RTDS

Fig. 8. Case 2 result of 51 IED and RTDS reaction Fig.

verify the dynamic performance of proposed method.

Using the RTDS, the power system transients are simulated, and the transformer magnetizing inrush current is generated. When the TMIC occurs, the 87T IED sends out a magnetizing inrush block GOOSE to the 50/51 IED through IEC 61850 based network. The 51 IED prevents the malfunction caused by magnetizing inrush current using that received GOOSE interlock signal.

To verify the proposed method and confirm the reaction of simulated power system responding to the operation of IEDs, this paper performs two case studies. In case that the proposed method is not used, the conventional 50/51 IED malfunctions. On the other hand, the 50/51 IED which uses the proposed method operates normally.

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