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Adaptive undervoltage protection scheme for safety bus in nuclear power plants

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ABSTRACT

In the event of a short-circuit accident on a 4.16 kV non-safety bus, the voltage is temporarily lowered as backflow occurs on the safety bus. In such cases, the undervoltage relay of the safety bus shall not pick up the undervoltage so as not to interfere with the operation of the safety motors. The aim of this study is to develop an adaptive undervoltage protection scheme for the 4.16 kV safety bus considering the faults on the 13.8 kV and 4.16 kV non-safety buses connected to secondary windings of the three winding transformers, UAT and SAT. The result of this study will be the adaptive undervoltage protection scheme for the safety bus of nuclear power plants satisfying functional requirements of the safety related medium voltage motors. The adaptive undervoltage protection scheme can be implemented into an integrated digital protective relay to make user friendly and reliable protection scheme.

1. Introduction

Redundant power from offsite and standby onsite power shall be provided to maintain the functioning of structures, systems, and components important to safety in nuclear power plants. A 4.16 kV medium voltage (MV) safety bus receives power from one of two independent transmission lines via the three winding transformers, unit auxiliary transformer(UAT) or standby auxiliary transformer(SAT). In addition, an emergency diesel generator is connected to the 4.16 kV safety bus for the supply of power when there is loss of offsite power (LOOP). The transfer from the offsite power to onsite standby power is made by undervoltage (UV) relays and a dedicated control scheme.

Detail protection requirements of safety equipment classified as Class 1E equipment are provided by IEEE Std-741, “Standard criteria for the protection of Class 1E power systems and equipment in nuclear power generating stations”. It is recommended that two levels of undervoltage detection and protection be provided on the Class 1E electrical distribution system. The first level of undervoltage protection is provided by the loss of voltage relays of which function is to detect the electric power outage and disconnect the Class 1E buses from the normal power of the offsite power line. The second level of undervoltage protection is provided by the degraded voltage relays that are set to detect a low-voltage condition.

Each protection scheme shall monitor all three phases. Single phasing condition shall not cause incorrect operation nor prevent correct operation. The selection of undervoltage and time delay set points shall be determined from an analysis of the voltage requirements of the Class 1E loads at all on-site distribution levels. Another challenge of this study is that the Class 1E switchgear bus receives power from the same transformer with the Non-1E bus.

When transferring from normal power to alternate or emergency power, the undervoltage protection scheme should be used. As shown in Fig. 1, the 4.16 kV Class 1E bus and the 4.16 kV Non-1E bus receive power from the same UAT and SAT, so the short circuit fault of neighboring bus affects other bus. In the event of a short-circuit accident on a 13.8 kV or 4.16 kV non-safety bus, the voltage is temporarily lowered as backflow occurs on the safety bus. In such cases, the pickup of the undervoltage relay of the safety bus shall be delayed so as not to interfere with the operation of the safety motors.

The aim of this study is to develop an adaptive undervoltage protection scheme for the 4.16 kV safety bus considering the faults on the 13.8 kV or 4.16 kV non-safety buses connected to the secondary windings of the same transformers of UAT and SAT. Assuming a multifunctional digital relay is included in the electric power bus system, we used ETAP software for circuit analysis. With the result in this study, we propose an adaptive undervoltage

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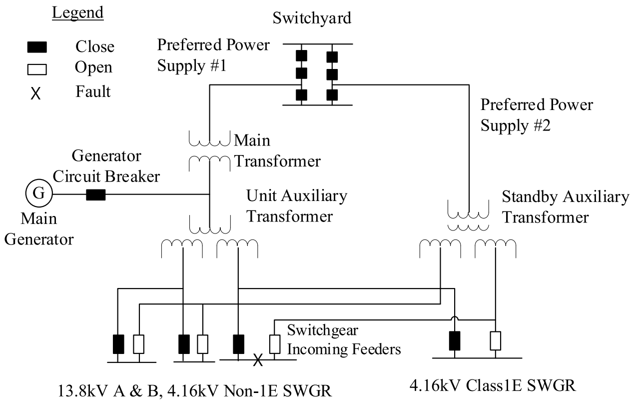

Fig. 1. Conceptual diagram of electric power system of a nuclear power plant.

protection logic for the safety bus of nuclear power plants satisfying functional requirements of the safety related medium voltage motors. The adaptive undervoltage protection scheme can be implemented into an integrated digital protective relay to make a user friendly and reliable protection scheme.

2. Safety bus undervoltage detection scheme

2.1. Basis for undervoltage protection

BTP PSB-1 requires two time delays for the degraded voltage relay [1]. The first time delay is of a duration that establishes the existence of a sustained degraded voltage condition that is something longer than a motor starting transient. Following this delay, an alarm in the main control room should alert the operator to restore the degraded condition. The second time delay is of a limited duration such that the running Class 1E loads will not be damaged. Following this delay, if the operator has failed to restore adequate voltages, the Class 1E bus should be automatically disconnected from the offsite power system. Basis and justification must be provided in support of the actual delay chosen. Time delay shall override the effect of expected short duration grid disturbances, preserving availability of the offsite power source(s) [2].

2.2. Undervoltage relay setting criteria

The setpoint shall be established with sufficient margin between the nominal setpoint and plant technical specification limits for the process variables. This will allow for relay inaccuracy, uncertainties in calibration, and setpoint drift that may occur during the interval between each [3]. The criteria for the degraded voltage and undervoltage protection shall be as follows:

1) Medium voltage buses supplying unit substation transformers should have a minimum voltage of 93% of bus rated voltage to allow for the voltage drop in the unit substation transformer and still maintain 90% of bus rated voltage at the 480V switchgear buses.
2) The minimum acceptable voltage during motor starting is 80% of motor rated voltage
3) When medium voltage safety-related motors are started from the emergency diesel generator (EDG), the starting voltage is allowed by Regulatory Guide 1.9 to dip to 78% of motor rated voltage (75% of EDG rated voltage). For the same reason, it is recommended that a 75% starting voltage be specified for 460V safety-related motors.

2.3. Undervoltage relay design and protection scheme for safety buses in a nuclear power plant

There are four (4) redundant undervoltage relays in the 4.16 kV safety (Class 1E) bus. An undervoltage relay is set to two (2) voltage levels, one is for degraded voltage and the other one is for a loss of voltage. The degraded voltage element is set to about 95% of bus nominal voltage, and the time delay is 4 min. Loss of voltage element is set to 70% of motor terminal voltage, and it's a definite time delay is 1.0 s. Coincidence logic is used to minimize false operation of undervoltage relays [2]. Two (2) out of four (4) voting logic is preferred as shown in Fig. 2.

If the degraded voltage does not recover for four (4) minutes, the safety bus is disconnected from the offsite power and at the same time emergency diesel generator is started. When loss of voltage is detected, immediately, within 1 s, the safety bus is disconnected from the off-site power and at the same time the emergency diesel generator is started.

3. Temporary voltage drops due to short circuit fault on non-safety buses

3.1. Review of overcurrent relay coordination in the non-safety bus

In Fig. 1, the 3 winding UAT feeds power to Non-1E 13.8 kV and Non-1E 4.16 kV switchgears and Class 1E 4.16 kV switchgear.

A 3-phase short circuit fault on the Non-1E switchgear bus will result in a voltage drop across both the Non-1E and Class 1E switchgear buses. Fig. 3 shows the overcurrent relay setting and coordination curves for a Non-1E 4.16 kV switchgear. The 3 phase fault on the switchgear bus is cleared by the incoming feeder breaker relay in 450–500 ms after the fault and the 3 phase fault on the branch feeder close to a switchgear bus is cleared by the branch feeder breaker relay in100~150 ms after the fault. Total fault clearing time includes relay detection and circuit breaker operation time.

As it is shown in Fig. 4, the motor is *decelerated* after fault and accelerates again after short circuit fault is cleared in the Non-1E switchgear.

3.2. Impact on the safety bus by non-safety bus fault

The induction motor torque is proportional to the square of the motor terminal voltage. This means that the voltage drop results in reduced motor torque, reduced motor speed, increased slip and increased motor current [4]. Fig. 5 shows the effect on the safety motors connected to the Class 1E switchgear bus when a short

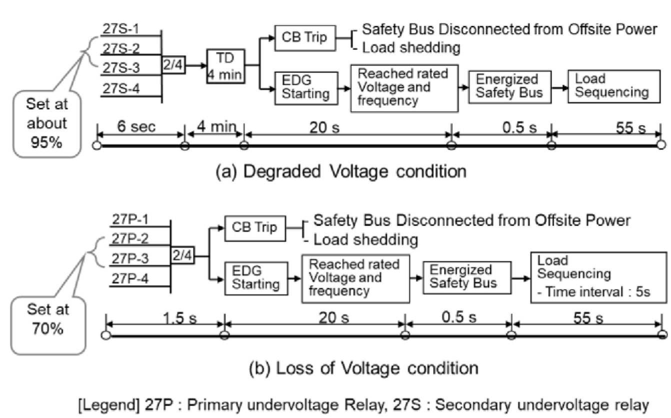

Fig. 2. Undervoltage relay protection scheme.

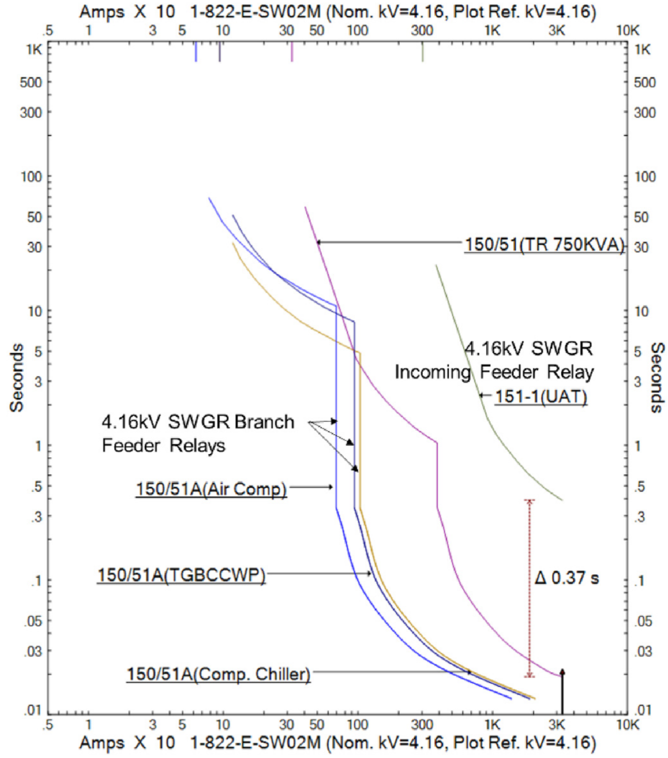

Fig. 3. 4.16 kV SWGR bus short circuit protection coordination curves.

circuit fault occurs in any motor connected to the Non- 1E switchgear bus. The instantaneous overcurrent relay of the faulted motor opens the circuit breaker within 131 ms.

On the other hand, if the short circuit fault occurs on the Non-1E switchgear bus, the voltage quickly decreases, and the Class 1E switchgear bus voltage also drops and motors decelerate until the fault is cleared. Clearing time of the bus fault is longer than the fault on the motor due to the relay coordination between down and upstream relays.

It is desirable to delay the pickup time of the undervoltage relay of the Class 1E bus by the time required to clear the short circuit fault on the Non-1E bus for the security of the undervoltage relay. The undervoltage protection with a shorter time delay to prevent the tripping of all critical and voltage-sensitive loads is required. The longer time delay setting of undervoltage relays can cause more loads to trip if the system faults are severe enough and last longer [5]. In the current system, the undervoltage relay is set to 70% of the motor rated voltage, and the time delay is 1.0 s. A time-delay relay is also used to enable it to override momentary sags and thus prevent nuisance operation [6]. The challenge is, Class 1E motors will trip by overcurrent due to very high re-acceleration currents and long duration, if the Non-1E bus fault condition continues for 461 ms as shown in Fig. 6, nonetheless the undervoltage voltage relay delay time is 1.0 s.

Therefore, in this paper, we propose an adaptive low-voltage protection scheme using the control logic shown in Fig. 7. A zone selection interlock (ZSI) is employed for bus fault detection and also uses the ZSI signal to make an adaptive undervoltage protection scheme. ZSI is based on currents comparison between protective zones. It has a communication control logic system between downstream and upstream breakers. The IEC61850 GOOSE based ZSI scheme always concern about blocking time. It is used to improve the level of protection in the electrical protection power system, through communication between protective relays across the protected zones to reduce the fault clearing time [7].

4. Adaptive undervoltage protection scheme for safety bus

An adaptive protection system is defined as the system that automatically changes the protection parameters corresponding to the variation of the system state to provide the reliable relay of protection device [7]. Nowadays digital protective relays are used in the newly constructed nuclear power plants. Existing nuclear power plants are also replacing analog relays with digital relays steadily. Most of digital relays support the standardized substation communication protocol, which means they are ready for GOOSE implementation. By using GOOSE communication, the digital relays can share their status data between each other and their fast operating time would provide adaptive protection to reduce surplus delay time.

4.1. Control logic and scenarios for adaptive undervoltage protection

When an undervoltage relay detects voltage loss from two out of four logic and sends a low-voltage signal to the adaptive undervoltage protection logic shown in Fig. 7, it collects overcurrent trip signals from the Non-1E switch gear branch circuit and incoming circuit protective relays. Then, the output of the control logic is sent to the circuit breakers of the Class 1E switchgear as follows:

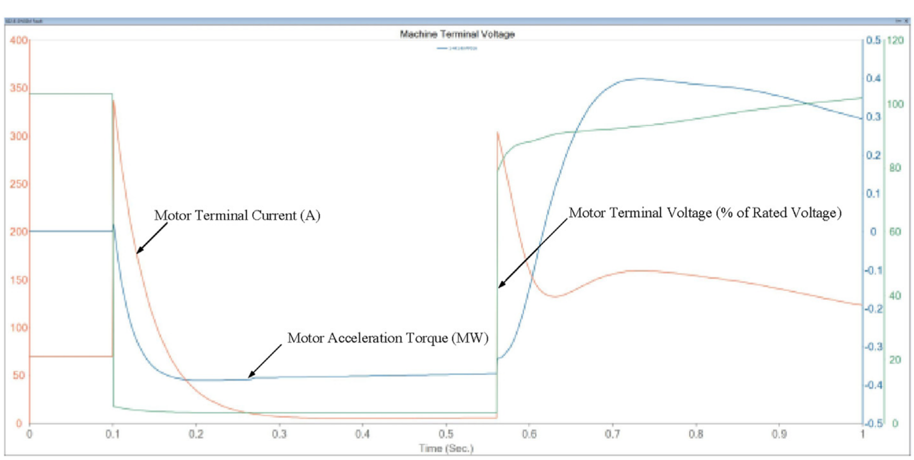

Fig. 4. Transient voltage recovery after 3 phase fault at Non-1E 4.16 kV switchgear bus.

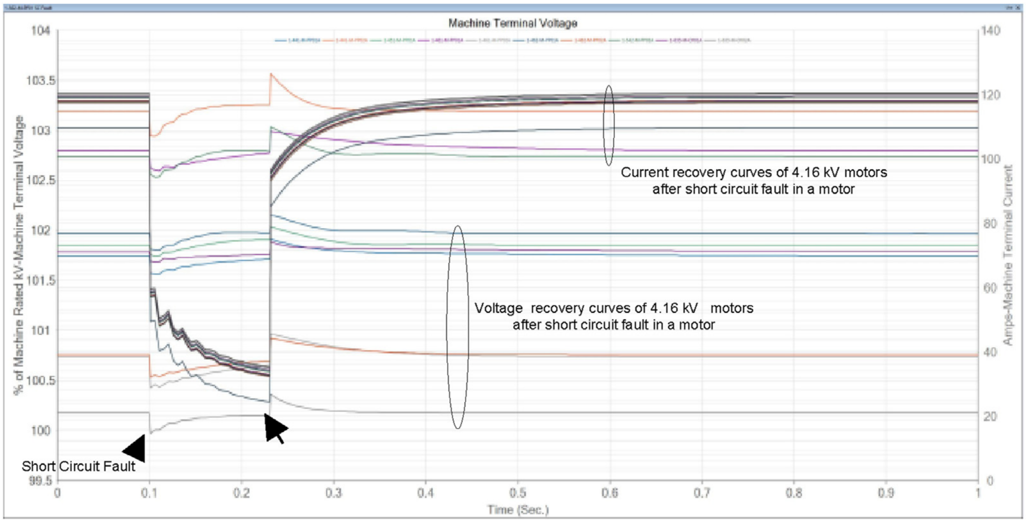

Fig. 5. Voltage and current curves of safety motors during short circuit fault on Non-1E motor.

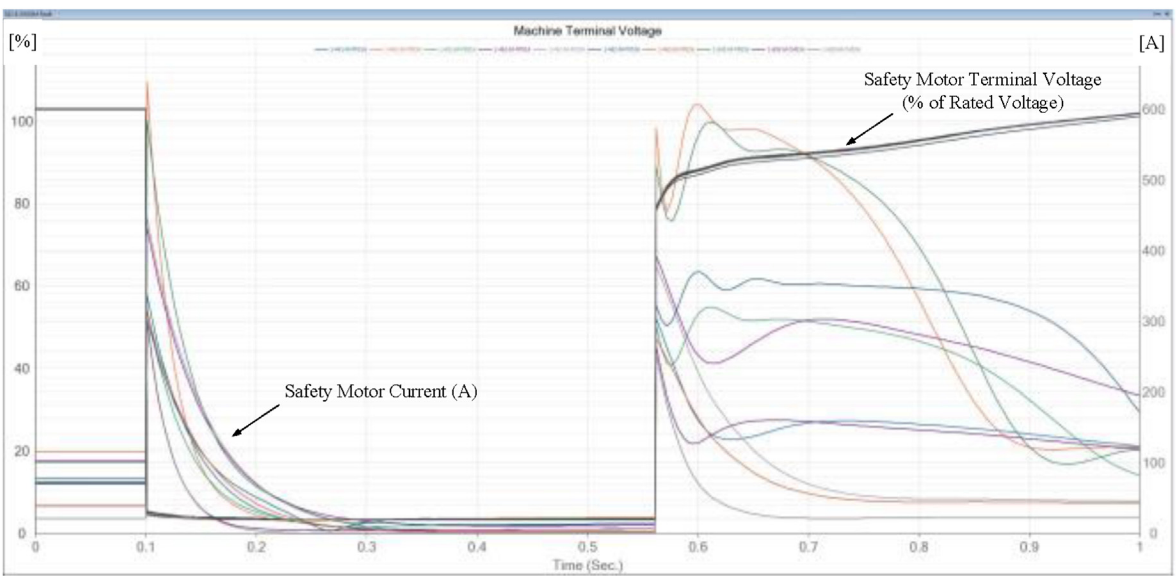

Fig. 6. Voltage and current curves for the safety motors during short circuit fault at the Non-1E Bus (Non-1E bus fault is cleared 461 ms after fault).

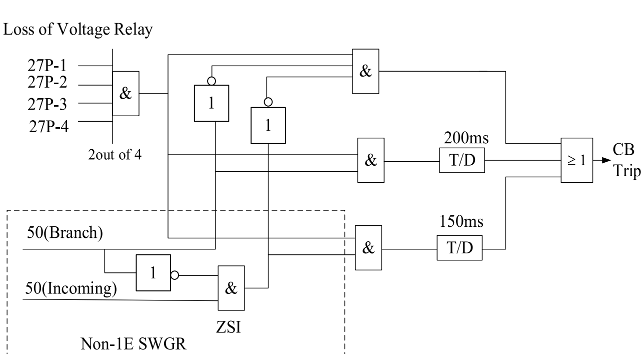

Fig. 7. Control logic of adaptive undervoltage relay.

1) No short circuit fault in the non-safety switchgear; No information is received from the overcurrent relays and the logic shown in Fig. 7 outputs a trip signal to the circuit without time delay.
2) Short circuit fault in the branch feeder of non-safety switchgear; By combination of undervoltage signal and short circuit signal (50 of Branch feeder) the control logic makes a circuit breaker trip signal with 200 ms time delay.
3) Short circuit fault in the incoming feeder of non-safety switchgear; By combination of undervoltage signal and short circuit signal (50 of Incoming feeder) the control logic makes a circuit breaker trip signal with 150 ms time delay.

4.2. GOOSE communication between protective relays

In the IEC61850 standard, five types of communication profiles are defined: the abstract communication service interface profile (ACSI), the generic object oriented substation event profile (GOOSE), the generic substation status event profile (GSSE), the sampled

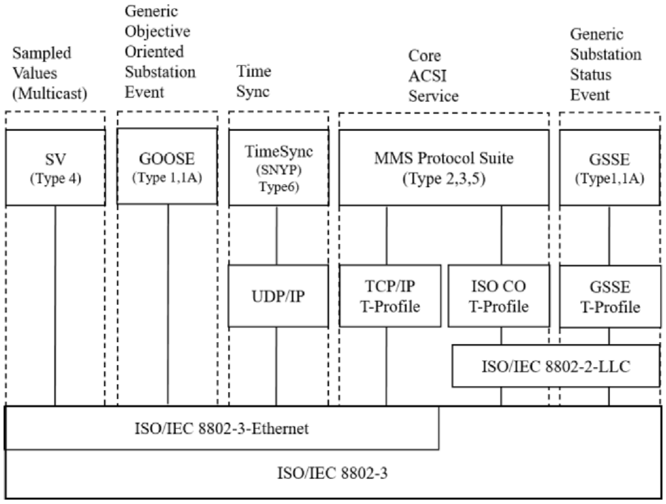

Fig. 8. IEC61850 Communication mapping.

measured value multicast profile (SMV), and the time synchronization profile. ACSI services enable client-server style interaction between applications and servers. GOOSE provides a fast data exchange method on substation buses and GSSE provides a quick data exchange method on substation level. Sample measured value multicast provides an effective way to exchange data on a process bus [8]. Communication mapping diagram is shown in Fig. 8.

IEC61850-5 classifies application types based on the speed of message to be transmitted between networked intelligent electronic device(IED). The standard also specifies the performance of each type of application that was named according to the time duration of message transmission [9]. Message performance is divided into two groups. One is control and protection and the other is instrumentation and power quality applications. Table 1 lists the message type, applications and requirement of transfer time. The generic object oriented substation event is defined in the IEC61850 part 7-1. This message is classified within type1 performance that means high-speed message to deliver status and event changes. Among these classified messages is Type 1-A, which is mission-critical, requiring less than 4 ms end-to-end (ETE) latency [9].

GOOSE supports the exchange of a wide range of possible common data organized by a data-set. GOOSE messages are used to replace the hard wired control signal exchange between IEDs for interlocking, protection purposes, sensitive missions, time critical and high reliability [10].

4.3. Coordination between IEDs and message transfer time

Fig. 9 shows the key single line diagram of the 4.16 kV medium voltage switchgears (SWGR) in a nuclear power plant. All protective relays are digital integrated relays. Relays are indicated by ANSI device number.

The short-circuit overcurrent relay (IED1) in the Non-1E 4.16 kV SWGR bus sends a fault signal to the undervoltage relay (IED2) in the Class 1E 4.16 kV SWGR bus. The control logic of adaptive undervoltage relay in the Class 1E bus receives the fault signal and determine delay time by the control logic shown in Fig. 6. After a delay time, it outputs trip signal to the circuit breakers of the Class 1E SWGR.

According to the definition of transmission latency in IEC 61850-5, the whole information transmission process includes the transmission latency on the link and the processing latency at the sending and receiving ends as shown in Fig. 10 [11].

Table 1
Message type and performance classes.

Message Type	Performance Class	Application	GOOSE Transmission
1A	Fast (Trip) Message	P1	10 ms
		P2/P3	3 ms
1B	Fast (Other) Messages	P1	100 ms
		P2/p3	20 ms
2	Medium Speed		100 ms
3	Low Speed		500 ms
4	Raw Data	P1	10 ms
		P2/P3	3 ms
5	File Transfer		≥1000 ms
6	Time Synchronization	T1(time)	±1(Accuracy)
		T2(time)	±0.1(Accuracy)

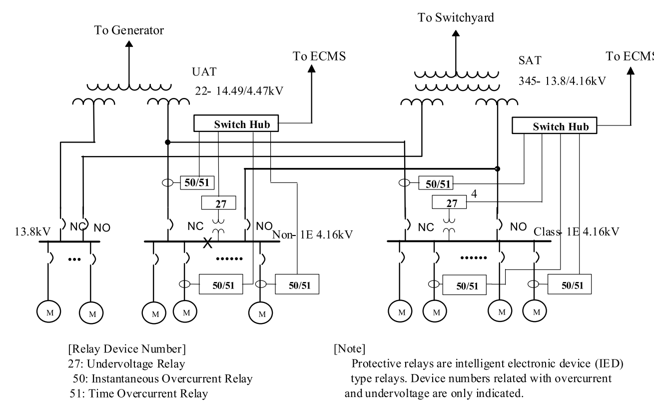

Fig. 9. GOOSE communication architecture.

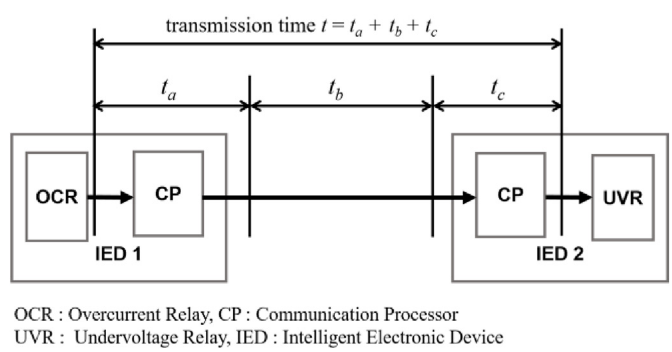

Fig. 10. IEC 61850 definition of message transmission time.

Table 2
Comparison of undervoltage relay delay time.

Types of Fault at Non-1E 4.16 kV Bus	Existing UVR	Adaptive UVR
No short circuit fault	-	-
Short Circuit fault at branch feeder	1 s	200 ms
Fault on the bus	1 s	150 ms

Wherein, t_a is the internal processing time of the sender (IED 1), including the delay of packet segment, encapsulation and queuing time to arrive to the GOOSE process transmitter in the sender. The t_b is the network transmission time, including the delay through each node (switches, routers, etc.) and its corresponding communications link. The t_c is the internal processing time of the receiver (IED 2), including the whole time of message parsing, data assembly connection, arrival notification of GOOSE message and data replication to GOOSE applications in the GOOSE message receiver [12].

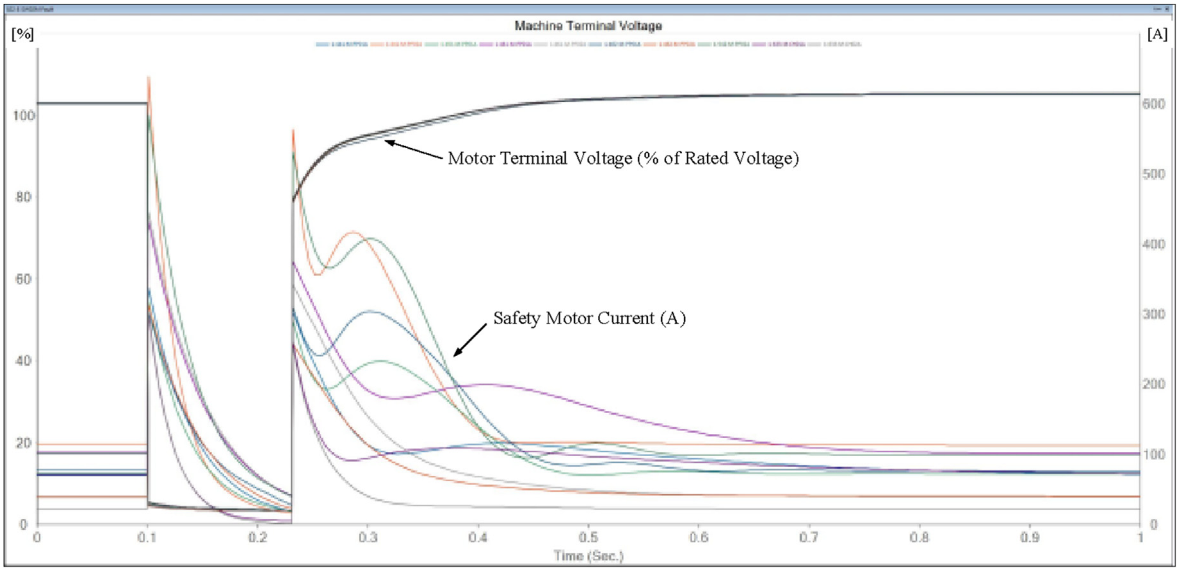

Fig. 11. Voltage and current curves for the safety motors during short circuit fault at the Non-1E Bus (Non-1E bus fault is cleared 131 ms after fault).

According to Ref. [11], the maximum transmission latency between IEDs measured was less than l0ms, which satisfies the specification in Table 1.

5. Results and discussions

In principle, an undervoltage relay must not pick-up a fault if the undervoltage is caused by the short circuit on the other switchgear bus connected to the same transformer. Until clearing short circuit fault, undervoltage relay trip is delayed. In the existing medium voltage system, loss of voltage fault trip delay time is one (1) second regardless the type of fault. However, if the voltage loss persists for 1 s, the residual voltage of the 4.16 kV bus rapidly drops, making it impossible to reaccelerate most of the motors [13].

By application of an adaptive undervoltage protection scheme on the 4.16 kV SWGR bus, trip delay time of the undervoltage relay is reduced. In the event of a short circuit fault, an undervoltage voltage relay has the trip delay time specified in Table 2. Table 2 is the comparison of the trip times of the existing undervoltage relays and the adaptive undervoltage relays.

Fig. 11 shows the effect of applying the adaptive undervoltage protection system. The motor voltage momentarily drops below 30%, but returns to the normal voltage after 150 ms, and the re-acceleration current of the motor is also greatly reduced, showing that continuous operation is feasible.

When a loss of voltage on the bus is continued longer than the delay time specified in Table 2, the undervoltage relay switches off circuit breakers. Then, the normal feeder's circuit breaker opening and the standby feeder's circuit breaker closing is made simultaneously by the bus transfer scheme.

Applying zone selective interlocking (ZSI) protection scheme to the 4.16 kV bus short-circuit fault protection, the fault clearing time can be reduced to less than 200 ms. Therefore, if the adaptive undervoltage relay and ZSI are applied together on the 4.16 kV switchgear buses, an optimized undervoltage protection is possible.

6. Conclusions

In the event of a short-circuit fault on a 13.8 kV or 4.16 kV Non-1E bus, the voltage is temporarily lowered as backflow occurs on the safety bus. In such cases, the undervoltage relay of the Class 1E bus shall not pick up the undervoltage so as not to interfere with the operation of the safety motors.

The aim of this study is to develop an adaptive undervoltage protection scheme for the 4.16 kV Class 1E bus to avoid unintended trip by the faults on the Non-1E switchgear buses or feeders. Fig. 7 shows the adaptive undervoltage protection scheme proposed by this paper.

Application of multifunctional digital relay has been assumed. This digital relay supports IEC61850 standard communication protocol. In this study, the transmission time of relay trip data by GOOSE communication was assessed as less than 10 ms. As a result, 150–200 ms optimum trip delay time is provided to the class 1E switchgear bus undervoltage relay. By shortening of the loss of voltage duration, it is possible to reaccelerate the motors before trip.

The result of this study will be applicable to the protection scheme for the safety bus of nuclear power plants to prevent the nuisance trip of the safety related medium voltage motors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] U. S. NRC, NUREG-0800, Appendix 8-A, PBS-1,"Adqueacy of Station Electric Distribution System Voltage, U.S. Nuclear Regulatory Commission, 1981.
[2] U. S. NRC, “Nuclear Regulatory Issue Summary 2011-12 Adequacy of Station Electric Distribution System Voltages.” U.S. Nuclear Regulatory Commission, pp. 1–12.
[3] R.K. Das, A. Julka, Selection of setpoint for the degraded voltage relays at commercial nuclear power plants, in: IEEE Conference On Nuclear Science Symposium And Medical Imaging, 1992, pp. 775–777.
[4] M. Proctor, T. Smith, Application of undervoltage protection to critical motors, in: 2019 IEEE IAS Pulp, Paper And Forest Industries Conference, PPFIC 2019, 2019.

[5] C.S. Chen, Y.D. Lee, C.T. Hsu, H.J. Chuang, Design of undervoltage relay setting for an industrial plant with cogeneration units to enhance power quality of critical loads, IEEE Trans. Ind. Appl. 44 (4) (2008) 1295–1302.

[6] I. The Institute of Electrical and Electronics Engineers, IEEE Std 242 IEEE Recommended Practice For Protection and Coordination Of Industrial And Commercial Power Systems, Institute of Electrical and Electronics Engineers, Inc., 2001.

[7] M.A.M.M. Moustafa, C. koo Chang, Preventing cascading failure of electric power protection systems in nuclear power plant, Nucl. Eng. Technol. 53 (1) (2021) 121–130.

[8] Y. Liang, R.H. Campbell, Understanding and Simulating the IEC 61850 Standard, 2007.

[9] A. Altaher, S. Mocanu, J. Thiriet, Evaluation of time-critical communications for IEC 61850-substation network architecture, in: International Conference Surveillance 8, Jean Mon- net University; Roanne Institute of Technology-; Laboratoired'Analyse des Signaux et Processus Industriels, Oct 2015, Roanne, France. hal-01242297 HAL, 2015, p. 4.

[10] N. Nguyen-Dinh, G.S. Kim, H.H. Lee, A study on GOOSE communication based on IEC 61850 using MMS ease lite, ICCAS 2007 - Int. Conf. Control. Autom. Syst. (2007) 1873–1877.

[11] International Electrotechnical Commission, International Standard IEC 61850 Part 5: Communication Requirements for Functions and Device Models, 2003.

[12] Y. Fan, Q. Wang, H. Peng, S. Lin, K. Fan, Y. Chen, GOOSE over UDP transmission mechanism for real-time data fast transmission in distribution network, in: *2016 7th International Green and Sustainable Computing Conference*, IGSC 2016, 2016.

[13] S. Byun, S. Kim, Motor bus residual voltage characteristics at nuclear power plant, in: Korean Institute of Electrical Engineers 2009 Summer Conference, 2009, pp. 662–663.