PRACTICAL APPLICATIONS FOR THE ESSENTIAL GENERATOR MONITORING AND PROTECTION SYSTEM

Paper No. PCIC-(do not insert number)

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Abstract – This paper is focused on the refurbishment projects for the generator protection and control system in SK energy, which is the largest refining and petrochemical company in South Korea. The paper reviews basic principles for generator protection. It also shares various field experiences and new ideas for the generator monitoring system, and the primary current testing method using a single power source for testing the step-up transformer differential protection relay.

Index Terms – Synchronous Generators, Generator Protection, Generator Monitoring, Step-up Transformer, Primary Current Test, Differential Protection.

I. INTRODUCTION

Synchronous generators are one of the most critical pieces of equipment to ensure the reliability of the power supply. Several industries, like refining and petrochemical companies, have their power plants to avoid unwanted interruptions from commercial plants. Power failure in specific processes like producing sulfur and toxic chemicals could lead to dangerous exposures to toxic substance leaks or explosions. Among the generator auxiliary systems, the protection and Automatic Voltage Regulator(AVR) system are critical to operating the generators reliably without any interruption.

As the generator systems reach the expected lifetime, end-users consider retrofitting them. Replacing from the existing system to the state of the art system is challenging due to system complexity and compatibility, as well as the lack of understanding of generator system requirements. Also, the retrofit project may face abnormal phenomena during the commissioning test. This paper describes the outcomes of a long-term retrofit project for essential generators and provides the methodology and the best practices gained through the field experiences in refining and petrochemical plants.

II. THE FUNDAMENTALS OF GENERATOR PROTECTION

A. Generator Connected to an Infinite Bus

The generator capability curve for a generator connected to an infinite bus is shown in Fig. 1. The vector diagrams of an internal and external generator circuit are also shown in Fig1.

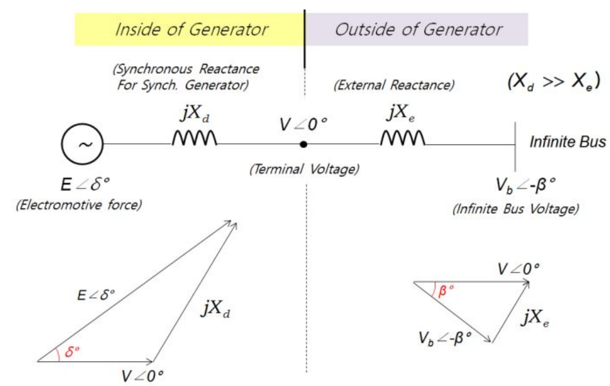


Fig. 1 The Infinite bus and a generator

Typically, the synchronous reactance for the generator is much higher than external reactance. Therefore, it is possible to ignore external reactance shown in Fig. 1.

B. The Voltage Vector Diagram

Fig. 2 shows the voltage vector diagram of the Infinite bus and a generator. If the ratio between internal and external reactance of generators is known, the relations can be represented below.

$$\overline{OA} = \frac{X_d}{X_e}V \tag{1}$$

$$\frac{\overline{OB}}{\overline{OC}} = \frac{X_d}{X_e} = \frac{\frac{X_d}{X_e}V}{V} = \frac{\overline{OA}}{\overline{OO'}} \tag{2}$$

Where
X_d : synchronous reactance, X_e : external reactance.

Therefore, ΔOO'C and ΔOAB are similar triangles. (∠OAB = ∠OO'C=β) When δ+ β=90°, A triangle ΔO'AB is inscribed in the circle. Thus, the electromotive force(E∠δ°) locus is to be a half-circle that the diameter is:

$$\overline{O'A} = \left(1 + \frac{X_d}{X_e}\right)V \quad (3)$$

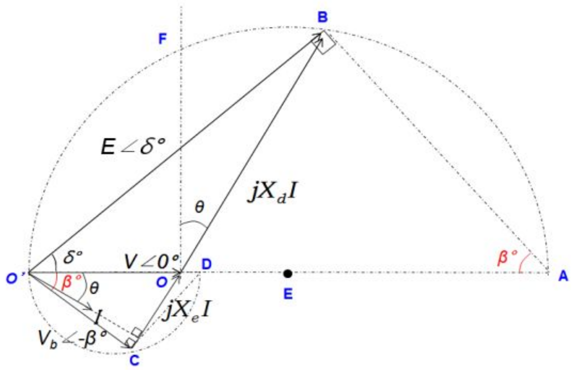


Fig. 2 The voltage vector diagram

C. *Steady-State Stability Limit(SSSL) Curve*

If the voltage vector diagram is multiplied by a current, the Steady State Stability Limit (SSSL) Curve for generators is obtained. Fig. 3 and 4 indicate the SSSL curve.

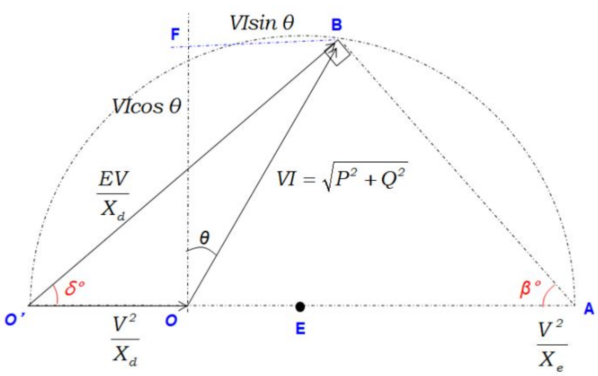


Fig. 3 The Steady-State Stability Limit (SSSL) -1

- Apparent power:

$$\overline{OB} = X_d I \times \frac{V}{X_d} = \sqrt{P^2 + Q^2} \quad (4)$$

- Active power:

$$\overline{OF} = VI\cos\theta = P \quad (5)$$

- Reactive power:

$$\overline{BF} = VI\sin\theta = Q \quad (6)$$

- The diameter of the circle:

$$\overline{O'A} = \frac{V^2}{X_e} + \frac{V^2}{X_d} \quad (7)$$

- The radius of the circle:

$$\frac{\overline{O'A}}{2} = \frac{V^2}{2}\left(\frac{1}{X_e} + \frac{1}{X_d}\right) \quad (8)$$

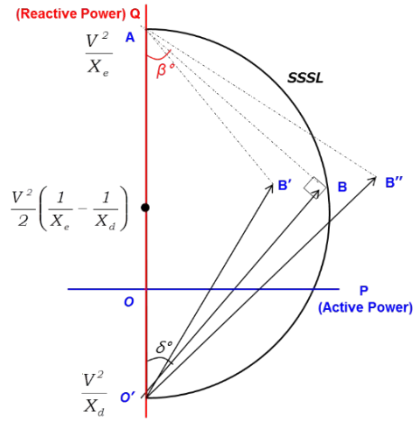


Fig. 4 The Steady-State Stability Limit (SSSL) -2

The generator stability is determined by the power angle (β+δ). Table 1 shows the stability status depending on the power angle in Fig. 4.

TABLE I
POWER ANGLE AND STABILITY OF GENERATOR

Point	Power Angle	State
B	δ + β = 90°	Critically Stable
B′	δ + β < 90°	Stable
B″	δ + β > 90°	Unstable

D. *Generator Capability Curve (GCC) Curve*

The Generator Capability Curve consists of three limits. Fig. 5 shows the Generator Capability Curve and limit curves.

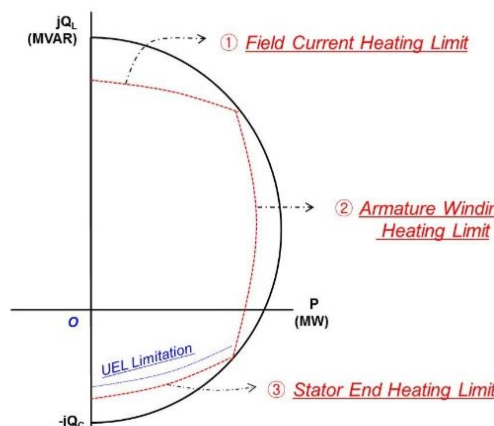


Fig. 5 The Generator Capability Curve

1) *Field Current Heating Limit*: This is an over-excitation condition when the power factor lags. It leads to a high field current, causing the temperature in the field circuit to increase incrementally.

2) *Armature Winding Heating Limit:* The limitation at the rated power factor(lag 0.85~ lead 0.85) is the maximum current that can be carried by the armature without exceeding the heating limitations.

3) *Stator End Heating Limit*: The iron core is saturated by effective flux when the power factor of the generator is lagging; in this case, the leakage flux is very low. But if the generator

operates leading beyond the rated power factor, the leakage flux passes stator endpoint. At this time, the induced electromotive force occurs because the leakage current rotates at the synchronous speed of the rotor. Therefore, the stator endpoint is overheated rapidly by this induced electromotive force. Moreover, the leakage flux passes the stator-core laminations vertically and it occurs with the eddy current on laminations. This effect causes overheating at the stator endpoint.

III. THE ELECTRICAL SYSTEMS FOR THE RETROFIT PROJECT

A. Typical power system configuration

Fig. 6 shows the one-line diagram of how the synchronous generators is connected at the site. There is a double bus system, double breakers, three tie-breakers, and generators. Typically generators operate in parallel to the grid. But if power from the grid fails, the bus tie-breakers will open automatically using frequency protection relays to disconnect from the grid. The generators will supply power to the loads connected to bus B1 and bus B2 without any power interruption. If the loads receive power from bus A, the related factories may be shut down. The bus A is called a normal bus because it can experience an outage due to a grid power failure. On the other hand, bus B is called the essential bus because power will be supplied by essential generators without any interruption when power from the grid fails.

Supplying normal power or essential power needs to meet the following criteria:

1) The pollution limit of the environment
2) The operating safety of the factories
3) Utility loads

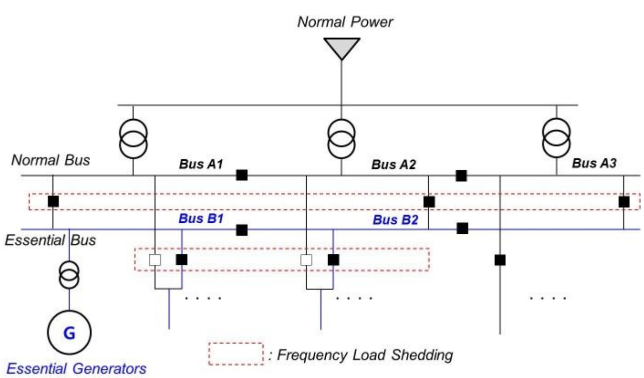


Fig. 6 The one-line diagram of the power system connection

B. The Generator Protection Functions

Fig. 7 shows the generator protection functions that need to be maintained in the retrofit project of the generator control system. In total, 13 functions are used for the synchronous generator as standard protection functions.

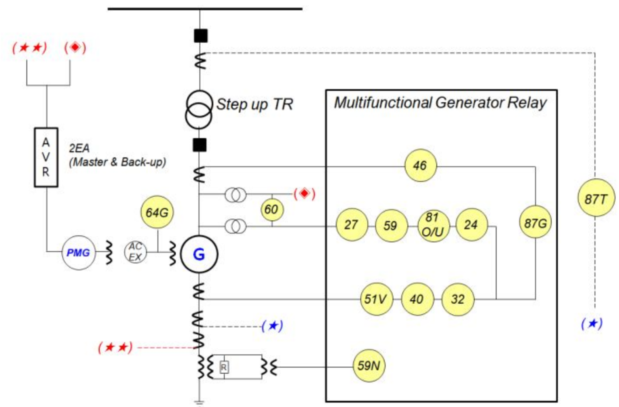
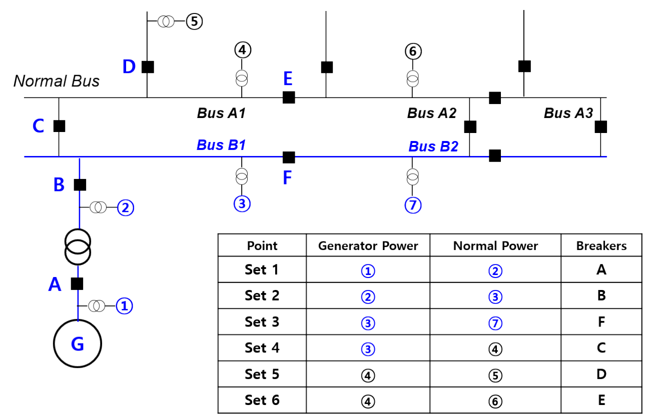


Fig. 7 Generator protection functions

C. Synchronizing Points

There are six synchronizing points in the electrical system for ease of operation. Fig. 8 shows the available synchronizing points.



Point	Generator Power	Normal Power	Breakers
Set 1	①	②	A
Set 2	②	③	B
Set 3	③	⑦	F
Set 4	③	④	C
Set 5	④	⑤	D
Set 6	④	⑥	E

Fig. 8 The synchronizing points

IV. GENERATOR PROTECTION FUNCTIONS

A. Voltage-controlled Overcurrent Protection (51V)

The steady-state fault current for a three-phase system fault may result in generator current magnitudes less than the full load current. But the failure will cause the generator terminal voltage to drop significantly. To properly operate for faults uncleared by a current relay, the voltage-controlled overcurrent relay should be used.

B. Overvoltage Protection (59)

Generator overvoltage is usually caused by sudden load rejection or failure of AVR. Generally, generators are designed to operate continuously at a maximum voltage of 105% of the rated voltage while delivering rated power at rated frequency. Sustained overvoltage above the permissible limit may produce over fluxing (due to high V/Hz) and excessive electrical stress on the insulation system. The over-fluxing leads to overheating of the iron core.

C. *Undervoltage Protection (27)*

The generators can operate continuously at a minimum voltage of 95% of rated voltage. But if the voltage is lower, unexpected effects such as the reduction in stability limit, resulting in an import of excessive reactive power from the grid, may occur. Therefore, the generator's under-voltage condition should be detected.

D. *Voltage Balance Protection (60)*

Voltage balance protection relays aim to avoid malfunctioning from incorrect operation resulting from blown fuses or other faults in a voltage instrument transformer circuit.

E. *Over Excitation Protection (24)*

The V/Hz protection is to serve as a back-up in case of the failure of the V/Hz limiter within the excitation control. The flux in the stator core of a generator is directly proportional to voltage and inversely proportional to frequency. Over excitation of a generator will occur whenever the ratio of the voltage to frequency(V/Hz) applied to the terminal of the generator exceeds 1.05PU. [over excitation (over flux) → saturation of iron core → eddy current on iron core → overheating of the iron core].

F. *Over/Under Frequency Protection (81O / 81U)*

The generator and turbine are limited to the degree of the abnormal frequency operation that may be tolerated. The specific frequency may impact turbine blades and result in damage to the bearings due to vibration.

1) *Over Frequency:* This phenomenon is due to sudden loss in load or loss of key transmission lines exporting power. The islanding of generation with load may cause over frequency when the amount of generation exceeds the amount of the load.

2) Under Frequency: Under a sudden reduction in input power or loss of crucial interties importing power, the frequency can decrease. The under frequency situation occurs when the amount of load exceeds the amount of generation.

G. *Reverse Power Protection (32)*

If there is not enough active power, the synchronous generators are operated like synchronous motors. Reverse power protection is used to detect the generators going into a motoring mode. The minimum power when generators start operating as synchronous motors are shown in table 2.

Table II
The criteria of reverse power setting

Type	Percent of rated power
Condensing Turbine	1 ~3 %
Non-condensing Turbine	3%
Hydraulic Turbine	0.2 ~ 0.25%
Gas Turbine	50%

H. *Unbalance Current Protection (46)*

The imbalance in currents produces negative sequence components of current that induce a double frequency current. These rotor currents may cause high and possibly dangerous overheating in a short time. Table 3 shows the percent of permissible negative current.

Table III
The permissible negative sequence current

Type	Capacity	Negative Seq. Curr [%]
Salient pole	-	10 %
Cylindrical rotor (Direct cooled)	Up to 1250 MVA	8 %
	1251 ~ 1600 MVA	5 %

I. *Generator Rotor Field protection (64G)*

The field circuit of a generator is an ungrounded system. A ground fault should not lead to any trouble with the generator operation. However, when a second ground fault occurs, a portion of the field winding will be short-circuited. This may cause rotor vibration that may quickly damage the machine. Under this situation, the field ground protection relay is needed. Fig. 9 shows the configuration of the field ground protection for the brushless machine.

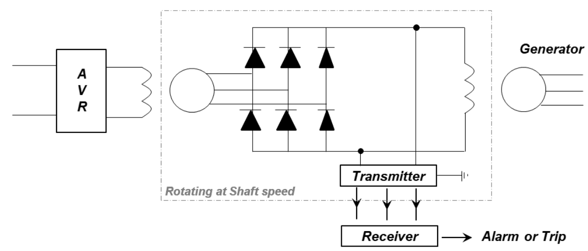


Fig. 9 The field ground Protection

J. *Stator Ground Protection (59N)*

The stator ground fault protection for a high impedance grounded generator is provided with a neutral overvoltage relay, which covers 95% of the winding measured from the output terminal. If the winding is grounded, the ground voltage will be increased up to the maximum single-phase voltage. The grounded circuit acts the same as a single transformer.

K. *Synchronizing protection (25)*

Uncontrolled synchronizing leads to undesirable damages to generators. The synchronizing check relays have been applied to avoid this problem. Fig. 10 shows the maximum and minimum voltage difference when the frequency is different. The synchronizing operation should start just before the minimum voltage difference because of the operating time delay of a breaker and protection relays.

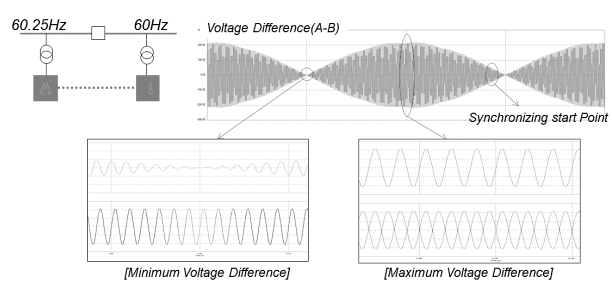


Fig. 10 The voltage difference for synchronizing

L. Current Differential Protection (87)

Generator stator faults are considered critical because they may cause severe and costly damage to insulation. These faults need to be cleared as fast as possible to reduce the damage to generators and the impact of power surge in the system. For these reasons, the differential protection relays are installed for generator protection. They must operate only for faults inside of the generator, and should be blocked for external faults. Fig. 11 shows the current flow and actual current vector diagram when normal operation is the same as the external failures.

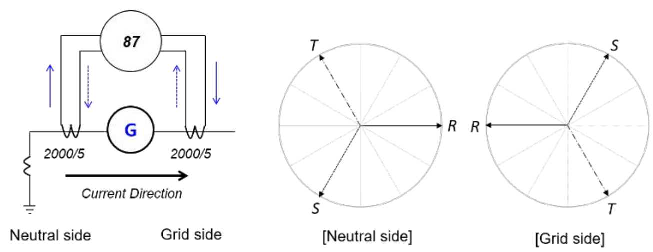


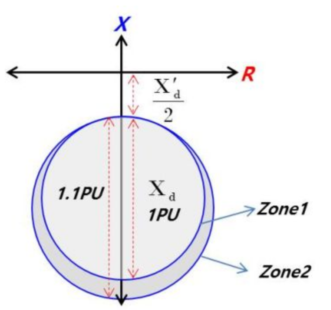
Fig. 11 The current flow and real current vector

M. Loss-of-field Protection (40)

The loss-of-field phenomenon comes from losing the excitation power of generators, which happens by opening a field breaker, experiencing short circuits in the excitation system and failure of the AVR system, and occurring irregularities in the rotating part. No matter what the causes are, the synchronous generator can get damaged.

When a generator loses excitation, it will operate as an induction generator. It will continue to supply active power to the system. In general, the most severe condition for the generator is when a generator loses excitation while operating at full load. For this condition, the stator current may be over 2.0pu, and such a condition may cause damaging overheating of stator windings.

For the loss-of-field relay setting, two set values are needed: transient reactance(X'_d) and synchronous reactance (X_d). Fig. 12 shows the setting of loss-of-field protection. The offset (maximum current) is decided when the impedance is minimum during transient state.



Maximum current

$$I_f = \frac{E_A - E_B \cos 180°}{X'_d} = \frac{E-(-E)}{X'_d} = \frac{2E}{X'_d} = \frac{E}{\frac{1}{2}X'_d}$$

So, Minimum impedance $\frac{I_f}{E} = \frac{1}{2}X'_d$

Fig. 12 The setting of the loss-of-field protection

The SSSL (Steady State Stability Limit), GCC (Generator Capability Curve), and Under Excitation Limit (UEL) are presented on the P-Q plane, and the loss-of-field settings are presented on the R-X plane. The P-Q and R-X planes are compatible with each other. Therefore, it is possible to present the SSSL (Steady State Stability Limit), GCC (Generator Capability Curve), and Under Excitation Limit (UEL) together on the R-X plane to confirm the coordination of loss-of-field protection. Fig. 13 shows the SSSL, GCC, and UEL operating characteristics on the R-X plane. Also, the loss-of-field protection setting curve can be shown on the P-Q plane. Fig. 14 shows the SSSL, GCC, UEL, and loss-of-field protection characteristics on the P-Q plane.

$$Z = \frac{kV^2}{MVA} \times \frac{CT_{Ratio}}{PT_{Ratio}}$$

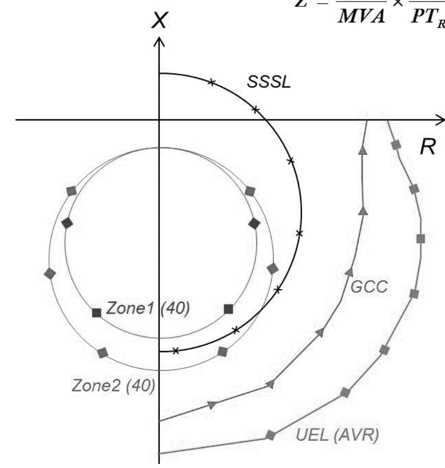


Fig. 13 The protection curves for R-X plane

$$MVA = \frac{kV^2}{Z} \times \frac{CT_{Ratio}}{PT_{Ratio}}$$

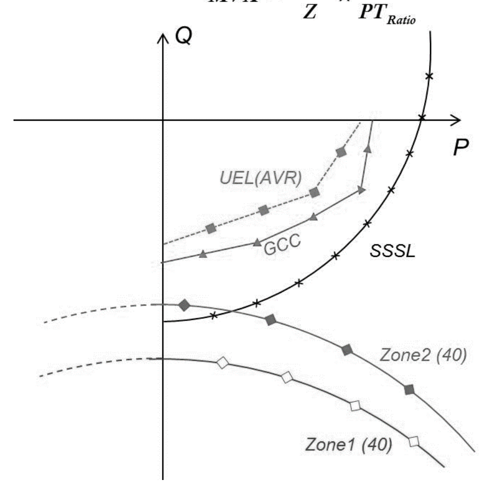


Fig. 14 The protection curves for P-Q plane

For testing loss-of-field protection relays, one needs to calculate the values of voltage or current. If the voltage is fixed, the current values for each point can be calculated, like it is shown in Fig. 15.

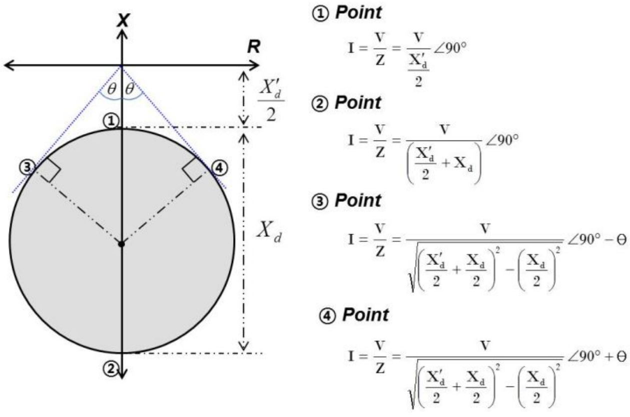


Fig. 15 The current values for each point

V. FIELD EXPERIENCES DURING COMMISSIONING

A. Differential Protection Relays Wiring Check Using a Single Power Source

Recently, most of the protection relays are digital. They have a high sensitivity of current detection and also can display the current vector view of three phases. With this characteristic of digital protection relays, the idea is to inject a constant current to the generator protection directly and then checks the current vector diagram depending on each transformer`s vector group. This method is beneficial for reducing testing time and testing budgets. Fig 16 shows the connection diagram of the current test used for the transformer differential protection relay. In this case, the generator was bypassed because the impedance of the generator is high.

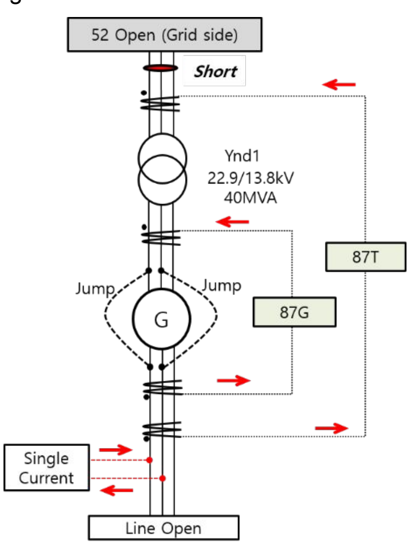


Fig. 16 The connection diagram of the current test for the transformer differential protection relay

When the turn ratio of the transformer is 1:1, the current magnitude and vector group for the Ynd1 show like Fig. 17.

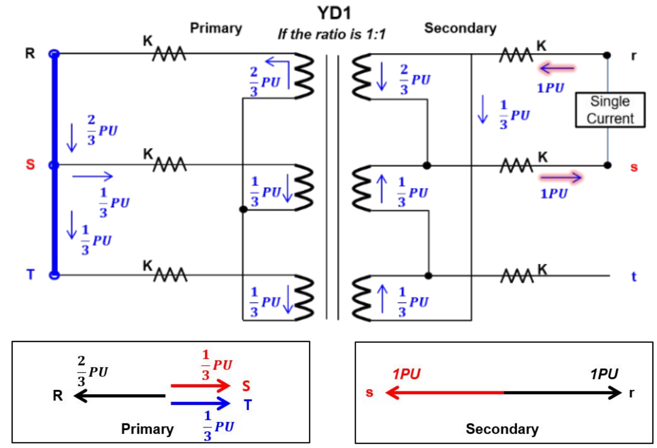


Fig. 17 The current magnitude and vector diagram for Ynd1 when input the current from TR secondary side R and S

Fig. 18 shows the current vector diagram for the test result from the differential protection relay. It is exactly the same as Fig. 17. (the transformer and CT ratio should be considered)

COMPONENT	MAGNITUDE / ANGLE	COLOR	ASSIGN TO
13.8kV (SRC 1)-Phasor Ia	5.157 A 0.0 deg		Phasor Set 1
13.8kV (SRC 1)-Phasor Ib	5.225 A -178.8 deg		Phasor Set 1
13.8kV (SRC 1)-Phasor Ic	0.000 A 0.0 deg		Phasor Set 1
22.9kV (SRC 2)-Phasor Ia	3.523 A -179.4 deg		Phasor Set 2
22.9kV (SRC 2)-Phasor Ib	1.753 A -359.3 deg		Phasor Set 2
22.9kV (SRC 2)-Phasor Ic	1.802 A -2.4 deg		Phasor Set 2

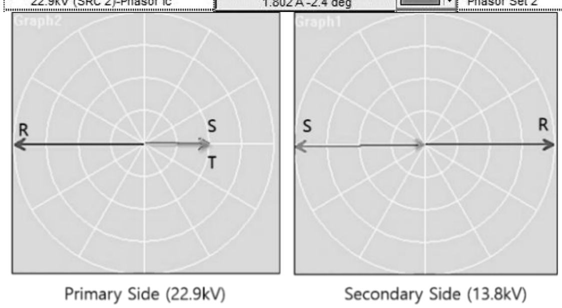


Fig. 18 The current vector diagram for the test result from the differential protection relay

Fig. 19 shows the current magnitude and vector diagram for Ynd1 when input the current from TR secondary side S and T.

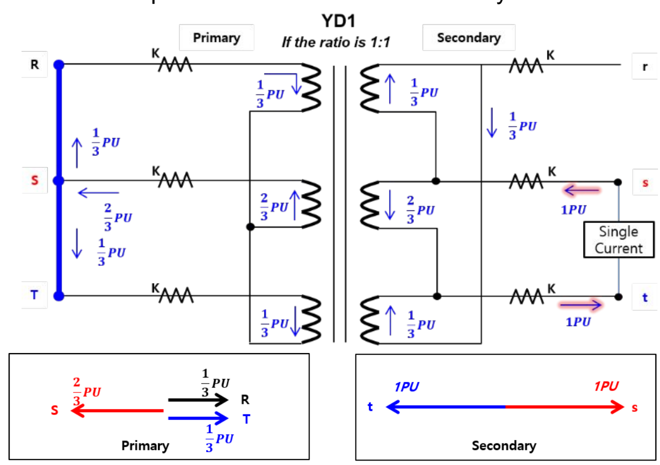
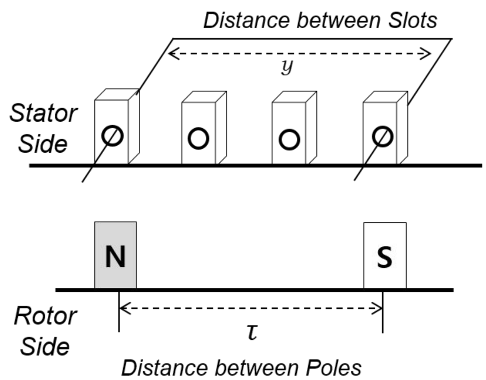


Fig. 19 The current magnitude and vector diagram for Ynd1

when input the current from TR secondary side S and T

B. Generator Stator Ground Protection (59N)

Although the 3rd harmonic setting level is followed in typical practice, the protection relay can trip during normal operation. This is because the 3rd harmonics may occur due to a short pitch factor of winding. Fig. 20 shows the meaning of the short pitch factor. During commissioning, the value of the 3rd harmonic had almost reached the trip setting value (5% of single-phase voltage) by increasing the generator load. Therefore, the maximum value of the 3rd harmonic should be measured to make an appropriate protection setting before going into service. If not, it may cause an unexpected trip during normal operation.



$$\text{Short Pitch Factor} = \sin \frac{n\beta\pi}{2} \left(\beta = \frac{y}{\tau}\right)$$

(n : n st Hamonics)

Fig. 20 The definition of short pitch factor

Therefore, $If\ \beta = \frac{2}{3}$, $The\ third\ harmonics\ will\ be\ 0\%$.

$$\text{Fundamental Harmonic} = \sin\frac{2\pi}{2\times 3} = 0.866$$

$$\text{Third Harmonics} = \sin\frac{3\times 2\pi}{2\times 3} = 0$$

C. Abnormal Inrush Current

Transformer differential protection relays may be operated by inrush current caused by closing an incoming breaker, even if the blocking function for the 2nd harmonic current is activated. Fig. 21 shows the waveform for the 2nd harmonic inrush current that operated the differential relay. When the breaker was closed, initially, the 2nd harmonic blocking function was activated because the setting of the 2nd harmonic blocking was 15%, and the actual value was higher than the setting value. But the value of 2nd harmonic dropped rapidly from 60% to 9% during 0.052s, and it led to operating the protection relay. The 2nd harmonic blocking function was operated again (0.13s later) when the value was 15.1%. Although manufacturers are using a variety of techniques to prevent operation by the inrush current, it is not enough to protect against all kinds of inrush current. Therefore, the application engineers have to distinguish the cause of transformer differential protection operation due to inrush current after checking waveforms for different application cases.

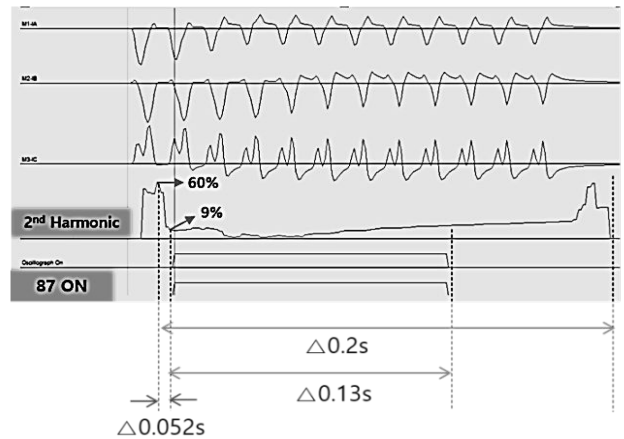


Fig. 21 The waveform for 2nd harmonic inrush current that operated the relay

VI. THE GENERATOR MONITORING SYSTEM

A. Overview

Generally, the generator manufacturers supply a monitoring system package, including the generator control panel or synchronizing panel, according to the global manufacturers' standards. Sometimes, it is hard to incorporate the end-users' ideas or special requirements, although they may have novel ideas. During this retrofit project, the generator monitoring system was developed in consideration of efficient monitoring, ease of testing, and operation from the end user`s perspective. The concept of the Generator Monitoring System comprises the integration of all information for the generator operation. The user can check all operating conditions of synchronous generators using the Human-Machine Interface(HMI). The generator monitoring system does not interfere with the operation of the protection and control system. Hence the protection and control system can operate without any interruption even if the monitoring system experiences troubles. Fig. 22 shows a configuration of the generator control panel and synchronizing panel.

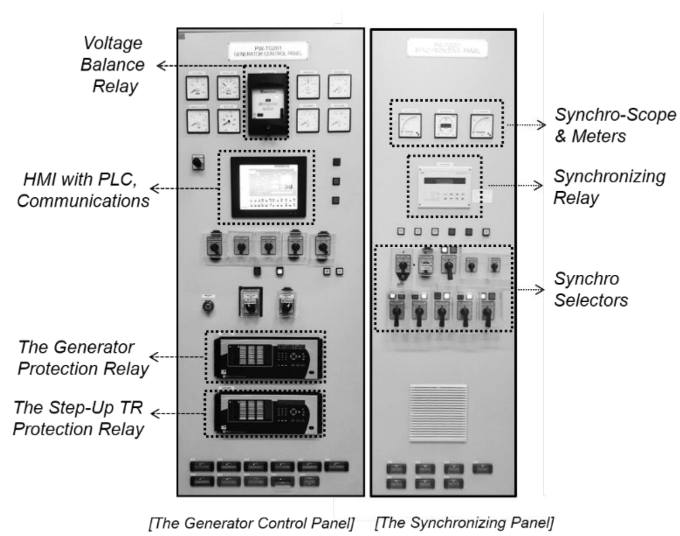


Fig. 22 The configuration of the front panel

B. Configuration of Communication

The Generator Monitoring System integrates AVR, protection relays, PLC, HMI (Panel PC), and synchronizing relays in one system. One of the most important requirements for this monitoring system is connecting all devices with proper communication without any error. Notably, the data transfer speed should be very fast among AVR, PLC, and HMI. Fig. 23 shows the configuration of the connection for a generator monitoring system.

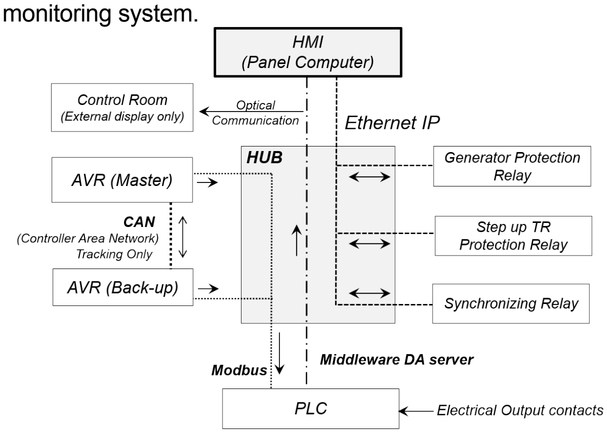


Fig. 23 The configuration of the interface

C. Configuration of Displays

1) *Main display*: Operating conditions for all devices and meters are displayed with visual effects. This allows users to understand the operating conditions of the generator easily. Fig. 24 shows the overview display for the generator monitoring system.

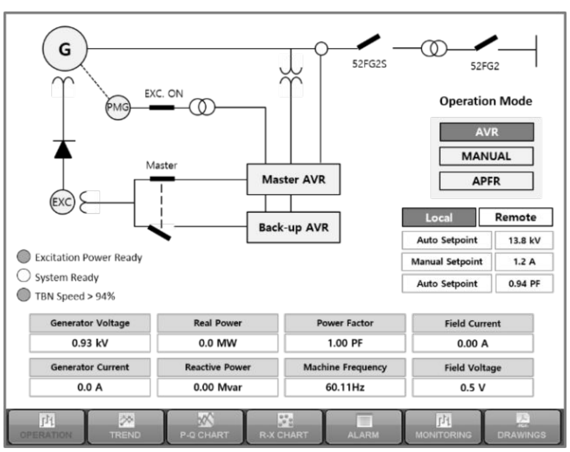


Fig. 24 The overview display

2) *Displays for P-Q, R-X plane:* There are different viewpoints on SSSL (Steady State Stability Limit), GCC (Generator Capability Curve), Under Excitation Limit (UEL), and the field loss protection although the definition is the same. The HMI can represent the P-Q and R-X plane not only to make testing protection relay easier but also to give an exact operating point to the operators. Fig. 25 shows the P-Q & R-X plane display on the HMI screen.

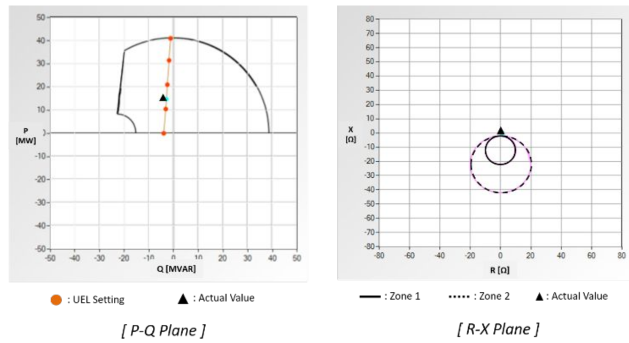
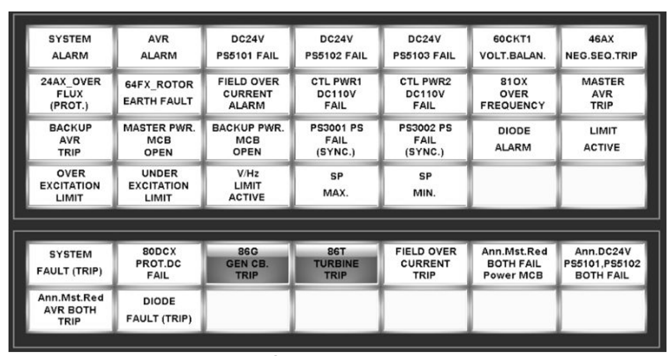


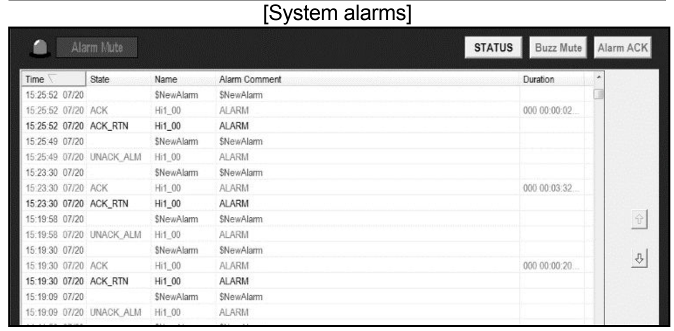
Fig. 25 The P-Q & R-X plane

3) *Displays for protection relays*: The digital protection relays have their unique display functions in customized software. Connecting all digital relays and Automatic Voltage Regulators through HMI(panel PC) and installing all relay software in HMI, makes an effective solution to test protection relays. All digital devices like the AVR system, multifunctional generator, transformer protection relays, and synchronizing relay were connected through HMI. This is useful when testing relays because it is possible to change settings through HMI and view unique display functions in relay software.

4) *Additional displays*: There are also several additional displays. The system alarm display shows total alarms for the generator system, including AVR, protection relays and remote control. The synchronizing point display shows the voltage and frequency at the selected synchronizing points with a one-line diagram. The drawings display shows all of the drawing and reference data for this generator. The event recorder saves all alarms and trips caused by thousands of events with time stamp and message. Fig. 26 shows the additional displays about the integrated system alarms and the event recorder in HMI.



[System alarms]



[Event Recorder]

Fig. 26 The additional displays

VII. CONCLUSION

It is widely agreed that the generator protection and control system is one of the most complicated to understand for end-users. Therefore, performing retrofit projects on this system is challenging and demanding.

Based on an extensive long-term retrofit experience, this paper presents not only the generator protection system overview but also some new ideas on how to improve system reliability using cost-effective methods. Here are a few experiences learned from the retrofit projects:

- The end-users have to select their particular criteria for the setting value for their generators. Also, there are urgent needs to replace electromechanical relays with numerical relays.
- Testing the integrity of wiring connection on the primary side using a single power source for step-up transformer differential protection relays can improve work efficiency and testing reliability. It was demonstrated that the new test method reduced around 80% of the cost and time compared to the traditional way.
- A dedicated generator monitoring system can check all operating situations of the generator system quickly through HMI by integrating information during testing and normal operating conditions.

VIII. REFERENCES

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IX. VITAE

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