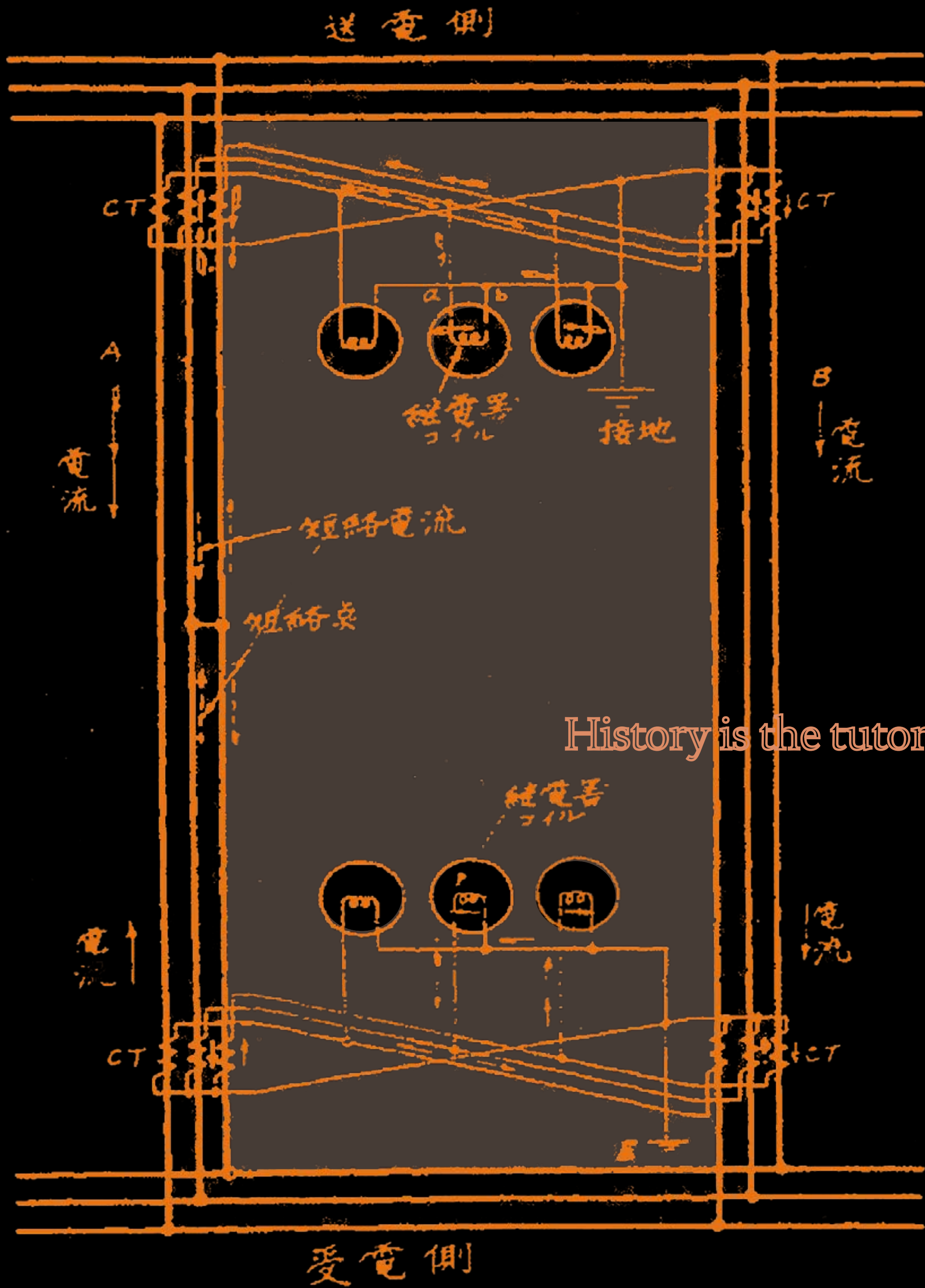

History is the tutor of life

Balance Protection for parallel lines
(Shibaura Review 1926)

第　一　圖

by Phil Beaumont, Toshiba , UK, Tadashi Nakamura and Noriyoshi Suga, Toshiba, Japan

Protection History

Protection Relaying in Japan

A Short Story

Introduction

No article on the history of protection relaying in Japan would be complete without a brief introduction to some of the unique attributes of the Japanese power system. The peak demand in Japan is around 180 GW and as illustrated in Figure 4, Japan comprises four main islands Hokkaido, Honshu, Shikoku and Kyushu along with Okinawa and many other smaller islands. The main islands are connected via AC/DC converters with the exception of the connection between Kyushu and Honshu, which is connected via a 500 kV AC transmission line rated at 5570 MW. The undersea DC links from Honshu to Hokkaido and Shikoku to Honshu are rated at 600 MW and 1400 MW respectively. Shikoku is also connected to Honshu via a 500 kV 2400 MW overhead transmission line.

There is also an AC/DC 300 MW back-to-back converter located in Minami-Fukumitsu in the center of Japan to improve power system stability in the area of the Hokuriku-Kansai-Chubu interconnection. Frequency converters are installed approximately in the center of Honshu Island to connect the 50Hz and 60Hz systems, each one serving half of Japan. The frequency conversion stations are located in Sakuma 300MW and Shin-Shinano 600 MW. There is a third frequency 300 MW converter also in Chubu in Higashi-Shimizu (not shown in Figure 4.)

Japanese engineers are often asked why Japan is separated into 50Hz and 60Hz systems. The reason is quite logical and of historic interest. Prior to 1890 the Tokyo area was served by a DC network owned and operated by Tokyo-Dentou ho began to supply electric power in 1887. In the early 1890s they purchased an AC generator from AEG Germany. The generator was a 3-phase machine rated at 3 kV and 265 kW operating at 50Hz and was installed in the Tokyo area. In Osaka, in the west of Japan, Osaka-Dentou purchased a 60 Hz generator rated at 2.3 kV and 150 kW from GE in the United States. The network grew up around these first installations into the system found in Japan today. Another interesting feature of the Japanese power system is that the topography evolved from that of a radial network and today features many multi-terminal and double circuit lines which explains the widespread use of current differential protection and multi-phase auto-reclosing described later in the article.

Early Beginnings

The advent of protection relaying in Japan began more than 100 years ago, in 1907 with the manufacture of the first plunger type protection relay shown in Figure 2. The first application was for the 55 kV Yatsuzawa line in Tokyo.

This was followed by the introduction of the induction disc type overcurrent protection shown in Figure 1, which

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was manufactured in 1920. The sensitivity of operation and the accuracy of the operating time were dramatically improved compared to that of the plunger type relay.

During this period the construction of large power plants was widespread in response to an increase in the demand for power which resulted in the rapid expansion of the transmission network. A large number of parallel line configurations were adopted to meet the requirement for high reliability power transmission. With regard to protection, great importance was attached to selectivity and therefore in the early 1920s a transverse differential type protection relay was adopted - an advanced protection scheme at the time giving much improved selectivity to that of overcurrent protection.

The transverse differential relay utilizes the phenomenon that the currents in parallel lines flow at almost the same level under both normal and external fault conditions, however under internal fault conditions the balance between the parallel lines collapses as shown in Figure 5, because a larger current will flow in the faulted line. This type of protection has been applied in other countries such as the U.S. as early as 1938 but is now so widely applied in Japan that it can be considered a characteristic feature of protection relay engineering in Japan. The principle has since been implemented in numerical protections and is typical of the protection schemes used for 66/77kV applications to this day.

Cultivated through the development of the plunger and induction disc type relays the technology employed in electromechanical relays advanced rapidly and resulted in a high performance induction cylinder device offering faster operation, better accuracy and increased sensitivity for the post-war period.

The arrangement of the induction cylinder or induction cup type relay is shown in Figure 6. This relay has magnetic poles which consist of iron cores and coils surrounding a rotating cylinder in the center. The rotating flux generated in the magnetic poles causes the cylinder to rotate. A high operating speed can be achieved because the rotating cylinder is hollow and the moment of inertia is small. Following earlier experience in overcurrent applications, the induction cylinder

Japan is separated into 50 Hz and 60 Hz systems due to the purchases of generators from Europe and North America.

arrangement was adopted in the "Mho type distance relay'" developed in 1951.

Network Expansion

Following the increase in power demand in the post war period, planning for the construction of the EHV system began and the 275kV 320km trunk line between Narude power station in Toyama prefecture and Hirakata substation in Osaka prefecture went into operation in 1951. The protection scheme was the first directional comparison carrier scheme using a Mho type distance relay as shown in Figure 10.

A directional comparison scheme using power line carrier communication is illustrated in Figure 9. The scheme isolates the faulted section of the power system when the protection terminals judge that a fault has occurred within the protected section. Therefore, this scheme requires that each terminal has the means of transmitting the result of the directional decision to the opposite terminal. For transmission line applications, power line carrier communication was used to transmit the information using a high frequency signal over the transmission line itself. The scheme was installed in the Kansai area in 1952 on the Shin Hokuriku trunk line which used single phase auto-reclosing for the first time in Japan.

The directional comparison scheme was in use for many years in Japan for the protection of trunk power system EHV transmission lines. Microwave transmission was adopted for the Kushiro trunk line in Hokkaido in 1958 for the first time providing a new means of communication between protection terminals. Following experience gained with vacuum tube technology in a phase comparison carrier relay system in 1956 the protection relay advanced through innovations in peripheral technology. A protection relay using transistors

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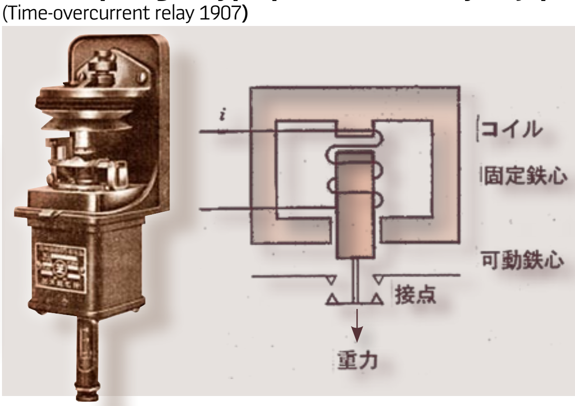
1 Induction disc type protection relay

2 First plunger type protection relay in Japan
(Time-overcurrent relay 1907)



3 Current balance protection relay for 154kV lines (approximately 1945)

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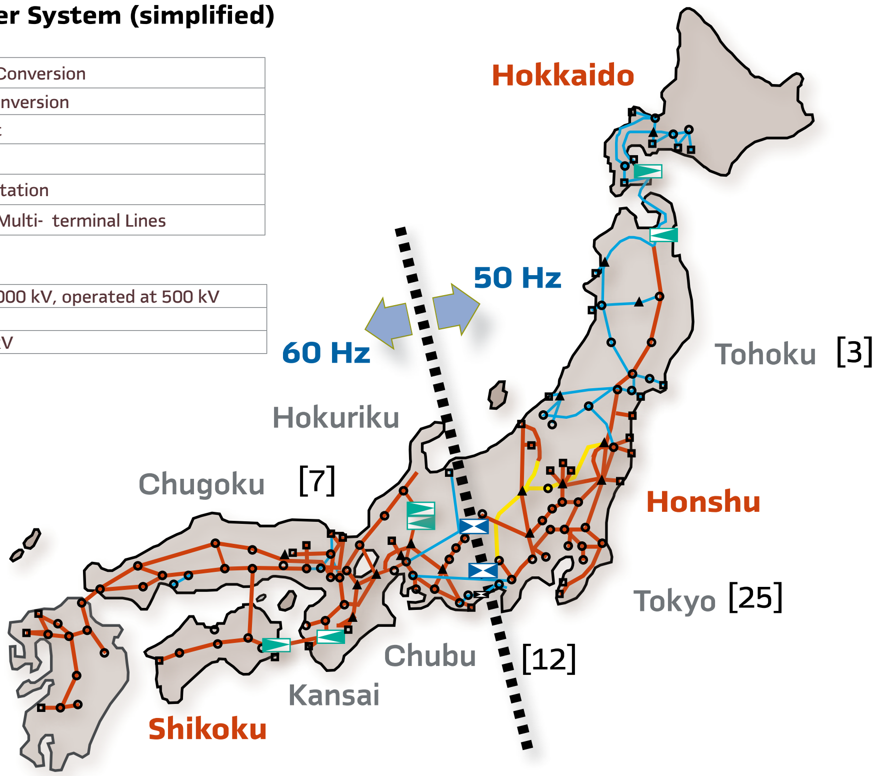
4 Japanese Power System (simplified)

	Frequency Conversion
	AD / DC Conversion
	Power Plant
	Substation
	Switching Station
[ ]	Number of Multi- terminal Lines

	Designed 1000 kV, operated at 500 kV
	500 kV
	275 -- 187 kV

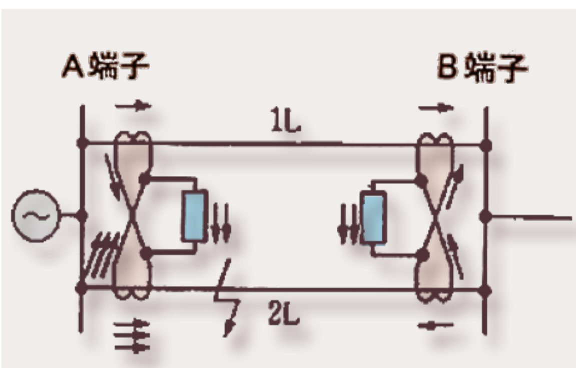


was developed in 1959. This was referred to as a static type relay when compared with the aforementioned relays which were all various forms of electromagnetic mechanical relays with moving parts. In 1962 the first transistor based distance protection was launched using germanium transistor technology. This was a physically large device with a high power consumption with limited popularity. However by 1971 subsequent evolutions had led to smaller, lower power consumption devices and transistorized distance protection was in widespread use.

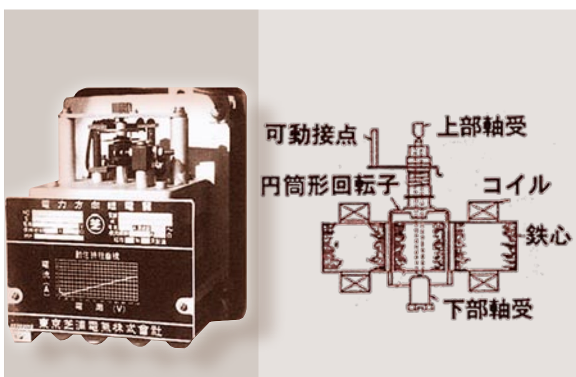
Towards enhanced reliability

With rapid economic growth, power demand increased and large power stations were constructed in remote locations. This resulted in the requirement to develop a 500kV network. One of these was the 500kV Fukushima trunk line in the North East of Japan. With greater interconnection, the power system also became more complex and as a consequence of large-scale blackouts, both at home and overseas, in 1965 the decision was made to enhance the reliability of protection relays. Automatic supervision and continuous monitoring

5 Transverse differential protection



6 Induction Cylinder Relay



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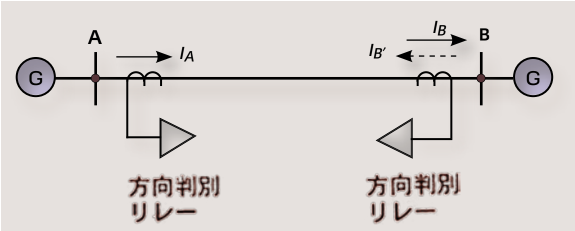
9 Principle of directional comparison scheme



features were introduced as countermeasures to improve the reliability of protection. These features were provided for both primary and back-up protections. Supervision covered current and voltage transformer circuits as well as binary input and trip output signals. Fault detection relays were another addition. In this scheme, the trip outputs for each of the two main protections are individually connected in series with the trip outputs from each of the two fault detection relays in order to avoid false tripping. This arrangement also presented the opportunity to individually test trip output contacts without tripping the circuit breaker. This new approach reduced the time required to detect and clear failures, reduced the need for manual testing and maintenance, and significantly reduced the occurrence of human errors.

The static type relay system shown in Figure 11 featured an automatic supervision function and the introduction of multiphase auto-reclosing. This type of auto-reclosing is widely used in Japan for reclosing on double-circuit lines. In this form of auto-reclosing, only the faulted phases are tripped and reclosed when the terminals of double-circuit lines are interconnected during the dead time through at least two or three different phases. Multi-phase auto-reclosing enables high-speed auto-reclosing for multi-phase faults without synchronism and voltage check, and minimizes the possibility of outages in the case of double faults on double-circuit lines. Figure 13 shows all of the fault types that could occur on a parallel line, the possibility of auto-reclosing for these faults using multi-phase auto-reclosing, and the conditions necessary to permit auto-reclosing for the case where two different healthy phases are available.

With the economic growth power demand increased and large power stations were constructed.

Because this type of auto-reclosing can be relied upon to avoid a complete power failure, even in the event of multiple faults which extend over two lines, it was adopted for Extra-High-Voltage critical main lines. Note that the protection devices that are used in conjunction with multi-phase auto-reclosing must be able to ensure identification of the faulted phase.

In 1969, a static phase comparison scheme was developed for the 275kV system in Fukushima, offering improved selectivity to that of directional comparison schemes. This protection uses the principle that the phase currents at both ends of the protected line tend towards the in-phase condition for internal faults, and are in anti-phase for load or through fault currents (Figure 16). This was a phase-segregated scheme enabling multi-phase auto-reclose, and included self-supervision features. A successor to this relay was the 'sliced-level' type phase comparison relay, which was developed to overcome the difficulties of its application to multi-terminal lines and was presented to the IEEE PES Summer Meeting held in Mexico City in 1977.

As the power system evolved it became increasingly complex, and the use of multi-terminal lines became more widespread. Although multi-terminal lines introduced difficulties with regard to maintenance outages, stability issues and fault clearance times their use was principally driven by the availability and cost of land in addition to the usual economies relating to primary equipment. These problems pressed the development of PCM current differential relaying which is the main protection scheme in use today. Before we focus on the PCM relay it is worth mentioning its predecessor - the Frequency Modulation (FM) current differential protection, which was introduced in 1977 and is shown in Figure 7. The phase comparison scheme could not be expected to operate

7 FM Current Differential Protection

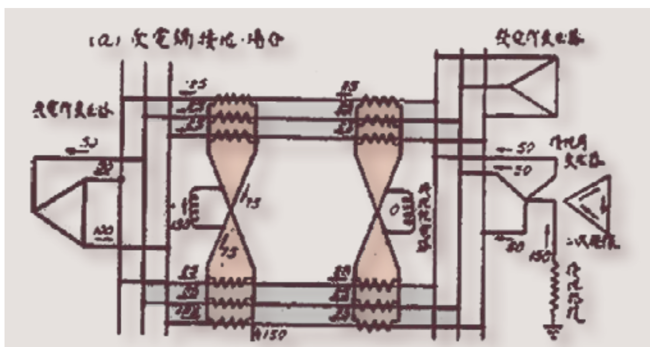
8 Static type relay (T-series)

10 Directional comparison protection

First EHV in Japan

11 All-static type carrier relay panel

12 Parallel double lines and principle of transverse protection relay (1923)



properly to clear internal faults on three terminal lines when current flowed out of the protected section, and therefore the FM current differential scheme was introduced to achieve a much improved selectivity overcoming the 'outflow' effect for internal faults on multi-terminal lines. The new scheme also included a countermeasure to improve the speed of the relay for faults on transmission lines adjacent to underground power cables for delays caused by transient harmonic oscillation. Frequency modulation technology was used to transmit the current data between terminals with the vector summation of currents at each terminal being calculated to determine whether or not the fault was internal, or external to the protected circuit. It is also worthy of note that this protection was also applied in the UK at 400 kV as a teed feeder protection after first undergoing switching and fault throwing tests in 1985 as part of a system trial.

Digital Relaying

The advent of the microcomputer began to influence protection relaying and in the 1970s a digital relay that would use a microcomputer was actively researched in Japan. In order to gain experience with this new technology, field tests were arranged in 1968 with participating manufacturers and utilities using a current differential relay for application on long-haul multi-terminal transmission lines. Digital data transmission using high-quality, high-accuracy pulse code modulation was employed in this relaying system as a means for transmitting the current waveform from one terminal to the other. However, the demodulated analogue waveform was used as the relay input quantity. Although the relay was extensively tested in the field, it did not directly result in the practical use of the system, but the tests did provide valuable experience for manufacturers and utilities to aid further development of the digital relay. The experience gained highlighted the need for high-quality, high-accuracy analogue-to-digital conversion techniques, digital transmission techniques, and how disturbances in the microwave network affect data transmission for digital relaying.

In 1973 Japanese manufacturers commenced with the full-scale development of digital relays using a new element; - the microprocessor. Two approaches were adopted for the digital relaying algorithm:

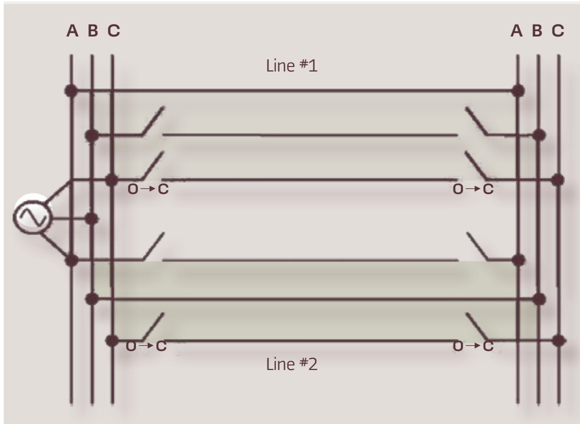
- One was based on the fundamental wave
- The other on travelling wave phenomena

Extensive simulation studies were also conducted to develop an algorithm which had both high computation efficiency, and excellent protection capability.

In terms of hardware, the development of a high speed microcomputer using bit slice type bipolar microprocessors was adopted because of the requirement for high speed computation. Around this time the technology of optical data transmission was introduced with its associated immunity to interference.

Based on these developments in July 1977 a field test of a current differential relay for EHV transmission lines commenced, and in 1978 the field test was extended to include a digital distance protection. The first digital relays went into

13 Multi-phase auto-reclosing



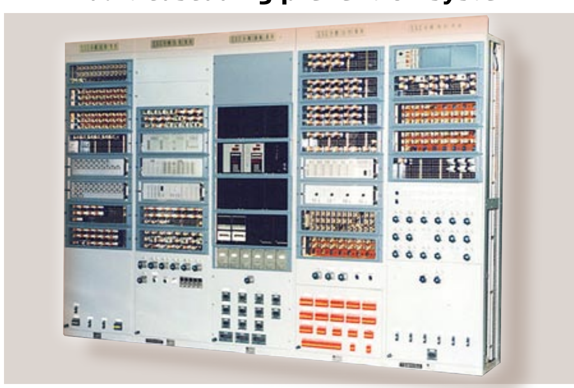
Possibilities with 2 & 3 phase interconnection

Case	Faulted Phase Line #1 A	B	C	Line #2 A	B	C	Operation of M2	Operation of M3
1	X			-	-	-	O ---> C	O ---> C
2	X	X		-	-	-	O (FT)	O (FT)
3	X	X	X	-	-	-	O (FT)	O (FT)
4	X						O ---> C	O ---> C
5	X			X			O ---> C	O (FT)
6	X	X					O ---> C	O ---> C
7	X				X		O ---> C	O ---> C
8	X	X		X			O ---> C	O (FT)
9	X	X		X	X		O (FT)	O (FT)
10	X	X	X				O ---> C	O ---> C
11	X	X				X	O ---> C	O ---> C
12	X	X			X	X	O ---> C	O (FT)
13	X	X	X	X			O ---> C	O (FT)
14	X	X	X	X	X		O (FT)	O (FT)
15	X	X	X	X	X	X	O (FT)	O (FT)

M2	*Two-phase connection*	*FT*	*Final trip*	*X*	*Fault*
M3	*Three-phase connection*				
-	*Line out of service*	*O*	*Open*	*C*	*Close*

Figure 13 Shows all of the fault types that could occur on a parallel line, the possibility of auto-reclosing for these faults using multi-phase auto-reclosing and the conditions necessary to permit auto-reclosing for the case where two different healthy phases are available.

14 Fault cascading prevention system



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Today Japan boasts digital products covering microprocessor technologies spanning more than 30 years.

service in the early 1980s (Figure 17), when a PCM current differential relay was applied to a 275kV transmission line and a digital distance protection was applied at 66kV. The use of digital relays increased, and in the mid-1980s protections using 16-bit multiprocessor designs with sampling rates of 600/720Hz for 50/60Hz devices became available. Digital transformer protections were now commercially available and in 1990 decentralized digital busbar protections entered into service. These busbar protections employed distributed bay units from multiple vendors featuring a countermeasure for CT saturation. The current data and binary status information was retrieved over a dedicated fiber-optic LAN using IEEE 802.4 (Token Bus), a level of interoperability being achieved by unifying the data format and the characteristics of the analog filters used by the various vendors.

Before moving on, it is also worth mentioning the introduction of the fault recording function to digital protection relays in 1989. Today this function is making a major contribution to the analysis of relay operations and is implemented in IEDs all over the world.

The next step in technology came in the mid-1990s with the move to high performance microprocessors such as 32-bit devices along with the adoption of 16-bit A/D converters. Higher sampling rates were introduced typically 4800/5760Hz for 50/60Hz devices. The rest you might say is history. Product ranges expanded to provide new solutions and features covering the entire spectrum of substation protection, control and automation. New technologies and techniques were embraced such as IEC 61850 enabling interoperability, and along the way continuous improvements were made to reliability and cost effectiveness.

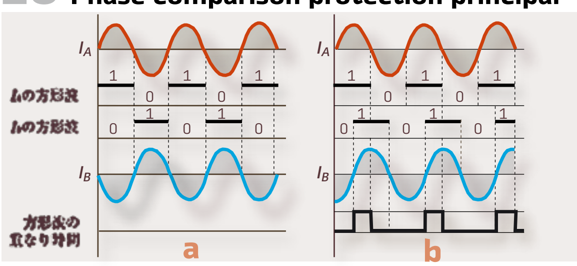
Before we conclude it is briefly worth mentioning the development of Special Integrity Protection Schemes or SIPS in Japan. The story began in 1968 with the implementation of a fault cascading prevention relay employing operational amplifiers. In 1978 a digital System Stabilising Controller SSC went into service for system frequency control. As the power system evolved and digital technology advanced, the development of other types of SIPS such as islanded operation systems and transient/voltage stability countermeasure systems took place throughout the 1980s, culminating in an Islanding Protection System providing active and reactive power balancing control. In 1999, the benefits of one such system were called upon when on the 29 of November one of the sub-power systems within the Metropolitan power system owned and operated by Tokyo Electric Power Company was separated from the main power system in an accident involving an Air Self-Defence Force jet training plane, which severed the 275kV tie transmission lines. The successful operation of the Islanding Protection System ensured that the most important customers in the metropolitan area were not affected by the power failure. The latest systems provide Transient Stability Control and Integrated Stability Control SPS/FACTS, (STATCOM).

Today Japan boasts digital products covering microprocessor technologies spanning more than 30 years, from the bit-slice MPU to the typical devices that we see today that utilize 64-bit high performance MPUs.

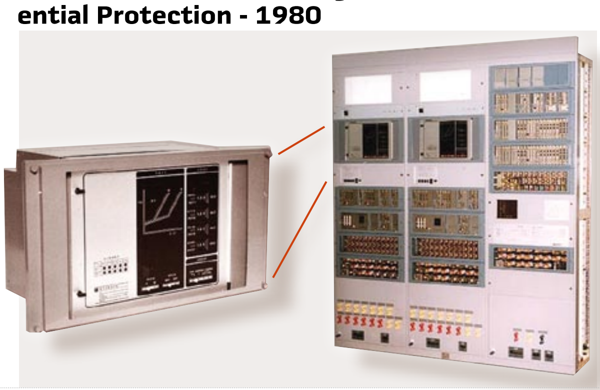
If this article has inspired anyone to learn more about the history of the development of Japanese relaying technology we would be pleased to share the technical papers that we used in the preparation of this review.

15 Second generation digital relay (1985)

16 Phase comparison protection principal



17 First Generation Digital Current Differential Protection - 1980



18 Phase comparison protection system

This Phase comparison protection system is featuring transient harmonic oscillation countermeasure.

(1969 - 1977)