

## Impact of optical current transformer on protection scheme of hybrid transmission line

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### ABSTRACT

Continuity of power transmission is important to ensure the reliability of the electricity supply. As most system faults are temporary, the auto reclose (AR) scheme has been used extensively to minimise the outage duration, prevent widespread outages, thus increase system stability. Meanwhile, the hybrid transmission line (HTL) combining overhead line (OHL) and high voltage cable has been introduced to provide an inexpensive solution for an urban power grid. Protecting HTL with a conventional protection system would forbid the operation of the AR scheme due to difficulty to ensure whether the fault occurred on the OHL or cable section. Therefore, the circulating current protection (CCP) scheme is used in the cable section to ensure the fault location and block the AR scheme. The technology of an optical current transformer (OCT) as one of the non-conventional instrument transformers (NCIT) has emerged to provide a solution to drawbacks on the conventional current transformer (CCT). Consequently, this paper investigated the impact of using OCT over the CCT for CCP of the HTL. The result shows that OCT could be used for CCP on much longer cable sections thus increase its reliability as the AR scheme can be used on longer or multiple cable section.

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## 1. INTRODUCTION

Overhead line (OHL) and cable-based transmission line have been used widely across the globe to provide reliable transmission grid. OHL has known for its simplicity and cost-effectiveness while the high voltage (HV) cable has more advantages on its much better immunity to short circuit and less safe distance despite its higher cost drawback. Therefore, hybrid transmission line (HTL) incorporating underground HV cable and an OHL has been used to balance investment cost, social risk, aesthetic value, and reliability of transmission especially in an urban area that would have less area for the right of way of the transmission line.

As the HTL could consist of two or more different types of conductors and mechanical structures, actual impedance along the line would be varied. Therefore, accurate fault location prediction from impedance measurement only by distance protection would not be applicable [1], [2]. Along with this, employment of line current differential (LCD) protection could provide selective and reliable unit protection for the HTL although it would not be able to determine exact fault location [1]. Furthermore, installation of circulating current protection (CCP) which share a similar concept with LCD protection to protect the cable

section along with separated LCD or distance protection for the whole circuit of a HTL would be preferred [2], [3]. However, this scheme would face another problem as the current transformer (CT) would need to be installed at the junction point between HV cable and the OHL.

Distance protection, LCD protection, and over current protection has been employed for years to provide a secure, selective, and reliable protection system for transmission and distribution systems [4], [5]. As the conventional power grid grows to a smart grid, continuous operation of power transmission is very important to provide a secure and reliable electricity supply, hence prolonged outage duration would be a serious issue to avoid. Therefore, auto reclose (AR) scheme has been used for years to reduce outage duration due to system fault by incorporating automatic control to re-close the circuit breaker (CB) on both side of substation after certain defined dead time [6]. The impact of auto reclose would be vary depends on the grid configuration and the type of the electric generator. Previous technical studies in PLN Indonesia shows that the incorporation of a correctly configured auto reclosing scheme on high voltage transmission lines would be beneficial on both synchronous [7] and inverter-based generator [8].

As most system faults are transient or temporary, AR scheme has been used extensively only on OHL [9]. AR scheme would not be preferred to be implemented on a cable circuit due to the nature of cable that would sustain short circuit only in condition of permanent faults such as insulation breakdown or mechanical failure. In the case of the HTL, incorporation of the AR scheme could be varied depends on the length and location of the cable section in the circuit [3]. The use of CCP on the cable section of the HTL would be limited. Characteristic of conventional current transformer (CCT) employed in the CCP which is limited by external burden load and knee point voltage would limit the length of the cable section. So, this paper proposes and studies the use of optical current transformer (OCT) with IEC 61850-9-2 compatibility to replace the CCT to have flexible current measurement placement along the HTL and other potential advantages.

## 2. CURRENT TRANSFORMER

Instrument transformer has been widely used across the globe to scale down the primary value of current and voltage in a modern power grid to a lower level that would be compatible with any measurement peripheral including energy meter and protective relay [9]. Such transformers share the same principle with a power transformer and replicate the input quantity to a lower level with certain expected accuracy and efficiency for measurement purpose. In the case of power transmission and distribution grid, the performance of overcurrent (51), distance (21), and LCD protection (87L) that measure current value would rely on the accuracy and reliability of the CT. Consequently, the CT takes an important task for the protective relay used in the grid. As the technology of CT develops, modern power grid uses both conventional and OCT technology to perform according to the acceptable standard such as IEC 61869-2 [10]. In this case, accuracy class and accuracy limit factor (ALF) have been used to determine the measurement performance of the CT during normal operation and transient conditions [10], [11].

Basic determination of a CT would be based on its secondary current rating, whether it is 1 or 5 Ampere. The CT also categorised according to its function for measurement purpose with an energy meter or protection purpose with a protective relay. Whilst both measurement and protection CT share a similar basic concept, each type operates distinctively. In this case, measurement CT is designed to provide the required accuracy until 120% of rated current, it would easily be saturated when the current goes too high. Other than that, ALF value that applies only in protection CT would ensure that this CT would provide required accuracy up to relatively high current during a fault. It is written after accuracy class and the letter "P" which stand for protection such as 10P20 or 5P10.

### 2.1. Conventional current transformer

Secondary value of an ideal CT would be proportional with current measured on the primary side. However, as the operation of a CCT based on the electromagnetic principle, the existence of the core and winding between the primary and secondary terminal would cause flux and produce magnetisation that affects operation performance and accuracy as its simplified equivalent circuit and parameters depicted in Figure 1 and Table 1 [9], [12]. Moreover, one basic operational requirement of a CCT is keeping the total burden including the external burden impedance ( $Z_B$ ) not to exceed its rated secondary burden although in a very high current condition. In terms of common secondary current circuit, burden impedance ( $Z_B$ ) would mainly be composed of resistive burden ( $R_B$ ), thus  $Z_B \approx R_B$  with detailed parameters calculated in (1) and (2).

As shown above,  $R_L$  is lead resistance,  $\rho$  is conductor resistivity,  $S$  is wire cross section, and  $R_{r2}$  is relay resistance. Another basic requirement of a CCT is knee point voltage ( $V_K$ ) that represents RMS value of the sinusoidal voltage at rated frequency applied to secondary terminal of the CT when primary terminal being jumped, that, when increased by 10% causes RMS value of the exciting current ( $I_{eK}$ ) to increase by 50% as depicted in Figure 2 [12] and calculated with (3).

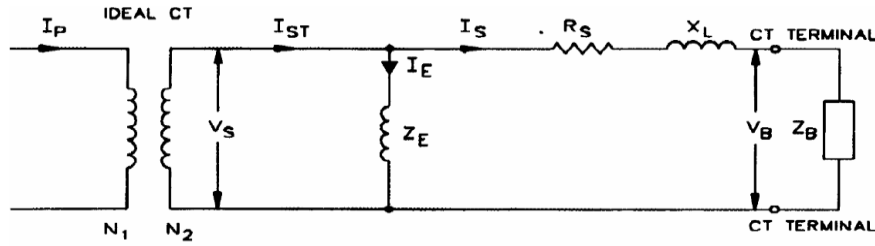


Figure 1. Simplified equivalent circuit of a conventional CT [12]

Table 1. Parameter in equivalent circuit of ideal CT

Parameters in Figure 1			
$V_s$	Secondary excitation voltage	$V_B$	CT terminal voltage across burden
$I_p$	Primary current	$Z_E$	Excitation impedance
$I_{ST}$	Total secondary current	$R_s$	Secondary resistance
$I_s$	Secondary load current	$X_L$	Leakage reactance
$I_E$	Excitation current		(Negligible in Class C CTs)
$N_2/N_1$	CT turn ratio	$Z_B$	Burden impedance

$$R_L = \rho \times \left( \frac{l+250}{s} \right) \tag{1}$$

$$R_{B'} = (2 \times R_L) + R_{r2} \tag{2}$$

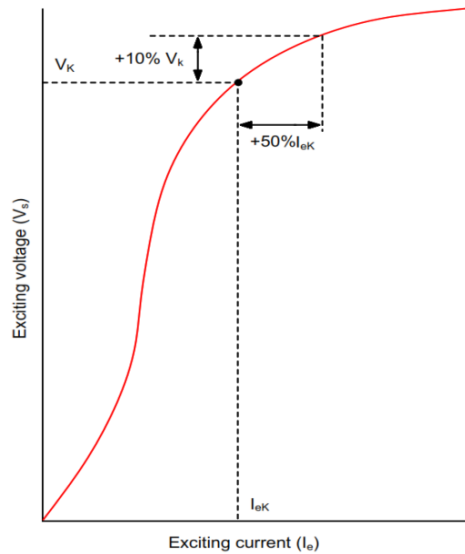


Figure 2. CT performance according to knee point voltage ( $V_k$ ) [9]

$$V_K = K_x \times (R_s + Z_B) \times I_n \tag{3}$$

$$E_{al} = K_{SSC} \times K_{td'} \times (R_s + Z_B) \times I_n \tag{4}$$

In this case,  $K_x$  is dimensioning factor of the CCT,  $I_n$  is nominal secondary current,  $K_{SSC}$  equal to symmetrical short circuit current factor, and  $K_{td'}$  represents actual transient period dimensioning factor. On that account, knee point voltage would determine the maximum current measurement limit before it reaches saturation, and the rated burden value would limit the external load on its secondary side [9], [12]. On the other hand,  $V_K$  should never exceed secondary circuit electromagnetic field ( $E_{al}$ ) as well. For example,

protection class CT expressed with 40VA Class 5P20 means that it has rated burden of 40 VA, accuracy class of 5P and ALF of 20. A different approach used for TPX, TPY, and TPZ class which mention  $V_K$ ,  $I_{eK}$ , and secondary winding resistance on CT specification. In detail, the technical design and performance parameters of the CCT in this paper are calculated according to IEC 61869-2 [10].

## 2.2. Optical current transformer

The technology of fibre optic (FO) has helped rapid development of non-conventional instrument transformer including OCT. It is obvious that the OCT has important advantages over CCT [13] thus providing proven solution for future substation [14]. In this case, incorporation of the optical sensor allows a smaller dimension and lighter weight that would not be significantly influenced by the power rating, ratio, and insulation level of the whole OCT [9], [15]. The basic design of an optical sensor used in the OCT has been discriminated in two structures which are the hybrid and the all-optical sensor as follows [9], [16]. The hybrid sensor type in Figure 3(a) and (b) uses a conventional electrical circuit such as the magnetic concentrator or CCT that is coupled into an optically isolated converter system [9]. Apart from that, the all-optical sensor uses optical sensing principles such as optical path around the measured conductor, fibre optic, or witness sensor [16]. In all-optical model, the current measurement process relies on the sensitivity of an optical sensing material such as glass, crystals, or plastics to electric and magnetic fields that affect the polarisation of light beam passed through these materials [9] as shown at Figure 3(c) and (d).

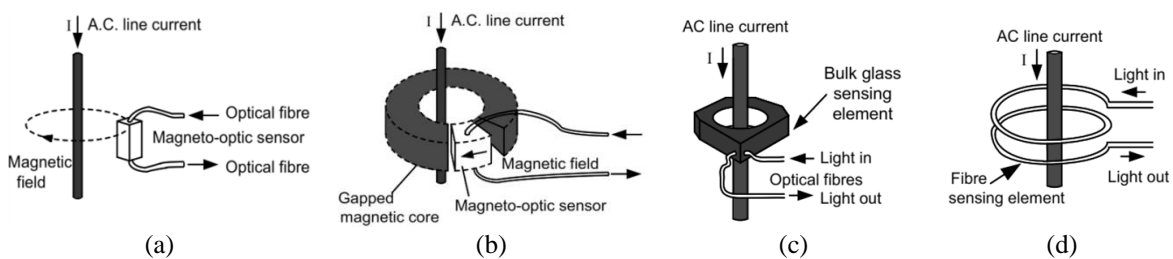


Figure 3. Basic design of (a) a free field type, (b) a field-shaping type sensor on hybrid OCT, (c) optical path approach and (d) all-fibre optic sensor on all-optical CT [9]

Although the operating principle of an OCT could be completely different with CCT depends on the structure type, its operational and design requirements such as accuracy, maximum transient current, and insulation level would be according to the same standard such as the superseded IEC 60044-8 [17] and the new IEC 61869-2 [10]. Moreover, the output of the OCT on the secondary terminal could be an analogue voltage, an analogue current, or digital signal in IEC 61850-9-2 sampled value format depends on the project requirement [15], [18].

## 3. PROTECTION SCHEME OF HYBRID TRANSMISSION LINE

### 3.1. Concept of hybrid transmission line

Power system transmission over a far distance has been shaped since the inauguration of the Miesbach-Munich 2 kV direct current (DC) OHL in 1882 [19]. As the system develops, both DC and alternating current (AC) transmission has been incorporated around the world to electrify the civilisation ever since. Nowadays modern electrical power system engineering balances performance, reliability, and cost. As a result, HTL has been formed by combining OHL and HV cable in one transmission line.

Combination of an HV OHL and cable altogether in one circuit of a transmission line would mostly benefit on its installation flexibility in any power grid configuration. The benefit of less installation area and better insulation from the cable and less cost from the OHL would fit to reduce installation cost and provide better aesthetic value in an urban area. In this case, placement of OHL and cable section along the HTL can be varied depends on requirement as common scenarios depicted in Figure 4.

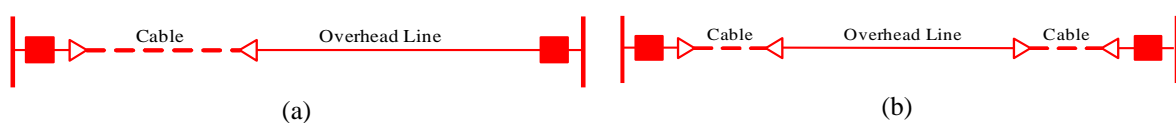


Figure 4. General arrangement of the hybrid transmission line with (a) one and (b) two cable sections

**3.2. Protecting hybrid transmission line**

As the HTL would physically combine normal OHL and HV cable circuit, its protection scheme would be similar with a normal OHL or cable transmission. In this case, various protection scheme with LCD or distance protection has been used on hundreds of operational HTLs worldwide by considering each own advantage and shortcoming. Common main protection scheme for HTL would be the same with a normal transmission line by employing LCD or distance protection with two measurement point on both endpoints as depicted in Figure 5. High-speed auto recloses could be enabled in condition when the cable section only 15 to 25% of the total HTL length [2]. Otherwise, auto reclose would need to be disabled due to a higher possibility of permanent fault on the cable section.

The use of distance protection would lead to bigger inaccuracy due to impedance non-uniformity along the HTL [1]. A fault location determination problem also occurred on the LCD protection as it could not provide exact fault location although it could provide reliable unit protection for any fault along the protected HTL. Consequently, more complex protection scheme with three measurement points has been used to resolve this problem as shown in Figure 6.

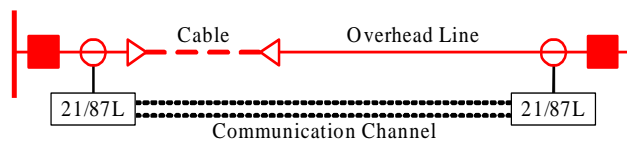


Figure 5. Distance protection or LCD protection on HTL with 2 CT [2], [3]

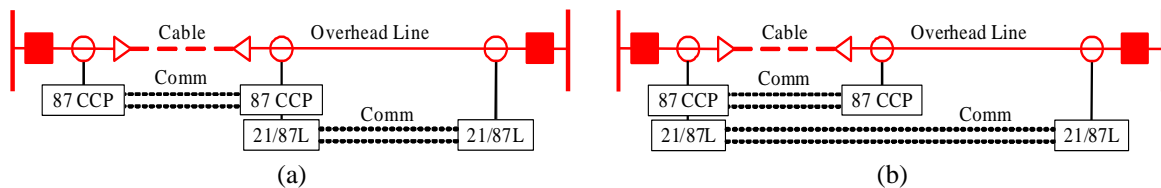


Figure 6. Incorporation of CCP for cable section with distance protection or LCD protection to protect (a) OHL section only and (b) the whole length of HTL [2], [3]

In the case of the three-measurement points scheme, employment of CCP on the HV cable section could be used to determine the operation of the AR scheme on the HTL. Once the CCP of the cable section detects an internal system fault, it would send AR block signal to the LCD or distance relay, hence the relay would not initiate AR order to the CB. The opposite scenario occurred when the CCP detects an external fault, where the LCD or distance relay in the HTL would detect and isolate the fault then initiates AR to the CB.

**4. METHODOLOGY**

This paper proposes the use of optical CT with IEC 61850-9-2 sampled value compatibility to replace the conventional CT to have flexible current measurement placement along the hybrid transmission line. In the case of potential protection scheme for the HTL, the current measurement would be a critical issue. Therefore, any technical advantages or drawbacks due to the technical characteristic of a CT would affect performance, technical design, and structure of the protection scheme on the HV cable section. Technical comparison in Table 2 summarises benefit and drawback of each available schemes to provide suitable protection for the HTL. It shows that the three-measurement points method which combines LCD (87L) and 87 CCP provides the most selectivity as it could precisely detect the fault location at cable section thus blocks the AR initiation.

Due to this advantage, the 87L+87 CCP scheme is employed on the HTL with one set of a three-phase CT installed on the junction point between the OHL and the HV cable section. So, the CT needs to be tough and flexible enough to be installed in the middle of a transmission line. In detail, this paper investigates the technical consideration of both conventional and OCT for CCP scheme in an Indonesian 150 kV HTL with a 50 Hz of frequency, short circuit current rating of 40 kA, assumed system impedance ratio ( $X_s/R_s$ ) of 30, and rated CT ratio of 1000:1 A. Technical consideration of the conventional CT to determine its limit is obtained by calculating the feasible burden and the longest copper wire between the CT and the protective relays according to [10], [11]. On the other hand, technical consideration to determine the feasible performance of the optical CT is acquired according to the test result performed by GE following to the IEC 61869-2 standard [10].

Table 2. Technical comparison of protection scheme on hybrid transmission line

Measurement Scheme	Protective Relay	Auto Reclose	Benefit	Drawback
2 points	Distance protection (21)	Fully blocked	Simple, reliable, and cost effective	Less accuracy
2 points	Line current differential (87L)		Selective and reliable	More expensive while doesn't have fault locator
3 points	Distance protection (21) + 87 CCP	Blocked for fault at cable section	Selective on the cable section and more reliable	More expensive and complex
3 points	Line current differential (87L) + 87 CCP		The most selective and reliable	The most expensive

## 5. RESULTS AND DISCUSSION

### 5.1. Incorporation of conventional current transformer

As the conventional CT operates using electromagnetic principle, its secondary current distribution would rely on circuits of conventional copper wire. In this case, parameters of the CCT used for calculation are displayed in Table 3 while the circuit parameters on the secondary side of the CCT are mentioned in Table 4. Referring to section 3.1, burden impedance ( $Z_B$ ) would be assumed as equal to resistive burden ( $R_B$ ) since the secondary circuit of the CCT would consist of copper wire and a protective relay.

Furthermore, the technical design and performance parameters of the CCT are calculated according to [10], [11]. When the total resistive burden ( $R_{B'}$ ) is less than the rated resistive burden ( $R_B$ ) and the knee point voltage ( $V_K$ ) does not exceed actual electromagnetic field ( $E_{al'}$ ) in the core, the CCT would be technically suitable to be installed for the HV cable section. To know the maximum length of a cable section that is technically suitable to use a CCT for CCP purpose, In (1) to (4) were repeated until the total resistive burden ( $R_{B'}$ ) exceed the rated  $R_B$  and the  $V_K$  surpass the  $E_{al'}$  of the CCT. Also, the calculation also performed in two cases, which is using  $6 \text{ mm}^2$  (10 AWG) and  $10 \text{ mm}^2$  (7 AWG) wire of the CCT as the result shown in Table 5 and Table 6. Further, these two wire sizes were chosen to demonstrate the impact of different wire size used for analogue current signal in the substation to reduce the connected burden [20].

In this case, Table 5 shows that the CCT would not be technically appropriate to be used in an HV cable section more than 690 m for a  $6 \text{ mm}^2$  wire as the total resistive burden ( $R_{B'}$ ) surpass the rated resistive burden ( $R_B$ ) of the CT although the knee point voltage ( $V_K$ ) remains less than the electromagnetic field ( $E_{al'}$ ) of the core until 2455 m. On the other hand, incorporation of a  $10 \text{ mm}^2$  wire that has less resistance than the  $6 \text{ mm}^2$  wire would double the length of the HV cable section up to 1150 m as shown in Table 6. However, this length is considered as relatively short since a normal cable-based transmission line could be in the range up to tens of km. Moreover, the facts shown in Table 5 and Table 6 verifies that a larger cross-section area on the secondary circuit would reduce the total burden that would lead to a longer HV cable section. However, this larger wire on the secondary circuit of conventional CT would lead to another technical problems such as thicker and heavier instrument cable, less flexible installation condition, and more expensive installation cost on the conventional CT and the cable itself.

Table 3. Technical specification

Parameter	Value
Accuracy Class	TPX
Rated Resistive Burden ( $R_B$ )	$5 \Omega$
Secondary Winding Resistance ( $R_S$ )	$10 \Omega$
Magnetization Current ( $I_m$ )	40 mA
Dimensioning Factor ( $K_x$ )	65
Transient Dimensioning Factor ( $K_{td}$ )	11.5
Duty cycle	C-70 ms-O

Table 4. Secondary circuit parameter of the conventional CT

Parameter	Value
Relay resistance ( $R_{r2}$ )	$0.2 \Omega$
Relay operating time ( $t_{al}$ )	30 ms
Copper resistivity ( $\rho$ )	$0.0204 \Omega \text{mm}^2 \text{m}^{-1}$
Cable cross section (S)	$6 \text{ mm}^2$ and $10 \text{ mm}^2$

Table 5. Total burden and knee point voltage of the studied CCT for varied length of HV cable section with 6 mm<sup>2</sup> secondary circuit

Distance (m)	Rated Burden R <sub>B</sub> (Ω)	Total Burden R <sub>B'</sub> (Ω)	E <sub>al</sub> (Volt)	V <sub>K</sub> (Volt)	Remarks
250	5.00	2.01	1236	768	Total burden < Rated burden
500	5.00	3.71	1331	878	Total burden < Rated burden
690	5.00	5.00	1395	962	Total burden = Rated burden
750	5.00	5.41	1413	989	Total burden > Rated burden
1000	5.00	7.11	1485	1099	Total burden > Rated burden
1250	5.00	8.81	1546	1210	Total burden > Rated burden
2455	5.00	17.01	1742	1742	Total burden > Rated burden, V <sub>K</sub> = E <sub>al</sub>
3750	5.00	25.81	1838	2315	Total burden > Rated burden, V <sub>K</sub> > E <sub>al</sub>
4500	5.00	30.91	1864	2646	Total burden > Rated burden, V <sub>K</sub> > E <sub>al</sub>

Table 6. Total burden and knee point voltage of the studied CCT for varied length of HV cable section with 10 mm<sup>2</sup> secondary circuit

Distance (m)	Rated Burden R <sub>B</sub> (Ω)	Total Burden R <sub>B'</sub> (Ω)	E <sub>al</sub> (Volt)	V <sub>K</sub> (Volt)	Remarks
250	5.00	1.33	1194	724	Total burden < Rated burden
500	5.00	2.35	1256	790	Total burden < Rated burden
750	5.00	3.37	1313	856	Total burden < Rated burden
1000	5.00	4.39	1365	922	Total burden < Rated burden
1150	5.00	5.00	1395	962	Total burden = Rated burden
2500	5.00	10.51	1599	1320	Total burden > Rated burden
3750	5.00	15.61	1718	1652	Total burden > Rated burden
4090	5.00	17.00	1742	1742	Total burden > Rated burden, V <sub>K</sub> = E <sub>al</sub>
4500	5.00	18.67	1767	1851	Total burden > Rated burden, V <sub>K</sub> > E <sub>al</sub>

**5.2. Improvement with optical current transformer**

Since the first development of photonic sensor in 1967 [21], a high degree of technology maturity [22], long-term reliability [23], simplicity, lighter weight, installation flexibility, measurement accuracy, worldwide standard compliance [15], and the digital substation compatibility [9] has led the optical CT which uses fibre optic technology to be easily adapted in a modern power grid despite its more expensive investment cost than conventional CT [18], [24], [25]. Unlike the CCT that operates according to the electromagnetic principle on its winding and highly affected by the existence of the flux across its core, the OCT would not be affected by external burden or knee point voltage limit [9].

As shown in Table 7, wide current and frequency bandwidth on the OCT is combined with accuracy, performance, and design parameters according to [10]. To guarantee its performance in digital substation, [15] states that OCT shall have an anti-aliasing filter with a bandwidth of one-third or one-fourth of its sampling rate. Furthermore, [26] defines that all protection classes of digital CT shall have ≥20 dB of anti-aliasing filter attenuation. Previous studies and field tests also show that OCT has various useful applications in power system [27] while also had performed satisfactorily for digital measurement [22], CCP protection [28], and LCD protection [29], even in various temperature conditions [30]. Test result on GE's OCT in Table 8 [31] shows that magnitude and phase accuracy of the proposed OCT would satisfy required error limits in [10]. Result of short circuit withstand test shown in Table 9 and Figure 7 shows that the proposed optical CT could satisfy the referred standard in [11]. Consequently, the optical CT would perform better than the conventional CT as it would have satisfying accuracy level with more compact design, flexible dimension, and higher measurement limit thus having more flexible dynamic measurement range [32].

Table 7. Technical specification of the optical CT

Parameter	Value
Accuracy class (protection)	5P (IEC 61869-2)
Accuracy class (metering)	0.2s (IEC 61869-2)
Ratedration (A)	1000:1
Current bandwidth (kA)	0.01-160
Frequency bandwidth (Hz)	10-3000
Interface	Single mode fibre optic
Protocol	IEC-61850-9-2LE
Degreebof protection	IP 66

Table 8. Record of the accuracy test on the proposed optical CT [31]

Test Level (%)	Reference (A)	Test CT (A)	Magnitude Error (%)	Phase Error (deg)	Phase Error (min)	Remarks
200	2006.90	2010.10	0.16%	-0.03	-1.8	Error <1% and 60 min, comply IEC 61869-2
200	2008.80	2012.40	0.18%	-0.03	-1.8	Error <1% and 60 min, comply IEC 61869-2
200	2006.80	2011.00	0.21%	-0.03	-1.8	Error <1% and 60 min, comply IEC 61869-2
100	1003.60	1003.70	0.01%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
100	1003.70	1003.90	0.02%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
100	1003.70	1004.00	0.03%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
50	498.90	500.00	0.22%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
50	498.00	499.10	0.22%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
50	499.20	500.30	0.22%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2
5	51.18	51.50	0.63%	-0.09	-5.4	Error <1% and 60 min, comply IEC 61869-2
5	51.18	51.37	0.37%	-0.08	-4.8	Error <1% and 60 min, comply IEC 61869-2
5	51.21	51.16	0.10%	-0.02	-1.2	Error <1% and 60 min, comply IEC 61869-2

Table 9. Record of the short circuit withstand test on the proposed optical CT [31]

Test current	Waveform	Physical	Remarks
30 kA, 2 sec	No disturbance or saturation	No sign of damage	comply IEC 61869-6
50 kA, 3 sec	No disturbance or saturation	No sign of damage	comply IEC 61869-6
63 kA, 1 sec	No disturbance or saturation	No sign of damage	comply IEC 61869-6
216 kA, 10 cycles	No disturbance or saturation	No sign of damage	comply IEC 61869-6

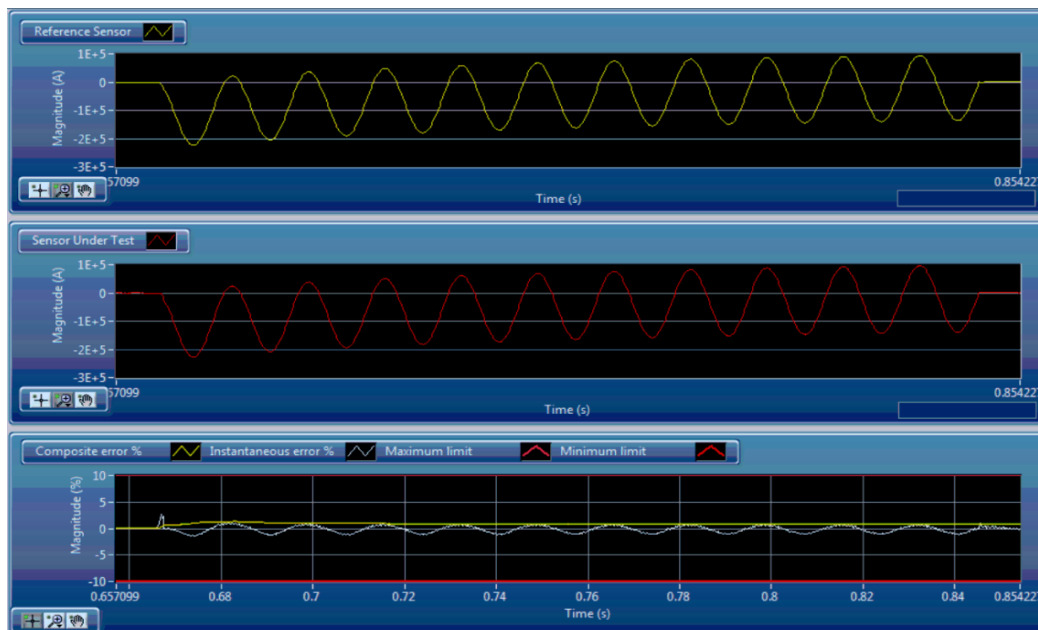


Figure 7. 216 kA transient current test for 10 cycles on the proposed optical CT [31]

Moreover, incorporation of an all-optical transducer would lead to a fully passive sensing system that would withstand any losses due to eddy current or winding magnetisation [13]. Consequently, the use of IEC 61850-9-2 sampled value for a communication protocol between the OCT with merging unit (MU) and any kind of intelligent electronic devices (IED) using fibre optic interface would be preferable due to its accuracy, simplicity, immunity to electrical losses, and immunity to signal interference [33].

In case of using OCT on the CCP scheme in HTL, the OCT would need to be installed at the junction point between HV cable and the OHL section that might be far from the substation. So, an industrial OCT could be used for that purpose as it would be able to communicate up to 10s of km without signal repeater or virtually unlimited using signal repeater [18] and installed hanging on the OHL tower or an HV cable dead-end bushing due to its compactness [34], [35].

In detail, the maximum length of fibre optic cable between the optical CT box and the merging unit or IED in the substation could be calculated with power budget analysis according to [36] using output power of the



optical CT [31], typical losses parameters [36], and the IED’s optical input cut-off power [37]. This case assumes that the CCP scheme for the cable section utilise the GE MiCOM P64x IED with 9/125-µm 1300 nm single mode fibres for communication connection using sampled value with IEC 61850-9-2 protocol [37]. Table 10 clearly shows the 6.72 dB as total power margin including the typical power cut-off on the GE MiCOM P64x IED. Further, the 6.72 dB total power margin is divided with the attenuation per kilometre of the optical fibre cable between the optical CT and the protection IED to obtain the maximum length that would be technically feasible.

Table 10. Power margin between the optical CT and IED in substation

	Component	Quantity	dB
Power	OCT Output	1	25.52
	Connector losses	2 @ 0.5 dB/connector	-1.00
	Mechanical splice	2 @ 0.5 dB/ splice	-1.00
	Patch panels	2 @ 0.5 dB/ panel	-1.00
Losses	Dispersion margin	1	-1.00
	Optical safety and repair margin	1	-3.00
	IED optical input cut-off	1	-11.80
	Total Power Margin		6.72

By assuming the use of SMF graded index 9/125-µm cable at 1300 nm with attenuation level of 0.5 dB/km, total distance between the protection IED and the optical CT MU box can be calculated as follows:

$$Optical\ Distance = \frac{Total\ Power\ Margin}{Attenuation\ of\ Optical\ Cable} = \frac{6.72\ dB}{0.5\ dB/km} = 13.44\ km \tag{5}$$

Moreover, the optical distance on (5) clearly shows that the optical CT would technically satisfying for the proposed protection scheme due to its longer maximum distance. Furthermore, due to those many potential advantages, the OCT has been chosen to be incorporated on a pilot project in a new Indonesian 150 kV HTL between Pasar Kemis and Gajah Tunggal substation with ±2.5 km HV cable section as shown in Figure 8. This project uses a modified three-measurement points protection scheme that combines CCP and LCD protection as discussed in Section 3.2 and depicted in Figure 6(b). In this design, the 87 CCP relay would send an AR block signal to the 87L relay on both substations for any fault in the HV cable section and a direct transfer trip (DTT) signal to local CB and remote substation as shown in Figure 8. In short, the existence of the OCT at the junction points between OHL and the HV cable section would significantly improve the selectivity and performance of the HTL protection since the power grid operator could enable AR scheme for fault in the OHL section.

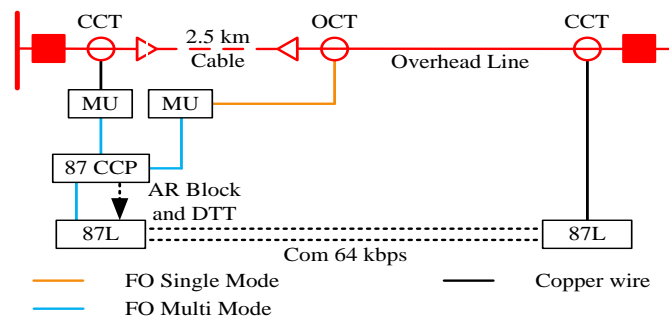


Figure 8. Combination of conventional and optical CT for protection scheme of a 150-kV HTL

## 6. CONCLUSION

This paper aims to investigate the effect of using OCT to replace CCT in an HTL to improve its performance in terms of activating the auto reclose scheme and having a longer cable section in the high voltage circuits. The three-measurement points protection scheme with CCP on the HV cable section has been chosen to be studied and implemented due to its better selectivity for any fault on the OHL and HV cable section of the HTL. In the case of a relatively short HV cable section which is less than or equal to 690 m and 1150 m for 6 mm<sup>2</sup> and 10 mm<sup>2</sup> secondary current circuits respectively, the CCT would operate within its rated burden value and knee point voltage during normal operation and fault condition. Therefore, the CCT would be technically suitable to be used as a measurement unit on all three measurement locations along the HTL only for this relatively short length. On the other hand, the use of an OCT complies with the accuracy and performance requirements in IEC 61869-2 and IEC 61869-6 with digital measurement data exchange method according to

the IEC 61850-9-2 sampled value standard protocol would drastically affect the three-measurement points protection scheme on the HTL. In this case, the power budget analysis has shown that the placement location of the current measurement points between the OHL and cable section could be prolonged up to 13.44 km from the substation via single-mode fibre optic cable without any single signal repeater.

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