

Virtual Difference Voltage Scheme for Fault Detection in VSC-HVDC Transmission Systems

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Abstract—In this paper, a fast fault detection scheme for voltage source converter based high-voltage direct current (VSC-HVDC) transmission systems is proposed. Based on Bergeron model equations, the remote terminal voltage of an adopted transmission system is calculated in terms of the local measured current and voltage signals. Subsequently, the computed voltage of the remote terminal is compared with the corresponding actual measured-communicated value. Provided that the considered transmission system is functioning well, the difference between the computed and measured voltages is almost zero. However, a considerable virtual voltage arises for fault conditions. When the voltage difference exceeds a predetermined threshold, a fault condition can be detected. Although a reliable communication link is required, the delay for detecting the fault is not caused by the communication time. For evaluation purpose, a detailed simulation is developed using PSCAD/EMTDC with various fault locations, including the cases near the inside or outside of the protected transmission system. The results corroborate a fast detection scheme depending on a moderate sampling/processing frequency level. A high security level is verified even with the worst external faults, or with the misaligned measured samples at the terminals. This corroborates the suitability of the proposed scheme for protecting multi-terminal HVDC systems.

Index Terms—Fault detection, high-voltage direct current (HVDC), voltage source converter (VSC), transmission system.

I. INTRODUCTION

HIGH-VOLTAGE direct current (HVDC) transmission systems are considered to be a promising scheme for connecting unsynchronized power systems or transmitting bulk power over long distances [1], [2]. Voltage source converter (VSC) based schemes are more distinctive compared with conventional current source converter (CSC) based schemes. They are characterized by their decoupled control features between active and reactive power components, the non-requirement for reactive power compensation, and the feasibility of multi-terminal operation [3]–[7].

Regarding protection issues, VSC- and CSC-based schemes are different. Unlike most VSC types, CSC units can control the current into the DC side under DC fault conditions. Hence, DC fault cases with the VSC schemes should be detected quickly [8], [9]. Moreover, reliable approaches are still required to discriminate the faulty line in multi-terminal systems [10]–[12].

Different schemes have been proposed to provide fault detection with the capability of localizing faulty lines in multi-terminal DC systems [13], [14]. These schemes are based on the derivative of the local measured voltage at the line side of current-limiting inductors. These schemes cannot be applied without reactors at the terminals.

To realize a selective fault detection approach, some schemes have been proposed depending on the differential protection concept based on communication channels between line terminals [15], [16]. The most typical problem in using the communication system is the delay for transferring data between terminals.

Other methods require high sampling frequencies, such as those depending on wavelet analysis [17]–[19]. The requirement of high-frequency handling is not recommended owing to the need for processing units with high-frequency capabilities.

The proposed scheme is based on the Bergeron model of the transmission system. This model has been utilized successfully in different applications for protection, particularly with HVDC systems [20], [21]. As reported in [20], the fault location can be determined using model equations. It involves the calculation of voltage distribution along the length of the transmission system based on monitored signals at the end. Two voltage distribution profiles are obtained based on the calculations at both terminals of the transmission system. The fault location is the point at which the voltage distributions from both ends are identical. However, this approach is inappropriate for online fault detection owing to its long execution time.

Another current differential protection principle has been presented in [21] based on the current distribution along the transmission system through Bergeron line modeling. A specific point should be selected appropriately along the transmission system. Subsequently, the current at this point is calculated in terms of the measured signals at each end of the transmission line. When the current difference between the calculated currents exceeds the predetermined threshold, a

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fault condition is recognized. This scheme is suitable for CSC systems, where a large tripping time is included. However, it is not suitable for VSC schemes as the fault detection should be rapid.

This paper presents a fast detection approach for DC faults in VSC-HVDC transmission systems. It has been validated that there is no requirement for high sampling or processing frequency, where 10 kHz is adopted. Moreover, the proposed approach is the unit type, which does not operate for external faults even if it is immediately beyond the line terminals. Consequently, the proposed approach can be applied to multi-terminal systems with the capability of discriminating the faulty line only. Moreover, the proposed approach is suitable for systems with or without boundary inductors. Although it is based on a communication system, the data transfer time does not represent a delay for detecting the fault. This is primarily because the proposed approach is designed such that the data transfer time does not represent a delay, particularly with underground cable systems.

II. PROPOSED FAULT DETECTION APPROACH

A. Fault Detection Criterion

The proposed approach has been derived considering the representation of the transmission system with the Bergeron line model. The voltage of one terminal of the transmission system is calculated as a function of the monitored current and voltage signals at the other terminal. The calculated voltage is equal to the measured value provided that the transmission system is functioning well. If a fault exists in the transmission system, the calculated voltage would be virtual, which differs from the actual measured value. This is because the calculations are based on a well-functioning line equivalent circuit. Based on this criterion, the proposed fault detection approach is designed.

For the selected line or cable segment, the two terminals are designated by J and K . Taking terminal K as an example, the voltage difference would be:

$$\Delta V_K = |V_{K, \text{calculated}} - V_{K, \text{measured}}| \quad (1)$$

where ΔV_K is the voltage difference of terminal K ; $V_{K, \text{calculated}}$ is the calculated voltage of terminal K obtained through the Bergeron model equation as a function of the monitored signals at terminal J ; and $V_{K, \text{measured}}$ is the measured voltage of terminal K , which represents the actual value. Furthermore, $\Delta V_K = 0$ implies that the line or the cable is functioning well. With the occurrence of fault, ΔV_K would be a certain value depending on the fault condition.

Both terminals of the transmission system are considered with two voltage differences, one for each terminal, ΔV_K and ΔV_J . The proposed fault detection approach depends on the monitoring of both values to verify the condition of the transmission system.

B. Transmission System Model

The Bergeron model for calculating the voltage of termi-

nal K in terms of the voltage and current at terminal J is given as:

$$\begin{aligned} V_{K, \text{calculated}}(t-\tau) = & \frac{1}{2} \left(\frac{Z_c + \frac{rl}{4}}{Z_c} \right)^2 \left[V_J(t) - i_{JK}(t) \left(Z_c + \frac{rl}{4} \right) \right] + \\ & \frac{1}{2} \left(\frac{Z_c - \frac{rl}{4}}{Z_c} \right)^2 \left[V_J(t-2\tau) + i_{JK}(t-2\tau) \left(Z_c - \frac{rl}{4} \right) \right] - \\ & \left(\frac{rl}{4Z_c} \right)^2 V_J(t-\tau) - \frac{rl}{4} \frac{Z_c + \frac{rl}{4}}{Z_c} \frac{Z_c - \frac{rl}{4}}{Z_c} i_{JK}(t-\tau) \end{aligned} \quad (2)$$

where Z_c is the characteristic impedance of the transmission line or cable; r is the resistance per unit length; l is the length of the transmission line or cable; τ is the traveling duration for the traveling wave to propagate along the entire length; V_J is the measured voltage at terminal J ; and i_{JK} is the measured current at terminal J flowing toward the other end.

Considering the other terminal (terminal J), (3) is used to calculate the voltage of terminal J in terms of the measured signals at terminal K .

$$\begin{aligned} V_{J, \text{calculated}}(t-\tau) = & \frac{1}{2} \left(\frac{Z_c + \frac{rl}{4}}{Z_c} \right)^2 \left[V_K(t) - i_{KJ}(t) \left(Z_c + \frac{rl}{4} \right) \right] + \\ & \frac{1}{2} \left(\frac{Z_c - \frac{rl}{4}}{Z_c} \right)^2 \left[V_K(t-2\tau) + i_{KJ}(t-2\tau) \left(Z_c - \frac{rl}{4} \right) \right] - \\ & \left(\frac{rl}{4Z_c} \right)^2 V_K(t-\tau) - \frac{rl}{4} \frac{Z_c + \frac{rl}{4}}{Z_c} \frac{Z_c - \frac{rl}{4}}{Z_c} i_{KJ}(t-\tau) \end{aligned} \quad (3)$$

As mentioned previously, the Bergeron model represents the core of many algorithms developed for transmission systems. The Bergeron model is based on the traveling wave equivalent circuit. The transmission system is represented by two sections of ideal circuits. The losses are considered by including the resistance as a lumped parameter element with four parts, as shown in Fig. 1. Based on the traveling waves along the lossless sections, the model equations can be derived [20]–[23].

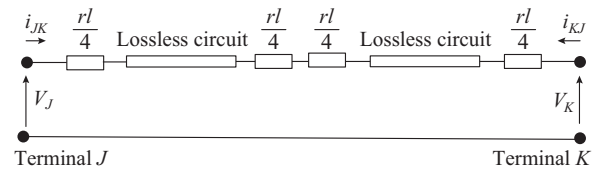


Fig. 1. Equivalent circuit of Bergeron model.

It is noteworthy that all the calculations herein are executed by employing the aerial mode parameters of the transmission system (1-mode). The aerial mode topology has been utilized as it provides a decoupled circuit without the mutual

coupling effect between positive and negative poles [20]–[23]. To obtain 1-mode signals as a function of the positive and negative signals, the following calculation is performed.

$$\begin{bmatrix} V_1 \\ V_0 \end{bmatrix} = \mathbf{S}^{-1} \begin{bmatrix} V_p \\ V_n \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} V_p \\ V_n \end{bmatrix} \quad (4)$$

where V_p and V_n are the positive voltage and negative voltage, respectively; $\mathbf{S}$ is the transformation matrix for calculating the modal components; and V_1 and V_0 are the 1-mode and 0-mode voltage components, respectively. It is the same equation for calculating the modal currents. All processing for calculating the voltage difference value are performed based on the 1-mode components, which are more stable than the 0-mode components [20]–[23].

C. Location of Relaying Units

The paper focuses on the strategy of the proposed approach considering one terminal of the transmission system. For terminal K , its voltage can be calculated according to (2). Subsequently, the required voltage and current samples monitored at terminal J are as follows:

- 1) $V_J(t)$ and $i_{JK}(t)$ represent the latest monitored samples at the processing instant t .
- 2) $V_J(t-\tau)$, $i_{JK}(t-\tau)$, $V_J(t-2\tau)$, and $i_{JK}(t-2\tau)$ represent the previously monitored samples before the moment of processing, i.e., at instants $t-\tau$ and $t-2\tau$, respectively.

Owing to the need for the previously monitored samples, storage data windows have been assigned to save the captured voltage and current samples at terminal J with a window size of 2τ . Figure 2(a) presents the data windows for the measured signals V_J and i_{JK} .

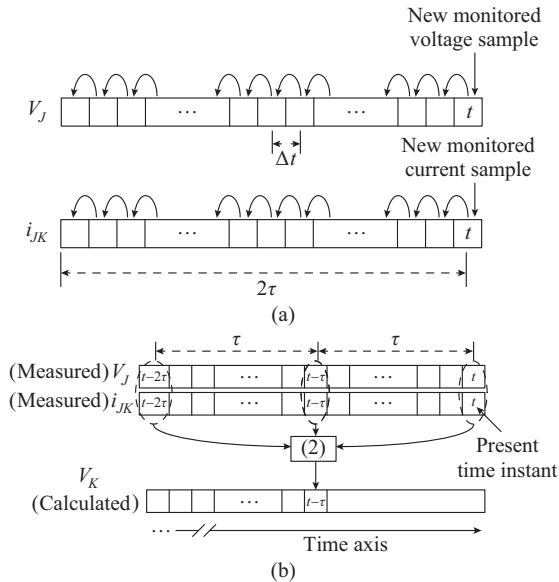


Fig. 2. Calculation process of V_K . (a) Storage data windows for voltage and current signals at terminal J . (b) Corresponding time instants for the employed samples of V_J and i_{JK} and the calculated sample of V_K .

At each time step, the new monitored sample is assigned in the most recent location in the window, and the previously stored samples are shifted back by one sample. Through the calculation process of the voltage of terminal K , the pre-

ceding samples of V_J and i_{JK} at instants $t-\tau$ and $t-2\tau$ can be fetched from these data windows. Figure 2(b) shows the calculation of V_K in terms of the captured samples of the voltage and current signals V_J and i_{JK} , respectively. By conducting the processing at time instant t , the calculated voltage sample corresponds to the preceding instant of $t-\tau$ prior to the instant of processing by the traveling wave time duration τ .

After obtaining the calculated voltage, its value was compared with the actual measured value. Therefore, the voltage difference ΔV_K is determined. The processing or relaying unit used to calculate ΔV_K is located near terminal J . The calculated voltage sample $V_{K, \text{calculated}}(t-\tau)$ is obtained as a function of the local measured signals $V_J(t)$ and $i_{JK}(t)$. The measured voltage sample $V_{K, \text{measured}}(t-\tau)$ is transmitted via the communication channel because it is monitored at the other remote end, which is shown in Fig. 3(a). As depicted in the corresponding table in Fig. 3(a), the measured voltage sample $V_{K, \text{measured}}(t-\tau)$ is available at terminal J at time instant t after being transmitted via the communication channel, as it has been measured before the instant of processing in duration τ . The time span between moments $t-\tau$ and t is exploited for transmitting the data via the communication system. Accordingly, the problem of communication time delay is mitigated. Provided that the communication time is equal to or shorter than the duration of the traveling wave time τ , a delay will not occur owing to the communication for calculating $\Delta V_K(t)$ and detecting the fault. This point will be clarified in the subsequent section, where a study regarding the relative speed between the communication system and traveling wave along the power transmission system is provided.

Although both $V_{K, \text{measured}}(t-\tau)$ and $V_{K, \text{calculated}}(t-\tau)$ correspond to a previous instant, i.e., $t-\tau$, the later is obtained in terms of the voltage and current samples at instant t , i.e., $V_J(t)$ and $i_{JK}(t)$. This implies that any recent disturbance at instant t would be reflected on the calculated voltage sample $V_{K, \text{calculated}}(t-\tau)$, which consequently affects the voltage difference value $\Delta V_K(t)$. Although the voltage difference ΔV_K is calculated in terms of the samples that correspond to the previous instant $t-\tau$, a delay would occur when monitoring the system condition.

It is noteworthy that GPS receivers are recommended so as to capture the signals at the line terminals simultaneously. Hence, the time stamping of the monitored samples at the terminals would be with reference to a common clock [24]. Furthermore, the proposed approach has been tested with an alignment error existing between the monitored samples at the line ends. This is presented in Section VII-B.

The aforementioned discussion is with respect to the voltage difference ΔV_K . The other voltage difference value ΔV_J can be calculated similarly using a devoted processing unit located at terminal K , which is shown in Fig. 3(b). The relaying unit installed near terminal K is responsible for calculating ΔV_J by $\Delta V_J = |V_{J, \text{calculated}}(t-\tau) - V_{J, \text{measured}}(t-\tau)|$, where $V_{J, \text{calculated}}(t-\tau)$ is calculated based on local measurement (3), and $V_{J, \text{measured}}(t-\tau)$ is received via the communication.

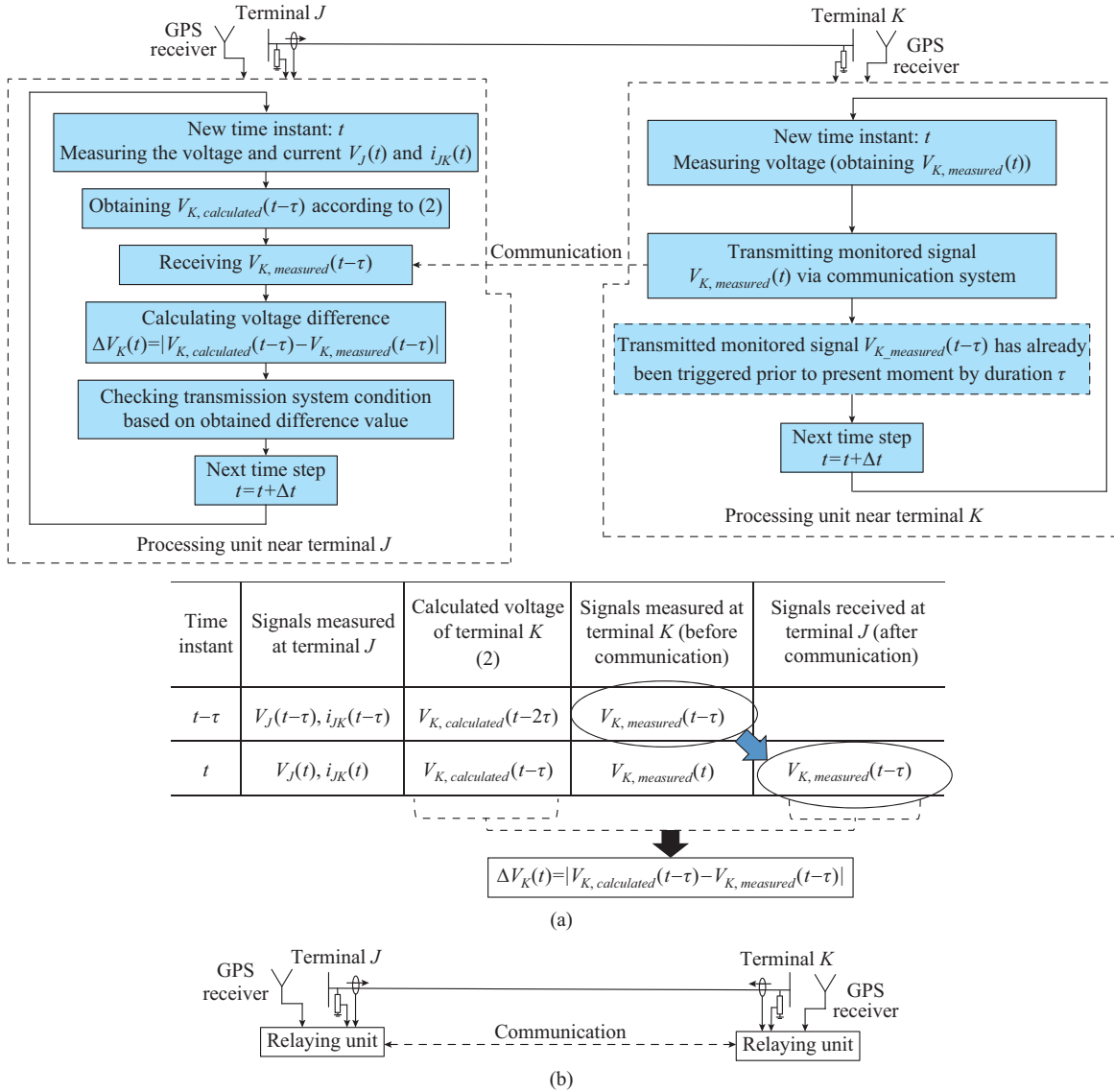


Fig. 3. Proposed approach. (a) Calculation of voltage difference ΔV_K . (b) Required relaying units at terminals J and K for calculating ΔV_K and ΔV_J , respectively.

D. Communication Delay

To verify whether the communication system would result in delay, the relative speed between the communication system and the traveling waves has been analyzed. Both the underground cables and overhead lines are tested. Regarding the recommended communication system, the fiber optic based systems are the most typically used, which require approximately 0.5 ms per 100 km length for data transfer [25], [26]. To determine the speed of the traveling wave along the transmission line or cable, the line constant program in PSCAD environment is utilized. The time required for the traveling wave to propagate along the same length (100 km) is determined for both the underground cable and overhead transmission systems. The configurations of the transmission systems are described in Fig. 4. It is discovered that the traveling time is approximately 0.34 ms for the overhead transmission line and 0.64 ms for the underground cable along the 100 km length, respectively. This means that the data transfer time by the fiber optic scheme is shorter than τ in

the underground cable and longer than τ on the overhead line. If an underground cable is utilized, the communication signal will spend less time than τ to reach the other end. Consequently, the required processing for fault detection will not be delayed owing to the communication. This is considered as a unique advantage of the proposed approach.

Meanwhile, if an overhead line is utilized, a slight delay will occur, which is estimated by the difference between the communication time and the traveling time. For example, it would be 0.16 ms per 100 km ($0.5 - 0.34 = 0.16$ ms) according to the overhead line. This time represents a waiting duration until the required samples to be processed are received, which is acceptable for detecting faults in HVDC systems.

III. EVALUATION OF VIRTUAL VOLTAGE DIFFERENCE

To validate the proposed scheme, a bipolar VSC-HVDC system (± 400 kV) is simulated using the PSCAD/EMTDC program shown in Fig. 5.

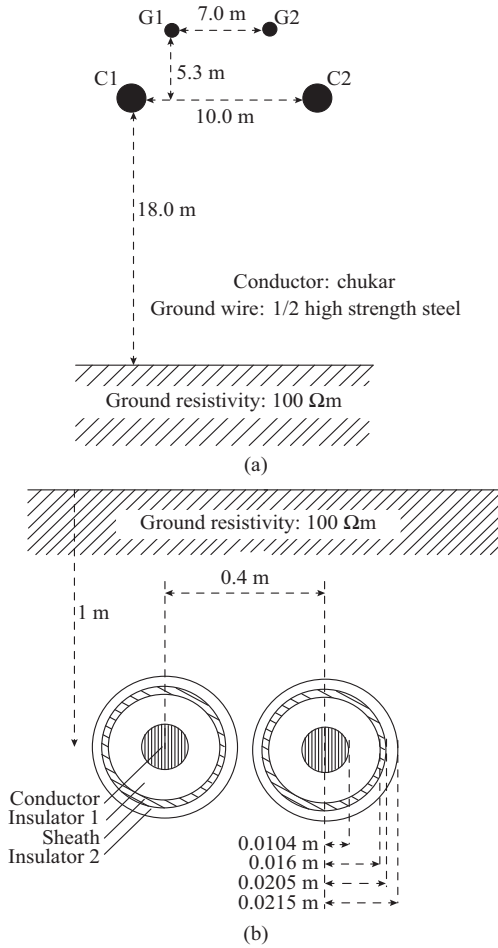


Fig. 4. Employed configurations of transmission systems. (a) Overhead line. (b) Underground cable.

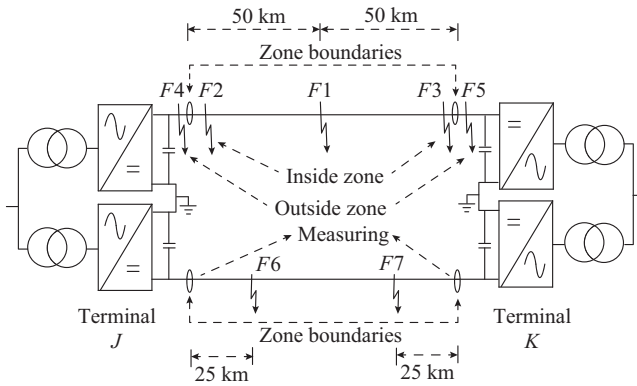


Fig. 5. Two-terminal HVDC system.

The system details are given in Table I. A frequency-dependent model for the employed transmission system is utilized to obtain accurate simulated results. The underground cable configuration in Fig. 4(b) is adopted to represent the transmission system with a 100 km length. The converter units are two-level-based types and represented by their detailed models. It is noteworthy that the boundary inductors are not included in this test system. This will be described in Section VII-C. The virtual voltage differences ΔV_K and ΔV_J are calculated through a MATLAB program. The signals are

monitored with a 10 kHz sampling rate, whereas the solution time step within the simulation is 20 μ s.

TABLE I
DETAILS OF VSC SYSTEM

Component	Item	Detail
VSC unit	Type	Two-level
	DC Capacitance at each converter unit	150 μ F
	AC reactor inductance	0.072 H
	Control mode at terminal <i>J</i>	<i>P-Q</i>
	Control mode at terminal <i>K</i>	V_{DC} - <i>Q</i>
DC cable	Core conductor resistivity	2.82×10^{-8} Ω m
	Length	100 km
	Relative permittivity of 1 st insulator	4.1
	Relative permittivity of 2 nd insulator	2.3
AC transformer	Power rating	250 MVA
	Leakage reactance	0.1 p.u.
	Ratio of each transformer at terminal <i>J</i>	420 kV/230 kV
	Ratio of each transformer at terminal <i>K</i>	500 kV/230 kV
AC system at terminal <i>J</i>	Nominal voltage	420 kV
	Impedance	26.45 Ω
	Impedance phase angle	80°
	Operation frequency	60 Hz
AC system at terminal <i>K</i>	Nominal voltage	500 kV
	Impedance	26.45 Ω
	Impedance phase angle	80°
	Operation frequency	50 Hz

To validate the proposed approach, a severe positive-pole-to-ground fault condition is applied at the middle of the transmission system at *F1*, as depicted in Fig. 5. Figure 6 show the virtual voltage difference values ΔV_J and ΔV_K , considering the fault case. It shows the response of the actual voltage signal along with the calculated one. The inception instant of the applied fault is at 0.6 s. As shown in the results, the calculated voltage signal deviates from the actual measured signal owing to the fault condition. It is noteworthy that both voltage differences yield similar responses, because the selected location of this fault is at an equal distance from both ends of the transmission system.

The response is also performed considering the negative-pole fault condition at the same point (50 km away from terminal *J*). As shown in Fig. 6(c), the response under a negative-pole-to-ground fault condition is similar to that obtained at a positive faulty pole. This is because the voltage difference is calculated considering the 1-mode parameters. The same response is obtained in the aerial mode analysis regardless of the polarity of the pole.

A. Faults Near Terminals

To investigate the selectivity of the proposed approach, the voltage difference values are monitored with the faults, which are extremely close to the line ends, i.e., near the inside and outside of the line zone. As shown in Fig. 5, the zone boundaries are determined by the points at which the signals are monitored, particularly at the current measuring

transducers. First, the proposed approach is tested by considering an internal fault at $F2$, which is severe and near the inside of the line zone. Figure 7 shows both of the voltage differences under this fault case. The calculated voltage of terminal K deviates significantly from the measured one, resulting in an extremely discriminative voltage difference value. As this fault is near terminal J , the voltage difference ΔV_J does not change significantly. As depicted in Fig. 7(b), the calculated voltage follows the measured one without a significant difference. This means that detecting such fault conditions would be flagged by only one of the voltage differences. The same response is obtained with the internal fault condition at $F3$, and the fault would be detected via monitoring the other voltage difference ΔV_J , which will be discussed in detail in Section VI.

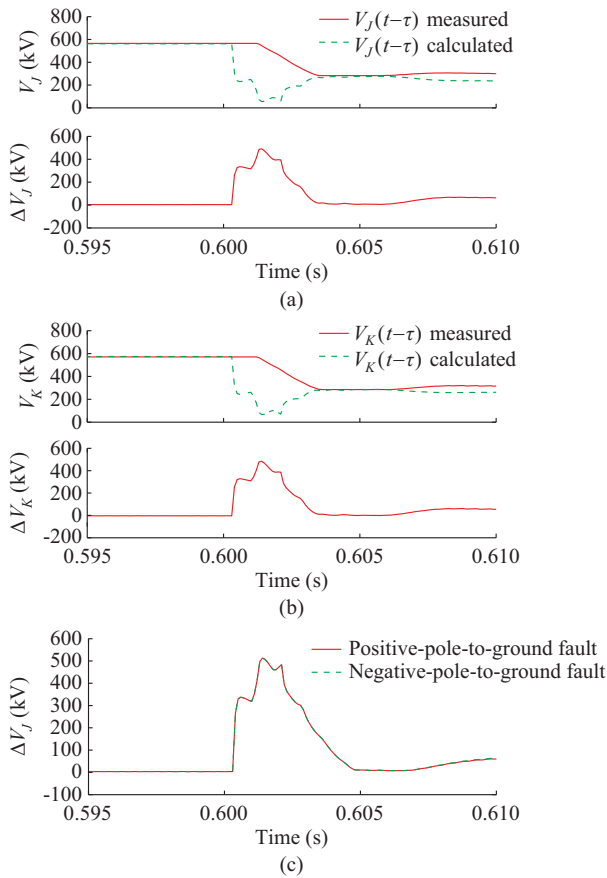


Fig. 6. Transient response of virtual voltage differences with pole-to-ground fault at $F1$. (a) Voltage and voltage difference of 1-mode components at terminal J . (b) Voltage and voltage difference of 1-mode components at terminal K . (c) Responses to both positive- and negative-pole-to-ground faults.

The voltage differences are verified for external severe faults near the outside of the line zone (i.e., $F4$ or $F5$). Figure 7(c) and (d) present the response to the fault at $F5$. As depicted from the results, both difference values do not differ significantly as the calculated voltage is similar to the measured one. This is a unique advantage of the proposed approach as it facilitates in providing a highly secure scheme, where maloperations are avoided even with severe external faults.

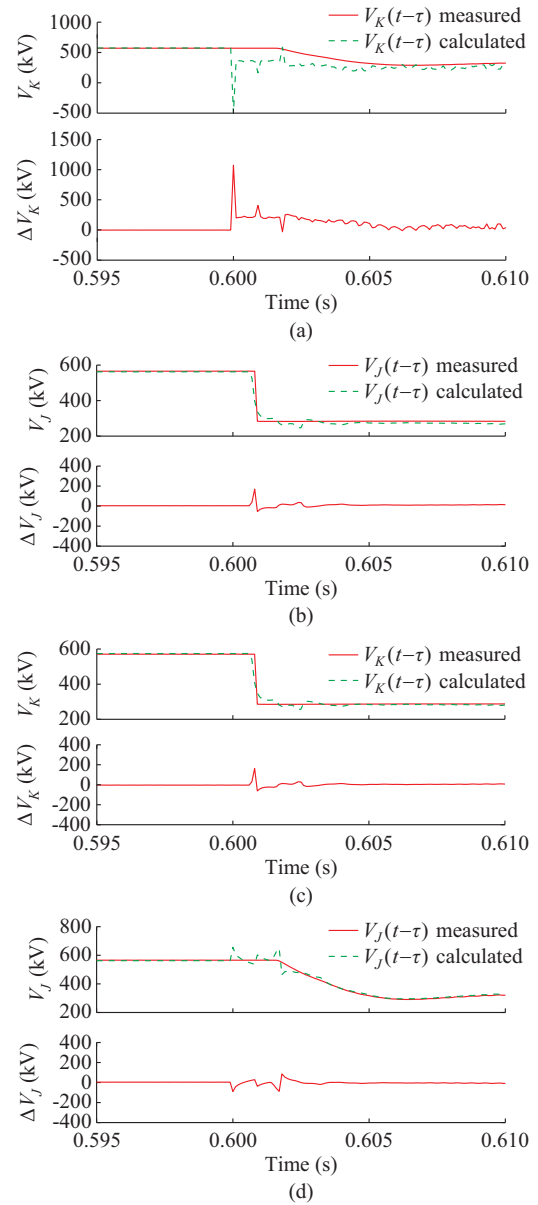


Fig. 7. Voltage difference response considering faults near terminals. (a) Voltage difference of terminal K with internal pole-to-ground fault at $F2$. (b) Voltage difference of terminal J with internal pole-to-ground fault at $F2$. (c) Voltage difference of terminal K with external pole-to-ground fault at $F5$. (d) Voltage difference of terminal J with external pole-to-ground fault at $F5$.

B. Voltage Difference Profile Versus Fault Location

From the obtained results shown in Fig. 7(a) and (b), it can be concluded that the voltage difference value is affected by the fault location with respect to the terminals. The value of ΔV_K is higher or lower if the fault is near terminal J or K , respectively. Different fault cases are investigated at various locations to clarify the voltage difference profile. Figure 8 presents the obtained maximum value of the voltage differences ΔV_K and ΔV_J versus the fault locations, i.e., 0, 25, 50, 75, and 100 km with reference to terminal J .

Moreover, the voltage difference depends on the fault type. Its value is higher in the pole-to-pole fault condition compared with that in the pole-to-ground fault condition.

This is because the degree of divergence associated with the calculated voltage signal is higher in the pole-to-pole fault condition.

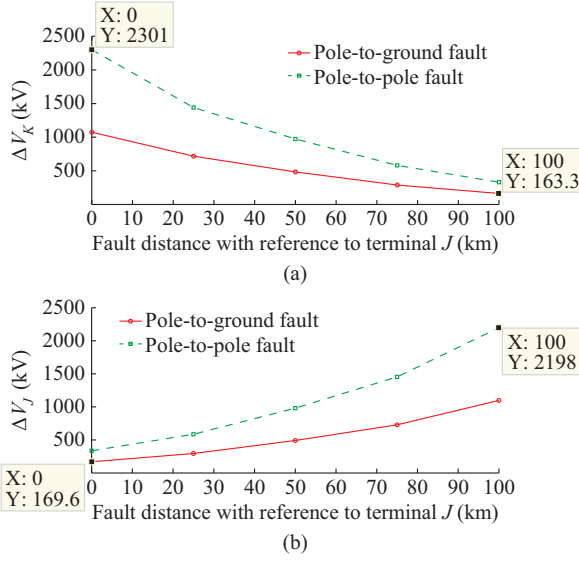


Fig. 8. Voltage difference maximum value versus fault location with pole-to-pole and pole-to-ground faults. (a) ΔV_K versus fault location. (b) ΔV_J versus fault location.

IV. PICKUP SETTING OF PROPOSED APPROACH

The proposed approach is profiled precisely such that the faults within the adopted line or cable could be detected successfully, and that the maloperations with external faults near the outside of the line zone are avoided. The pickup setting of the proposed fault detection scheme is designed based on a threshold level for the voltage difference value.

The pickup setting is regulated to attain a good security level. If a low level of the pickup setting is selected, the fault detection scheme may over-reach the protected line zone. The pickup threshold is regulated such that only approximately 80% of the transmission line length is covered. This accounts for inaccuracies owing to the variations of parameters or unsynchronized signals at the terminals. The remaining 20% of the line or cable is protected through the other voltage difference value at the other terminal.

Figure 9 shows the pickup setting and the corresponding protected area of the transmission system based on the values of ΔV_K and ΔV_J . Based on both differences ΔV_K and ΔV_J , the entire length of the transmission system is well included. As shown in Fig. 9(c), the relaying unit installed at terminal J would cover approximately 80% of the line length with reference to the Zone I of terminal J, and the operation variable is ΔV_K . Similarly, the other relaying unit at terminal K is adopted to encompass 80% of the line length with reference to the Zone II of terminal K, where ΔV_J is the operation variable. Furthermore, it is apparent that 20%-80% of the area is overlapped by the jurisdiction areas of both relaying units.

To determine the pickup setting level, the following criterion is proposed:

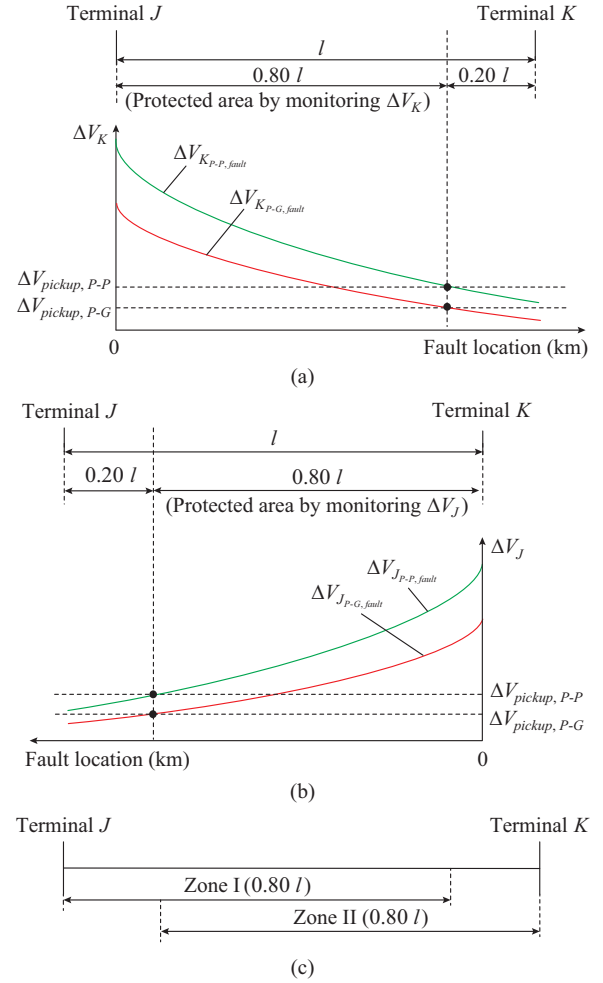


Fig. 9. Pickup settings for voltage differences and corresponding protected areas. (a) Pickup settings of ΔV_K and corresponding protected area. (b) Pickup settings of ΔV_J and corresponding protected area. (c) Jurisdiction areas of both relaying units.

$$\begin{cases} \Delta V_{pickup, P-P} = 1.4 \times \min \{ \Delta V_{P-P, fault} \} \\ \Delta V_{pickup, P-G} = 1.4 \times \min \{ \Delta V_{P-G, fault} \} \end{cases} \quad (5)$$

This criterion provides an approximate value for the voltage difference with the fault at approximately 80% of the transmission system length. As the profile of the voltage difference depends on the fault type, the pickup setting is adaptive.

Two pickup settings are proposed in (5). $\Delta V_{pickup, P-P}$ and $\Delta V_{pickup, P-G}$ are the pickup thresholds for the pole-to-pole and pole-to-ground faults, respectively. It is not appropriate to depend on one setting to guarantee a secure performance. Utilizing only $\Delta V_{pickup, P-P}$ may result in an unprotected area for pole-to-ground faults. Meanwhile, depending on the setting of pole-to-ground faults only may result in the length of the protected transmission system with pole-to-pole faults that are over-reached, thereby causing maloperations with external faults.

As two different pickup settings exist, a preliminary step should be performed to select the appropriate pickup setting. The voltage difference value is to be compared with the pickup setting $\Delta V_{pickup, P-G}$ if the fault is recognized as a pole-to-ground fault. The other pickup setting $\Delta V_{pickup, P-P}$ is consid-

ered for pole-to-pole fault cases. The pole-to-ground faults are discriminated by the imbalance between the positive and negative poles. Hence, the current or voltage imbalances are verified as a preparatory step before verifying the voltage difference value. As shown in Fig. 10(a), this verification depends on the asymmetry between the positive and negative signals (V_p , V_n , I_p , and I_n). If an imbalance occurs between the positive and negative voltages or currents, $\Delta V_{pickup, P-G}$ will be adopted as a reference before verifying the voltage

difference value ΔV . As depicted in Fig. 10(a), the verification of the imbalance between the positive and negative signals is not the main fault detection criterion. The main criterion depends on the verification of the voltage difference value ΔV . If an imbalance without fault occurs, ΔV maintains at zero. Meanwhile, if the fault is pole-to-pole type, an imbalance will not occur between the positive and negative signals.

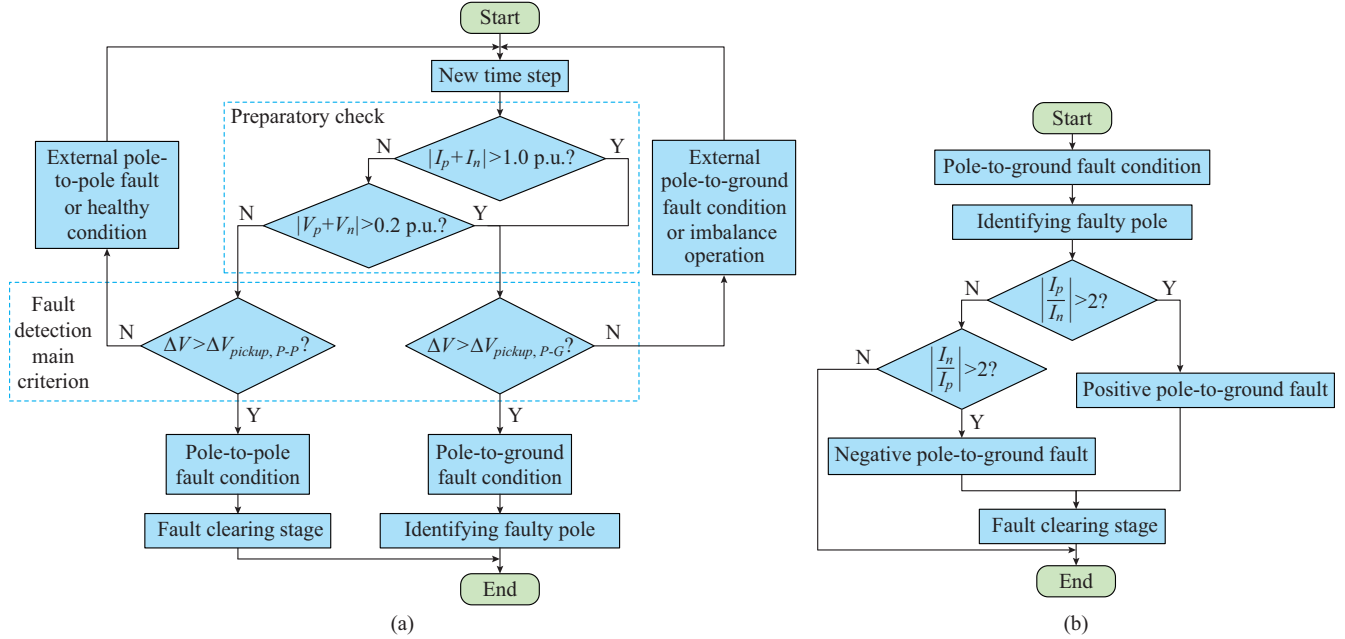


Fig. 10. Verification of signal imbalance for both selecting appropriate pickup setting and identifying faulty pole. (a) Selection of appropriate pickup setting before verifying voltage difference value. (b) Identification of faulty pole after confirming a pole-to-ground fault type.

It can be concluded that ΔV will be compared with $\Delta V_{pickup, P-G}$ if an imbalance occurs between the positive and negative voltages/currents. Meanwhile, verification with reference to $\Delta V_{pickup, P-P}$ must be performed if the imbalance conditions are not satisfied. It is noteworthy that the proposed approach should be tested if the power delivered through the poles are not balanced prior to the fault. This aspect will be discussed in the following section.

After confirming that the fault is a pole-to-ground fault, the faulty pole can be determined as either a positive-pole or negative-pole fault. This is performed by verifying the relative values of the positive and negative currents. If the ratio ($|I_p|/|I_n|$) is higher than two, the fault condition is recognized as a positive-pole-to-ground case, where the positive-pole current is significantly higher than the negative-pole current under this condition. Meanwhile, this ratio is reduced if the fault is a negative-pole fault, where the negative current is increased. This is clarified in Fig. 10(b).

In conclusion, the imbalance between the positive and negative signals is verified in two separate steps. First, the currents or voltages are verified according to the conditions in Fig. 10(a) as a preparatory step to select the appropriate pickup setting level. Next, after confirming that the fault type is a pole-to-ground fault, the faulty pole can then be identified as either a positive or negative pole by verifying

the ratio of the currents of the poles shown in Fig. 10(b).

V. RESPONSE UNDER IMBALANCE OPERATION PRIOR TO FAULT

The proposed approach should be tested if an imbalance operation occurs before the fault. This can be performed by controlling the delivered power through poles prior to the fault. Three test cases have been examined: positive-pole-to-ground, negative-pole-to-ground, and pole-to-pole faults. In the worst condition, these tests are performed with an extremely high imbalance before the fault occurrence. The ratio of the positive-pole current to the negative-pole current is approximately two prior to the fault.

The tested fault cases are at the middle of the transmission system length, whereas the fault instant is at 0.6 s. The results obtained for the three cases are presented in Figs. 11, 12, and 13, respectively.

Figure 11 shows the positive-pole-to-ground fault case. The following findings are obtained from the results.

1) As shown in Fig. 11(a), a significant current imbalance occurs prior to the fault. However, the voltage difference ΔV maintains at zero before the fault occurrence. This confirms that the proposed scheme is not negatively affected by imbalances in well-functioning operations.

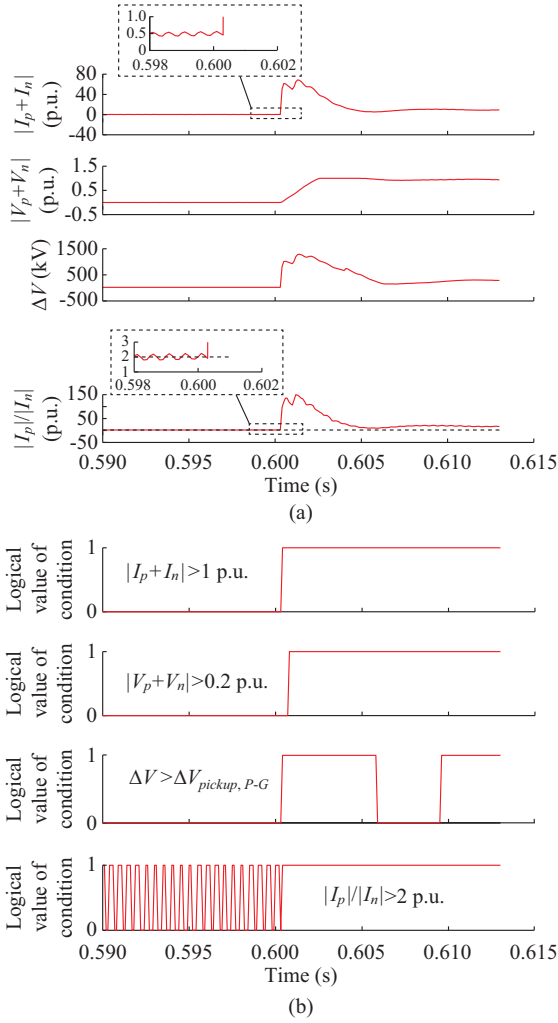


Fig. 11. Response under positive-pole-to-ground fault with a significant imbalance prior to fault. (a) Signal imbalance and voltage difference value. (b) Logical values of conditions.

2) Once the fault occurs, the imbalance between the positive and negative currents/voltages becomes highly significant. Hence, the appropriate pickup setting can be accurately selected, i.e., $\Delta V_{pickup, P-G}$.

3) As shown in Fig. 11(b), the current imbalance provides a slightly faster response than the voltage imbalance.

4) After confirming the fault by verifying the voltage difference value ($\Delta V > \Delta V_{pickup, P-G}$), the faulty pole is identified by verifying the ratio of the pole currents ($|I_p|/|I_n|$). Currents are preferred over voltages owing to their faster response.

5) The obtained results have proved that no problems are encountered by adopting the current imbalance in verifications, even when an imbalance operation occurs prior to the fault.

The negative-pole-to-ground fault condition has been tested as well. The results obtained are presented in Fig. 12. As shown in Fig. 12, a similar response is obtained and the faulty pole is finally identified by verifying the relative values of the currents of poles.

In addition, a test case for the pole-to-pole fault has been performed with the same imbalance condition prior to the

fault. The obtained results are presented in Fig. 13. Although a current imbalance occurs prior to the fault occurrence, this imbalance does not increase significantly after the fault occurrence. This is because the fault is a pole-to-pole fault. Hence, $\Delta V_{pickup, P-P}$ is selected appropriately. After detecting the pole-to-pole fault, the relative values of the currents of poles do not need to be verified because it is a pole-to-pole fault case.

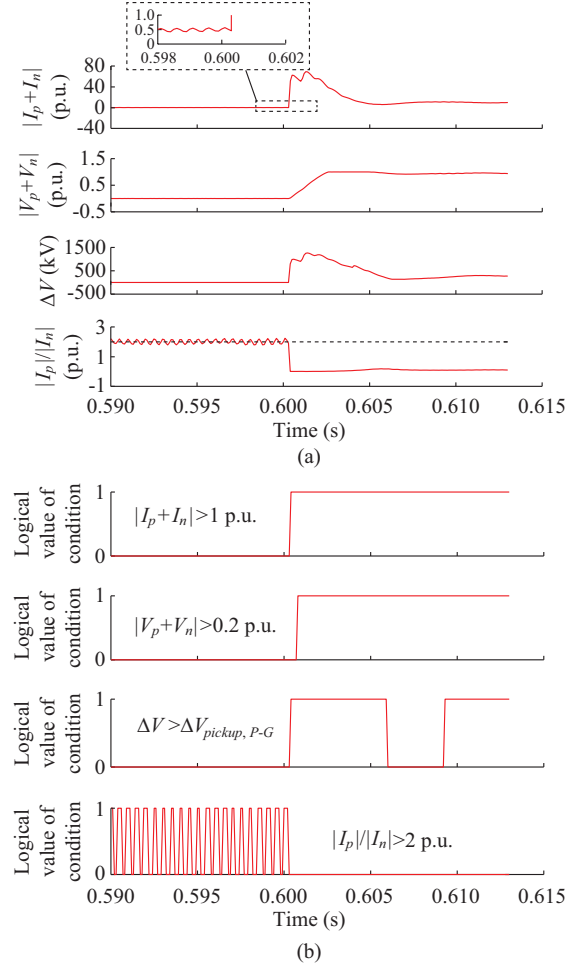


Fig. 12. Response under negative-pole-to-ground fault with a significant imbalance prior to fault. (a) Signal imbalance and voltage difference value. (b) Logical values of conditions.

Finally, it can be concluded that the imbalance operation does not affect the performance of the proposed approach. This is because the voltage difference value ΔV maintains at zero in well-functioning conditions. In addition, with the adopted processing and conditions in Fig. 10, the faults can be detected successfully and the faulty pole defined appropriately even with a significant imbalance prior to the fault.

VI. DETECTION TIME AND CLEARING STRATEGY

A. Characterization of Detection Time

Using the simulated system, the fault detection time can be recorded with the tested pole-to-ground and pole-to-pole fault cases at various locations. The results obtained for the

fault detection time are illustrated in Table II.

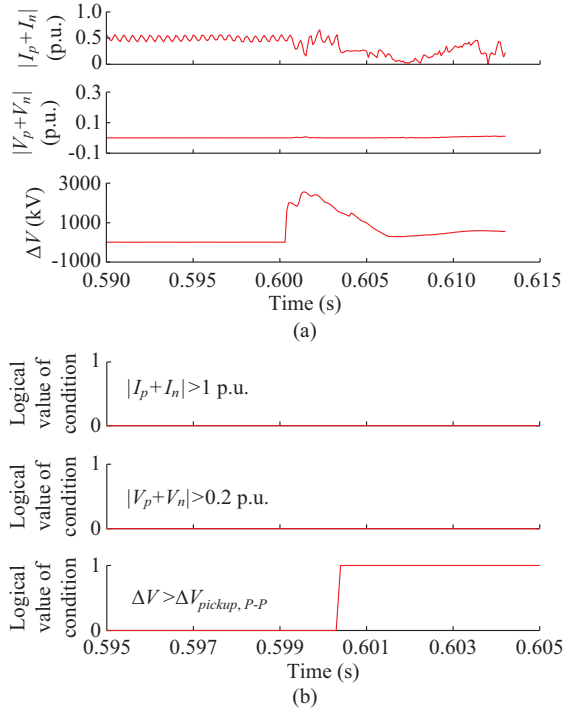


Fig. 13. Response to pole-to-pole fault with a significant imbalance prior to fault. (a) Signal imbalance and voltage difference value. (b) Logical values of conditions.

TABLE II
FAULT DETECTION TIME

Fault location	Pole-to-pole fault				Pole-to-ground fault			
	$\Delta V_K > \Delta V_{pickup, P-P}$		$\Delta V_J > \Delta V_{pickup, P-P}$		$\Delta V_K > \Delta V_{pickup, P-G}$		$\Delta V_J > \Delta V_{pickup, P-G}$	
	Delay time at J (ms)	Detection time (ms)	Delay time at K (ms)	Detection time (ms)	Delay time at J (ms)	Detection time (ms)	Delay time at K (ms)	Detection time (ms)
F4	×	×	×	×	×	×	×	×
F2	0	0.1	×	×	0	0.1	×	×
F6	0.16	0.1	0.48	0.3	0.16	0.1	0.48	0.3
F1	0.32	0.1	0.32	0.1	0.32	0.1	0.32	0.1
F7	0.48	0.3	0.16	0.1	0.48	0.3	0.16	0.1
F3	×	×	0	0.1	×	×	0	0.1
F5	×	×	×	×	×	×	×	×

Note: × means that the fault detection scheme does not operate.

The delay times of the traveling waves are determined based on detecting the first change in the currents or voltages by referring to the instance at which the fault occurs. To determine accurate values for these times, the sampling frequency at which the signals are monitored is increased with a reduced time step of 20 μ s.

B. Fault Isolation Strategy

The results obtained imply that the proposed fault detection approach can be considered as a unit protection approach. After detecting the fault, the faulty zone should be isolated. Hence, a direct current circuit breaker (DCCB) must be set at each terminal of the adopted transmission section. Various technologies are associated with the selected

For each fault case, the detection time is measured with reference to the arrival moment of the fault-generated waves at the terminals. The table presents the time consumed by the generated traveling wave from the fault point to reach the terminal along with the detection time. These results are clarified as follows:

1) The proposed fault detection approach does not maloperate with severe external faults, even if they are located extremely close to the outside of the cable ends.

2) The fault detection process is rapid, as it only takes a sub-millisecond after the arrival of the incident-traveling wave from the fault point at the transmission system terminals. The fault detection times remain at the same level for faults in different locations because the detection time is measured with reference to the arrival moment of the fault-generated waves at the terminals. Changing the fault location affects primarily the wave arrival delay time. However, the detection time does not change significantly.

3) Based on ΔV_K , the faults in Zone I can be detected. Similarly, faults in Zone II can be discriminated successfully based on ΔV_J .

4) Those faults located at one of the terminals of the adopted cable at either 0 or 100 km are detected within a short detection time of 0.1 ms, equal to the sampling time step employed. Hence, by utilizing a shorter time step with a higher sampling frequency, the detection of such faults could be facilitated within a time duration of less than 0.1 ms.

DCCB. Solid-state-based types provide a fast clearing process, but the high conduction loss is a limitation [27], [28]. Hybrid circuit breakers (CBs) distinguished by fast clearing and low conduction losses are recommended within the proposed approach [29], [30].

The triggering signals for these CBs would be provided by the relaying units at the line ends. As shown in Fig. 14 (a), both of the processing units at the line ends may trigger both CBs. The remote breaker is triggered by the distant relaying unit via the communication system. Based on this strategy, both of the breakers are correctly triggered to isolate the faulty line even if the faults are detected by only one relaying unit, as in the case of F2 or F3.

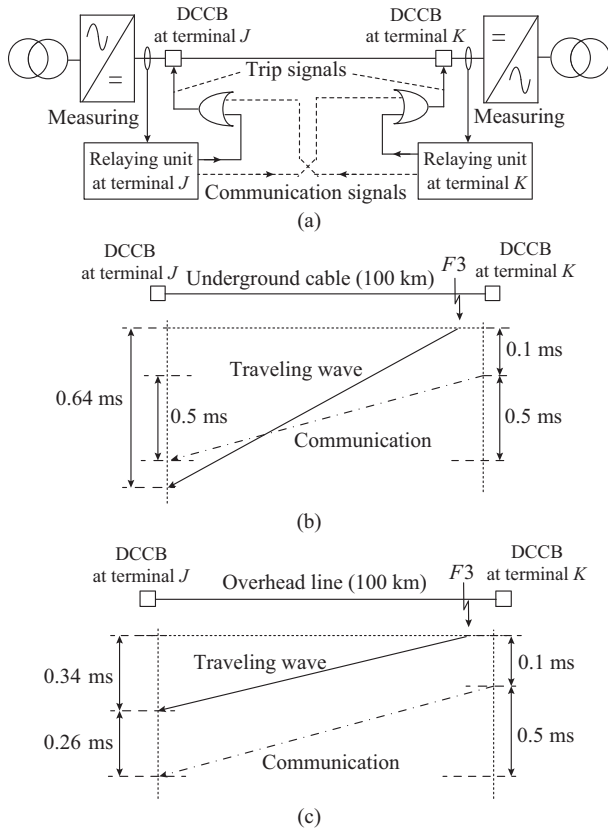


Fig. 14. Triggering strategy for DCCBs and behavior under remote fault condition. (a) Triggering strategy for DCCBs. (b) Performance under remote fault $F3$ with underground cable system to trigger CB at terminal J . (c) Performance under remote fault $F3$ with overhead line system to trigger CB at terminal J .

It is noted that for Fig. 14(b), the fault detection time by relaying unit at terminal K is 0.1 ms; the fault traveling wave time to reach terminal J with underground cable is 0.64 ms; and the communication time to transfer the trip signal to CB at terminal J is 0.5 ms. For Fig. 14(c), the fault detection time by relaying unit at terminal K is 0.1 ms; the fault traveling wave time to reach terminal J with overhead line is 0.34 ms; and the communication time to transfer the trip signal to CB at terminal J is 0.5 ms.

If the fault is detected by only one relaying unit, as in the case of $F3$, the remote CB at terminal J will be triggered via the communication, as shown in Fig. 14(a). Although the communication time is included, a significant delay will not occur in triggering the remote CB. This aspect is depicted in Figs. 14(b) and (c), where underground and overhead line systems are considered, respectively. The figures are introduced in the form of a lattice diagram representation. Since the fault is far from terminal J and close to terminal K , as shown in Fig. 14(b), it is detected within a short time by the relaying unit at terminal K , and the fault-generated wave consumes the traveling time duration to reach terminal J . After detecting the fault, the relaying unit sends a trip signal to CB at terminal J . As depicted in the figure, if the communication system is relatively faster than the traveling waves, as in the case of underground cables, the trip signal would be received before the arrival of the incident fault traveling

wave. Therefore, the remote CB is triggered without delay. This is considered as an advantage of the proposed scheme.

If the transmission system is an overhead line, as in Fig. 14(c), the trip signal would be received by the remote CB after the arrival of the fault incident traveling wave in 0.26 ms, which is considered acceptable. Therefore, the communication time does not represent a delay, particularly with underground cable systems, although the communication is employed to trip the CB under remote fault conditions.

VII. PERFORMANCE EVALUATION WITH MULTI-TERMINAL SYSTEMS

A. Response Under Fault Near A Typical Busbar

The applicability of the proposed protection system can be extended to multi-terminal systems, where each transmission element has its own separate zone. To investigate the security of the proposed detector, a three-terminal 200 kV symmetric-monopole system is simulated by the PSCAD program, as described in Fig. 15. The converter station (VSC1) is the slack terminal, whereas the other two terminals operate in a constant power control mode. A severe pole-to-pole fault case is conducted near the typical busbar as a worst condition, as shown in Fig. 15(a).

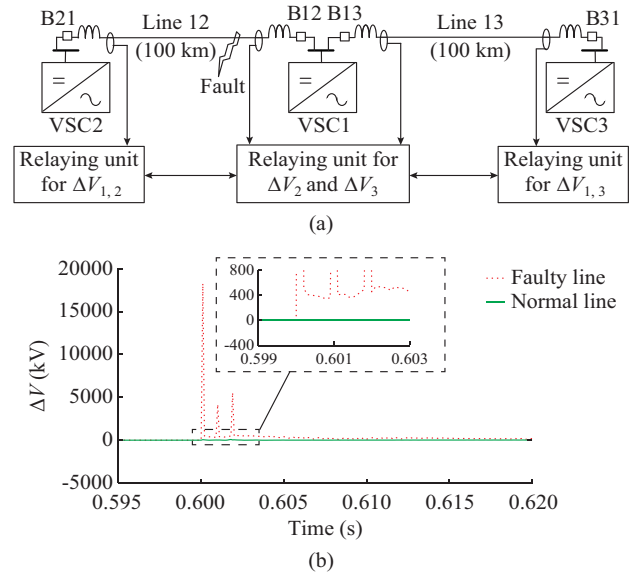


Fig. 15. Proposed approach applied in a multi-terminal system. (a) Simulated three-terminal system. (b) Voltage differences for faulty and non-faulty lines.

The fault inception instant is at 0.6 s. The voltage differences considering both faulty and non-faulty lines are monitored, as shown in Fig. 15(b). The voltage difference value with the faulty line ΔV_2 is significant, and therefore, the fault is detected successfully. Meanwhile, the voltage difference with the non-faulty line ΔV_3 does not exceed the pick-up setting and maloperation is avoided. This implies that the security of the proposed scheme is confirmed even when the worst fault conditions are included.

B. Response Under Misaligned Samples at Terminals

This section investigates the response when synchroniza-

tion errors are included within the signals measured at the terminals. This is investigated by considering the applied fault condition according to Fig. 15(a) as the worst case. Figure 16 shows the responses of the voltage differences ΔV_2 and ΔV_3 , respectively. The voltage difference value with the faulty line, i.e., ΔV_2 , is not negatively altered. The same response has been obtained regardless of the misalignment. This is because the measured voltage signal is specified at a certain DC level without the negative effects of the asynchronization condition, which is a unique advantage of the proposed scheme.

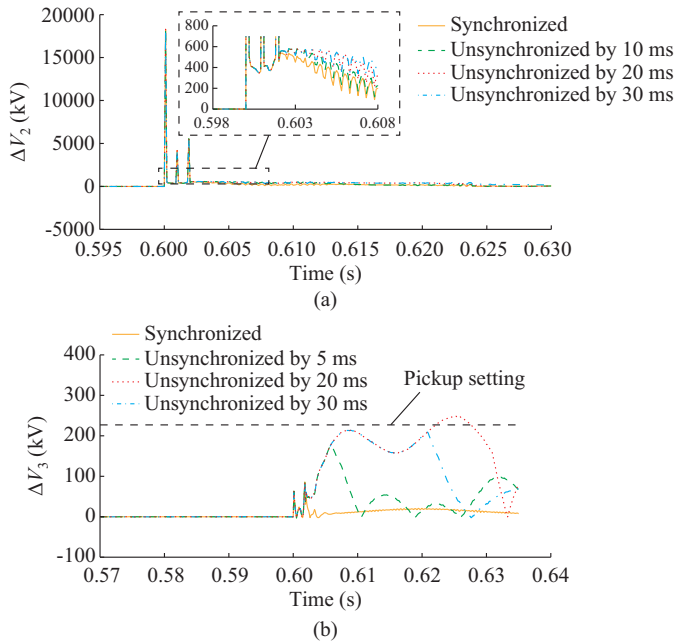


Fig. 16. Effect of unsynchronized samples at terminals. (a) Voltage differences for faulty line with unsynchronized samples at terminals. (b) Voltage differences for non-faulty line with unsynchronized samples at terminals.

Meanwhile, the response of ΔV_3 is also monitored to verify the security of the proposed approach if the samples are misaligned. Figure 16 shows how ΔV_3 is affected by the asynchronization condition. The voltage difference is presented with reference to the corresponding pickup setting with the simulated system. It is discovered that maloperation could be avoided if the samples are unsynchronized with a duration less than 20 ms. Therefore, the security of the proposed scheme is corroborated.

C. Boundary Inductors at Line Terminals

Boundary inductors are recommended to be used with VSC-HVDC systems to limit the increase rate of the current in fault cases. This is an important aspect, where the DCCB can be selected with reduced current breaking capability. The response of the proposed scheme is verified by considering the boundary inductors. The behavior is not affected, as the measurement devices are installed at the line side of the boundary inductors, as shown in Fig. 15(a). In other words, the Bergeron equations are still applicable because the inductors are excluded at the ends of the transmission system.

The same multi-terminal system shown in Fig. 15(a) has

been tested for this condition. The profile of the voltage difference is elaborated considering the inductors at the terminals, as shown in Fig. 17(a). Two different values for the inductances, 110 mH and 45 mH, have been adopted. The values are selected such that the increase rate of the fault current can be limited to 3.5 and 7.5 kA/ms, respectively [30]. As depicted in Fig. 17, the profile of the voltage difference is lowered with higher inductance values owing to the damping effect of the inductance. However, the proposed approach is not affected. The profile of the voltage difference is still discriminative for detecting the fault. Using boundary inductors will only cause the employed pickup setting to be updated according to the profile of the voltage difference.

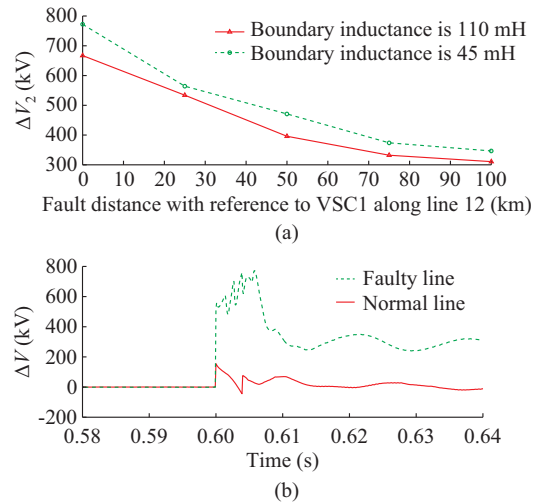


Fig. 17. Effect of boundary inductors on proposed scheme. (a) Effect of boundary inductance value on voltage difference profile. (b) Response with boundary inductors in multi-terminal system under fault near a typical terminal.

The security of the proposed approach is tested and the abovementioned inductors are adopted. Considering the fault case shown in Fig. 15(a), which is a severe pole-to-pole fault near the typical terminal at VSC1, the voltage difference values for both the faulty and non-faulty lines are shown in Fig. 17(b). The difference values deviate significantly such that the fault is successfully detected and that the maloperation is avoided using the healthy line.

VIII. VOLTAGE DIFFERENCE PROFILE IN LONGER TRANSMISSION SYSTEMS

The length of the employed transmission system in the previous analysis is 100 km. However, in future practical conditions, the transmission system may be slightly longer. Therefore, the proposed scheme is verified using a longer transmission system of 400 km. The voltage difference profile is investigated in different fault cases, including pole-to-pole and pole-to-ground cases at different locations (0, 100, 200, 300, and 400 km). The results obtained are presented in Fig. 18 for ΔV_K and ΔV_J . As shown in Fig. 18, the voltage difference profile is still discriminative with the increased length of the transmission system. This confirms that the proposed scheme is applicable in long transmission systems.

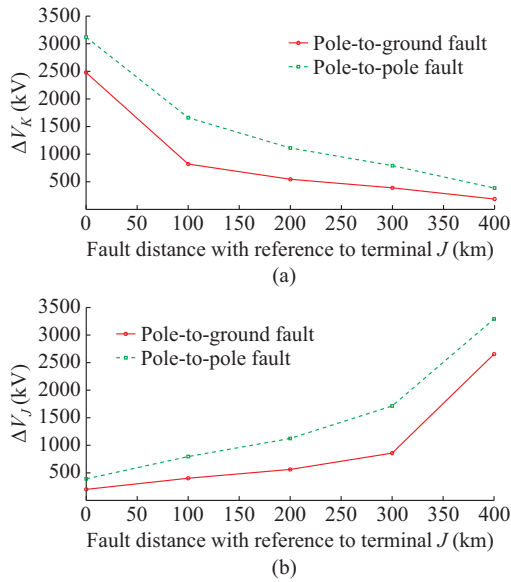


Fig. 18. Voltage difference profile for 400 km transmission system. (a) ΔV_K versus fault location under pole-to-pole and pole-to-ground faults. (b) ΔV_J versus fault location under pole-to-pole and pole-to-ground faults.

IX. CONCLUSION

A fast fault detection scheme is proposed herein for VSC-HVDC transmission systems by computing the virtual difference in the terminal voltages of a protected line. A communication system is required for transferring data between the line terminals. However, the proposed detector does not have an intended delay owing to the communication system. The proposed approach successfully detects the fault and identifies the faulty pole in pole-to-ground fault cases. The high immunity of the proposed approach to maloperations has been verified in different worst-case scenarios such as severe and extremely close external faults, misaligned samples at terminals, and significant imbalance operation prior to fault occurrence. Furthermore, it has been discovered that the proposed scheme can be utilized successfully in multi-terminal systems. The results reveal the reliability, versatility, and accurate fault detection capability of the proposed approach for VSC-HVDC transmission systems.

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