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A Study on Application of Recloser Operation Algorithm for Mixed Transmission System Based on Travelling Wave Method

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Abstract: Recently, the operation of a mixed transmission system has increased due to rapid urbanization and the purpose of a good view. Therefore, a proper protection scheme for a mixed transmission system is required. Generally, when a fault occurs on a transmission line, auto reclosing is performed for the purpose of improving the continuity of service by clearing the fault and restoring the power system. However, the auto reclosing scheme should be applied to a mixed transmission system carefully because the mixed transmission system involves underground cable sections. When a fault occurs in the underground cable section, it is mostly a permanent fault. If auto reclosing is performed on a permanent fault condition, it may cause excessive overcurrent and switching surge, which can generate a serious impact on the whole transmission system and even cause an explosion. Due to this, many utilities worldwide do not allow auto reclosing or only apply it very restrictively on a mixed transmission system based on their practice. However, there is no clear guidance or standard related to auto reclosing on a mixed transmission system. Therefore, in this paper, an application of a recloser operation algorithm is proposed. Based on the proposed algorithm, reclosers can work properly and protect the transmission system. To verify the proposed algorithm, simulations were conducted using the ElectroMagnetic Transient Program (EMTP).

Keywords: auto reclosing; combined transmission system; mixed transmission system; recloser operation algorithm; travelling wave

1. Introduction

These days, due to rapid urbanization, there has been an increase in the requirement for a good view and efficient use of space and as a result, the application of underground cables is increasing. Additionally, as DC systems are widely used, this requires the need for the application of underground cables. As a result, a mixed power system that consists of an overhead line section and underground cable section is in wide operation. Therefore, as the portion of underground cable becomes larger in the whole power system, the need for a proper protection scheme to protect the mixed power system has also increased.

In the auto reclosing procedure, circuit breakers open to isolate the fault from the main system and close to restore the system, according to the command of the protective relay. In this way, auto reclosing can improve the continuity of service when a transient fault occurs on the power system. For this reason, many utilities have adopted an auto reclosing scheme and operate a recloser in their power system [1–3].

However, in a mixed transmission system, to adopt an auto reclosing scheme, there are some considerations regarding the characteristics of underground cables. In underground cables, faults are mostly permanent in nature, so there are many risks associated with auto reclosing. If auto reclosing is performed on a permanent fault, switching surges and overcurrent are generated across the whole system. These phenomena may affect power equipment such as generator, transformer, cable, etc., in particular, if a cable is exposed to this kind of phenomena, the cable insulation can be broken down and can even generate explosions, according to the type of cable. Therefore, to operate a recloser in a mixed transmission system, a proper operation algorithm is required with special considerations. It must include a special protection scheme to discriminate between faults in the overhead line section versus the underground cable section. In fact, in some documents, it is mentioned that an auto reclosing scheme on a mixed transmission system should consider the fault location whether the fault is on an overhead line section or underground cable section [4–8]. However, many utilities operate reclosers according to their practice, which may not consider this kind of factor [9–12].

To detect and locate the fault in the transmission system, many studies have been conducted. To detect and locate faults, generally, the impedance-based method or travelling wave-based method are used [13,14]. Among these methods, the travelling wave-based method consists of the single ended method and double ended method [15]. While the single ended method observes and uses information from only one terminal of the line, the double ended method uses information from both terminals of the line. So, in case of the double ended method, the synchronism problem is important and has to be considered [16,17]. In [18], Lee proposed a fault locator based travelling wave using a global positioning system (GPS). Additionally, in [19], Naidu proposed a selective auto-reclosing scheme for a multi-terminal mixed system using synchrophasor measurements. To provide synchronized measurements, a synchrophasor based on GPS was used. In [20], Hong proposed a fault location method using pattern analysis based travelling wave theory and signal processing. In [21], Han and Crossley proposed a hybrid method that consisted of the impedance method and travelling wave method. The multiple zone quadrilateral impedance relay model and double ended travelling wave fault locator were used to calculate the fault location precisely and the hybrid method was verified using the PSCAD/EMTDC (Power System Computer Aided Design/Electromagnetic Transients program including DC) simulator by J. Han in [21].

By Lin, Abur and Hamidi, in [22–24], various research related to fault location in a general transmission system based on the travelling wave method was conducted. Lin, in [22], proposed a single ended travelling wave method based on the Lipschitz exponent. In that study, to obtain the Lipschitz exponent of the second transient wave-front signal, wavelet transform and the least square method were used. Furthermore, by Abur and Hamidi, in [23,24], wavelet transform, which applies a different mother wavelet, was utilized to calculate the fault location. However, in these studies, different signal processing methods were applied to detect and locate the fault, so time to process the signal is required. It can also cause an inefficiency when the recloser operates on a mixed transmission line. By Lin, in [25], to improve the fault location accuracy of the travelling wave method, the universal wavefront positioning correction method was proposed. By Mardiana, in [26], a travelling wave related to high frequency transient voltage was introduced to calculate the fault location for the ground fault. By Lopes, in [27], an innovative fault location method based on two terminal travelling waves was proposed where only the fault location formulation was utilized to calculate the fault location instead of applying the signal processing method. Han, in [28], introduced the empirical mode decomposition (EMD) concept to a single-pole adaptive reclosure. EMD is a one type of data analysis method and its concept is to decompose the signal into a set of functions.

Although research related to fault detection and location have matured deeply, the application of these methods to the practical operation of a power device has not been developed sufficiently. In other words, for a practical recloser operation, research related to a simpler method that is easy to adjust on the recloser should be considered.

In this paper, we propose a novel recloser operation algorithm that considers the faulted section on a mixed transmission system by using travelling wave theory. The proposed algorithm includes functions such as fault detection, fault location, and transferring the reclosing signal to provide a proper reclosing procedure on a mixed transmission system. In Section 2, conventional recloser operation principles and preceding research related to fault detection/location method in mixed transmission system are introduced. In Section 3, the principle of the proposed algorithm based on travelling wave theory and the concept of the proposed algorithm are introduced. In Section 4, to verify the proposed algorithm, the simulation results are presented. Finally, in Section 5, we present our conclusions.

2. Conventional Recloser Operation Principles

A mixed transmission system consists of overhead lines and underground cables. As referred to in the Introduction, when a fault occurs on a mixed transmission system, an auto reclosing scheme has to be applied carefully by considering which section is at fault (overhead line or underground cable). Therefore, the utilities in many countries operate a recloser, according to their own operation principle, but is based on practice. For this reason, there are no specific standards or guidelines for applying an auto reclosing scheme in a mixed transmission system. In Table 1, the auto reclosing principles adopted by the utilities in some countries are presented, and shows that each auto reclosing principle is different to each other because it follows the practice of each individual utility.

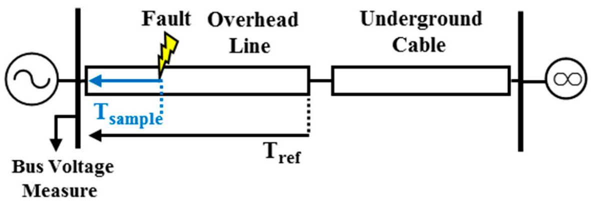
Table 1. Auto reclosing principles adopted by utilities on a mixed transmission system [29].

Nation	Voltage Level	Auto Reclosing Principle
South Korea	(1) 154 kV	(1-1) Auto reclosing allowed: when portion of underground cable <30% (total system) (1-2) Auto reclosing prohibited: when "OF (Oil-Filled) cable" is used
	(2) 345 kV	(2) Auto reclosing prohibited: when underground cable section exists
Brazil	138 kV, 230 kV	Among the total '12' mixed system, (1) Auto reclosing allowed: '9' systems (2) Auto reclosing allowed only for overhead line fault: '2' systems (3) Auto reclosing prohibited: '1' system
Japan	(1) <154 kV	(1) Auto reclosing allowed: when following conditions are met -Short circuit current < 1000 A, Fault clearing time <1 s, -Fire prevention measure is applied to exposed part of cable and adjacent cable, -Length of underground cable < 1 km, Length of underground cable <1/3 of overhead line length, -Fault will not affect the other cable
	(2) >154 kV	(2-1) Auto reclosing allowed: when following conditions are met -Length of underground cable <1 km, Length of underground cable <1/3 of overhead line length, -Fault will not affect the other cable (2-2) Auto reclosing prohibited: when underground cable fault occurs
Canada	(1) 60~345 kV	(1) Auto reclosing allowed: only for overhead line fault or according to portion of overhead line
	(2) >500 kV	(2) Auto reclosing prohibited
Sweden	132 kV	(1) Auto reclosing allowed: when overhead line section is enough long or only for overhead line fault (2) Auto reclosing prohibited: when overhead line section is short

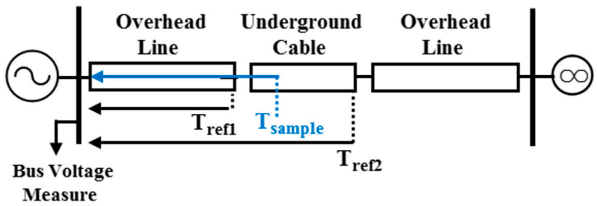
As shown in Table 1, the recloser operation principles of many utilities are different from each other, and confirms that there are no specific standards or guidelines for performing reclosing behavior on a mixed transmission system. It is common that auto reclosing is allowed only for overhead line faults, but for underground cable faults, auto reclosing is generally prohibited, except for cases in which the length of the underground cable section is relatively shorter than the overhead line section.

3. Proposed Recloser Operation Algorithm for Mixed Transmission System

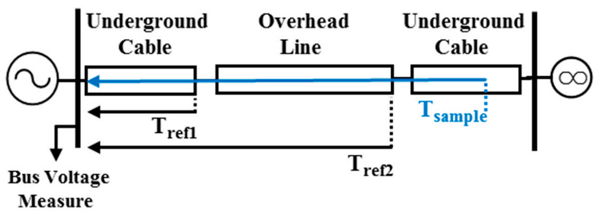
In this paper, the proposed algorithm provides a proper recloser operation for a fault that considers whether the faulted section is an overhead line or underground cable on a mixed transmission system when using the travelling wave of voltage. As shown in Figure 1, there are three types of mixed transmission systems. In Figure 1a, the first configuration is Case 1, which consists of an overhead line section and underground cable section, assumed as "OL + UC (Overhead Line + Underground Cable)". The second configuration (Figure 1b) is Case 2, which consists of three sections located in a row, assumed as "OL + UC + OL (Overhead Line + Underground Cable + Overhead Line)". The last configuration (Figure 1c) is Case 3, which consists of an underground cable, overhead line, and underground cable, assumed as "UC + OL + UC (Underground Cable + Overhead Line + Underground Cable)". In each case, T_{ref} including T_{ref1}, T_{ref2} is the reference value to distinguish the faulted section on the mixed transmission system. T_{ref} can be calculated and set by the utility based on the characteristics of the target system. The essential characteristics of the system are line length and velocity of travelling wave in each section.



(**a**)



(**b**)



(**c**)

Figure 1. The concept of the proposed algorithm considering three configurations of mixed transmission system: (**a**) Overhead Line + Underground Cable (OL + UC) configuration; (**b**) Overhead Line + Underground Cable + Overhead Line (OL + UC + OL) configuration; (**c**) Underground Cable + Overhead Line + Underground Cable (UC + OL + UC) configuration.

T_{ref} can be calculated using Equation (1) and can be considered as the required time that the travelling wave propagates on the whole section (overhead line or underground cable). Therefore, T_{ref} can be preset by the utilities because they know the line length and the velocity of the travelling wave in their system, depending on the characteristics of the conductor.

$$T_{ref} = L/v \tag{1}$$

where T_{ref} is a reference value to distinguish the faulted section; L is the length of overhead line or underground cable; and v is the propagation velocity of the travelling wave on the overhead line or underground cable depending on characteristic of conductor.

T_{sample}, presented in Figure 1, is the arrival time that the travelling wave propagates from the fault point to the measuring point, which is the sending end. If the fault occurs on a mixed transmission system, then the travelling wave propagates and reaches at the measuring point. Then, the voltage of the measuring point will fluctuate. Assume the time when this voltage fluctuation occurs as T_{sample}. Using T_{sample}, the proposed algorithm calculates the difference between the fault occurring time and T_{sample}. Assume this difference as T. Next, the proposed algorithm compares the T with T_{ref}, so it can finally distinguish the faulted section according to the condition of the mixed transmission system.

The detailed conditions for each configuration of a mixed transmission system to distinguish the faulted section are mentioned in the following sub-sections.

3.1. Configuration: (OL + UC)

Considering configuration (a) in Figure 1, if a fault occurs on an overhead line section, T, which is measured at the end of the line is smaller than T_{ref}. In contrast, if the fault occurs on an underground cable section, T is larger than T_{ref}. This relation is presented as follows:

$$T_{ref} = L_1/v_1 \tag{2}$$

where T_{ref} is a reference value that the travelling wave propagates on an overhead line; L_1 is the length of the overhead line; and v_1 is the propagation velocity of the travelling wave on the overhead line.

Then,

$$T \leq T_{ref}:\ \text{Overhead line fault} \tag{3}$$

$$T > T_{ref}:\ \text{Underground cable fault} \tag{4}$$

3.2. Configuration: (OL + UC + OL)

Considering configuration (b) in Figure 1, if a fault occurs on the overhead line section, T is smaller than T_{ref1} or larger than T_{ref2}. In contrast, if a fault occurs on the underground cable section, T is larger than T_{ref1} and smaller than T_{ref2}. This relation is presented as follows:

$$T_{ref1} = L_1/v_1,\ T_{ref2} = T_{ref1} + L_2/v_2 \tag{5}$$

where T_{ref1} is a reference value that the travelling wave propagates on an overhead line located in front of the underground cable; T_{ref2} is a reference value that the travelling wave propagates on the overhead line and underground cable; L_1 is the length of the overhead line located in front of the underground cable; v_1 is the propagation velocity of the travelling wave on the overhead line located in front of the underground cable; L_2 is the length of underground cable; and v_2 is the propagation velocity of the travelling wave on the underground cable.

Then,

$$T \leq T_{ref1}\ or\ T \geq T_{ref2}:\ \text{Overhead line fault} \tag{6}$$

$$T_{ref1} < T < T_{ref2}:\ \text{Underground cable fault} \tag{7}$$

3.3. Configuration: (UC + OL + UC)

Considering configuration (c) in Figure 1, if a fault occurs on the overhead line section, T is larger than T_{ref1} and smaller than T_{ref2}. In contrast, if a fault occurs on the underground cable section, T is smaller than T_{ref1} or larger than T_{ref2}. This relation is presented as follows:

$$T_{ref1} = L_1/v_1,\ T_{ref2} = T_{ref1} + L_2/v_2 \tag{8}$$

where T_{ref1} is a reference value that the travelling wave propagates on the underground cable located in front of the overhead line; T_{ref2} is a reference value that the travelling wave propagates on the underground cable and overhead line; L_1 is the length of the underground cable located in front of the overhead line; v_1 is the propagation velocity of the travelling wave on the underground cable located in front of overhead line; L_2 is the length of the overhead line; and v_2 is the propagation velocity of travelling wave on overhead line.

Then,

$$T_{ref1} < T < T_{ref2}: \text{ Overhead line fault} \quad (9)$$

$$T \le T_{ref1} \text{ or } T \ge T_{ref2}: \text{ Underground cable fault} \quad (10)$$

Based on these conditions, the proposed algorithm can distinguish the faulted section on a mixed transmission system. Figure 2 presents the flow chart of the proposed algorithm. In this algorithm, "OC" represents the (OL + UC) configuration, "OCO" represents the (OL + UC + OL) configuration, and "COC" represents the (UC + OL + UC) configuration, respectively. Additionally, to detect fault occurrence and voltage fluctuation, V is used. When the travelling wave due to the fault arrives at the measuring point, voltage fluctuation, which exceeds the range of voltage variation in the steady state, is caused. Based on the result of the comparison between the fault occurrence time and voltage fluctuation time, the proposed algorithm distinguishes the faulted section and provides a proper reclosing signal for the recloser.

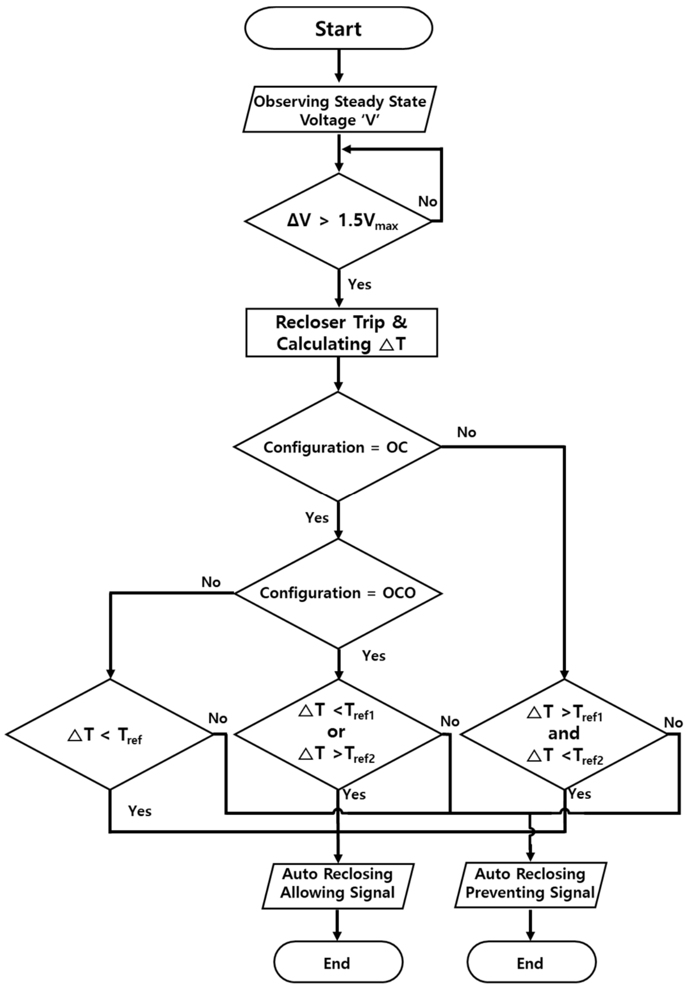


Figure 2. Proposed recloser operation algorithm on a mixed transmission system.

4. Simulation and Verification

4.1. Simulation Conditions

To verify the proposed algorithm, three types of AC 154 kV mixed transmission systems were modeled as shown from Figures 3–5. Each system represents three configurations: (OL + UC), (OL + UC + OL), and (UC + OL + UC), respectively. In each case, the total length of overhead line was 10 km and the underground cable was 2.4 km. In addition, the actual conductor data of ACSR 410 mm^2 and XLPE 2000 mm^2 were used to represent the overhead line and underground cable section, respectively. Both sections were modeled by the Bergeron model of ATP because of the necessity of the consideration related high frequency phenomena. For the underground cable section, crossbonding was applied every 400 m. With a sampling frequency equal to 30.72 kHz (512 samples/cycle), bus voltage at the sending end was observed. Table 2 shows the simulation conditions. Additionally, according to the characteristics of the used conductors, the propagation velocity of the travelling wave on the overhead line was calculated as 2.8×10^8 m/s, and as 1.68×10^8 m/s for the underground cable. Based on these data, the reference values T_{ref}, T_{ref1}, T_{ref2} were preset as shown in Table 3.

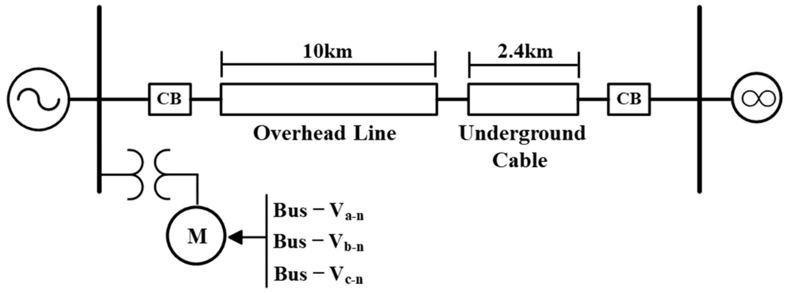


Figure 3. One-line diagram of the modeled system for the (OL + UC) configuration.

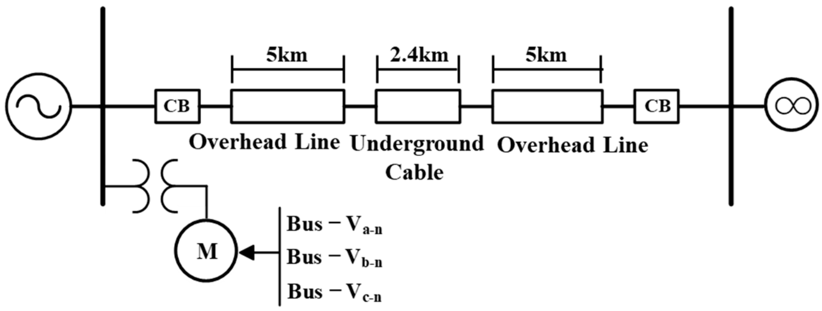


Figure 4. One-line diagram of the modeled system for the (OL + UC+ OL) configuration.

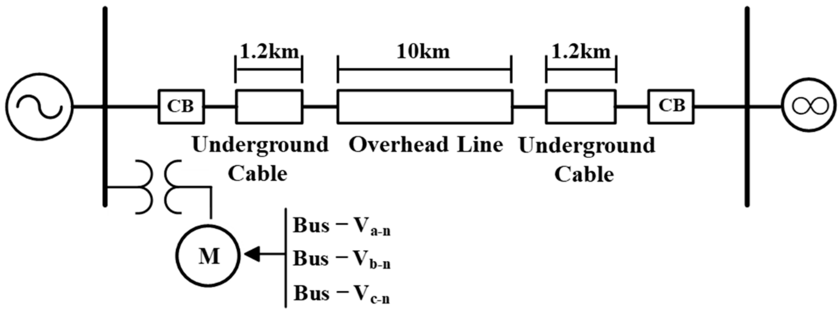


Figure 5. One-line diagram of the modeled system for the (UC + OL+ UC) configuration.

Table 2. Simulation conditions.

Fault Type	Sampling Frequency	Total line Length
(1) Single line to ground fault (2) 3-phase fault	30.72 kHz (512 samples/cycle)	(1) Overhead line: 10 km (2) Underground cable: 2.4 km

Table 3. Reference values T_{ref}, T_{ref1}, and T_{ref2}.

Configuration (OL + UC)	Configuration (OL + UC + OL)	Configuration (UC + OL + UC)
(1) T_{ref}: 35.71 µs	(1) T_{ref1}: 17.9 µs (2) T_{ref2}: 32.19 µs	(1) T_{ref1}: 7.1 µs (2) T_{ref2}: 42.81 µs

As shown in Figure 3, in the case of the (OL + UC) configuration, a 10 km overhead line was placed in front of the underground cable. In this case, only T_{ref} exists. Using the propagation velocity of the travelling wave on the overhead line which equals to 2.8×10^8 m/s, the reference value T_{ref} can be calculated as follows:

$$T_{ref} = 10\ km/\left(2.8 \times 10^8\ m/s\right) = 35.71\ \mu s \tag{11}$$

According to Equations (3) and (4), when the fault occurs, if the measured T is smaller than 35.71 µs, therefore, the faulted section is the overhead line.

The detailed conditions for each configuration of the mixed transmission system to distinguish the faulted section are mentioned in the following sub-sections.

As shown in Figure 4, in the case of the (OL + UC + OL) configuration, 2.4 km of underground cable section was placed between two overhead line sections with a length of 5 km. In this case, two reference values (T_{ref1}, T_{ref2}) are required because there are two transition points that connect the overhead line and underground cable. Therefore, T_{ref1} and T_{ref2} can be calculated as follows:

$$T_{ref1} = 5\ km/\left(2.8 \times 10^8\ m/s\right) = 17.9\ \mu s \tag{12}$$

$$T_{ref2} = T_{ref1} + 2.4\ km/\left(1.68 \times 10^8\ m/s\right) = 32.19\ \mu s \tag{13}$$

According to Equations (6) and (7), when the fault occurs, if the measured T is smaller than 17.9 µs or larger than 32.19 µs, the faulted section is the overhead line.

As shown in Figure 5, in the case of the (UC + OL + UC) configuration, 10 km of the overhead line section was placed between two underground cable sections with lengths of 1.2 km. In this case, two reference values (T_{ref1}, T_{ref2}) are also required. In this case, T_{ref1} and T_{ref2} can be calculated as follows:

$$T_{ref1} = 1.2\ km/\left(1.68 \times 10^8\ m/s\right) = 7.1\ \mu s \tag{14}$$

$$T_{ref2} = T_{ref1} + 10\ km/\left(2.8 \times 10^8\ m/s\right) = 42.81\ \mu s \tag{15}$$

According to Equations (9) and (10), when the fault occurs, if the measured T is larger than 7.1 µs and smaller than 42.81 µs, then the faulted section is the overhead line.

4.2. Simulation Results and Verification

For the above three configurations of a mixed transmission system, various fault points were applied along the whole mixed system. After a fault occurrence, the measured T of each case were as presented in Tables 4–6. Furthermore, based on T, the results of the recloser operation are also shown in Tables 4–6.

Table 4. Results of the reclosing operation using the proposed algorithm on the (OL + UC) configuration.

Obtained $\triangle T$ and Result of Comparison with T_{ref}				
Fault Position		**$\triangle T$ (µs)**		**Recloser Operation Signal**
		Single Line to Ground Fault	**3-Phase Fault**	
Overhead line	2 km	7.2002	7.2002	Auto Reclosing Allowed ($\triangle T < T_{ref}$)
	4 km	14.2932	14.2932	
	6 km	21.4010	21.4010	
	8 km	28.5983	28.5983	
	10 km	35.7062	35.7062	
Underground cable	10.4 km	37.8966	37.8966	Auto Reclosing Prevented ($\triangle T > T_{ref}$)
	10.8 km	40.2063	40.2063	
	11.2 km	42.6054	42.5011	
	11.6 km	44.9002	44.7959	
	12 km	47.2993	47.195	

Table 5. Results of the reclosing operation using the proposed algorithm on the (OL + UC + OL) configuration.

Obtained $\triangle T$ and Result of Comparison with T_{ref}				
Fault Position		**$\triangle T$ (µs)**		**Recloser Operation Signal**
		Single Line to Ground Fault	**3-Phase Fault**	
Overhead line	1 km	3.5942	3.5942	Auto Reclosing Allowed ($\triangle T < T_{ref1}$)
	3 km	10.7020	10.7020	
	5 km	17.8993	17.8993	
Underground cable	5.4 km	20.1046	20.1046	Auto Reclosing Prevented ($T_{ref1} < \triangle T$ and $\triangle T < T_{ref2}$)
	5.8 km	22.3994	22.3994	
	6.2 km	24.7985	24.6942	
	6.6 km	27.0933	27.0039	
	7 km	29.4030	29.4030	
	7.4 km	31.6978	31.6978	
Overhead line	7.9 km	33.6051	33.5008	Auto Reclosing Allowed ($T_{ref2} < \triangle T$)
	9.4 km	38.8950	38.8950	
	10.9 km	44.3041	44.1998	
	12.4 km	49.5940	49.5940	

In the case of the (OL + UC) configuration, T_{ref} equaled 35.71 µs, as shown in Table 3. When a fault occurred on an overhead line section, the measured T was smaller than 35.71 µs in all cases. As a result, the recloser received an auto reclosing signal and then conducted a reclosing procedure according to the proposed algorithm. In the case of the (OL + UC + OL) configuration, T_{ref1} and T_{ref2} were equal to 17.9 µs and 32.19 µs, respectively. When a fault occurred on the overhead line section, the measured T shown in Table 5 was smaller than 17.9 µs or larger than 32.19 µs. Only for these cases was the auto reclosing signal transferred to the recloser. In the case of the (UC + OL + UC) configuration, T_{ref1} and T_{ref2} were equal to 7.1 µs and 42.81 µs, respectively. When a fault occurred on the overhead line section, the measured T shown in Table 6 was larger than 7.1 µs and smaller than 42.81 µs. Auto reclosing was allowed only for this T range and the results shown in Table 6 verified this. As shown in Tables 4–6, the proposed algorithm operated the recloser successfully for various conditions. In other words, the proposed algorithm could distinguish the faulted section on a mixed transmission system and operated the recloser only for the overhead line fault in all cases. To support clear understanding about the results, voltage waveform of an example case and detailed code of the proposed algorithm are presented in Appendices A and B, respectively.

Table 6. Results of the reclosing operation using the proposed algorithm on the (UC + OL + UC) configuration.

Obtained $\triangle T$ and Result of Comparison with T_{ref}				
Fault Position		**$\triangle T$ (μs)**		**Recloser Operation Signal**
		Single Line to Ground Fault	**3-Phase Fault**	
Underground cable	0.4 km	2.4021	2.4021	Auto Reclosing Prevented ($\triangle T < T_{ref1}$)
	0.8 km	4.6968	4.6968	
	1.2 km	7.0065	7.0065	
Overhead line	1.7 km	8.7053	8.7053	Auto Reclosing Allowed ($T_{ref1} < \triangle T$ and $\triangle T < T_{ref2}$)
	3.2 km	14.0995	14.0995	
	4.7 km	19.4043	19.4043	
	6.2 km	24.7985	24.7985	
	7.7 km	30.1033	30.1033	
	9.2 km	35.4975	35.4975	
	10.7 km	40.8024	40.8024	
	11.2 km	42.6054	42.6054	
Underground cable	11.6 km	45.0045	44.9002	Auto Reclosing Prevented ($T_{ref2} < \triangle T$)
	12 km	47.2993	47.1950	
	12.4 km	49.6984	49.5940	

4.3. Setting for Different Conditions and Results

The proposed algorithm was verified only for specific conditions that used conductors, which were ACSR (Aluminum Conductor Steel Reinforced) and XLPE (Cross Linked Polyethylene). However, there are many conductor types that can be used in a mixed transmission system. Therefore, in this section, how to apply the proposed algorithm to different conditions is discussed.

The oil-filled (OF) cable is one of the most widely used conductors in underground cables, but because it is filled with oil, it carries the risks of explosion and fire when exposed to overvoltage or overcurrent. Therefore, it is especially important to prevent auto reclosing when the fault occurs on an OF cable section. To apply the proposed algorithm to a mixed transmission system that includes an OF cable section, there is a need to set the reference values considering the characteristics of an OF cable. The XLPE cable has a propagation velocity of travelling wave equal to 1.68×10^8 m/s, and an OF cable has one equal to 1.324×10^8 m/s. Therefore, due to the difference in the propagation velocity, when an OF cable is used, the reference values have to be set properly. In Table 7, the settings of the reference values considering an OF 2000 mm^2 cable are shown.

Table 7. Settings of the reference values T_{ref}, T_{ref1}, T_{ref2} considering an oil-filled (OF) cable.

Settings for Reference Values in OF Cable System			
Cable Type	**Configuration (OL + UC)**	**Configuration (OL + UC + OL)**	**Configuration (UC + OL + UC)**
XLPE cable	(1) T_{ref}: 35.71 μs	(1) T_{ref1}: 17.9 μs (2) T_{ref2}: 32.19 μs	(1) T_{ref1}: 7.1 μs (2) T_{ref2}: 42.81 μs
OF cable	(1) T_{ref}: 35.71 μs	(1) T_{ref1}: 17.9 μs (2) T_{ref2}: 36.03 μs	(1) T_{ref1}: 9.06 μs (2) T_{ref2}: 44.77 μs

Using these values, simulations were conducted to verify the proposed algorithm in a mixed transmission system that included an OF cable section. Tables 8–10 present the results of the recloser operation on a mixed system including the OF cable section, according to the configuration. As shown in Tables 8–10, the proposed algorithm could distinguish the faulted section in a mixed transmission system that includes an OF cable section and operate the recloser only for overhead line faults in all cases.

Table 8. Results of the reclosing operation on an OF cable system in configuration (OL + UC).

Configuration (OL + UC)			
Fault Position		**△T (μs)**	**Recloser Operation Signal**
Overhead line	2 km	7.2002	Auto Reclosing Allowed (△T < T_{ref})
	4 km	14.2932	
	6 km	21.4010	
	8 km	28.5983	
	10 km	35.7062	
Underground cable	10.4 km	38.4927	Auto Reclosing Prevented (T_{ref} < △T)
	10.8 km	41.3984	
	11.2 km	44.3041	
	11.6 km	47.2993	
	12 km	50.205	

Table 9. Results of the reclosing operation on an OF cable system in configuration (OL + UC + OL).

Configuration (OL + UC + OL)			
Fault Position		**△T (μs)**	**Recloser Operation Signal**
Overhead line	1 km	3.5942	Auto Reclosing Allowed (△T < T_{ref1})
	3 km	10.7020	
	5 km	17.8993	
Underground cable	5.4 km	20.7007	Auto Reclosing Prevented (T_{ref1} < △T < T_{ref2})
	5.8 km	23.6064	
	6.2 km	26.4972	
	6.6 km	29.403	
	7 km	32.3981	
	7.4 km	35.3038	
Overhead line	7.9 km	37.1963	Auto Reclosing Allowed (T_{ref2} < △T)
	9.4 km	42.5011	
	10.9 km	47.8953	
	12.4 km	53.2001	

Table 10. Results of the reclosing operation on an OF cable system in configuration (UC + OL + UC).

Configuration (UC + OL + UC)			
Fault Position		**△T (μs)**	**Recloser Operation Signal**
Underground cable	0.4 km	2.9981	Auto Reclosing Prevented (△T< T_{ref1})
	0.8 km	5.9638	
	1.2 km	8.7947	
Overhead line	1.7 km	10.5977	Auto Reclosing Allowed (T_{ref1} < △T < T_{ref2})
	3.2 km	15.9025	
	4.7 km	21.2967	
	6.2 km	26.6016	
	7.7 km	31.9958	
	9.2 km	37.3006	
	10.7 km	42.6948	
	11.2 km	44.3935	
Underground cable	11.6 km	47.2993	Auto Reclosing Prevented (T_{ref2} < △T)
	12 km	50.2944	
	12.4 km	53.2001	

In this way, utilities who operate mixed transmission systems can apply the proposed algorithm through proper reference values that consider their system conditions (system configuration, cable type), thus avoiding improper recloser operation.

5. Conclusions

In this paper, a novel recloser operation algorithm on a mixed transmission system was proposed using the travelling wave. In a mixed transmission system, proper auto reclosing has to be applied because some risks such as explosion, fire, and insulation breakdown can occur by reclosing for underground cable faults. Therefore, in this paper, the proposed algorithm distinguished the faulted section using voltage waveform caused by the travelling wave and there was no need for any signal processing. Thus, the proposed algorithm can provide a simple, fast, and correct recloser operation command. Moreover, utilities can easily apply the proposed algorithm to their recloser according to their system condition. Additionally, if the discontinuity problem at a converter station and a transition point fault case can be overcome through advanced study, the proposed method can also be applied to an AC/DC hybrid system. What is new, compared to the existing methods, and why the proposed approach is needed are summarized as follow.

- Simple and convenient to use: The proposed approach uses instantaneous voltage information, which is sampled data by PT (Potential Transformer) on buses, and did not apply signal processing. Thus, there are no requirements for additional devices and the signal processing procedure when utilities try to apply the proposed algorithm on their recloser.
- Cost efficiency: As above-mentioned, except PTs, additional equipment (including GPS or computation device) is not required to apply the proposed approach. Additionally, because the function of the proposed algorithm performs simple subtraction and comparison, it has a low computation time. Thus, the proposed approach has a low computation cost. In addition, because the proposed algorithm is based on a single ended method, which differs from existing approaches that are mostly based on a double ended method, it requires a relatively smaller number of devices.
- Expansion ability: The proposed approach uses the characteristics of various conductors that consist of a mixed transmission line. According to the type of conductor, characteristics including the propagation speed of the travelling wave are changed. By considering the propagation speed of the travelling wave and setting proper reference values (T_{ref}, T_{ref1}, T_{ref2}), the proposed algorithm can be applied to any type of conductors. Furthermore, a mixed transmission line is operated under many different topologies. In this paper, only three types (OL + UC, OL + UC + OL, UC + OL + UC) were considered, but this can be expanded to many topologies (OL + UC + OL + UC, OL + UC + UC + OL, and so on) by adding more reference values.

Author Contributions: Conceptualized the proposed algorithm and investigated this study. Also, he drafted the original article and revised it according to review process: S.-H.S. Also conceptualized and validated the proposed algorithm also, he reviewed and edited the first draft: G.-J.C. This study was carried out under the supervision and management of C.-H.K. He also conceptualized the proposed algorithm and reviewed this article. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

Variables	
T_{ref}	A reference value to distinguish the faulted section
T_{sample}	The arrival time that travelling wave propagates from fault point to measuring point
ΔT	The difference between fault occurring time and T_{sample}
L	length of overhead line or underground cable
v	propagation velocity of travelling wave

Abbreviations

OL	Overhead line
UC	Underground cable
OC	Overhead line + Underground cable
OCO	Overhead line + Underground cable + Overhead line
COC	Underground cable + Overhead line + Underground cable

Appendix A

Figure A1 shows the recloser operation results according to the proposed algorithm when a fault occurs on a mixed transmission system that has an (OL + UC + OL) configuration. Figure A1 also shows the voltage waveform when a single line to ground fault (a phase) is injected in the overhead line section (9.9 km point of whole system). In the case of Figure A1, the fault is distinguished as an overhead line fault by the proposed algorithm, thus based on this result, the recloser conducts reclosing behavior at 0.6 s. In contrast, in the case of an underground cable fault, the recloser did not conduct reclosing behavior by the proposed algorithm.

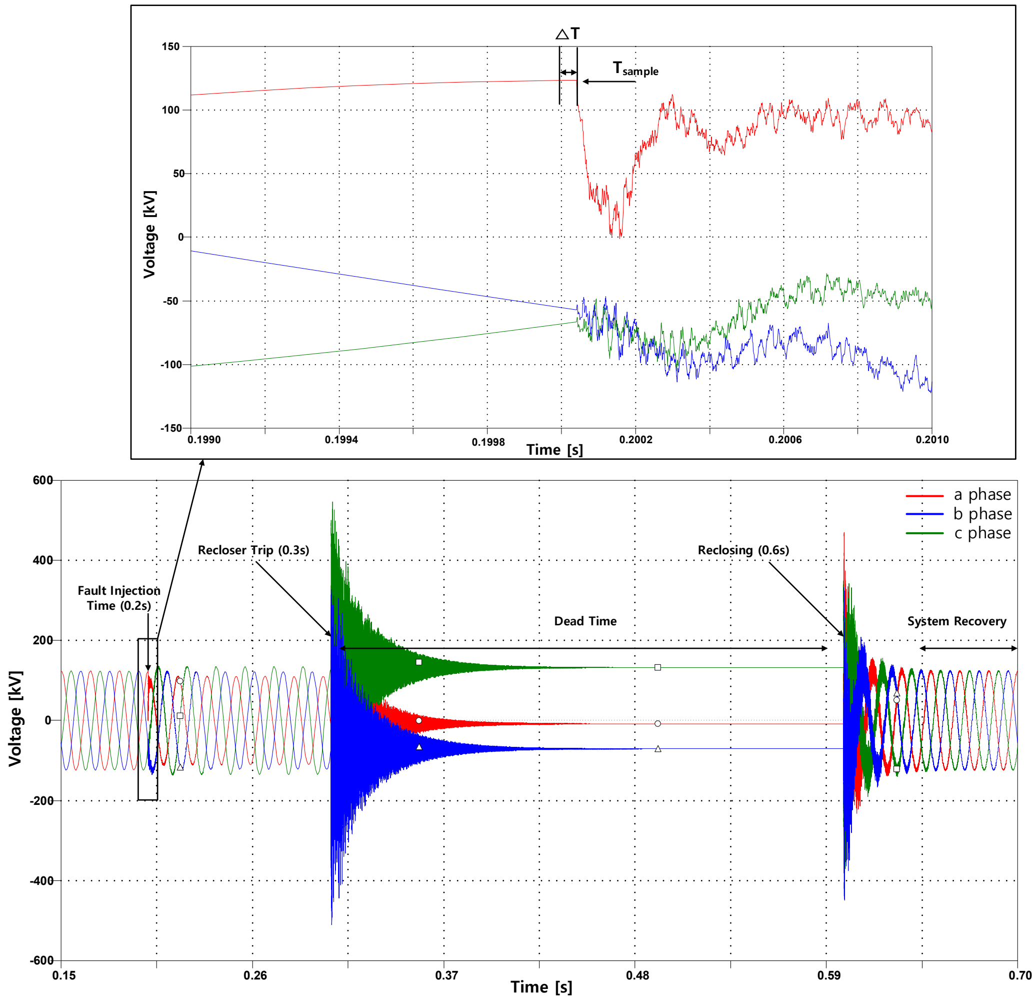

Figure A1. Example of a recloser operation result by the proposed algorithm when a fault occurs on an overhead line in the (OL + UC + OL) configuration.

Appendix B

In Figure A2, the pseudo-code of the proposed algorithm is shown. In step 1, the maximum value of the voltage difference between the sampled voltage in steady-state is obtained. In the next step, after a fault occurs, the proposed algorithm detects the voltage variation resulting from the travelling wave. In step 3, the proposed algorithm transfers the trip signal to the recloser. Finally, in last step, the proposed algorithm compares the T_{ref} with T, and then transfers the reclosing signal or prevents reclosing, according to the fault location.

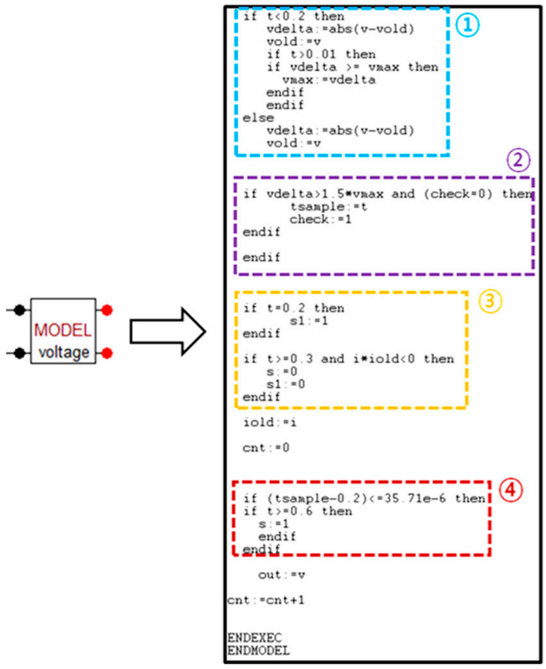

Figure A2. The pseudo-code of the proposed algorithm.

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