Analysis of Impact of UPFC on Single Pole Auto Reclosures

W. H. Jang, S. P. Ahn, C. H. Kim, R. K. Aggarwal

***Abstract*--This paper analyzes the effects of a Unified Power Flow Controller (UPFC) on an adaptive single pole auto-reclosing scheme in a power system. The application of the UPFC can play a very important role on the auto-reclosing scheme as it affects the voltage of a line when it controls the power flow of the system. The system implemented in this paper is based on a Korean 765kV system and the effectiveness of the UPFC applied to the system with the auto-reclosing scheme is investigated by Electro-Magnetic Transients Program (EMTP)/ATPDraw.**

***Keywords*: Auto-reclosing, EMTP, UPFC, Variable dead time**

I. Introduction

CONVENTIONAL single pole and three phase auto-reclosing techniques applied to Extra-High-Voltage (EHV) transmission lines adopt fixed time interval reclosing techniques, that is, the breaker recloses after a prescribed period (also known as the dead time) following tripping operation. With these techniques, unsuccessful reclosing with a fixed dead time or reclosing onto a permanent fault may threaten system stability and/or aggravate severe damage to the system and expensive equipment. Therefore, an alternative scheme of adaptive single pole auto-reclosing algorithm in the case of transient faults was suggested in the previous research [1]. The proposed algorithm in [1] was able to ascertain the secondary arc extinction time precisely using the RMS-value of the voltage at the fault point after the opening of a circuit breaker. As a part of the technique, waveform patterns of the voltage variation after the circuit breaker opening were analyzed by a RMS-value tracking method. The presented scheme using distinct characteristics of the voltage waveforms at the measurement point accurately classified whether a fault is transient or permanent in nature. Although this algorithm is verified as attractive and effective means of better management and operation of a high voltage transmission system, it could have different results in the system with a UPFC.

The UPFC is one of FACTS devices. There are several types of FACTS devices such as Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), etc. This paper sets up the UPFC in the system because it is only one FACTS device that allows simultaneous or selective control of active power flow, reactive power flow and voltage magnitude at the UPFC terminals [2]. The UPFC is a combination of a STATCOM and a Static Series Compensator (SSSC) which are coupled via a common DC link. In the UPFC, the active power for the SSSC is obtained from the line itself via the shunt unit STATCOM which is used for voltage control with control of its reactive power. UPFC is a complete controller for controlling active and reactive power control through the line, as well as line voltage control [2].

Since the adaptive single pole auto-reclosing algorithm is based on the method of tracking the voltage of a faulted phase and the UPFC also contributes to the voltage variations of the line, it is interesting to see what the impact of the UPFC on the adaptive single pole auto-reclosing scheme results in. Hitherto, the detailed effectiveness or accurate influence of the UPFC to auto-reclosing schemes has not been sufficiently analyzed. In addition, when the UPFC is applied to the power system, the previous research on the auto-reclosing scheme for the Korean 765kV system needs to be modified and more advanced studies need to be carried out. This paper, thus, analyzes the effectiveness of the UPFC on the auto-reclosing scheme for the Korean 765kV system under the variety of different conditions using EMTP/ATPdraw as following steps. To begin with, this paper introduces a variable dead time control algorithm in terms of the adaptive auto-reclosing scheme. In the second step, modeling of the UPFC is presented. In the last step, the UPFC is applied on the Korean 765kV transmission line to simulate the analysis according to the different fault locations especially focusing on the differences between the results with UPFC and without the UPFC.

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II. Adaptive Single Pole Auto Reclosing Scheme

A. Fault Type Classification

In terms of reliability of the power system, it is important to reduce the dead time to reclose breakers as soon as possible after the secondary arc extinction. The first prerequisite for the quick reclosing of breakers is the classification of fault type to avoid a second shock to the system by the breaker reclosure onto permanent faults. There is a unique feature of the voltage waveform of transient faults from permanent faults. That is a system frequency voltage component remained (also as called a recovery voltage) on the line after the extinction of the secondary arc due to the mutual coupling between the faulted phase and the two sound phases [3]. Fig. 1 shows the difference between the transient fault and the permanent fault. A fault occurs at point A and a primary arc characteristic is observed until point B. The voltage waveform of the transient fault has distortions due to the nonlinear characteristics of the secondary arc after the primary arc is cleared, but not for the permanent fault. After the secondary arc extinguishes at point C in Fig. 1 (a), the aforementioned recovery voltage remains on the line. There is a sudden different rms-value from point C and that is the indication of the extinction of the secondary arc [1].

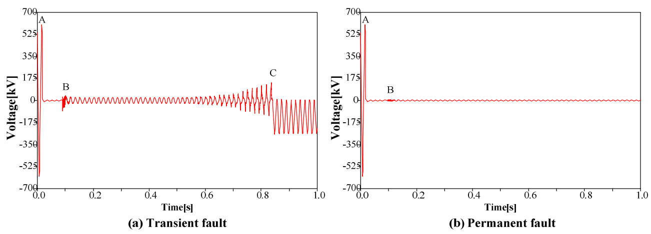


Fig. 1 Voltage waveforms of transient and permanent faults.

B. *Variable Dead Time Control Algorithm*

As pointed out above, there is a sudden variation of the rms-value of the voltage at the faulted line after the extinction of the secondary arc and it is the mark for the breakers to be reclosed. In the meantime, however, there should be approximately 10 cycles for the fault arc path to fully recover its system withstand voltage and approximately another 4 cycles for the breaker reclosing time [1]. Fig. 2 shows the rms-value tracking method of the algorithm to determine the arc extinction time.

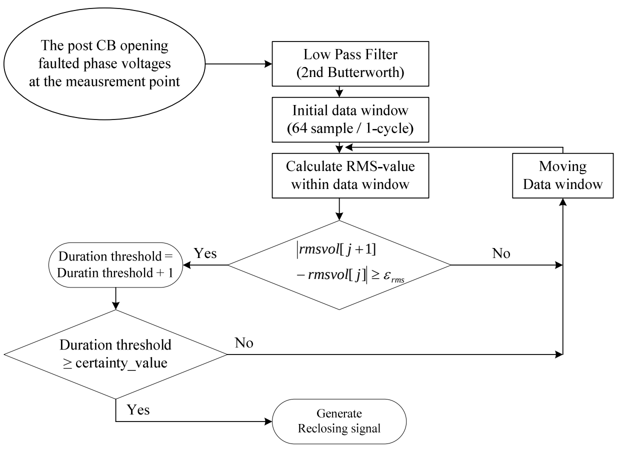


Fig. 2 Block diagram of the rms-value tracking method.

The detailed description of this algorithm is in [1]. Fig. 3 shows the graphical entire process of the voltage waveform and Delta, where Delta is the difference between the present rms-value and the previous rms-value at each time step.

$$\text{Delta} = |rmsvol[j+1] - rmsvol[j]| \quad (1)$$

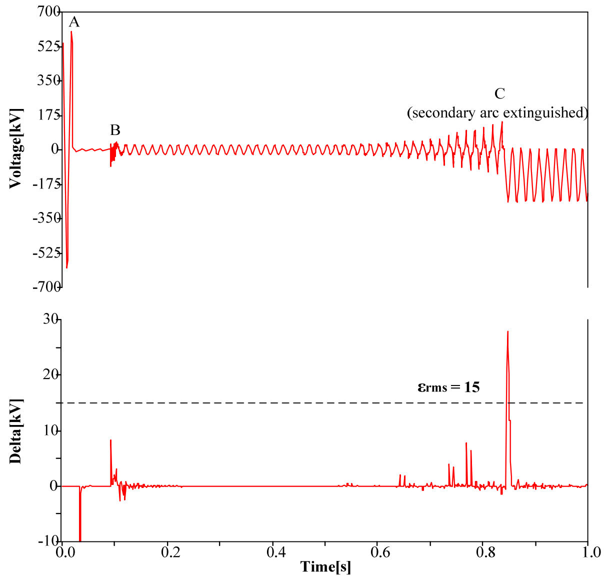


Fig. 3 Graphical illustrations of output waveforms in variable dead time algorithm.

As expected, rms-value of the voltage has a sudden change after the secondary arc is cleared and Delta shows the peak at the moment as well. The time for the extinction of the secondary arc is set to the moment that Delta goes beyond 15[kV] and the time for the breaker reclosure is set to be 14 cycles (about 0.23s in 60Hz) after the secondary arc extinction time for the aforementioned safety reason in this paper.

III. UPFC

A. *A Brief Review of UPFC*

A UPFC is a combination of a STATCOM and a Static Series Compensator (SSSC) which are coupled via a common DC link. Fig. 4 shows a simple diagram of the UPFC. The UPFC modeled in this paper consists of two voltage sourced three-phase inverters sharing a common capacitor on their DC side. With the shared DC link between the two inverters, the UPFC can simultaneously control both real and reactive power flow in the transmission line by injecting voltage in any phase angle with respect to the bus voltage with the series controller. The shunt controller supplies real power required by the series controller [4], [5]. Reactive power is mainly controlled by the shunt controller and active power is mainly controlled by the series controller. The UPFC receives system parameters to decide on and off ratio of gate signals for the Pulse Width Modulation (PWM) based inverters. In addition, a bypass is applied to protect the series transformer from the possible damage due to the excessive line current during the fault. The UPFC is installed in the middle of the transmission line to provide better efficiency of the power flow.

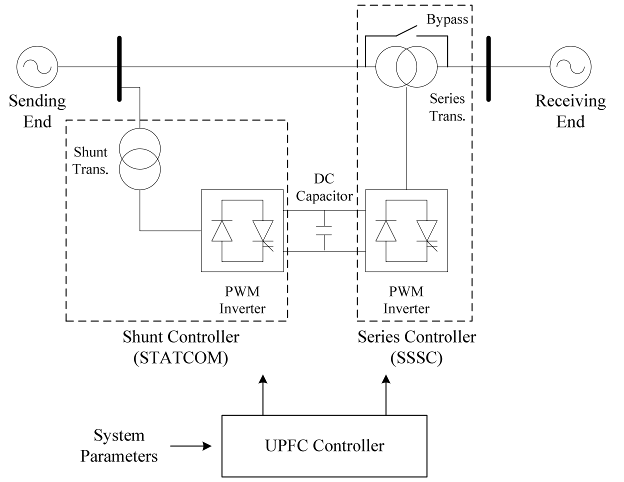


Fig. 4 Diagram of UPFC.

B. *Performance of the UPFC*

For the purpose of the paper, the UPFC will be operated in the single line to ground fault condition of the power system. Therefore, the UPFC is mainly functioning as a voltage compensator by controlling power flows for the transmission line where the UPFC is installed. Basically, the UPFC controls the power flow of a transmission line by changing the output of both inverters. This is easily achieved by the PWM technique controlling the inverter gain. The modulation factor (MF) is defined as a ratio of the magnitude of control signal to the one of the reference signal and the key to determine on/off switching intervals of the inverter to control the inverter gain [6].

$$MF = \frac{V_{con.peak}}{V_{ref.peak}} \qquad (2)$$

Fig. 5 shows that reactive power is controlled by the shunt controller. When the modulation factor of the series inverter is fixed to 0.8, the one of the shunt inverter changed from 0.5 to 1.2 to improve the reactive power. The reactive power is measured at the receiving end. The reactive power is increased from -81.1[MVAR] to -85.7[MVAR] which is 0.06[p.u.].

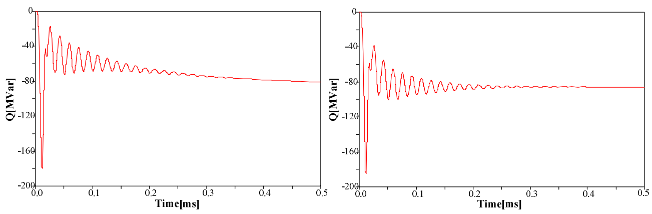


Fig. 5 Reactive power controlled by shunt controller.

Fig. 6 shows the change of the active power at the end of the line. When the modulation factor of the shunt inverter is fixed to 0.8, the one of the series inverter changed from 0.5 to 1.2 to improve the active power injected to the line. Since the series controller in connected to the shunt controller with the DC capacitor, there is no exchang of reactive power between two controllers. The active power is also measured at the receiving end. The active power is increased from 352[MW] to 365[MW] which is 0.037[p.u.].

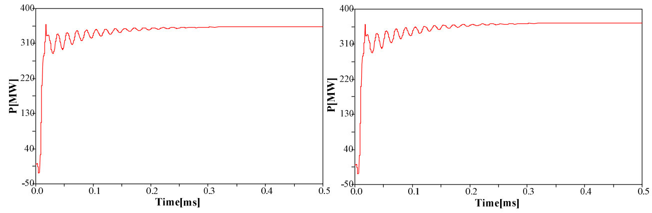


Fig. 6 Active power controlled by series controller.

For the most compensation in line to ground fault simulation condition, the modulation factors of both controllers are set to 1.2 in simulations.

IV. Simulation

A. *Simulation Models*

The entire simulation of the power system was carried out using the EMTP/ATPDraw. Transient Analysis of Control Systems (TACS) and MODELS were used to implement the both realistic nonlinear primary and secondary arc and the UPFC modeling. Fig. 7 shows the Korean 765kV system. The 765kV transmission line is located between Sin-Gapyung substation and Sin-Taebaek substation and the length of the line is 160km. Line parameters are calculated through the line constant program of EMTP. The governor and excitation system of ULCHIN nuclear power plant are modeled using a synchronous machine (SM) and TACS [7].

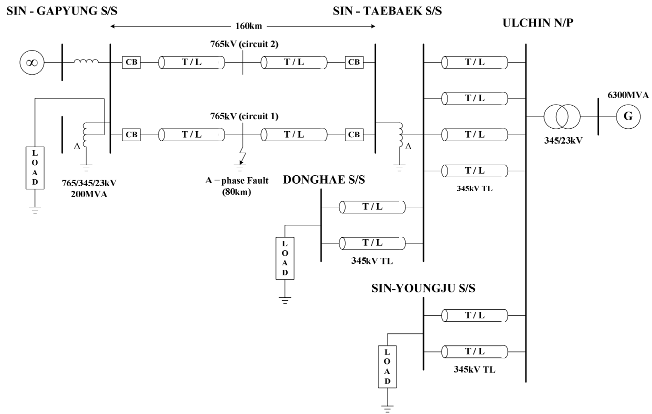


Fig. 7 Korean 765kV system.

Fig. 8 describes the complete diagram of the simulation sequence of the arc modeling. When a single phase-to-ground fault occurs, Johns and Aggarwal’s primary arc model [8] is brought into effect and produces primary arc characteristics. At each time step, the arc conductance is obtained by calculating the arc equation, and the reciprocal value of it is then used for the time varying arc resistance in TACS Type-91. The secondary arc is a highly complex phenomenon and is influenced by a number of factors. Two most influential factors are the characteristic of the arc conduction and the characteristic of the arc withstand voltage. The former is applied when the arc is conducting current and the latter is applied when the arc is not conducting. After circuit breakers open, the secondary arc is simulated; this is based on an inversely paralleled double diode circuit with the arc withstand voltage characteristics. When a single phase fault occurs on phase A, the phase is isolated at the designated time, isotim. The TACTS type-13 switch is normally closed and arc current is conducted to ground through the arc conduction circuit and the switch is opened on each fault current zero. The Korea 765kV system is simulated in which parameters of the line are calculated via the EMTP line constant program. Faults are generated on circuit 1 of the 765kV double circuit at different locations. The detailed description of the arc modeling is in [1], [9].

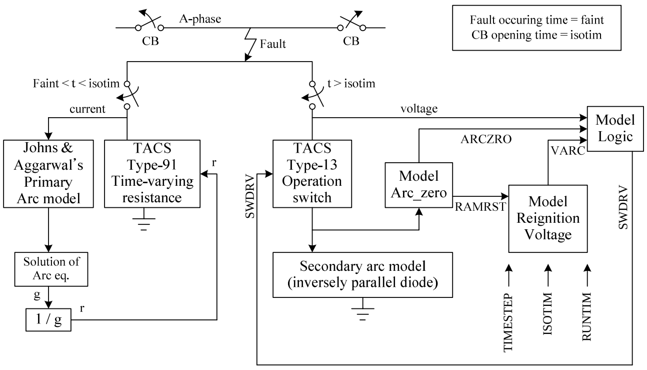


Fig. 8 Diagram of the arcing faults simulation.

B. Simulation Results and Analysis

Table I shows the simulation conditions to analyze the effect of the UPFC on the auto-reclosing.

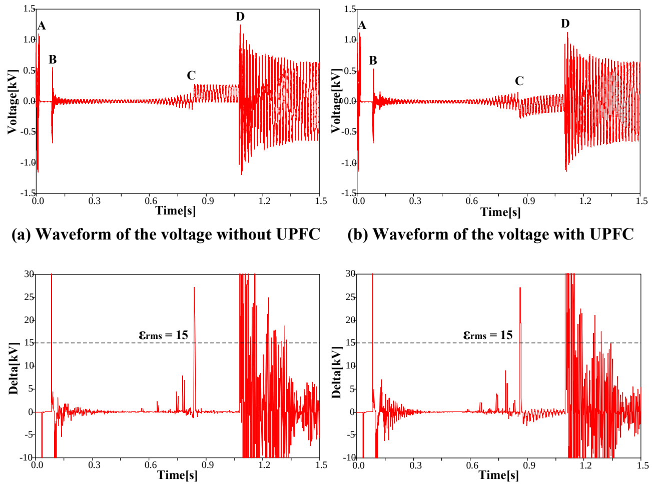
TABLE I

SIMULATION CONDITIONS WITH THE UPFC LOCATED AT THE MIDPOINT.

	Fault Locations [km]		
With UPFC	0(Sin-Taebaek)	80	160(Sin-Gapyung)
Without UPFC	0(Sin-Taebaek)	80	160(Sin-Gapyung)

At first simulation, the midpoint fault is simulated. The fault occurs at 0.01667s on the A phase in the middle of the transmission line (80km). Fig. 9 shows the voltage and Delta on the A phase at the fault point. The single phase line-to-ground fault occurs at point A and then the primary arc is cleared at point B. After the primary arc is cleared, the secondary arc is developed at point B and extinguished at point C. The recovery waveform is observed after the secondary arc is extinguished at point C. With the 14 cycles of safety period after the extinction of the secondary arc, the breakers are activated to be reclosed at point D. There are a couple of differences after the UPFC in installed.

The conspicuous difference in the graph is the recovery voltage generated after the secondary arc extinction. When the UPFC is not installed in the transmission line, the recovery voltage has a fixed magnitude of the sinusoidal waveform and this waveform has a rms-value of 160[kV]. In the latter case, the initial rms-value of the recovery voltage is similar to the former case, but it has decay.



(a) Waveform of the voltage without UPFC (b) Waveform of the voltage with UPFC

(c) Voltage difference without UPFC (d) Voltage difference with UPFC

Fig. 9 Waveforms of voltage and Delta at midpoint (80km) faults.

The secondary arc is extinguished at 0.842[s] without UPFC in Fig. 9 (a) and 0.867[s] with UPFC in Fig. 9 (b) so the delay due to the UPFC is about 0.025[s] which is one and a half cycles as shown in Fig. 11. In fact, the actual time that Delta goes beyond the threshold value is 0.836[s] in Fig. 9 (c) and 0.861[s] in Fig. 9 (d). This is because the secondary arc is considered to be extinguished by the algorithm when total number of samples (one cycle consists of 12 samples) of Delta over the threshold value becomes five to prevent misjudgment. The number of the sample is called the certainty value in the rms-value tracking method as shown in Fig. 2. Fig. 10 shows when the algorithm considers the secondary arc to be extinguished and the time delay with the UPFC. About 0.006[s] is delayed waiting for the certainty value to be 5 in Fig. 10. Fig. 11 shows how much the UPFC affects to the secondary extinction time. Another difference as the UPFC employed is that the Delta fluctuates more after both the primary arc and the secondary arc are extinguished. This is because of the switching of the UPFC controllers. As the UPFC conducts, the PWM voltage sourced inverters activate the switching and that cause the ripples on the voltage of the line. In this midpoint fault case, this phenomenon does not affect on the decision of the secondary arc extinction time by the variable dead time control algorithm.

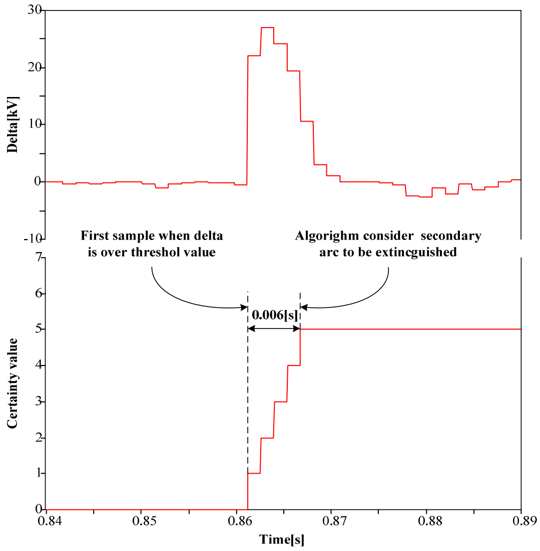


Fig. 10 Magnified Delta and certainty value when UPFC is installed (80km fault).

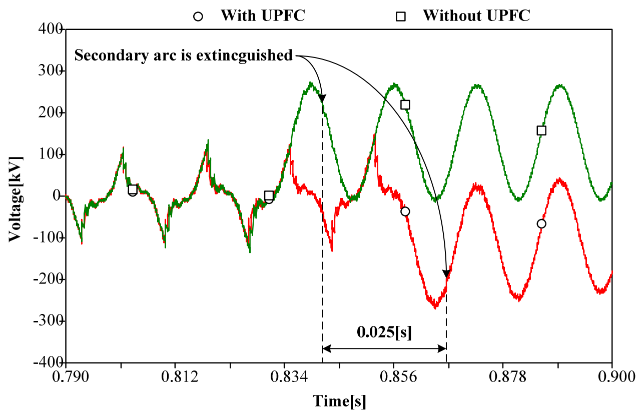


Fig. 11 Time difference of the secondary arc extinction at midpoint (80km) faults.

At second simulation, the fault is set to occur near Sin-Gapyung busbar (160km). Other conditions such as the fault inception time, the faulted phase, and so on are same as the previous case. Fig. 12 shows the results of the simulation.

In this case as well, the recovery voltage developed after the secondary arc extinction is changed when the UPFC is installed. DC offset is shown in Fig. 12 (b) and rms-value goes down with time from point C to point D. As the result of the DC offset, the waveform of Delta is affected. This may cause the delay of the secondary arc extinction. Delta shows peaks over the threshold value, 15[kV], around 0.9[s] as seen in Fig. 12 (d). The secondary arc is extinguished at 0.889[s] without UPFC in Fig. 12 (a) and 0.906[s] with UPFC in Fig. 12 (b) so the delay is about 0.017[s] which is about one cycles as shown in Fig. 14. Like the previous simulation, the algorithm waits for the uncertainty value to be 5. The certainty value becomes at 0.836[s] in Fig. 12 (c) and 0.861[s] in Fig. 12 (d). Fig. 13 shows when the algorithm considers the secondary arc to be extinguished and the time delay due to the condition. About 0.079[s] is delayed waiting for the 5th certainty value as shown in Fig. 13. Since there is a gap between the first and the second, the delay becomes longer than the one in Fig. 10. This certainly contributes the time difference of the secondary arc extinction in Fig. 14.

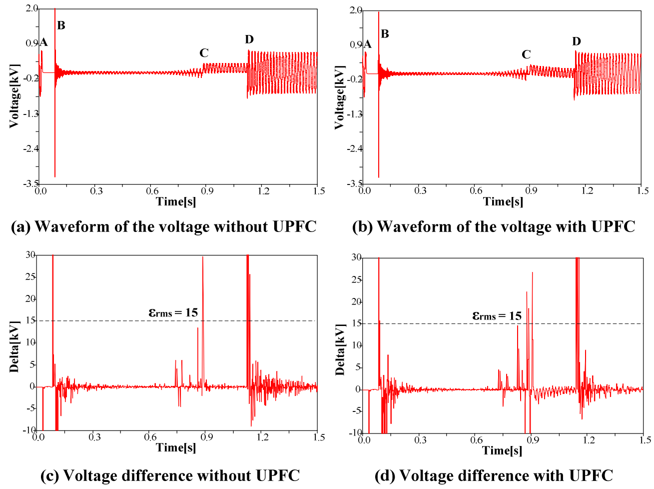


Fig. 12 Waveforms of voltage and Delta at Sin-Gapyung busbar (160km) faults.

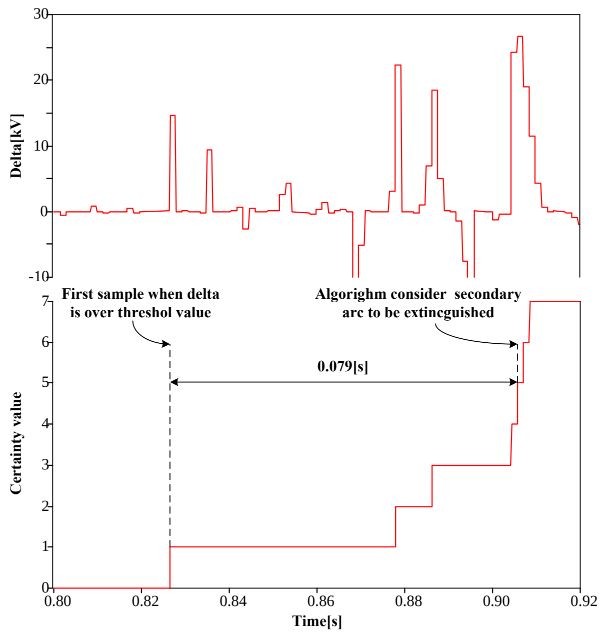


Fig. 13 Magnified Delta and certainty value when UPFC is installed (160km fault).

If the first peak were a little bit lower than the threshold value or the threshold value is set to a little bit higher, it would result in a more delayed detection of the secondary arc extinction. Therefore, this result supports that the adaptive auto-reclosing algorithm needs to be revised to resolve this possible issue. Fig. 14 shows how much the UPFC affects to the secondary extinction time. As UPFC is located in the midpoint and the fault occurs at 160km, there is similar effectiveness on the secondary arc extinction time as the previous simulation (80km fault). As the UPFC compensates the voltage of the line, the restrike voltage needs more time to be greater than the fault voltage. Since the fault is occurred 80km far away from the UPFC, the influence of the UPFC decreased so that the delay time also becomes shorter to about 0.017s, which is the period of one cycle, as shown in Fig. 14.

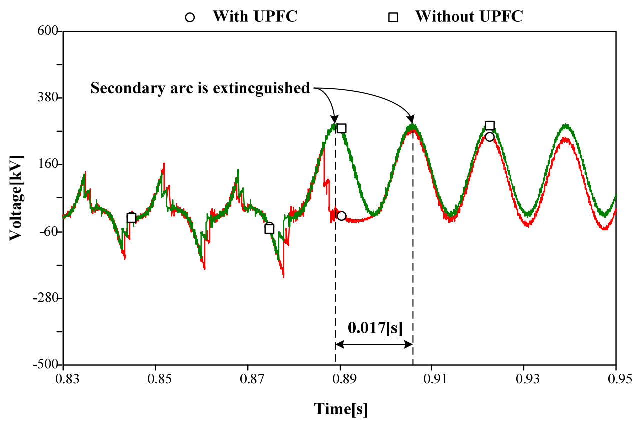


Fig. 14 Time difference of the secondary arc extinction at Sin-Gapyng busbar (160km) faults.

At third simulation, the fault is occurred near Sin-Taebaek busbar (0km). Other simulation conditions remained as of the former simulations. The results of the simulation are shown in Fig. 15 and Fig. 16.

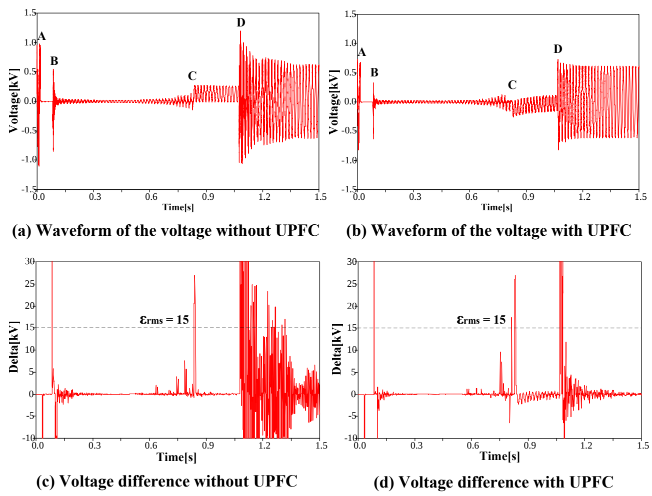


Fig. 15 Waveforms of voltage data at Sin-Taebaek busbar (0km) faults.

The secondary arc is extinguished at 0.836[s] without UPFC in Fig. 15 (a) and 0.842[s] with UPFC in Fig. 15 (b) so the time difference is about 0.008[s] which means that the UPFC does not influence on the secondary time extinction time. Like the previous simulations, there is the certainty value condition so the first certainty value is at 0.811[s] in Fig. 15 (c) and 0.833[s] in Fig. 15 (d). Fig. 16 shows when the algorithm considers the secondary arc to be extinguished and the time delay due to the condition. About 0.02[s] is delayed waiting for the 5th certainty value as shown in Fig. 16.

This case has a different feature from the former two cases. The recovery voltage has decay after point C when the UPFC is employed. Since the fault is located at the sending end of the line which means that the fault is located in front of the UPFC, the impact of the UPFC compensating the voltage drop of the fault line does not exist. The waveforms of the voltages in Fig. 17 verify that there is no influence of the UPFC on the algorithm; the secondary arc extinction time with the UPFC is even 0.008s (about a half cycle) earlier than the one without the UPFC. The waveform of Delta in Fig. 15 shows the similar issue that the second simulation had. If the threshold value is set to 17, the time differences would be greater. However, calibrating the threshold should be carefully handled to avoid providing wrong information, i.e. sending the signal about the extinction of the secondary arc too early or late, to breakers to be reclosed.

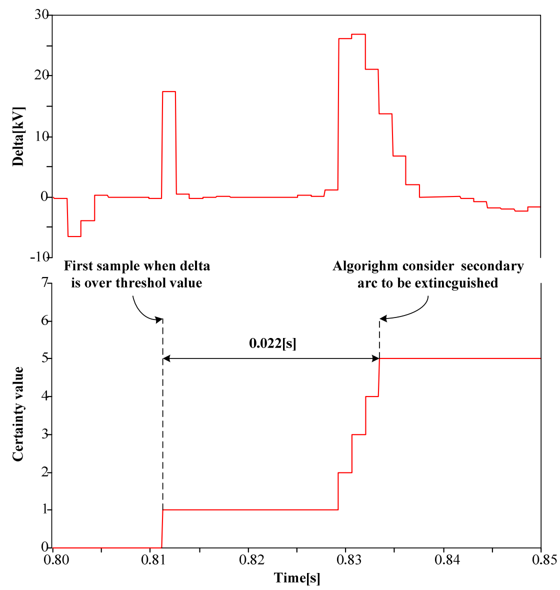


Fig. 16 Magnified Delta and certainty value when UPFC is installed (0km fault).

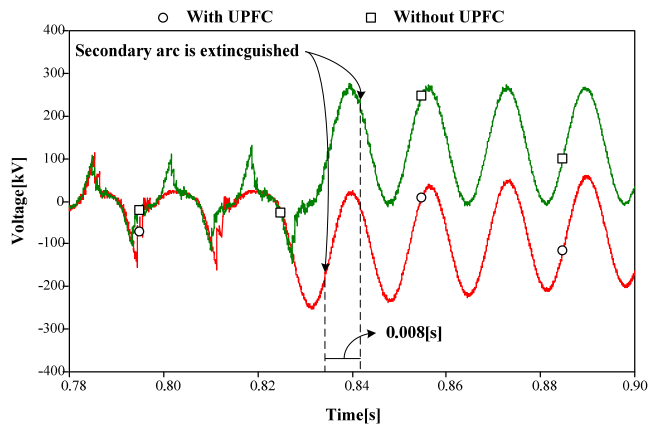


Fig. 17 Time difference of the secondary arc extinction at Sin-Taebaek busbar (0km) faults.

Table II compares the secondary arc extinction times of the all simulations conducted. The UPFC has no impact on the secondary extinction time where the fault is located before the UPFC. On the other hand, the secondary arc extinction time is postponed where faults are occurred behind the UPFC because UPFC compensates voltage drops of the line for a while. As the fault location is further behind from the UPFC, the effectiveness of the UPFC becomes less.

TABLE II

SECONDARY ARC EXTINCTION TIMES ACCORDING TO FAULT LOCATIONS WHEN UPFC IS LOCATED AT THE MIDPOINT (80KM)

Fault Location[km]	Secondary Arc Extinction Time[s]		Time Difference[s]
	Without UPFC	With UPFC	
0	0.842	0.834	-0.008
80	0.842	0.867	+0.025
160	0.889	0.906	+0.017

Table III shows the time delay due to the certainty value condition of the algorithm when the UPFC is installed with respect to the three fault locations. As the algorithm decides the extinction of the secondary arc at the fifth certainty value, there is a delay time. This delay could be shorter if the algorithm had second or third certainty value as an indicator for the secondary extinction as far as it does not jeopardize the algorithm of misjudgment of the secondary arc extinction.

TABLE III

DELAY TIME DUE TO THE CERTAINTY VALUE CONDITION OF THE ALGORITHM WHEN THE UPFC IS INSTALLED

Fault Location[km]	First certainty value[s]	Fifth certainty value[s]	Delay Time[s]
0	0.811	0.833	0.022
80	0.861	0.867	0.006
160	0.827	0.906	0.079

V. CONCLUSIONS

The impact of the UPFC on the auto-reclosing scheme has been presented in this paper. The analysis of the impact was performed with the Korea 765kV system modeled using TACS and MODELS in EMTP/ATPDraw. From the simulation results, the secondary arc extinction time can be changed and the variable dead time control algorithm still has capability to detect the secondary arc extinction time when the UPFC in installed. Therefore, it is confirmed that the adaptive auto-reclosing scheme can be applied to the system with the UPFC. According to the threshold value and the certainty value condition, however, there is also the probability of inaccurate detection for the secondary arc extinction time. Developing a reinforced variable dead time control algorithm with revised threshold value setting and the certainty value condition is left for the further study.

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