Transient Study for Single Phase Reclosing Using Arc Model on the Thailand 500 kV Transmission Lines from Mae Moh to Tha Ta Ko

K. Ngamsanroaj, S. Premrudeeprechacharn

***Abstract*—As a mean of further enhancing the operational availability of the transmission system, the clearing of temporary single line to ground faults by means of single phase reclosing was investigated. Neutral reactors for the line connected shunt reactor banks were optimized by minimizing sustained values of secondary arc fault current and post-fault recovery voltage. This paper addresses shunt compensation as it affects single phase reclosing. The work will illustrate transient study of single phase reclosing of the Thailand 500 kV transmission system between Mae Moh and Tha Ta Ko substations. The study has used EMTP simulation to determine the behavior of the system response to switching operation. The successful single phase reclosing is investigated by conducting fault clearing and reclosing cases utilizing dynamic arc model. The detail and results are described from series of simulation.**

***Keywords*: Single phase reclosing; Secondary arc current; Arc model; EMTP.**

I. INTRODUCTION

AT present, Electricity Generating Authority of Thailand or EGAT develops and operates Thailand's transmission network. EGAT has expanded to total more than 3,400 circuits-km of 500 kV and would require switching overvoltage studies in order to monitor them not to exceed the limit with respect to the Basic Switching Impulse Level (BSL) based on IEEE standard.

For EHV transmission levels, 90 – 95 % of all line faults involve only one phase. Of these, more than 90 % are temporary – usually caused by lightning strikes or lightning induced back flashovers – and can be cleared by three phase reclosing; consequently, phase-to-ground faults have received the most attention in system studies. The fault arc will extinguish and the fault path dielectric will restore completely during the dead time of the breaker, usually 500-600 msec. for 500 kV systems. However, three phases reclosing may cause system instability and result in system breakup and outages. In many instances, single phase switching can be used to enhance transmission system availability without causing system instability problems.

When single phase reclosing is used, then for a phase-to-ground fault, only the faulted phase is cleared. After a time delay the breakers at each line end are reclosed. With single phase switching, the energized phases capacitively and inductively couple energy into the faulted phase. This coupling results in a fault current which can sustain the arc. This coupled fault current is usually called the secondary arc current. The work will study the characteristic of the secondary arc current and single phase reclosing for the Thailand 500 kV lines from Mae Moh to Tha Ta Ko.

II. SINGLE PHASE RECLOSING AND ARC CURRENT

A. *Single Phase Reclosing*

Single phase switching consists of a protection system which determines that a single line to ground fault has occurred, and then opens only the breaker poles of the faulted phase at each terminal. The two unfaulted phases are left connected, and continue to carry approximately 50 % of the pre-fault power [1]. With the extinction of a transitory fault and successful single phase reclosing, the power system will probably remain stable. If the single phase fault is permanent or if the fault involves additional phases, all three phases will be cleared. After a faulted phase is isolated from both sides of a line, the secondary arc is supported for a period of time due to electro-magnetic and electrostatic influence of healthy phases, and then self extinguishes. As illustrated in Fig. 1, the primary arc current can be defined as the current flowing in the fault with all three breaker poles closed, and then the secondary arc current as the current flowing in the fault point because of the coupling from the other two phases. For single phase reclosing, the issue is to allow sufficient time for the secondary arc to disappear.

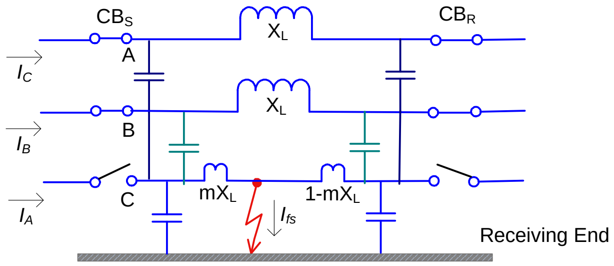

Fig. 1. Diagram concept of arc current

This work was supported in part by the Graduate School of Chiang Mai University Thailand.

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Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

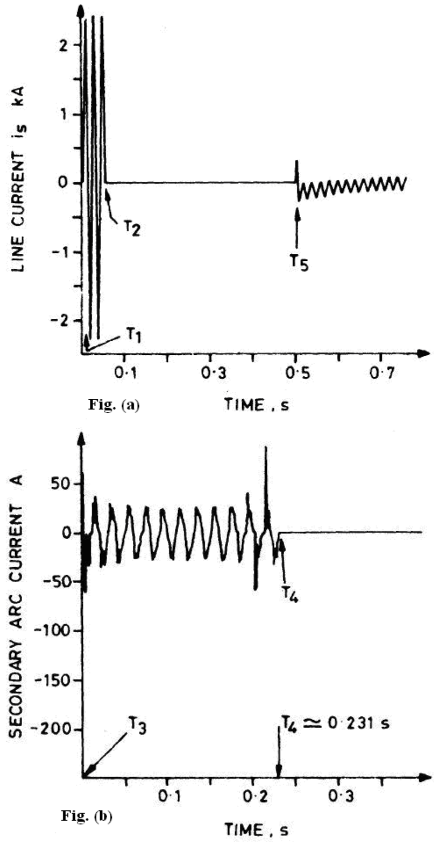

Fig. (a)

Fig. (b)

Fig. 2. Simulation of fault at sending end on uncompensated lines [4]
T1 = fault inception;T2 = clearance at sending end;T3 = clearance at receiving end (arc transition);T4 = final secondary arc extinction;
T5 = reclosing at sending end

The secondary arc current (I_{fs}) is basically the sum of two currents maintained by electrostatic (I_{fc}) and electromagnetic (I_{fm}) coupling from the two healthy phases [3].

$$I_{fs} = I_{fc} + I_{fm} \tag{1}$$

The inductive coupling is recognized as the smallest and the capacitive coupling as the largest contributor to the secondary arc current. When shunt reactors are present, these cancel the contribution of the shunt capacitance to the secondary arc current and the inductive component increases.

B. Arc Current

Fig. 2 shows the results of a typical 50 Hz study of a short uncompensated application of 500 kV line, 120 km [3]. The primary fault arc is taken during the primary arc period between fault inception and clearance at both ends (T_1-T_3), and the interruption of the primary arc current by sending end breaker at time T_2 is shown in Fig. 2(a). Following arc transition at time T_3, there is a gradual build-up of the voltage across the arc path until final extinction occurs at time T_4. Secondary arc extinction occurs at approximately 0.3 s and, in the period T_4-T_5 up to breaker reclosing, the characteristic offsetting of the recovery voltage is observed. The latter phenomenon occurs as a result of the faulted phase being effectively floating from T_4 to T_5. The detailed waveform of the secondary arc current presents in Fig. 2(b).

The simplified model of Johns, et al. [4] is used in this study for modeling the fault arc. This arc can be simulated by the following equation:

$$\frac{dg_{fi}}{dt} = \frac{1}{T_{fi}}(G_{fi} - g_{fi}) \tag{2}$$

Where subscript *fi* presents the phases of arc (*fp* for primary arc and *fs* for secondary arc), T_{fi} is the time constant of the arc path, g_{fi} is the time varying arc conductance and G_{fi} is the stationary arc conductance and can be evaluated from:

$$G_{fi} = \frac{|i|}{V_{fi} l_{fi}} \tag{3}$$

The stationary arc conductance can be interpreted as the arc conductance when the arc current is maintained for a sufficiently long time under constant external conditions. The V_{fi} is the stationary arc voltage drop per unit length. For primary arc, V_{fp} is constant and taken 15 V/cm if the range of the peak of primary current is from 1.4 kA to 24 kA [3]. V_{fs} is the function of the peak of the secondary current (I_{fs}) if the range of I_{fs} is from 1 A to 55 A., V_{fs} can be approximated by $V_{fs} = 75 I_{fs}^{-0.4}$ V/cm. While $|i|$ is the absolute value of arc current and l_{fi} is the arc length. The arc length assumed to be constant during primary arc duration. For secondary arc, the arc length is assumed to increase linearly with time [4]. The time constant can be evaluated from the following equation:

$$T_{fi} = \frac{\alpha_{fi} I_{fi}}{l_{fi}} \tag{4}$$

Where I_{fi} is the peak current. The coefficient α_{fi} is a constant and it is 2.85×10^{-5} for primary and 2.51×10^{-3} for secondary arc [4].

The probability of secondary arc extinction can be determined by two factors, the values of the sustained secondary arc current and the post-fault recovery voltage. Many researchers have concluded that a typical secondary arc current for 500 kV line is 20 A per 161 km. Typical recovery voltage values are 10-25 % of the line voltage without shunt reactor [2],[3], [5]-[8].

III. DESCRIPTION OF ARC MODEL

The secondary arc is a highly complex phenomenon. The arc model described in [4] will represent the successive partial arc extinctions and restrikes when the arc current and voltage pass through zero several times. The permanent arc extinction will occur when the voltage impressed across the discharge path lower than the arc reignition voltage. The fault arc is very vital in the equipment design, such as auto reclosing, because reclosing operation must be after secondary arc permanent extinction. Predicting the extinction for a secondary arc is subject to enough uncertainties that precision is not possible with the information and knowledge available to date. Practical experiences have been established and reported in the literatures [4], [7], [8].

A simplification of the secondary arc model of [4] has been modelled on EMTDC [6] and it was summarized that comparison of simulation results with published results show close correlation. The basis for the secondary arc model is described fully by Johns et al in the reference [4].

The arc was modelled as a custom model for EMTDC. It was based on a changing resistance for the primary arc and a changing current source after the transition to secondary arc. The primary arc resistance R_{fp} depends on the rms value of the primary arc current I_{fp} according to the equation [5]:

$$R_{fp} = 287 I_{fp}^{-1.4} \qquad \Omega / \text{cm} \qquad (5)$$

Where I_{fp} is rms value for primary arc current in amps.

The transition from primary arc to the secondary arc can be calculated from the time of the first current zero in the arc after the magnitude of primary arc substantially decreases. An thevenin equivalent of the network seen by the arc must be simulated which is accomplished by freezing all history terms in the electromagnetic transients solution at each time step. Once the thevenin network equivalent has been determined at the time step being computed, its characteristic is superimposed on the secondary arc characteristic. Where the intersection occurs, the current for the arc is robustly defined. The network solution is re-calculated with the determined arc current included as a current source.

For verifying on the degree of confidence of the model, validation tests needed to be determined. The comparisons between field tests and simulations are another direct way to validate the representation. However, field tests require resources and network outages which may affect the supply reliability. It is also not practical to test all configurations and operating conditions. Furthermore, in many field tests could not be conducted due to operational limitations. It is not easy to conduct the secondary arc test on the existing line, especially in Thailand; nevertheless, many researchers have published some important report on fault test results for EHV lines. Such tests are best done using actual system fault tests and compare results with simulations. In this study, the arc model will be investigated with the field test from reference [5], and the rest of studied system model and associated parameters will be calibrated with the field test for line energization.

The developed arc model will be examined with the staged fault tests which were undertaken at three locations along the 537 km of the Winnipeg-Twin Cities 500 kV ac interconnection [6]. Many details of the tests are given, but it is not known the accurate system equivalents at each end of the line at the times of the tests.

It was a relatively simple process to duplicate the fault and single phase operation of the circuit breakers. The fault current in the arc and recovery voltage for both actual and simulated tests are shown in Fig. 3 and Fig. 4 for one of the tests. The axes are scaled similar for ease of comparison. The simulated tests are duplicated directly from reference [6].

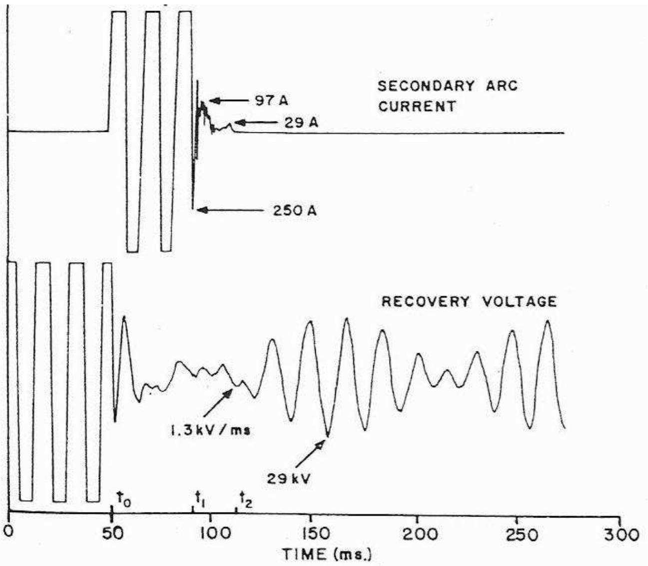

Fig. 3 Field test for a line fault with single phase reclosing (Test5) from [6]

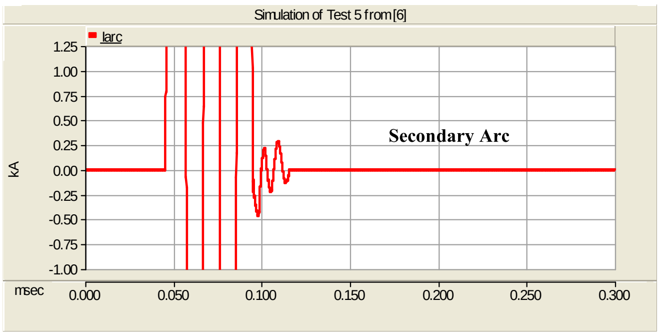

Fig. 4(a)

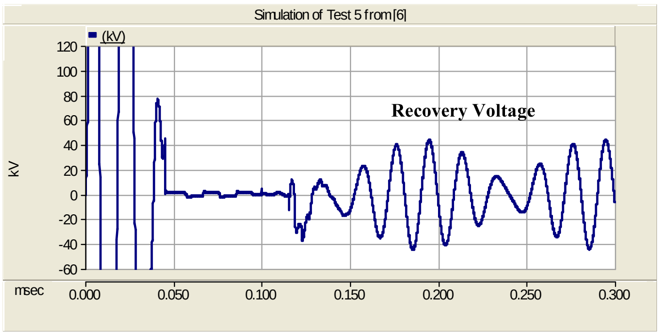

Fig. 4(b)

Fig. 4 Simulated arc model of field test for a line fault with single phase reclosing from [6]

It is very difficult to have a complete superposition of field and simulation cases for the same switching sequence. From the comparisons as depicted in Fig. 3 and Fig. 4 it was observed in general that the correspondence of waveforms is reasonably good for the closing operations with following comments:

- The simulated primary arc current wave shapes are quite similar in shape to the recorded primary arc current.
- The magnitude of the primary arc currents and recovery voltages are not always close in the peak value in comparison between actual and simulated tests.

- The duration of the secondary arc extinction time was similar or less in the actual tests compared with the simulated tests.

Although simulated results on secondary arc extinction times are favourable but not exact, the differences can be attributed to modelling in accuracies and imprecision of data.

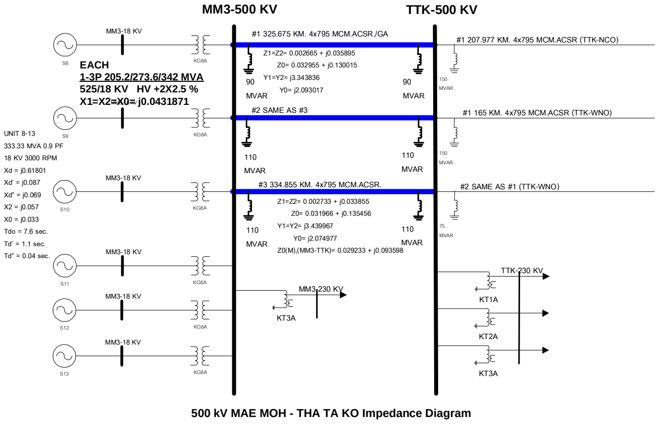

Fig. 5. Impedance diagram of studied system

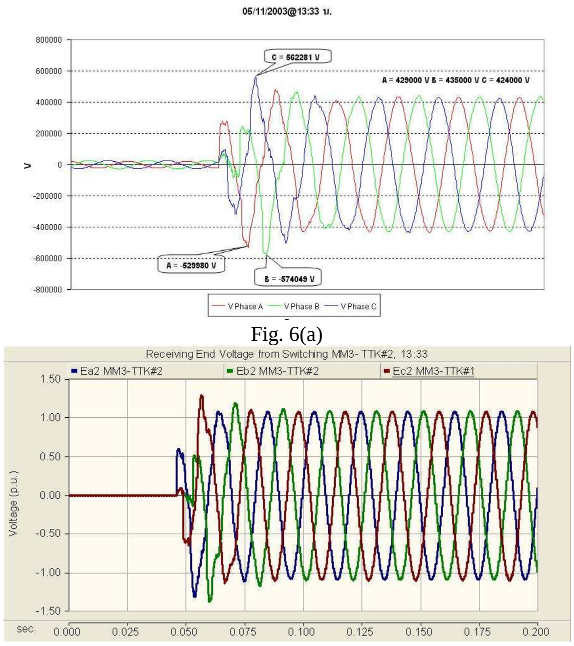

Fig. 6(a)

Fig. 6(b)

Fig. 6 The comparison of line energization field test (a) and simulation results (b)

For validating the system representation, the comparisons between field tests and simulations are also used. The accuracy of the system model as illustrated in Fig. 5 can be checked with the field tests from the existing studied system. Due to the system availability and stability, the scope of field tests was defined to line energization with all protection. TTK was the receiving end for each case, while the remainder of the system was in service. The receiving end voltage waveform during the field tests were recorded and compared with the corresponding simulation results.

Fig. 6 is one form many tests which describes the comparison result between field test recorded and simulation output of MM3 – TTK circuit no. 2. There was strong agreement between recorded field test results and the simulation waveforms [9], [12], [13]. The simulation had the identical system configuration as this field test. The voltage waveforms are almost identical, the comparisons give satisfactory results, further confirming the accuracy of the simulation model and parameters used [10], [11].

The validation tests for the secondary arc model and transmission line including system model from the above provide increased confidence in accuracy of representation for the study. The secondary arc, transmission line and system models were applied to study secondary arc extinction times in single line to ground fault on an EHV line.

IV. SYSTEM MODELING

For the method of analysis, the investigation is conducted at no load on the system. The scope of the simulation is three 500 kV lines from Mae Moh (MM3) to Tha Ta Ko (TTK) which is the longest section (about 330 km. for each line) in Thailand as depicted in Fig. 5. The simulation study is performed to investigate single phase reclosing using arc model occurring after single line to ground fault. The PSCAD/EMTDC is used for the study. The 500 kV circuits in the studied network have been modelled using the frequency dependent model. According to the proposed line, the 500 kV interconnected between MM3 and TTK substations consists of three circuits:

- Single circuit of 500 kV MM3 – TTK, using 4x795 MCM ACSR/GA conductor per phase, 325.675 km, with 3x90 MVAr/525 kV line shunt reactor and 6.046 MVAr neutral reactor at both ends.
- Double circuits of 500 kV MM3 – TTK , using 4x795 MCM ACSR conductor per phase, 334.855 km, with 3x110 MVAr/525 kV line shunt reactor and 3.2 MVAr neutral reactor at both ends.

The parameters of the line are calculated based on conductor sizes and their geometric spacing on the transmission towers. All inductive and capacitive coupling effects between the individual phases of each circuit, and coupling between circuits on the same transmission tower are therefore included in the network model. EGAT uses a transposition scheme that results in complete balance of the intra-circuit R, L and C parameters for each phase. Phase transposition and fixed compensating reactors are included. Each transformer and auto-transformer will be represented in detail with existing information: MVA rating, winding configuration and voltage, tap change ranges and normal setting, and leakage reactance between windings. The generators in the network are modelled using a 3-phase AC voltage source, with specified source and/or zero-sequence impedance. The locations of the circuit breakers that will be switched are identified on the studied system. Other parameters of the circuit breakers are determined: protection delay or clearing times, reclosing sequences, mechanical closing time and variation in pole closing times, and closing resistor. The installed location and rating of surge arresters are provided. At the boundary of the simulation, the external grid or the remaining parts of EGAT are modelled as a voltage source connected with driving impedance for feeding network.

For simulation of fault, when studying secondary arc phenomena more complicated model is taken into account. The fault can be modelled by time varying resistance model during primary arc period and for secondary arc till self-extinguish as previously described. The developed custom model for the fault arc can be used at the fault location as depicted in Fig. 7.

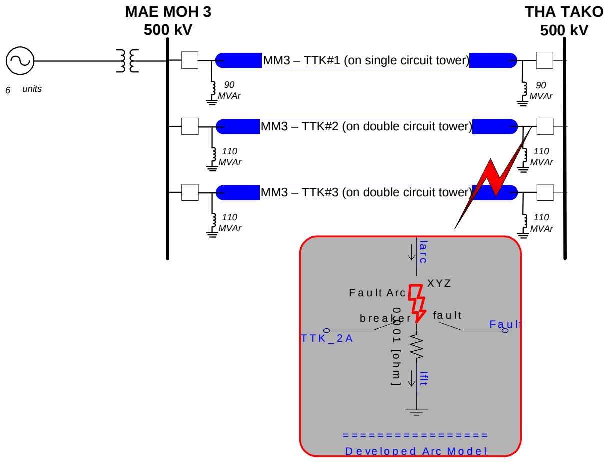

Fig. 7. Developed arc model for fault arc at the fault location

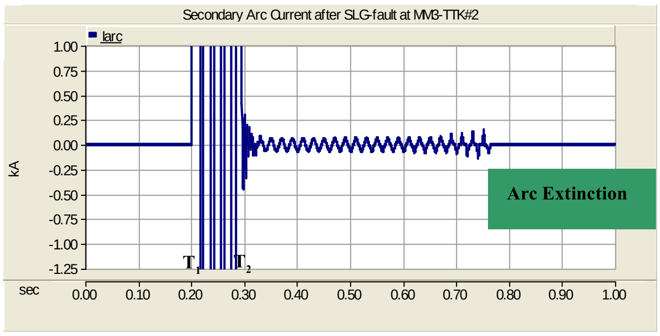

Fig. 8(a)

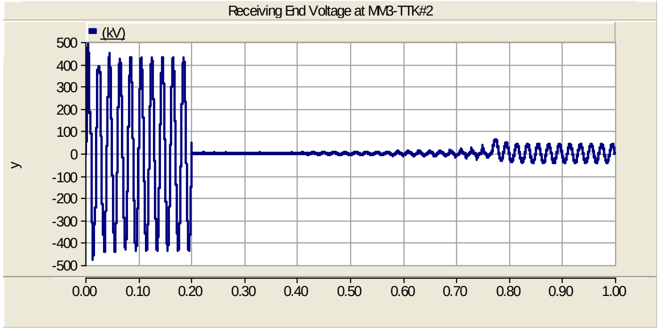

Fig. 8(b)

Fig.8. Simulation result, (a) for Secondary arc current and (b) for receiving end voltage,
(System response for phase A to ground fault at receiving end, MM3-TTK#2)

The studied system as shown in Fig. 7 is assumed to be at steady state condition prior to the occurrence of the fault at time T_1. The sending end breaker of the faulted phase opens first at time T_2, followed by the receiving end breaker opening at time T_3. The behaviour of the fault arc throughout the process of single phase reclosing is shown in Fig. 8. A series of studies have been carried out.

As the EMTP model [10]-[13] solves the system equations in the time-domain, it automatically allows for changes in the system admittances when circuit breakers operate. This makes the model practical for studying transient switching operations, such as sequential operation of circuit breakers, and single phase reclosing schemes.

V. STUDIES AND RESULTS

The modelled system from the above description can be referred in Fig. 7. For the single circuit of 500 kV MM3 – TTK#2, the simulated system is assumed to be at steady state operating condition prior to the occurrence of phase A to ground fault at time T_1. The sending end phase A breaker opens at time T_2, followed by the receiving end breaker opening at time T_3. The line is re-energized by reclosing sending end phase A breaker and then reclosing the receiving end. The characteristic of the fault arc throughout the process of single phase reclosing is shown in Fig. 8. The fault location is taken at the sending end, middle of the line and receiving end for each simulation.

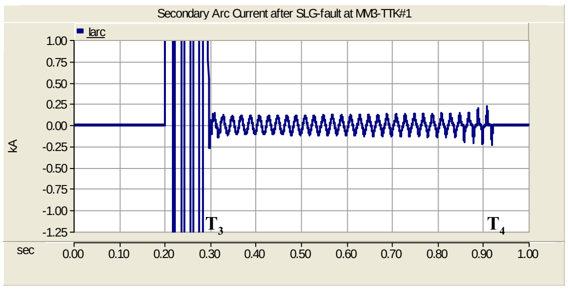

Fig. 9. System response for phase A to ground fault at receiving end, MM3 – TTK#1

A series of studies have been performed in similar manner for each one of another double circuit between MM3 and TTK (MM3 – TTK#1 and MM3 – TTK#3). Fig. 9 and Fig. 10 present the responses from the simulation.

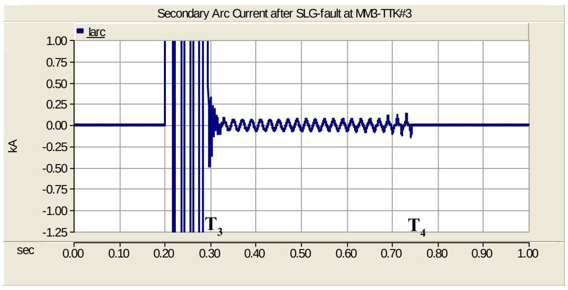

Fig. 10. System response for phase A to ground fault at receiving end, MM3 – TTK #3

Following the arc transition at time T_3, there is a gradual build up of the voltage across the arc path until final extinction occurs at time T_4. The secondary arc current and recovery voltage of each circuit are simulated when single phase to ground fault occur at phase A. Table I, II and III are the results of studies. It can be concluded that the electrostatic component of the secondary arc current and recovery voltage are below 20 A and 50 kV level respectively often regards as the limit for successful reclosing as reported in [4]. In the studied system, the three line reactor with a neutral reactor are shunted on the terminals, therefore the secondary arc current and recovery voltage are reduced. The single phase reclosing can be done successfully.

TABLE I
SECONDARY ARC CURRENT (I_{fs}) AND RECOVERY VOLTAGE FOR PHASE TO GROUND FAULT AT MM3 –TTK#1

Fault location	I_{fs}, A	Recovery voltage, kV
Mae Moh	15.20	43.60
Middle Line	14.10	41.45
Tha Ta Ko	9.10	32.84

TABLE II
SECONDARY ARC CURRENT (I_{fs}) AND RECOVERY VOLTAGE FOR PHASE TO GROUND FAULT AT MM3 –TTK#2

Fault location	I_{fs}, A	Recovery voltage, kV
Mae Moh	14.10	39.96
Middle Line	13.25	38.22
Tha Ta Ko	8.34	30.92

TABLE III
SECONDARY ARC CURRENT (I_{fs}) AND RECOVERY VOLTAGE FOR PHASE TO GROUND FAULT AT MM3 –TTK#3

Fault location	I_{fs}, A	Recovery voltage, kV
Mae Moh	13.91	39.21
Middle Line	13.07	37.54
Tha Ta Ko	8.18	30.35

VI. CONCLUSIONS

The work illustrates transient study of single phase reclosing of the Thailand 500 kV transmission system between Mae Moh and Tha Ta Ko substations. The model allows the transient performance of the system during sequential switching operations such as single phase reclosing to be studied. The results present especially emphasis on the effect of EHV transmission system on secondary arc current. The work considers the characteristic of secondary arc current after clearing of transitory fault and returning the system to normal operation. The secondary arc current and the post-fault recovery voltage, following the single phase isolation and clearing of a single line to ground fault, can be reduced by shunt reactors.

The study has used EMTP simulation to determine the behavior of the system response to switching operation. The arc behavior was implemented in the EMTP model as a time-varying resistance. The successful single phase reclosing is investigated by conducting fault clearing and reclosing cases utilizing arc model. The detail and results are described from series of simulation. The results could then be analyzed as a reference for further investigating the operation of the whole existing EGAT 500 kV system. Each line will be evaluated individually. The future study should be discussed on practical improvement of single phase reclosing scheme for the system.

VII. ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the contributions of of Dr. Suthep Chimklai from EGAT, Dr. Dharshana Muthumuni from Manitoba HVDC Research Centre, Canada and Assoc. Prof. Dr. Neville R. Watson of University of Canterbury, Christchurch, New Zealand on their technical and information supports.

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IX. BIOGRAPHIES

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