A Study on Adaptive Autoreclosure Scheme with Real-time Transient Stability

Sung-Ik Jang† , Myong-Chul Shin*, Chang-Dae Yoon* and Ryan C. Campbell*

Abstract - Since the power swing depends on the operating time of the relay, the swing's magnitude can be reduced by an autoreclosure relaying system with an optimal reclosing algorithm. This paper proposes a method for stability improvement using optimal reclosure relaying. An optimal reclosure algorithm is applied to identify both temporary and permanent faults, and to predict system stability by applying WAM and high speed communication technology. It provides optimal control by predicting and determining the degree of stability, considering the real time transient stability using EEEAC. For temporary faults, the algorithm determines the system's stability and either recloses optimally for stable systems, or inserts series capacitance before optimal reclosure for unstable systems. It also applies an optimal reclosure algorithm to minimize shock and damage to the power system when reclosure fails due to permanent faults.

Keywords: Adaptive Autoreclosure, EMTP, Transient Fault, Transient Stability

1. Introduction

The method of autoreclosure is an economical and effective technique for high capacity electric power systems to improve reliability and stability. If autoreclosure is successfully executed, it usually restores the stability of the system and maintains the continuity of electric power transmission.

Even if autoreclosure succeeds, the power swing depends on the time point of relay operation, therefore the power swing can be increased or decreased by adaptive reclosing algorithms [1-4]. Also, the system's transient stability is significantly affected by the reclosing time. Furthermore, unsuccessful reclosure, in the case of permanent faults, may even increase the potential damage to the system and equipment.

Therefore, it is very important to distinguish permanent faults from temporary faults and to apply an adaptive algorithm in each case. There are many advantages to this, such as an increased rate of successful reclosure, improved system stability, and a reduction in the shock to the system and equipment under a permanent fault [8, 9]. In addition, even if reclosing is successful, system stability may not be regained, so it may be necessary to add a controlled amount of series capacitance in some cases.

Recently, a transient stability control scheme was presented that is based on wide area measurement (WAM) and high-speed communication technology. When a fault occurs, phasor measurement units (PMU) acquire information from the generators during and after the fault, thus making it possible to predict, analyze, and estimate the degree of stability using the acquired data based on the emergency extended equal area criterion (EEEAC) [14].

For implementation and assessment of the proposed reclosure algorithm, various stability simulations are performed using EMTP MODELS.

2. Autoreclosure Relaying System

The proposed autoreclosure algorithm utilizes adjustable dead times by accurately identifying arc extinction times. In general, if the dead time is too short, it is possible to reignite the arc, which leads to restriking arc faults, so we must ensure a long enough dead time [1, 4].

Because we cannot ensure system stability with short reclosure durations using the equivalent generator analysis method, we can improve transient stability of the whole power system more easily by applying adaptive reclosing with optimal operating times [6].

2.1 Autoreclosure Schemes & Fault Conditions

There are two critical issues for autoreclosure operation: temporary faults from surges and switching, and permanent faults that cause damage to equipment by maintaining fault current during reclosure operation.

Reclosure operation is initiated after the extinction of the secondary arc since the secondary arc must extinguish be-

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fore successful reclosure can occur. Ideal operation, then, avoids restriking due to reclosure before the dead time [1, 2].

The complete extinction time of a secondary arc fault increases with transmission voltage and transmission line length. In general, it is not always advantageous to reduce dead times and reclose as fast as possible after secondary arc extinction, as this does not promote transient stability or reliability of the power system. Also, the power system becomes more unstable due to reclosure failure during a permanent fault, and it could create stress factors for turbine blades, thus damaging turbine generators [9, 10].

In current practice, autoreclosure generally operates the recloser, regardless of the type of fault, after a predefined dead time. This dead time allows the insulation to recover (i.e., the air to deionize).

Recently, there have been several techniques proposed to ascertain precisely the secondary arc extinction time, and to analyze the harmonic components of the acquired waveforms of faulted transmission lines for the purpose of distinguishing between permanent faults and temporary faults.

In this paper, power system stability can be improved by applying reclosure relaying at optimal time points that takes into account the energy of the transient state for each case after distinguishing temporary faults from permanent faults. Fig.s 1 and 2 show simulation results for a permanent and temporary fault on a 345kV system; Fig. 1 presents the arc currents, on which the point of secondary arc extinction is visible, while Fig. 2 presents the corresponding voltages.

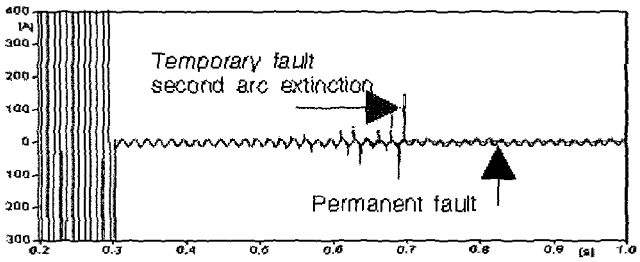

Fig. 1 Arc current for temporary and permanent fault on 345kV simulated power system

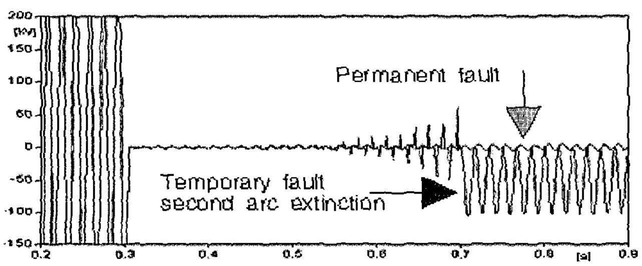

Fig. 2 Arc voltage for temporary and permanent fault on 345kV simulated power system

2.2 The Condition of Optimal Autoreclosure

As mentioned earlier, it is not always advantageous to reduce dead times and reclose as fast as possible after secondary arc extinction, as this does not promote transient stability or reliability of the power system.

For temporary faults, it is generally thought that the best reclosing practice for improvement of power system stability is to autoreclose as quickly as possible, however, rapid reclosing is not always conducive to the improvement of stability. Transient energy should be considered after reclosure operation.

Usually, successful reclosure requires two things: 1) time for a synchronization check, and 2) time for the air to deionize while the line is open so the arc doesn't restrike. Sufficient time elapsed helps ensure successful reclosure of both sides. Therefore, it is an important fact that optimizing the time of reclosure can improve the stability of the power system after clearing the fault.

Fig. 3, below, illustrates the relationship between phase angle and energy. Transient energy is the sum of kinetic energy and potential energy, and the peak amplitude of transient energy exists when all of the kinetic energy is converted into potential energy. At this point, the system becomes unstable, resulting in secondary damage from the impact of transient energy that follows the initial fault in the case of reclosure failure.

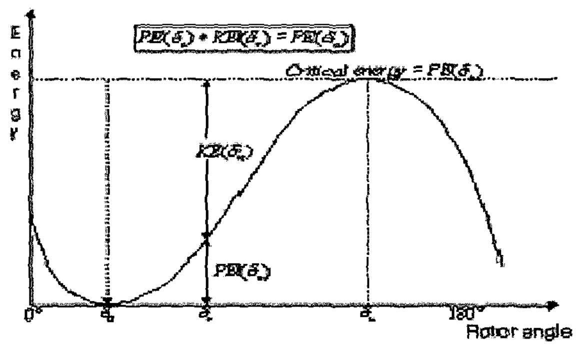

Fig. 3 Graph of Energy/Angle Equation

Equation (1), below, gives the transient energy after fault clearing for a one machine infinite bus power system:

$$M\left(\frac{dw}{dt}\right) = P_m - P_e \qquad (1)$$
$$\left(\frac{d\delta}{dt}\right) = w$$

where, t : time

ω : (rotor) speed or velocity

δ : angle

M : inertia coefficient (constant)
P_m : machine power (input)
P_e : electrical power (input)

If the total energy, Vx, is defined by the following equation

$$\mathrm{Vx} = \frac{1}{2}Mw^2 - \int_{\delta_0}^{\delta}(Pm - Pe)d\delta \qquad (2)$$

then, the critical energy is determined by Equation (3) after successful reclosure operation.

$$V_{cr} = -\int_{\delta_0}^{\delta_u}(P_m - P_{em}\sin\delta)d\delta \qquad (3)$$

where, δ^u ($\delta^u = \pi - \delta^0$) is the generator angle at the unstable equilibrium point following reclosure, and Pem is electrical power at that time.

The transient energy is given by Equation (4), on reclosing as follows:

$$\mathrm{Vth} = \frac{1}{2}Mw_{th}^2 - \int_{\delta_0}^{\delta_{th}}(P_m - P_{em}\sin\delta)d\delta \qquad (4)$$

where δth and ωth are the generator angle and velocity (speed) values at the point of reclosure.

The power system stability after reclosing is determined by the transient energy and critical energy: if transient energy is less than critical energy, then the power system is stable (i.e., Vth ≤ Vcr)

So, if transient energy following reclosure is minimized, then power swing should also be minimized.

2.2.1 Optimal Reclosure during Successful Reclosing

CASE 1) Stable Power System after Fault Clearance

Referring to Fig. 4, the phase angle that has maximum value is point *e*, and the recurring phase angle, which is the lowest speed, is point *f* (where Pm and Pe intersect). If the achieved deceleration area (A_2) and that area become the same at point *g*, then the lowest phase angle is attained. Because damping effects occur when the power swings, as time passes, the area of convergence decreases. And if, in reaching point *g*, the power system accelerates again in the amount of the area enclosed by *fgi*, the system does not receive the effects of kinetic energy because the speed is zero at point *g* and potential energy is again a maximum, such as at point *e*.

If reclosure operates at the lowest phase angle δmin, the driving point for recovery of the power system moves to point *h* and the acceleration area decreases the area *afgh* by the amount of *ahi*. As such, if the acceleration area decreases, the convergence speed changes quickly, thus greatly diminishing the level of the shock and damage to the rotor.

CASE 2) Unstable Power System after Fault Clearance

In the case where transient energy simply increases, the system becomes unstable after fault clearance. This is when the minimum angle of generator for optimal reclosure does not exist. Therefore, injection of series capacitance - calculated by contingency fault analysis - and reclosure operation after the deionizing time may improve system stability.

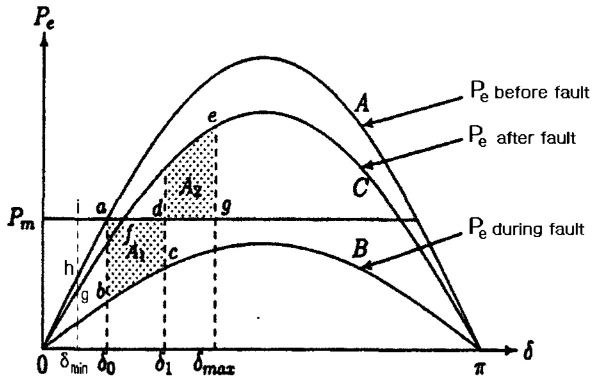

Fig. 4 Successful reclosing at δmin

2.2.2 Optimal Reclosure during Unsuccessful Reclosing

A successful reclosing operation can improve reliability and stability and minimize dangerous conditions in power systems. However, when reclosing fails due to a permanent fault, it may have serious impact on power systems. In the case of this kind of permanent fault, a point in time at which the impact of kinetic energy, which may occur again can be eliminated when w, the angular velocity, reaches its lowest value (see Fig. 5, minimum speed).

At this point, although the reclosing operation fails, convergence occurs faster than if there were no reclosing operation because the kinetic energies, which occur due to the primary fault, are eliminated.

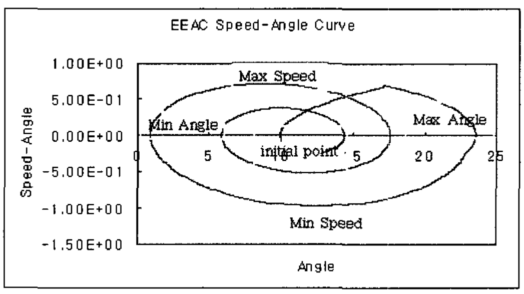

Fig. 5 Speed-angle curve

2.3 Optimal Reclosing Algorithm for Stability Improvement

This paper suggests an optimal reclosing algorithm that can improve the transient stability of power systems.

As indicated in the diagram of Fig. 6, the fault types can be divided into temporary and permanent faults. If a fault is determined to be temporary, then there are two kinds of situations to be addressed regarding power system stability. One is the case where the power system is assumed to be stable after clearing the fault, i.e., when the sign change of w is from positive to negative, which assists system stability with optimal reclosing when δ is at a minimum. The other case is where the power system is assumed to be unstable due to the lack of sign change in w and its constant increase. In this case, it is necessary to connect series capacitors to the system and deionize when the reclosing operation is performed.

Also, when considering possible failure of reclosure due to a permanent fault, power system stability should be achieved by performing the reclosing operation at the optimal time point of minimal w in order to eliminate the potential impact of reclosing.

2.3.1 Applying Transient Stability Based on EEEAC

Contrary to EEAC, the EEEAC is not attained via calculation, but with real-time measurement.

A multi-machine power system can be divided into two groups: critical and non-critical. These can then be equated to a two-machine system, which enables transient stability of the system to be estimated by EEAC.

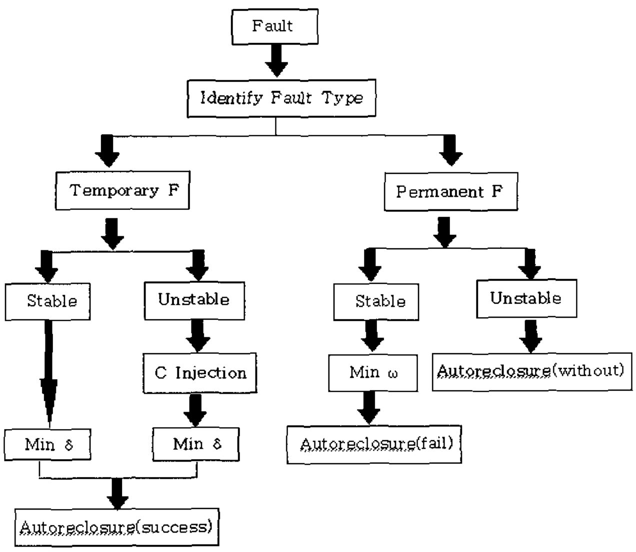

Fig. 6 Optimal reclosing operation algorithm

For estimation and discrimination of transient stability in a multi-machine system, the following equations apply:

$$\dot{\delta}_i = \omega^i$$

$$M^i \dot{\omega}_i = P^{mi} - P^{ei} \quad i = 1, 2, ...n \qquad (5)$$

$$P^{ei} = E_i^2 Y_{ii} \cos\theta_{ii} + \sum_{j=1, j\neq i} E_i E_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij})$$

where δ_i, ω^i, M^i : the rotor angle, speed, and inertia coefficient of the *i-th* generator

P^{mi}, P^{ei} : the machine and electrical power of the *i-th* generator

E^i : the voltage behind the direct axis transient reactance of the *i-th* generator

Y^{ij} : the *ij-th* element of the admittance matrix reduced at the internal generator node

θ^{ij} : the argument of Yij

EEEAC is measured and transmitted at a high rate of speed and is then used to estimate the power system's stability using the angle, angular velocity, and power measured by a PMU during fault occurrence and clearing.

The equations for the critical group of generators are given by (6):

$$M^S = \sum_{i\in s} M_i \qquad \delta^S = M_S^{-1} \sum_{i\in s} M_i \delta_i \qquad (6)$$

and the equations of the non-critical group are given by (7):

$$M^a = \sum_{j\in A} M_j \qquad \delta^a = M_a^{-1} \sum_{i\in A} M_j \delta_j \qquad (7)$$

These can be simplified to a two-machine system as follows:

$$\delta = \delta^S - \delta^a$$

$$M = M^a M^S (M^a + M^S)$$

$$P^m = M^{-1}(M_a \sum_{i\in s} P_{mi} - M_s \sum_{j\in A} P_{mj}) \qquad (8)$$

Thus, an equivalent circuit with a two-machine infinite bus is obtained.

Fig. 7 indicates variations of generator rotor angles when the fault's clearing time varies for two-phase to ground faults on one of the Korea Electric Power Corporation's (KEPCO's) 765kV transmission lines (ShinSeoSan – ShinAnSung T/L).

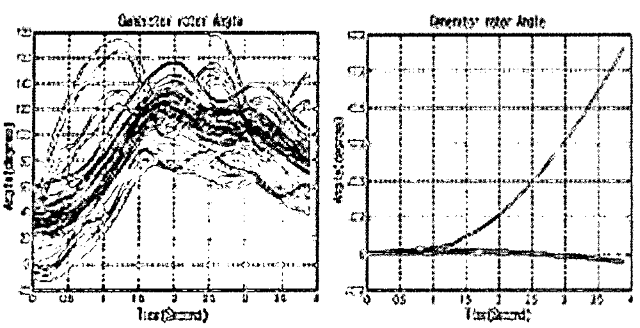

Fig. 7 Generator rotor angles at CT 0.12, 0.13

The acceleration area (additional kinetic energy) is obtained from real-time measurements and the deceleration area (potential energy) is predicted from measurements at the initial time of fault occurrence.

Moreover, optimal reclosing time can be estimated by real-time measurement of angle-velocity variation. To estimate the variation of angular velocity (w^i), three values of w^i at t^0, t^1 and t^2 have been used.

$$w^i(t) = w^i(t^2) + a^1(t-t^2) + a^2(t-t^1)(t-t^2) \quad (9)$$

where
$$a^0 = (w^i(t^1) - w^i(t^0))/(t^1-t^0)$$
$$a^1 = (w^i(t^2) - w^i(t^1))/(t^2-t^1)$$
$$a^2 = (a^1-a^0)/(t^1-t^0)$$

The estimation of the power angle $\boldsymbol{\delta}^i(t)$ is described by equation (10).

$$\delta^i(t) = \int_{t0}^{t} w_i(t) + \delta_i(t_0) \quad (10)$$

$$= \delta^i(t^0) + w^i(t^2)(t-t^0) + a^1(t^2 - t_0^2)/2 + a^1 t^2(t-t^0)$$
$$+ a^2[(t^3 - t_0^3)/3 - (t^1+t^2)(t^2 - t_0^2)/2 + t^1 t^2(t-t^0)]$$

The phase difference between two machines can be determined using equation (11).

$$\Delta\delta^{pr}(t) = \delta^r(t) - \delta p(t) + \Delta\delta^{pr}(0) \quad (11)$$

Where, $\Delta\delta^{pr}(0)$ is the power angle when disturbances have disappeared (i.e., at the new steady-state).

Simulation results show that, if If $\Delta\delta^{pr}(t)$ exceeds the threshold value δ^1, the system may become unstable.

2.4 Results of Case Study

Each case has been simulated in EMTP using a simplified multi-machine system (as described in the previous section), where the sending end generator is a model of the Ul Jin nuclear power plant.

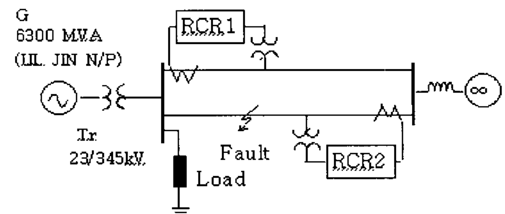

Fig. 8 Model system for simulation

2.4.1 Reclosing Operation for Temporary Fault

1) If the system is stable after clearing the fault

Equation (9) is used for estimating the optimal point in time for reclosure operation, and for predicting whether the system is stable or not after clearing the fault.

The measured values of w^i (t) for the series of three points in time immediately following the point where w^i (t) equals zero are represented below:

t^0 : 2.21sec $w^i(t^0)$: -0.01427

t^1 : 2.2464sec $w^i(t^1)$: -0.10589

t^2 : 2.2828sec $w^i(t^2)$: -0.19323

Therefore, the estimated and simulated optimal time points for reclosing are in close agreement: 3.06488 sec. estimated and 3.02016 sec. simulated.

These simulation results indicate that our optimal reclosing method makes the model system more stable, with satisfactory convergence characteristics, than the conventional reclosing method does (reclosing after 0.4s) from the standpoint of angle and speed-angle, as indicated in Fig. 9.

In a similar manner, the results of our optimal reclosing method for estimated time points for reclosing operation have faster convergence characteristics for system fluctuations than the conventional method; Fig. 10 shows that the changes in system stability by the proposed method nearly correspond to those of actual system stability with optimal reclosure.

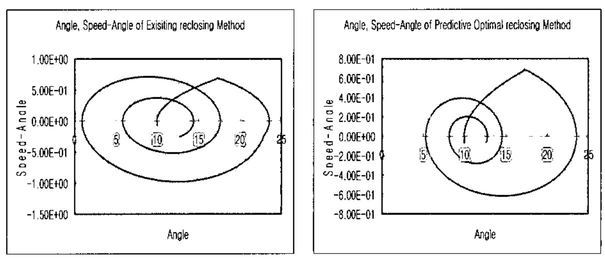

Fig. 9 Speed-Angle changes with and without optimal control for a stable system

2) If the system is unstable after clearing the fault

After clearing a three phase fault, if the system is unstable, it is impossible to estimate the time point for optimal reclosing operation and the results of conventional reclosing also are unstable (see Fig. 11).

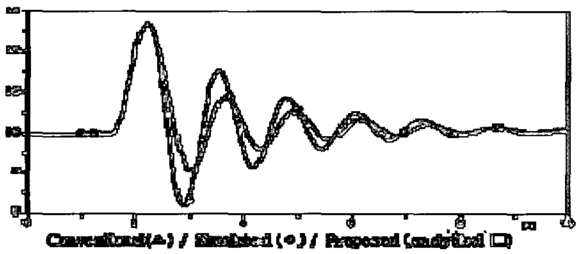

Fig. 10 Control result for a stable system following a disturbance

Simulation results obtained by applying the conventional method to the unstable system after clearing the fault (at 2.4s) show that the system remains unstable. However, as confirmed in simulation, the system can be stabilized by a reclosing method after extinction of the arc and insertion of series capacitance. The value of capacitance needed is calculated by contingency [12, 13] when the unstable time point is 2.8s using equation (10).

After clearing the fault (at 2.4s), the actual measured data given below are applied to equation (10), considering the estimated unstable starting time (at 2.8s) as the connecting time point of the capacitance to operate optimal reclosure.

T^0 : 2.418 δo : 54.19263 $w^i(t^0)$: 1.911316
t^1 : 2.4388 $\delta 1$: 56.438 $w^i(t^1)$: 1.856555
t^2 : 2.4596 $\delta 2$: 58.161602 $w^i(t^2)$: 1.798829

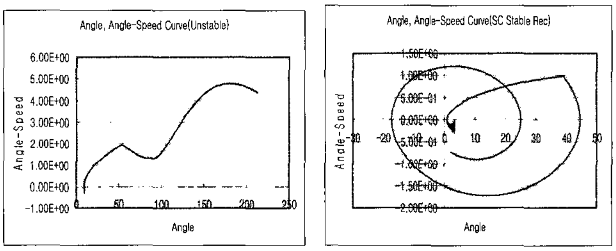

Fig. 11 Speed-Angle changes with and without optimal control for an unstable system

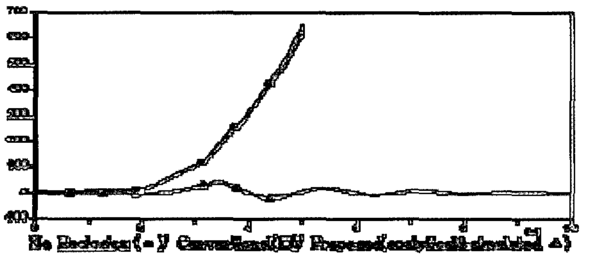

Fig. 12 Control result for an unstable system following a disturbance

Fig. 12 illustrates that the reclosing method with series capacitance increases the possibility of system recovery by damping system fluctuations.

2.4.2 Reclosing operation in case of a permanent fault

In the case of a permanent single phase to ground fault, the results of applying the conventional reclosing method after clearing the fault make the system more unstable. However, Fig. 13 indicates that system fluctuations could be decreased by an optimal reclosing method applied at the time of minimum w.

At 2.537 seconds, the optimal reclosing time-point is estimated from the past three values of wi(t), which are measured right after the estimation of stability following fault clearing:

t^0 (2.184) ; w^i (t)(-0.02942998)
t^1 (2.2204) ; w^i (t^1)(-0.0974016)
t^2 (2.2568) ; w^i (t^2)(-0.16167466)

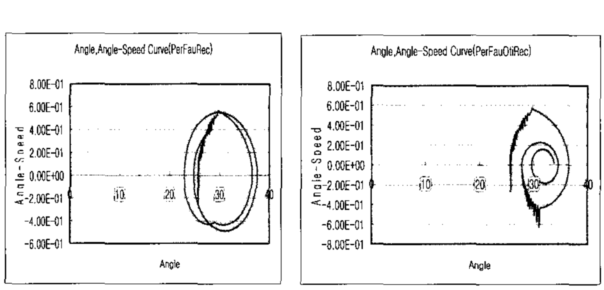

Fig. 13 Speed-Angle changes with and without optimal control for a permanent fault

There is no considerable difference in the time points for reclosing operation between the analytical solution of equation (9) and the simulated results. Furthermore, the stability waveforms for the analytical solution and simulations are almost identical.

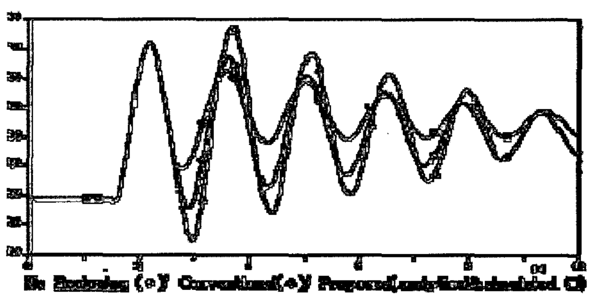

Fig. 14 Control result for a permanent fault following a disturbance

3. Conclusion

Power system disturbances can occur and they create the potential for system failure, so we need to execute economical and effective methods and techniques for autoreclosure relaying systems. However, to minimize disturbances and power swings, autoreclosure needs to occur at an optimal time. To minimize the system's power swing, optimal reclosure relaying must be applied to stabilize the system after temporary faults are eliminated. When reclosing after a fault results in an unstable system, the possibility of restoring stability is increased by inserting series capacitance in the line, the value of which is calculated by contingency.

Additionally, in cases where traditional reclosure would fail and result in further system instability following a permanent fault, optimal reclosure can be applied to reduce the impact on the power system.

An optimal reclosure algorithm was applied to identify and distinguish between temporary faults and permanent faults and to acquire generator information data from the power system by applying WAM and high speed communication technology. So, optimal control is achieved by predicting and determining the degree of stability, considering real-time transient stability using the EEEAC.

In this paper, adaptive autoreclosure relaying algorithms were suggested, which demonstrate various values of power system stability. The results were analyzed using simulations created in EMTP MODELS.

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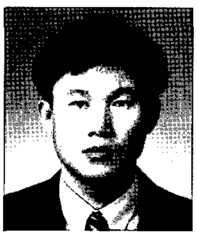

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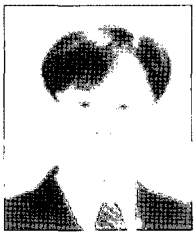

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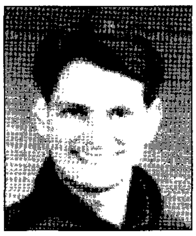

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