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Development of a Reclosing Scheme for Reduction of Turbine Generator Shaft Torsional Torques: A Decision Method to Achieve Optimal Reactor Capacity

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Abstract – It is well known that line switching operations like reclosing are able to cause transient power oscillations which can stress or damage turbine generators. This paper presents a reclosing scheme to reduce the shaft torsional torques of turbine generators by inserting an additional reactor. A novel method to determine optimal reactor capacity to minimize the torsional torque generated in a turbine generator is also proposed. In this paper, the turbine generator shaft is represented by a multi-mass model to measure torsional torques generated in the shaft between the turbine and the generator. Transmission systems based on actual data from Korea are modeled to verify the proposed scheme using ElectroMagnetic Transient Program (EMTP) software. The simulation results clearly show the effectiveness of the proposed scheme and torsional torque can be minimized by applying the proposed scheme.

Keywords: EMTP, Reactor, Reclosing, Shaft torsional torque, Turbine-generator

1. Introduction

Most faults occurring in transmission lines are temporary in nature; it is therefore very important to rapidly restore the power system using a reclosing operation [1-5]. However, line switching operations including reclosing can cause transient power and current oscillations that can affect the rotating shaft of a turbine generator. Such operations can result in transient mechanical forces on both the rotating and stationary components of the turbine generator. These forces can damage the turbine generator shaft; in the worst cases, even to the point of causing shaft breakage [6-12]. Thus, development of effective reclosing schemes that consider the effect on the turbine generator is necessary.

The impact on the turbine generator can be evaluated by the sudden power change ΔP generated by the switching operation. An IEEE Committee recommends that a ΔP value equal to 0.5 per unit be considered an acceptable screening level for evaluating steady-state switching if a turbine generator is operating under the allowable load condition [13]. If the ΔP value generated by a switching operation is less than 0.5 per unit, the loss-of-life of the turbine generator would generally be expected to be negligible and can be quantified as less than 0.01% per incident. Conditions that can cause higher ΔP values are related to angular phase differences between the two separate systems: as the angular difference between two systems increases, ΔP also increases. Reclosing operations should thus be prevented when the angular difference is high between the two systems. This is generally achieved with a synch-check relay [14-15].

Many researchers have investigated schemes for reducing turbine generator shaft torsional torques [16-18]. Field discharge resistors are applied to interrupt generator excitation for the duration of the fault. Also, new selective reclosing schemes have been developed which reclose the faulted phase only after determining that the fault is temporary. One such scheme uses a compensating capacitor to improve the stability of the system and thus reduce the turbine generator shaft torsional torques. These schemes are generally effective, but do not include methods to find the optimum capacity of each element. Hence, this paper focuses on finding the optimum capacity of each element as well as presenting a scheme for reducing turbine generator shaft torsional torques and that is the main objective of this paper.

In this paper, we present a reclosing scheme to reduce the shaft torsional torques in a turbine generator by inserting an additional reactor into the system. A novel method to determine optimum reactor capacity is also proposed to minimize the torsional torque generated in the turbine generator. The optimal reactor capacity is derived by considering an additional ΔP and secondary shaft torsional torque in the turbine generator due to an additional switching operation. In Section 2, the sudden power change ΔP is discussed specifically. In Section 3, a

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reclosing scheme using an additional reactor is presented. Then, the optimal reactor capacity is discussed in Section 4. Simulations are performed in Section 5 under various conditions to examine the proposed scheme. Finally, conclusions are discussed.

2. Sudden Power Change, *ΔP*

2.1 Power transfer equation

The power transferred between the two systems in Fig. 1 is represented by (1) [19].

$$P = \frac{V_S \times V_R}{X_L} \sin\delta \tag{1}$$

where V_S and V_R are the voltage magnitudes at the sending and receiving ends, respectively; X_L is the path impedance and δ is the angular phase difference between the two systems.

In (1), the path impedance X_L includes the reactance of the machine, transformer and transmission line. Normally, the voltage magnitude at both ends and the path impedance are fixed. Thus, it can be said that transferred power is a function of the angular difference between the two systems.

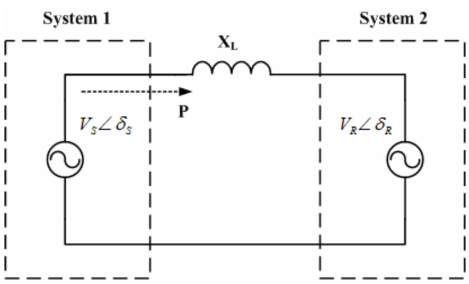


Fig. 1. Equivalent circuit of the transmission system

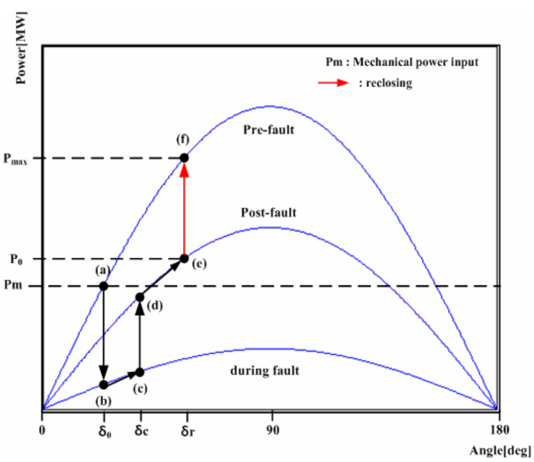


Fig. 2. P-δ curve according to the system conditions

2.2 Mathematical approach of ΔP

Fig. 2 shows the P-δ curve based on Eq. (1). In the steady-state, the operating point remains at (a), where the electrical power output is equal to the mechanical power input. When a fault occurs, power output drops to the "during fault" curve. Then, because the mechanical power input exceeds the electrical power output, the rotor angle accelerates until breakers open at (c). If the fault is cleared at (c), power output moves to the "Post-fault" curve and reaches point (e). When the reclosing operation is performed to restore the system at this point, a sudden power change ΔP occurs. This power change can stress or damage the turbine generators.

ΔP is defined mathematically by the following expression:

$$\Delta P = P_{pre} - P_{post} \tag{2}$$

where P_{pre} which is located on 'pre-fault' curve in Fig. 2 is the maximum power output at the instant of switching and the P_{post} which is located on 'post-fault' curve in Fig. 2 is the initial power output of the unit before the switch. Based on the Eq. (1), ΔP is represented by

$$\begin{aligned}\Delta P &= \frac{V_{S,pre} \times V_{R,pre}}{X_{L,pre}} \sin\delta_{pre} - \frac{V_{S,post} \times V_{R,post}}{X_{L,post}} \sin\delta_{post} \\ &= \alpha \sin\delta_{pre} - \beta \sin\delta_{post}\end{aligned} \tag{3}$$

We can substitute Eq. (4) for Eq. (3) because V_S, V_R and δ before the switching are similar to those at the instant of switching.

$$\begin{aligned}\Delta P &= \frac{V_{S,post} \times V_{R,post}}{X_{L,pre}} \sin\delta_{post} - \frac{V_{S,post} \times V_{R,post}}{X_{L,post}} \sin\delta_{post} \\ &= \alpha \sin\delta_{post} - \beta \sin\delta_{post} \\ &= (\alpha - \beta)\sin\delta_{post}\end{aligned} \tag{4}$$

In Eq. (4), α is larger than β and $(\alpha-\beta)$ has a positive value because $X_{L,pre}$ is smaller than $X_{L,post}$. Therefore, it is clear that ΔP increases as the angular difference between the two systems, δ, increases. This indicates that the reclosing operation should be prevented when the angular difference between the two systems δ is overly large.

2.3 IEEE screening guide

ΔP is a very important factor in assessing the impact of a reclosing operation on the turbine generator shaft. Based on this quantity, an IEEE Committee has published a screening guide for protection engineers to estimate if a particular switching event is severe enough to require greater study in consultation with the turbine generator manufacturer [13]. According to the report, a ΔP value of less than 0.5 per unit can be considered negligible in terms of the impact on the turbine generator.

3. Reclosing Scheme for the Reduction of Turbine Generator Shaft Torsional Torques

3.1 Reduction of ΔP via the insertion of an additional reactor

As shown in Section 2, the ΔP generated during a switching operation such as a reclosing operation can result in damage to the turbine generator. It is therefore necessary to reduce the impact on the turbine generator by decreasing the ΔP.

As was seen in (4), the angular difference ΔP can be quite large during a reclosing operation, in excess of 0.5 per unit, a typical IEEE screening guide value. In such a condition, we can reduce the ΔP by controlling the path impedance X_L following the switching operation. Because ΔP is inversely proportional to the path impedance X_L, the ΔP can be reduced by inserting an additional reactor that increases the total path impedance [20].

Eq. (5) presents ΔP when an additional reactor is inserted during reclosing, showing that ΔP can be reduced by inserting an additional reactor and thus increasing the total path impedance.

$$\Delta P_{insert} = \frac{V_{S,reactor} \times V_{R,reactor}}{X_{L,pre} + X_{reactor}} \sin\delta_{reactor} - \frac{V_{S,post} \times V_{R,post}}{X_{L,post}} \sin\delta_{post} \quad (5)$$

where the $X_{reactor}$ is a reactance of an additional reactor.

Fig. 3 shows the P-δ curve with the addition of another reactor during reclosing. In the case without any additional reactors, the power point on the P-δ curve changes from (e) to (f) during reclosing. On the other hand, the power point changes from (e) to (f') when an additional reactor is inserted, reducing ΔP by as much as the distance between (f) and (f').

3.2 Reclosing scheme including the insertion of an additional reactor

Fig. 4 shows a block diagram of the reclosing scheme including an additional reactor. In the figure, the reclosing scheme with an additional reactor is applied to circuit 2, the faulted circuit. As indicated in Fig. 4, this scheme first recloses CB2, connected to the additional reactor, to reduce the impact on the turbine generator. After a specific time delay, CB2 is tripped and CB1 closed to avoid steady-state losses caused by keeping the reactor in continuous service. In Fig. 4, voltages required for controller are easily collected by potential transformers.

CB1 and CB2 are controlled by a controller with a synch-check function to limit the impact associated with reclosing under Live-Bus/Live-Line (LBLL) conditions. A flowchart of the controller algorithm is shown in Fig. 5. The controller starts after the leader end is reclosed after a fixed deadtime and first checks LBLL and synchronism conditions. The magnitude and phase angle of the voltage at both ends as well as the magnitude of the line voltage are needed to verify the conditions that allow the reclosing of the follower end. If the LBLL and synchronism conditions are satisfied, CB2 (connected to the reactor) is closed and the timer is initiated. After the timer expires, CB2 is tripped and CB1 is closed to restore the system completely. There will be some little time delay inevitably to reclose the circuit breakers shown in Fig. 4 because of calculation procedure in controller. However, the time delay can be ignored in this scheme because performance of the proposed scheme is not dictated by a moment of reclosing and the time delay is not too much to guarantee the performance of that.

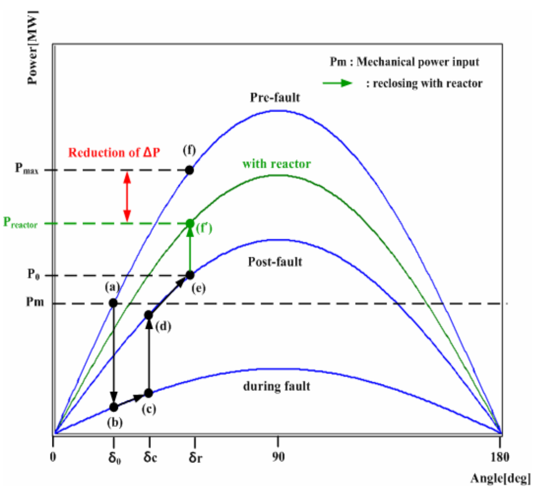


Fig. 3. P-δ curve when an additional reactor is inserted during reclosing

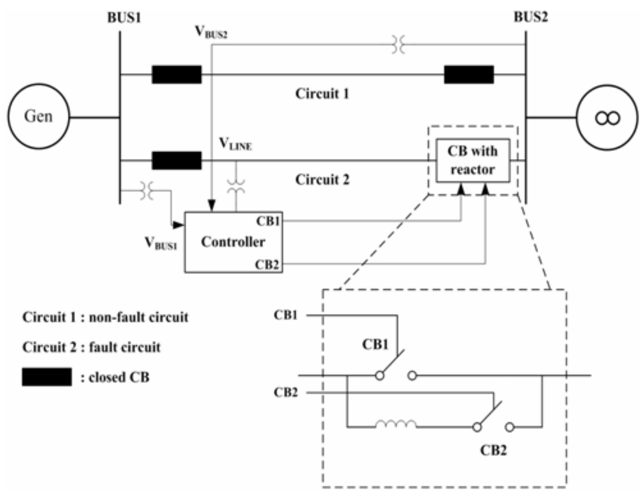


Fig. 4. Block diagram of the reclosing scheme using an additional reactor

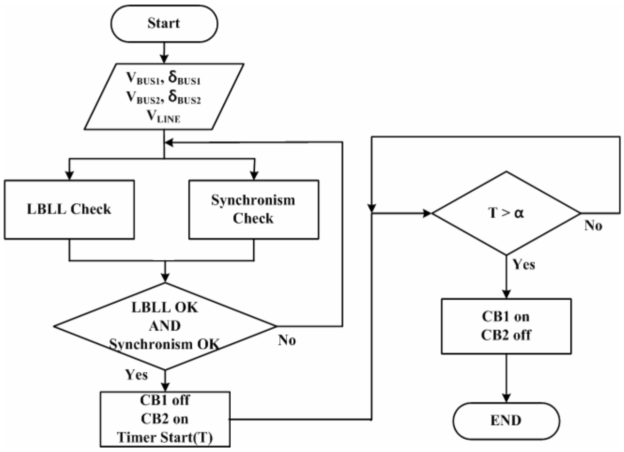


Fig. 5. Flowchart of the controller algorithm for the reclosing scheme using an additional reactor

4. Method to Determine the Optimal Reactor Capacity

4.1 Disadvantage of the reclosing scheme using an additional reactor

The reclosing scheme using an additional reactor has the advantage of reducing ΔP during the initial reclosing operation. However, if the circuit connected to the reactor is left in the circuit, steady-state losses due to the reactor are inevitable. Thus, the reactor should be removed from service after a specific time delay. To remove the reactor from a circuit, an additional switching operation is needed. This causes an additional ΔP and secondary shaft torsional torque in the turbine generator. Fig. 6 shows fluctuations in power output both with and without an additional reactor; ΔP is reduced in the case including the additional reactor compared with the case that does not include one. However, it is apparent that an additional ΔP is generated when removing the reactor.

The ΔP generated by removing the reactor is proportional to the capacity of the reactor and it is expressed by Eq. (6). It can be concluded that the larger the capacity of the reactor, the greater the ΔP_{remove} is.

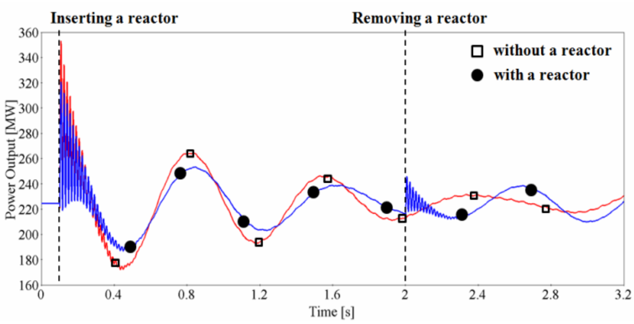


Fig. 6. Fluctuations in power output according to time and existence of the reactor

$$\Delta P_{remove} = \frac{V_{S,pre} \times V_{R,pre}}{X_{L,pre}} \sin\delta_{pre} - \frac{V_{S,reactor} \times V_{R,reactor}}{X_{L,pre} + X_{reactor}} \sin\delta_{reactor} \tag{6}$$

4.2 Optimal reactor capacity

The reclosing scheme using an additional reactor has disadvantages as well as advantages. Although the reclosing ΔP can be effectively reduced with an additional reactor, the advantages of the reclosing scheme disappear if large torsional torques are generated when the reactor is removed. It is therefore clear that we should also take into account the additional ΔP that is generated by removing reactor.

Considering the advantages and disadvantages of the additional reactor, the optimal reactor capacity is the value at which the ΔP generated by inserting a reactor is equal to that generated by removing a reactor, thereby balancing each ΔP. The torsional torque generated by removing a reactor can be limited to less than the torque generated by its insertion by applying the optimal reactor capacity; this allows us to simply reduce the impact on the turbine generator. Fig. 7 depicts the curves used for obtaining the optimal reactor capacity. The optimal reactor capacity is the point at which the two curves intersect.

The optimal reactor capacity can be expressed mathematically. Eq. (7) shows the optimal reactor capacity. In (7), it is assumed that the voltage magnitude of each state is the same. It is too difficult to find the optimal reactor capacity in (7) because there are too many variables associated the optimal reactor capacity; to accomplish this more expediently, in this paper we use ElectroMagnetic Transient Program (EMTP), an analytical program for transient phenomena, to find the optimal reactor capacity [21-22].

$$\begin{aligned} X_{op} &= \frac{2X_{L,pre} \cdot X_{L,post} \cdot \sin\delta_{reactor} - X^2{}_{L,pre} \cdot X_{L,post}}{X_{L,post} \cdot \sin\delta_{pre} + X_{L,pre} \cdot \sin\delta_{post}} \\ &= \frac{X_{L,pre} \cdot X_{L,post}(2 \cdot \sin\delta_{reactor} - X_{L,pre})}{X_{L,post} \cdot \sin\delta_{pre} + X_{L,pre} \cdot \sin\delta_{post}} \end{aligned} \tag{7}$$

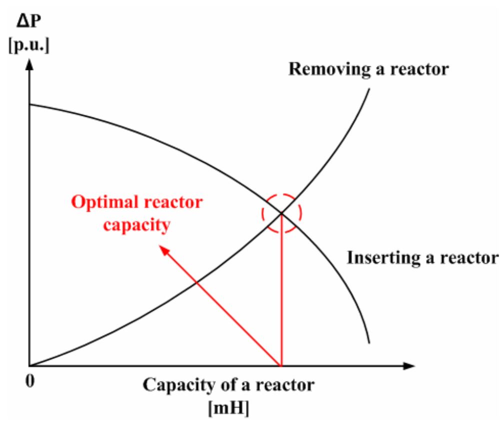


Fig. 7. Curves for obtaining the optimal reactor capacity

where X_{op} is the optimal reactor capacity.

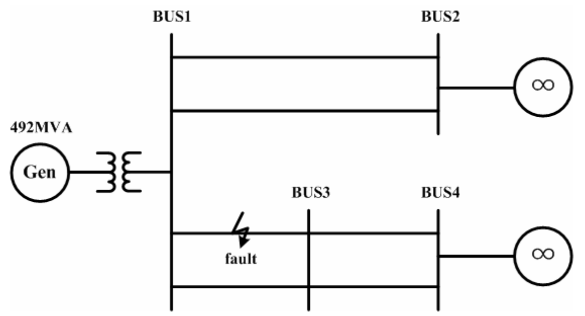
5. Simulation

5.1 Simulation model

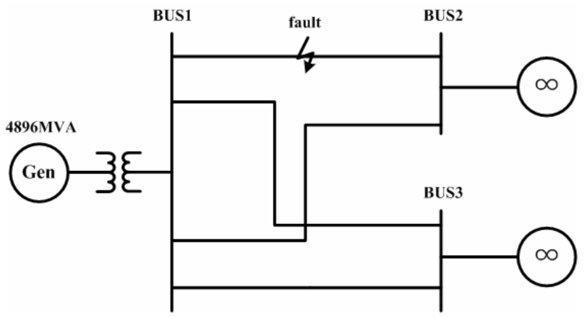
Fig. 8 shows models of the KEPCO 154 and 345 kV transmission systems used to verify the reclosing scheme and optimal reactor capacity. The systems are modeled using the EMTP-RV software package, based on actual data from Korea.

Fig. 9 depicts the multi-mass model of the turbine generator used to simulate the mechanical torques generated in a turbine generator shaft. Generally, the turbine generator is modeled as a single mass; however, a multi-mass model is necessary to perform time-domain simulations for the shaft torsional torques. The multi-mass model shown in Fig. 9 is composed of six masses with five shafts connecting each mass; those represent the exciter (EXC), the generator(GEN), two low pressure turbines (LPA and LPB), an intermediate pressure turbine (IP) and a high pressure turbine(HP).

The multi-mass models of the turbine generators in both the 154 and 345 kV systems are equal. The parameters associated with the turbine generator are shown in Table 1 and 2 [23]. The parameter values shown in Tables 1 and 2 are based upon the physical dimensions of the shaft system and its material properties. The most important parameter in Table 1 and 2 is the spring constant and it pertains to the elastic connection between adjacent masses and is directly involved with a torsional interaction.



(a) 154kV system



(b) 345kV system

Fig. 8. Transmission system model

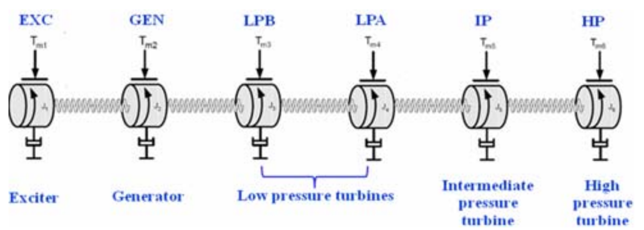


Fig. 9. Multi-mass model of the turbine generator used in the 154 and 345 kV transmission systems

5.2 Simulation conditions

In this paper, we perform the simulation in three parts. First, ΔP and torsional torques according to different angular differences between the two systems are calculated. Second, when the reclosing scheme using an additional

Table 1. Parameters of the turbine generator in the 154 kV system

Parameter	Value
Rated Power [MVA]	246
Number of poles	2
Moment of inertia [$lb \cdot ft^2 \cdot 10^6$]	HP = 0.009032 IP = 0.015130 LPA = 0.083480 LPB = 0.085970 GEN = 0.084440 EXC = 0.003327
Spring constant [$lbf \cdot ft \cdot 10^6$]	HP-IP = 10.988 IP-LPA = 19.883 LPA-LPB = 29.622 LPB-GEN = 40.335 GEN-EXC = 1.6064
Fraction of external torque [%]	HP = 30 IP = 26 LPA = 22 LPB = 22

Table 2. Parameters of the turbine generator in the 345 kV system

Parameter	Value
Rated Power [MVA]	612
Number of poles	2
Moment of inertia [$lb \cdot ft^2 \cdot 10^6$]	HP = 0.018358 IP = 0.030748 LPA = 0.169690 LPB = 0.174740 GEN = 0.171634 EXC = 0.006762
Spring constant [$lbf \cdot ft \cdot 10^6$]	HP-IP = 22.334 IP-LPA = 40.414 LPA-LPB = 60.210 LPB-GEN = 81.985 GEN-EXC = 3.2651
Fraction of external torque [%]	HP = 30 IP = 26 LPA = 22 LPB = 22

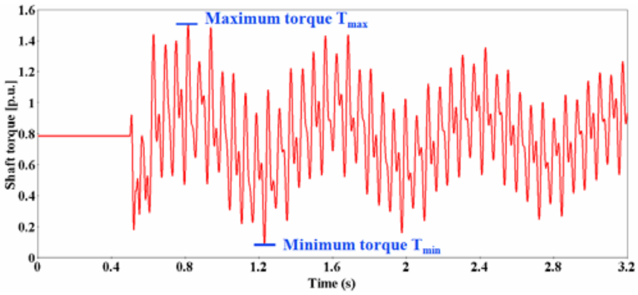


Fig. 10. Shaft torque generated between GEN and LPB

reactor is applied, ΔP and torsional torques are calculated according to various reactor capacities. Last, we find the optimal reactor capacity via the method presented in Fig. 7. The results are compared with reactor capacity causing the minimum torsional torque.

We present the torsional torque between the GEN and LPB only because it is generally the largest. Torsional torques in this paper are calculated by Eq. (8) [24].

$$Torsional\ torque = \frac{T_{\max} - T_{\min}}{2} \qquad (8)$$

where T_{max} and T_{min} are the maximum and minimum torques generated in the shaft, respectively.

Fig. 10 shows a simple example of the maximum and minimum torque.

5.3 Simulation results

We represent ΔP as per unit quantity. ΔP in per unit can be calculated by Eq. (9).

$$\Delta P[p.u.] = \frac{P_{pre} - P_{post}}{S_{MVA}} \qquad (9)$$

where S_{MVA} is the rated power of the turbine generator.

Fig. 11 shows the ΔP and torsional torques in the 154 and 345 kV transmission systems according to various angular differences. In the 154 and 345 kV systems, when the lines marked as being in fault in Fig. 8 are out of service, the maximum possible angular differences in credible operating conditions are 28° and 40°, respectively. We therefore choose the possible range of the angular differences to be below those angles.

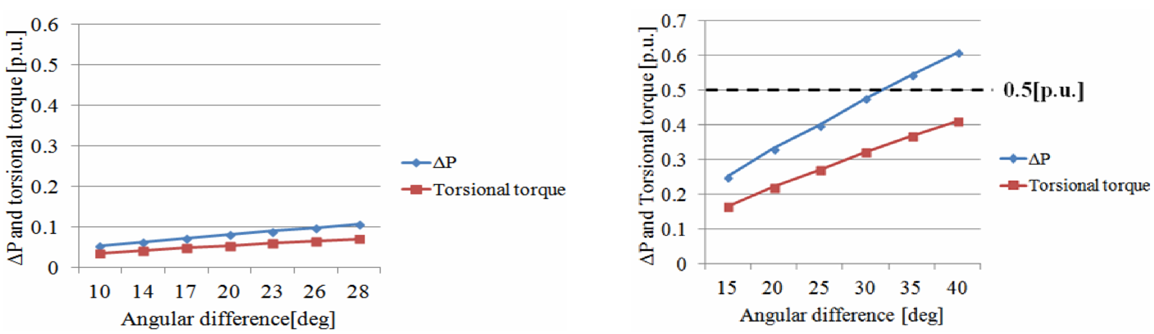
From the results shown in Fig. 11, it is easily seen that the ΔP and torsional torque increase as the angular difference is increased. Therefore, a reclosing operation should be avoided when the angular difference is large because of the impact on the turbine generator. Protection against a reclosing operation for large angular differences can be achieved by applying a synch-check relay. The ΔP values generated in the 345kV system are much greater than those in the 154kV system, making it particularly advantageous to apply the reclosing scheme using an additional reactor in the 345kV system.

Fig. 12 illustrates the ΔP_{insert} and torsional torque in the 154kV and 345kV transmission systems according to various reactor capacities when the reclosing scheme using an additional reactor is applied to them. When the reclosing scheme using an additional reactor is applied to both the 154kV and 345kV systems, the ΔP_{insert} and torsional torque are significantly reduced compared with when the proposed reclosing scheme is not applied. The results clearly show that we can decrease the ΔP to less than 0.5 per unit by using the proposed scheme.

In Fig. 12, ΔP_{insert} is reduced as the reactor capacity is increased. However, the torsional torque reduces to a minimum at a specific capacity, then begins to increase slightly with increasing reactor capacity. This is because ΔP_{remove} occurs when the reactor is removed after a time delay. The specific capacity, which corresponds to the optimal reactor capacity, can be found using the decision method shown in Fig. 7.

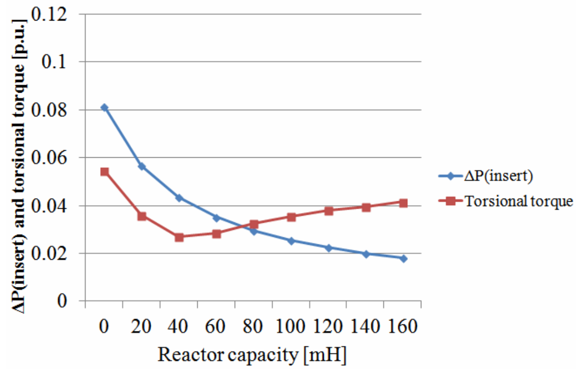
The optimal reactor capacities obtained using the proposed decision method are shown in Fig. 13. From the results in the subfigures, we can see that the optimal reactor capacities are not fixed. This is because the optimal reactor capacity depends on many variables, as indicated in Eq. (7). Those variables vary with the configuration and condition of the system.

Table 3 details the optimal reactor capacity results. In Table 3, the A and B results indicate the optimal reactor

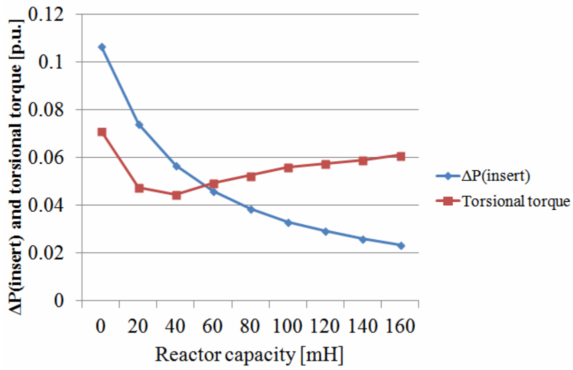


(a) 154kV system (b) 345kV system

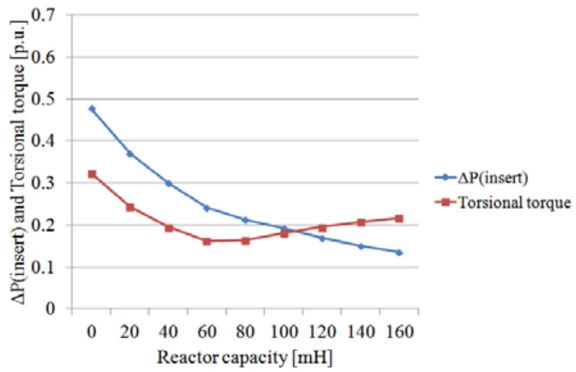
Fig. 11. ΔP and torsional torque according to various angular differences



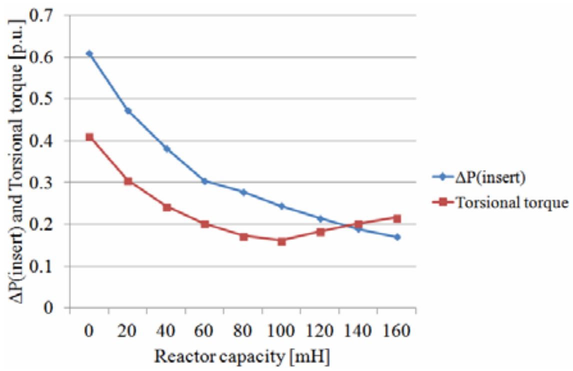
(a) 154kV, 20°



(b) 154kV, 28°

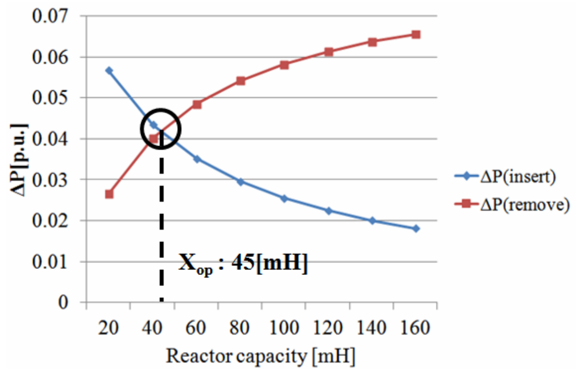


(c) 345kV, 30°

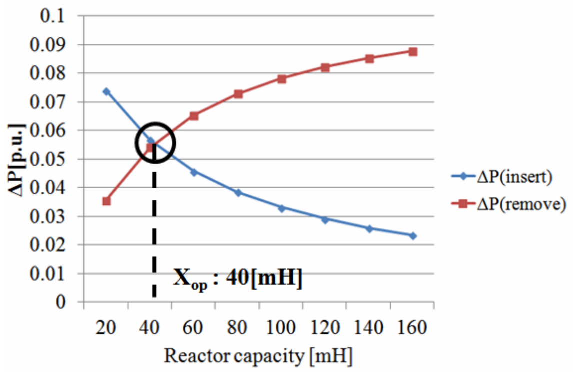


(d) 345kV, 40°

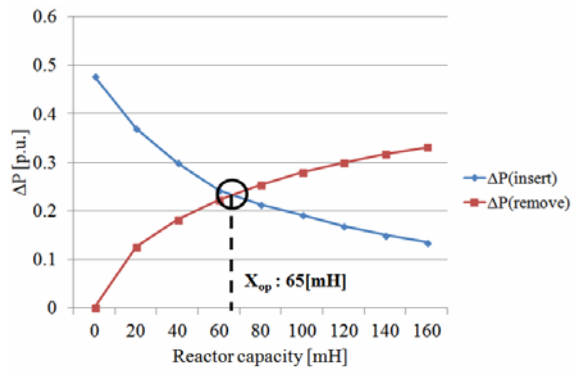
Fig. 12. ΔP(insert) and torsional torque according to various reactor capacities and angular conditions



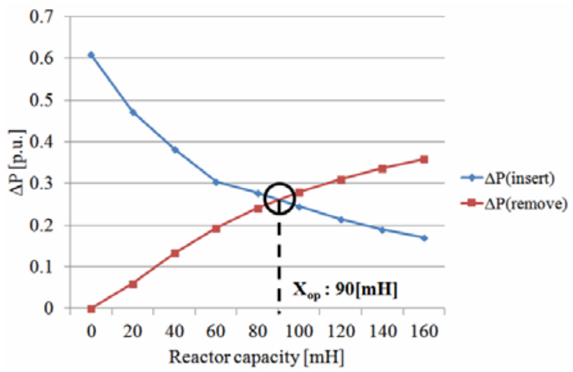
(a) 154kV, 20°



(b) 154kV, 28°



(c) 345kV, 30°



(d) 345kV, 40°

Fig. 13. Optimal reactor capacity according to various angular conditions

Table 3. Simulation results of the optimal reactor capacity

Rated voltage [kV]	Angular difference [deg]	Result [mH]	
		A	B
154	20	45	45
	28	40	30
345	30	65	70
	40	90	90

capacities obtained using the proposed method and those that result in the minimum torsional torque, respectively. These two simulation results are nearly the same for all cases. From the results shown in Table 3, it can be concluded that the proposed method is effective in finding the optimal reactor capacity.

6. Conclusion

This paper presents a reclosing scheme to reduce the shaft torsional torque in a turbine generator, accomplished by inserting an additional reactor into the circuit. A novel method to determine the optimal reactor capacity, able to minimize the torsional torque generated in turbine generator, is also proposed. The optimal reactor capacity can be derived by considering an additional ΔP and secondary shaft torsional torque in the turbine generator due to an additional switching operation which is a disadvantage of the scheme using an additional reactor.

The proposed scheme is simulated in models based on actual data in Korea 154kV and 345kV transmission line. Simulation results show that the proposed reclosing scheme using an additional reactor can significantly reduce the torsional torque generated in the shaft of a turbine generator under high angular difference system conditions, a condition that can cause large impacts on turbine generators. Moreover, the torsional torque is minimized by applying the optimal reactor capacity. Therefore, we can protect the turbine generator from the impact of a reclosing operation effectively. Practically, it is hard to apply this scheme in entire transmission lines because it takes cost. But, if it is applied to only where transmission lines are in proximity to generation facilities or a large angular separation is more likely to happen, we can protect turbine generators more efficiently by using the proposed scheme.

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