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전압붕괴 측면에서의 Zone3 보호동작 억제를 위한 제어방안

송화창　　　　이병준
군산대학교 전자정보공학부　　　　고려대학교 전기공학과

Control strategy against undesirable zone 3 protection with respect to voltage collapse

Hwachang Song　　　　Byongjun Lee
Kunsan National University　　　　Korea University

Abstract - This paper presents a framework for determining control strategies against unwanted tripping actions of relay operation that plays a very important role in cascading events leading to voltage collapse. The framework includes an algorithm for quick identification of possible zone 3 relay operation during voltage instability. The proposed approach comes up with control strategy of load shedding at the selected location with active power and relay margin criteria. In addition, Quasi Steady-State (QSS) simulation is employed to obtain time-related information which is valuable for both the timing and amount of control. The methodology is demonstrated through the modified New England 39-bus system.

1. Introduction

In most of the power system blackouts, the initiating event of tripping one of the system components played a very important role in spreading cascading events and finally wide-area voltage collapse [1-3]. This is in general as a result of relay action on the corresponding system facility for component protection. However, if the system has already been in stressed condition, component protection may lead to cascading events. This paper mainly discusses control strategies as a possible countermeasure against undesired actions of protective relays during the period of system alert condition to voltage instability.

Fig. 1 illustrates the sequence of the events that are mainly concerned in this paper. In the normal state, the system is operated at the point 'a'. After N-1 (or N-k) contingency, if the system is transiently stable, short-term dynamics settles down to the point 'b', and because of load recovery dynamics, the equilibrium of the short-term dynamics moves along the P-V curve of the contingency case. If the long-term load characteristic is constant power as shown in Fig. 1, equilibrium point of total system dynamics will reach the point 'c' and settles down. However, during the transition from the point 'b' to 'c', if one of the protective relays of main transmission facilities violates its normal operational limits or seriously exceeds its own rating, another event of tripping happens. If the trip of the transmission facility is in a set of severe contingencies, the systems may be in great danger, and it may lead to cascading events resulting in voltage collapse.

This paper proposes a methodology that identifies the conditions that may lead to possible operation of component protection systems during voltage instability. Then control strategies are proposed to improve the system condition that in turn avoids the tripping of important components in terms of voltage stability. The methodology is based on a quasi steady-state (QSS) simulation tool. The tool incorporates the model of nonlinear dynamic loads. In order to detect possible relay operations, the framework solves two equilibrium points that are related to short-term and long-term load characteristics after a given contingency. This calculation is performed by the time-domain simulation tool. At these two points, physical parameters that are monitored by relays such as loading impedances on components are calculated, and their locations are checked with relay parameters to see whether there are any possible relaying actions during the period of load recovery. If so, the framework provides control strategies against the undesired relay operations. The control strategies include when, where and how much control is needed to mitigate undesired relay operations.

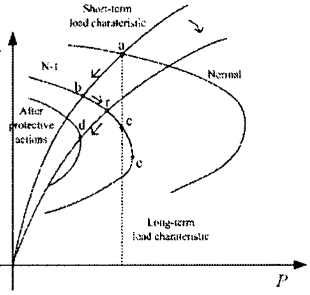

Fig. 1. Sequence of events of main interest in this paper

2. Identification of undesirable relay operation

In order to screen relaying devices that possibly trip their components, the framework of this paper solves two equilibrium points of fast dynamics ('b' and 'c') using short-term and long-term load characteristics. It checks whether loading impedances at the two points enter the zone 3 boundary. Fig. 2 shows three possible cases in which loading impedances at the two points are located in R-X plane, assuming that both of them are solvable.

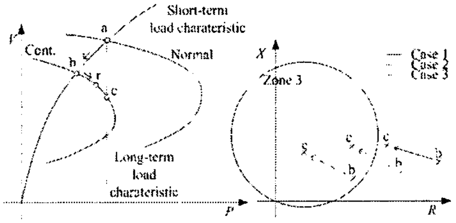

Fig. 2. Three cases of loading z locations ('c' solvable)

As for Case 1, the corresponding distance relay does not operate by the time load demand fully recovers, so the relay need not be considered in terms of voltage stability. As for Case 2, somewhere between 'b' and 'c', it may trip the component. Thus, the parameters monitored by the relay need to be carefully observed, and system status after the component trip should be checked. If voltage stability margin after the trip is not sufficient or the systems are not solvable, control strategies are determined in the framework. As for Case 3, the point 'b' (short-term load characteristic) is inside the boundary. This indicates that after the contingency the relay may immediately trip the component. If these kinds of cases occur during the simulation, trip of the corresponding component also needs to be applied.

3. Control strategy

3.1 QSS simulation

This study utilizes a numerical integration method to get information of when protective actions caused by zone 3 relays occur after severe contingencies. A general modeling relevant to voltage stability in different time scales is described from the following set of equations[4]: This includes differential, algebraic and discrete set of equations.

$$\dot{x} = f(x, y, z_D, z_C) \tag{1}$$

$$0 = g(x, y, z_D, z_C) \tag{2}$$

$$z_D(k^+) = h_D(x(k^-), y(k^-), z_D(k^-), z_C(k^-)) \tag{3}$$

$$\dot{z}_C = h_C(x, y, z_D, z_C, \lambda) \tag{4}$$

where f(·) in (1) describes the dynamics of synchronous machines, the excitation systems, the prime mover and speed governors, and g(·) in (2) represents the system network functions. (1) and (2) involve the transient state variables x and algebraic variables y respectively. The variable y usually relates to network bus voltage magnitudes and angles. The long-term dynamics are captured by discrete and/or continuous-time variables in (3) and (4) respectively. z_D relates to dicrete controls such as tap chagers. z_C represents continuos load recovery dynamics. For QSS simulation, (1) will be replaced by its equilibrium equation.

In this paper, the objective of the time-domain simulation is to detect zone 3 relay operations during time trajectory tracing. For this purpose, a detection module needs to be implemented. The detection module for zone 3 relay operation is performed at each time step during time integration. At the time step (t_{CROSS}) when a loading impedance crosses and enters the relay's zone 3 boundary, the zone timer is activated. If this condition continues during time delay (t_{DELAY}), the module trips the corresponding line at t_{DETECT} (=t_{CROSS}+t_{DELAY}). The main outputs from the module are t_{CROSS} and P_{CROSS}, where P_{CROSS} represents the system load demand at t_{CROSS}. These parameters have an important role in determining the quantity and timing of control.

3.2 Control location

When a relay is in a possible protective operation, alleviating loading on the transmission line that is monitored by the relay can be a good countermeasure for forcing the loading impedance out of the region of zone 3. Here we demonstrate the methodology by applying load shedding as a control variable.

For effective load shedding, adequate selection of control locations is crucial. In this paper, control locations are determined in such a way that the load shedding is effective to reduce the line loading measured by the critical relay. For this, the framework calculates electrical distance from the receiving end (for example, bus j) of the monitored line (i-j) to other buses. The buses that have the smallest components in the j-th row of $[B'']^{-1}$ (B'' is bus susceptance matrix) are chosen as control locations. Alternatively, the receiving end itself can be selected as control location, if it has load large enough to be shed. If the subsystem below the receiving end is radial, control locations can be easily determined without $[B'']^{-1}$.

3.2 Control amount

In order for determining control amount at the selected locations, two criteria are used in the framework. Fig. 3 illustrates the criteria. The first criterion is that system load should be less than P_{CROSS}, after control. In the second one, the distance of loading impedance from the boundary should be larger than a certain value (relay margin). If the corresponding relay has a circle-shaped boundary of zone 3, one can describe the second criterion as follows:

$$d_{LOAD} \geq (d_{RELAY} + d_{ADD})^2 \tag{5}$$

$$d_{LOAD} \equiv (r_{LOAD}(\underline{V}, \underline{\delta}) - r_{CENTER})^2 + (x_{LOAD}(\underline{V}, \underline{\delta}) - x_{CENTER})^2$$

where d_{LOAD} represents distance of the load impedance from the center (z_{CENTER}). d_{RELAY} is the diameter of the boundary; d_{ADD} is the relay margin. r_{LOAD} and x_{LOAD} denote resistance and reactance of a loading impedance after applying control. r_{CENTER} and x_{CENTER} describe resistance and reactance of $z_{C\ ENTER}$.

From the initial amount of control, $P_{LS}^{(1)}$(=$P_{o,TOT}$−P_{CROSS}), where $P_{o,TOT}$ represents system load at pre-fault state, adequate amount of load shedding can be found using a search method. The method sheds the load at the selected location by at each iteration, until it finds an equilibrium point satisfying the relay margin. To find the adequate amount of load shedding, then, a binary search is performed until d_{LOAD}−(d_{RELAY}+d_{ADD}) is within the given tolerance ($d\varepsilon$).

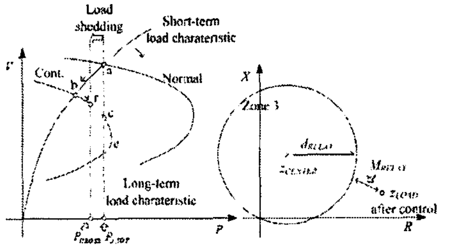

Fig. 3. Criteria for determination of control amount

4. Case study

This section provides an example for the proposed framework with the modified New England 39-bus system. In this simulation, we assumed that zone 3 relays are installed at both sides on 36 selected transmission lines.

The main issues of modeling in this simulation can be described as follows:

- For generators, two-axis dynamic model is used, and the model of each generator includes automatic voltage regulator (AVR), limits of field and armature current, and limit of active generation;
- For all loads except bus 39, the dynamic load model is applied. Load of bus 39 is represented with constant power model;
- Reach of each zone 3 boundary is set to cover the protected line, the adjacent line, and up to 30% of the line next to the adjacent line.

The equilibrium points ('b' and 'c') of fast dynamics are solved using the QSS simulation tool for the two contingencies. Both cases are solvable after applying long-term load characteristic to obtain 'c'. At each point, loading impedances are calculated at sending and receiving ends of the transmission lines monitored by zone 3 relays. By locating the loading impedances in R-X plane with the corresponding zone 3 boundary, critical relays can be identified which require further detailed simulation. For contingency #1, the loading impedance of 'c' measured at the sending end of line (16-15) enters the zone 3 boundary of the relay. For contingency #2, there is no loading impedance's entrance to the zone 3 boundaries. Fig. 4 shows positions of the loading impedances at two cases with the boundary.

When the system component monitored by the critical relay, which is determined by identification of possible relay operation, is tripped during load recovery, severity of this additional tripping action can be evaluated. For this purpose, trip of the system component is additionally applied from the corresponding equilibrium point 'c', and solvability or active power margin is verified. For contingency #1, it is not solvable after the additional trip of line (16-15) from 'c'. This implies that the zone relay operation of the line significantly deteriorates system voltage stability. Thus, the framework proposes a control strategy that improves the system condition and ultimately prevents this critical relay operation.

First, the framework needs to decide effective locations where load shedding is applied. Electrical distance from the receiving end (bus 15) is used. The buses that have the smallest element from the 15th row of $[B'']^{-1}$can be selected. In the modified New England 39-bus system, however, bus 15 itself has load demand enough to shed (3.14+j1.5 [pu]), so bus 15 is selected as location of control.

In order to determine control timing and amount, then, the time-domain simulation tool with QSS assumption needs to be executed. This execution involves integration of the dynamic load models for load recovery. In the simulation, the generator at bus 32 is tripped at 1 [s] for contingency #1. Fig. 5 shows t-V curves of four buses and Fig. 6 illustrates loci of the loading impedance during the simulation. The starting and ending points of the loci are close to those in Fig. 4.

From Fig. 5 and Fig. 6, it is shown that the loading impedance of the line (16-15) crosses and enters the zone 3 boundary at t_{CROSS}, 328 [s]. Assuming that t_{DELAY} is set to 1 [s], the relay may trip the line at 329 [s] if we consider only the long-term dynamics. For the case in which we apply the additional trip at 329 [s], there is no short-term equilibrium with the QSS simulation. Thus, control actions should be applied before the trip of the line.

Lastly, control amount of the selected location is determined. After the trip, system load is reduced to 5801 [MW], and by the dynamic load models, system load is restored to the load level of the pre-fault state 6041.9 [MW] ($P_{o,TOT}$). During this process of load recovery, the monitored loading impedance meets the zone 3 boundary when total load is 6027.9 [MW] (P_{CROSS}).

The MW difference between $P_{o,TOT}$ and P_{CROSS} is used for control amount as described in Fig. 6. Note that P_{CROSS} is evaluated from the QSS simulation. The diameter (d_{RELAY}) of the zone 3 boundary is 0.1833635. The additional diameter (d_{ADD}) to maintain a certain level of relay margin is set to 0.04, and tolerance ($d\varepsilon$) to 0.004. In the searching stage in the procedure, the initial control amount is selected to 14 [MW], and the final amount is decided to satisfy the active power and relay margin criteria. In this example, just two iterations are needed to decide the final amount of load shedding, P_{LS}, and it is 28 [MW]. Note that P_{LS} corresponds to the control amount of the fully restored load demand, Pc. During the period when the system experiences load recovery, the timing of control affects the amount of load shedding to some extent.

To prevent the zone 3 operation, control should be applied before the additional trip by the relay. In this simulation, we choose 80 [s] as the timing of control. Using (7), then, the amount of load shedding, P_{LS},(80s), can be obtained, and it is 25.44 [MW]. When applying the control strategy, the loading impedance measured at the sending end of the line does not touch the zone 3 region, as shown in Fig. 7.

In Fig. 8, the solid line indicates the time trajectory of voltage at bus 15 when the proposed control strategy (shedding 25.44MW load) is applied at 80 [s]. The dotted line describes the case in which the zone 3 relay trips the line at 329 [s] and needs load shedding of 110 [MW] at bus 15 to obtain the short-term solvability. However the system collapses 3s after this control (it encounters singularity induced bifurcation). Note that without any control the system does not have the short-term equilibrium after the zone 3 operation.

The framework comes up with a load shedding strategy to prevent undesirable zone 3 protection that possibly leads to voltage collapse. The strategy is established on the assumption that the monitored relays are allowed to trip the corresponding components. Another way to cope with this phenomenon is blocking zone 3 operation in system voltage insecure cases. Blocking zone 3 operation may need to be followed by adequate control actions, to keep the components from sustained overloading. In this context, coordination of protection and control are emphasized for system protection schemes. Blocking based approach also needs proper infrastructure such as communication networks and digitalization of protective relays. At the present time before establishment of the infrastructure, the proposed approach in this paper can be effectively utilized for control strategies to prevent critical relaying actions by zone 3 protection.

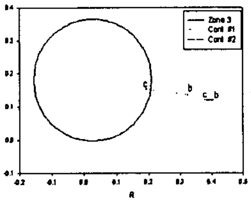

Fig. 4. Loci of the loading Z when applying the control

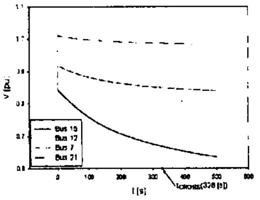

Fig. 5. t-V curves of the selected buses (cont. #1)

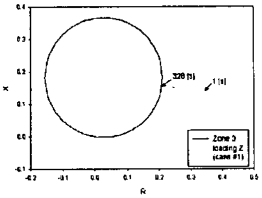

Fig. 6. Loci of the loading Z at the sending end of 16-15

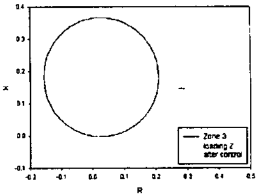

Fig. 7. Loci of the loading Z when applying the control

If no control action is applied before zone 3 protection of critical relays, to stabilize the system, the amount of load shedding required is very high. For example to obtain a short-term equilibrium, as mentioned before, load shedding of 110 [MW] is needed, but the long-term equilibrium cannot be restored. Fig. 9 describes t-V curves when applying different control amounts at bus 15. To restore long term stability at least 140MW load has to be shed. With 150MW of load shedding the voltage profile is better than that of 140MW case.

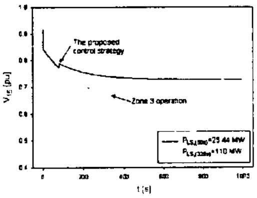

Fig. 5. t-V curves with and without control strategies w.r.t. zone 3 operation

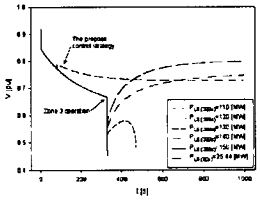

Fig. 6. t-V curves when applying the two controls before/after zone 3 operation

5. Conclusions

This paper proposes a framework for determining control strategies against undesired relay operations that play a very important role in cascading events possibly leading to voltage collapse. During voltage instability, physical parameters monitored by protective relays may enter the region of tripping action due to load recovery dynamics. This paper mainly focuses on undesired zone 3 distance relay operation. The framework contains a procedure of quick identification of possible zone 3 relay operations to screen critical relays for a given condition. For detail analysis, it performs QSS simulation to obtain time information which is useful for determination of control strategy. Based on active power and relay margin criteria, it comes up with the control strategy of load shedding that enhances system security and in turn reduces uncertainty of the additional trip by undesired relay operation.

[References]

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