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Control Strategy against Undesirable Zone 3 Relay Operation in Voltage Instability

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Abstract - This paper presents a framework for determining control strategies against unwanted tripping actions during 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. Furthermore, it comes up with the 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 that is valuable in the determination of control strategy. As a case study, an example applying the framework is shown with the modified New England 39-bus system.

Keywords: Control Strategy, Quasi Steady-State (QSS) simulation, relay margin, undesired relay operation, and voltage collapse.

1. Introduction

In the majority of power system blackouts, the initiating event of tripping one of the system components usually plays a very important role in spreading cascading events, which finally lead to wide-area voltage collapse [1-8]. 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 operating in a 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.

The main objective of this paper is to determine control strategies for preventing further tripping events resulting from unwanted protective actions making systems more vulnerable in terms of voltage stability. Fig. 1 illustrates the sequence of events that are of primary concern in this paper. In the normal state, the system is operated at point 'a'. After N-1 (or N-k) contingency , if the system is transiently stable, short-term dynamics settles down to point 'b', and because of load recovery dynamics, the equilibrium of the short-term dynamics moves along the P-V curve of the contingent case. If the long-term load characteristic is constant power as shown in Fig. 1, equilibrium point of total system dynamics will reach point 'c' and settle down. However, during the transition from point 'b' to 'c', if one of the protective relays of the main transmission facilities violates its normal operational limits or seriously exceeds its own rating, another tripping event occurs. If the trip of the transmission facility is in a set of severe contingencies, the systems may be in great danger, possibly leading to cascading events resulting in voltage collapse.

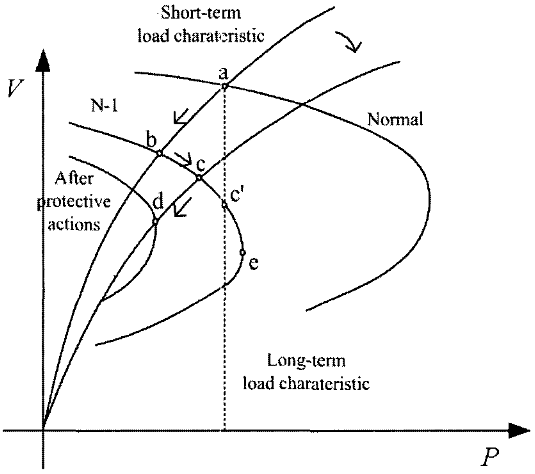

Fig. 1 Sequence of events of main interest in this paper

To prevent this kind of event caused by undesired protective actions, adequate setting of relay parameters in the corresponding protection equipment is required. In the recent deregulated environment, however, flow patterns and system states are constantly changing and setting of these equipments cannot cover all the possible undesired actions.

In [9], an adaptive scheme for preventing mal trips of zone 3 distance relay is proposed, which can be

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implemented on modern numerical relays. However, this scheme itself cannot remove the fundamental problem of low voltage and high reactive current during voltage instability, and sustained overloading can cause the corresponding facility to be in jeopardy. In [10-11], a system protection scheme involving coordination of protection and system requirement is emphasized to form a defense plan against system breakdown due to prohibitive cost of wide area blackouts. In [12], a scheme of adaptive wide area protection for mitigating voltage collapse is presented applying a fuzzy inference system whose inputs are fault detection, VSI (voltage stability index), and signals from component protection devices.

This paper considers control strategies such as shedding an amount of load against unwanted protective actions in one framework including determination of countermeasure against voltage collapse; i.e., the determined control measures force the system out of the conditions of undesired protective actions. Generally, countermeasure determination in voltage stability assessment first detects the margin boundary (e.g. 'e' in Fig. 1) with the given direction of load increase and then calculates control strategies by applying the normal vector at the margin boundary. However, the control strategies may fail when additional severe contingencies occur due to protective operation. Thus, consideration of tripping actions is required when deciding control strategies against 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 tool of continuation based time-domain simulation [13, 14] with quasi steady-state (QSS) assumption [6, 15]. The tool incorporates the model of nonlinear dynamic loads proposed in [16]. In order to detect possible relay operations, the framework solves two equilibrium points of fast dynamics applying 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.

2. Identification of Undesirable Zone 3 Relay Operation

There are various protective schemes available to safeguard power systems. This paper mainly considers the distance protection scheme. The distance relaying scheme is normally used for transmission lines [17]. Fig. 2 indicates the characteristics of a distance relaying scheme (admittance (mho) relay).

In this example, the scheme applied is stepped distance protection and it has three zones in the R-X plane. Zones 1 and 2 are for primary protection of the corresponding line, and zone 3 is for backup protection of the adjacent lines. If loading impedance measured by a relay enters one of the zone boundaries, it trips the component after a certain time delay. Typically, zone 1 has no inherent time delay, zone 2 is set for 20-30 cycles, and zone 3 is set for 0.5-3.0 seconds [18]. The sizes of the zones are usually determined based on the impedances of the transmission lines, so the centre of zone circles also depends on the line impedances. Usually the angle (α) of the centre is between 80° and 90°.

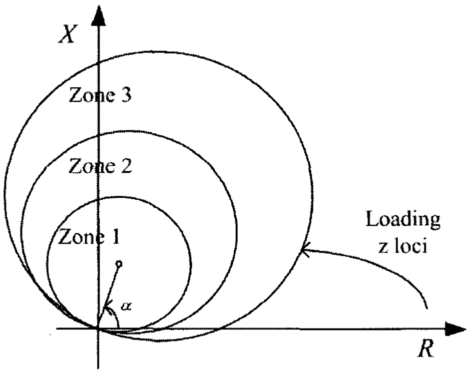

Fig. 2 Characteristics of a distance relay (mho relay)

In the normal state, loading impedance is far outside the zones to be operated. If the corresponding line is a long line with high impedance, the radius of zone 3 is quite large; during the period of voltage instability, loading impedance may cross the zone 3 boundary and trip the line due to low voltage and high reactive power flow, even though there are no faults in the systems. If models of relaying systems are properly applied, detecting this condition of distance relaying is not so difficult, because voltage instability is a phase symmetrical phenomenon. Monitoring relay parameters such as loading impedance is necessary during the simulation for voltage stability analysis.

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. 3 presents three possible cases in which loading impedances at the two points are located in the R-X plane, assuming that both of them are solvable.

As for Case 1, the corresponding distance relay does not operate by the time that load demand has fully recovered, so the relay can be discarded. As for Case 2, the component may be tripped somewhere between ‘b’ and ‘c’. 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 following the trip is not sufficient or the systems are not solvable, control strategies are determined in the framework. As for Case 3, point ‘b’ (short-term load characteristic) is inside the boundary. This indicates that after the contingency the relay may immediately trip the component. If this kind of case occurs during the simulation, trip of the corresponding component also needs to be applied.

Fig. 4 shows three cases of loading impedance locations when the equilibrium point ‘c’ applying long-term load characteristics cannot be solved. If one or more relay parameters enter the boundaries as shown in Fig. 4 (Case 5), the conventional control strategy for maintaining voltage stability may fail. In this case, control actions considering the relay operation should be applied before the contact of the boundary. To identify this sort of zone 3 boundary contact, QSS simulation is necessary for further analysis.

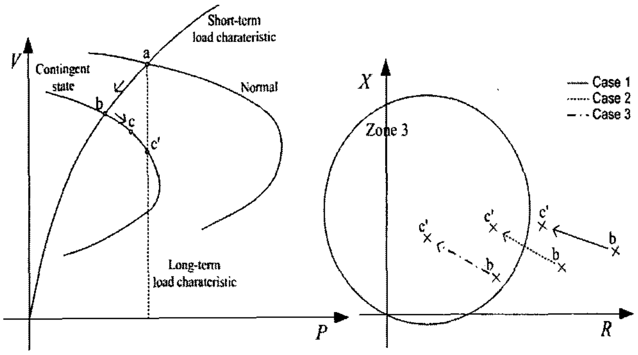

Fig. 3 Three cases of loading z locations (‘c’ solvable)

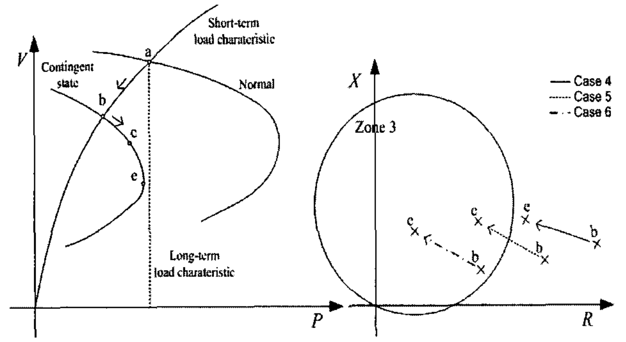

Fig. 4 Three cases of loading z locations (‘c’ unsolvable)

3. Identification of Undesirable Zone 3 Relay Operation

3.1 Control location

When a relay is in the condition of 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 to get out from the region of zone 3. Load shedding is the main control measure in this paper. Adequate locations of load shedding need to be selected for effective control to reduce the line loading. For control locations, the framework calculates electrical distance from the receiving end (for example, bus j) of the monitored line to other buses. For this calculation, B” (bus susceptance matrix) is inversed. The buses that have the lowest components in the j-$^{\text{th}}$ row of $[B"]^{-1}$ are chosen as control locations, from the buses with load demand.

3.2 Continuation based time-domain simulation

The framework utilizes a numerical integration method to get information pertaining to when protective actions caused by zone 3 relays occur after severe contingencies. This information is useful for determining control amount and timing. The dynamics of power systems can be described by a set of differential and algebraic equations (DAE) as follows:

$$\begin{aligned} \dot{Z} &= H(Z,X,Y) \\ \dot{X} &= F(Z,X,Y) \\ 0 &= G(Z,X,Y) \end{aligned} \tag{1}$$

where Z and X are the state vectors of long-term and short-term dynamics, respectively, and Y is the vector of algebraic variables. In (3), $H(\cdot)$, $F(\cdot)$ and $G(\cdot)$ are the functions of long-term, short-term dynamics and the algebraic equations (including the network and interface equations), respectively.

To trace time trajectory of the system (1) from an equilibrium point (Z_o, X_o, Y_o), time integration methods are usually applied. From the known solution at t_n, for this application, (1) needs to be converted to another set of algebraic equations incorporating time step $h_{n+1}(=t_{n+1}-t_n)$; that is, the algebraic equations for the solution at t_{n+1} are naturally parameterized by h_{n+1}. The continuation based time integration method [13, 14], which is used in the framework, solves the parameterized algebraic equations with predictor and corrector. For QSS simulation, $\dot{X}$ in (1) is forced to 0 at each time step.

The objective of the time-domain simulation tool is to detect possible zone 3 relay operations. For this purpose, a detection module needs to be implemented on the tool. Fig. 6 displays a brief flowchart of the tool including the module for detecting any relay operations. During the process of time integration, the module calculates loading impedances of the monitored lines and determines whether the loading impedances enter the region of zone 3. If so, it activates the corresponding zone timer for checking time delay (t_{delay}) of the relay operation. In Fig.5, t_{cross} denotes the time when the impedance crosses the boundary of zone 3. Unless the loading impedance gets out of the region, the relay may operate tripping of the corresponding component at t_{detect} (t_{delay} after t_{cross}).

The tool can solve the equilibrium points ('b' and 'c') of fast dynamics applying short-term and long-term load characteristics in order that it can quickly identify possible relay operations by comparing the loading impedances at the two points as described in the previous section. The selected relays in this process are mainly monitored in the QSS simulation.

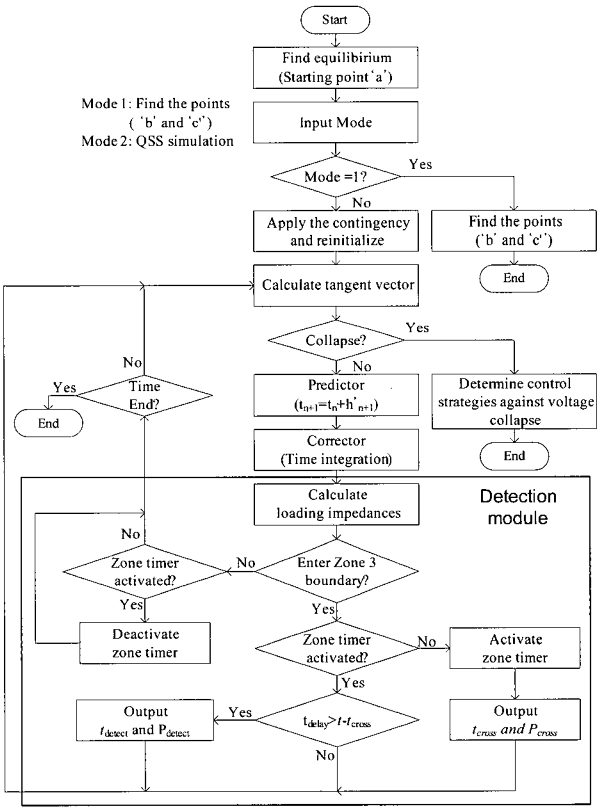

Fig. 5 Three cases of loading z locations ('c' unsolvable)

3.3 Control timing

Against zone 3 relay operations during voltage instability, control should be applied before t_{detect}, which describes detection time of the corresponding relaying action that is found in the time-domain simulation, assuming that the models in the simulation reflect quasi steady-state responses of the system appropriately. Active load demand (P_{cross}) at t_{cross} in the simulation can be a good measure for deciding control timing.

3.4 Control amount

In order for determining control amount at the selected locations, two criteria are used in the framework. Fig. 6 illustrates the criteria. The first one is that system load should be less than P_{cross}, after control, and the other is that the distance of loading impedance from the boundary should be larger than a certain value (relay margin). The concept of relay margin was proposed in [19] for transient stability evaluation. If the corresponding relay has a circle-shaped boundary of zone 3, one can describe the second criterion as follows:

$$\begin{aligned} d_{load} &\geq \left(d_{relay} + d_{add}\right)^2 \\ d_{load} &\equiv \left(r_{load}(\underline{V},\underline{\delta}) - r_{center}\right)^2 + \left(x_{load}(\underline{V},\underline{\delta}) - x_{center}\right)^2 \end{aligned} \tag{2}$$

where d_{load} represents distance of the load impedance from the center impedance (z_{center}). d_{relay} is the diameter of the boundary; d_{add} is the additional diameter to maintain a certain level of relay margin r_{load} and x_{load} denotes resistance and reactance of a loading impedance after applying control, respectively; r_{center} and x_{center} describe resistance and reactance of z_{center}.

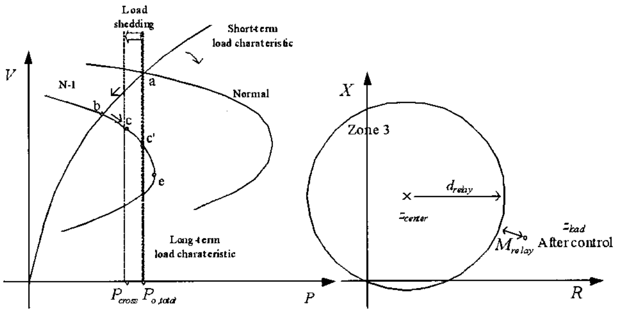

Fig. 6 Criteria for determination of control amount

From the initial amount of control, $P_{LS}^{(1)}$ ($=P_{o,total}-P_{cross}$), where $P_{o,total}$ represents system load at pre-fault state, an adequate amount of load shedding satisfying the criteria can be found using a search method that is explained in Fig 7. Until the equilibrium applying long-term load characteristics has sufficient relay margin for the corresponding relay, the amount of load shedding increases by the same amount of $P_{LS}^{(1)}$. Once the relay margin criterion is satisfied, to find the satisfactory amount of load shedding, a binary search is repeatedly performed until $d_{load}-(d_{relay}+d_{add})$ is within the given tolerance ($d\varepsilon$).

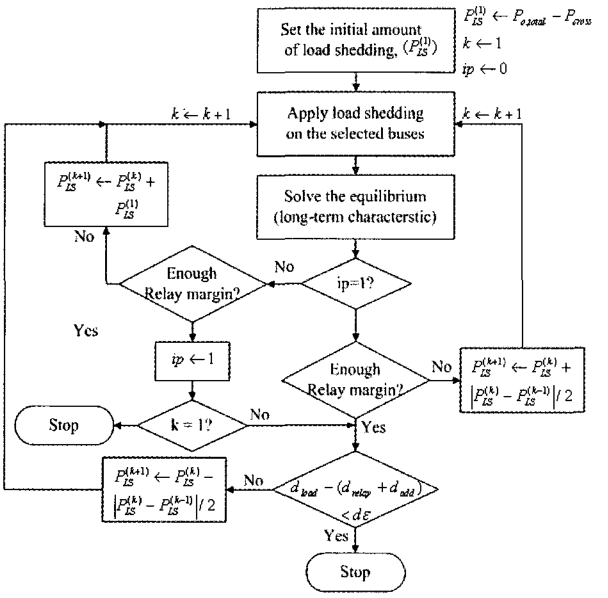

Fig. 7 Flowchart of the determination procedure for control amount

4. Numerical Example

This section provides an illustrative example applying the proposed framework to the New England 39-bus test system. To make some cases in which line loading on a transmission line enters the region of zone 3, we made some modifications to the system. Fig. 8 shows a one-line diagram of the New England 39-bus system.

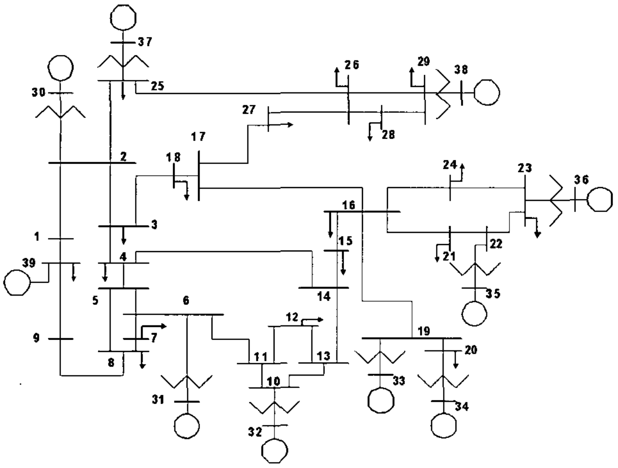

Fig. 8 One-line diagram of New England 39-bus system

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

- For generators, a 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 [16] is applied. Parameters of the model are set as shown in Table I. Load of bus 39 is represented with constant power model;
- At both sides of each transmission line admittance, relays with zone 3 relaying characteristics are equipped The reach setting of each zone 3 boundary is determined to cover the protected line, the adjacent line and up to 30% of the line next to the adjacent line.

Table 1 Parameters of dynamic load model used in this simulation

Real Power	α_S	α_T	T_P
	0	2.0	100.0 [s]
Reactive Power	β_S	β_T	T_Q
	0	2.0	80.0 [s]

In this simulation, two contingencies are applied; one is trip of a generating unit at bus 32 (contingency #1) and the other is outage of line (3-4) 32 (contingency #2). The former is much severer than the latter. The total load of the modified system under pre-fault condition is 6041.9 [MW].

First, the equilibrium points ('b' and 'c') of fast dynamics are solved using the QSS simulation tool with respect to the two contingencies. At each point, loading impedances at the sending and receiving ends of each transmission line, measured by each relay are calculated. For contingency #1, the loading impedance at the sending end of the line (16-15) enters the zone 3 boundary of the relay, at the equilibrium point 'c' applying long-term load characteristics (constant power in this simulation). For contingency #2, there is no crossing of impedances to zone 3 boundaries. Fig. 10 presents positions of the loading impedances at two cases with the boundary of zone 3.

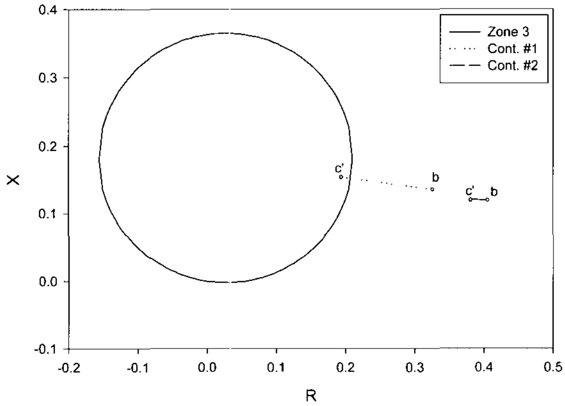

Fig. 9 Loading impedances at two cases with the zone 3 boundary at the sending end of line (16-15)

When line (16-15) is tripped at point 'c' of contingency #1, in order to check severity of the relay operation, the equilibrium cannot be solved by applying the long-term load characteristic. Without any control actions, that is, the relaying action may operate and lead the system to collapse. The framework proposes a control strategy that improves the system condition and ultimately prevents the critical relay operation. Active power on the transmission line (16-15) flows from bus 16 to 15. For determination of control location, electrical distances of buses from 16 to bus 15 (receiving end) need to be calculated using $[B'']^{-1}$. However, bus 15 itself has load demand (3.14+j1.5 [pu]), so bus 15 is selected as the control location.

For control timing and amount, time-domain simulation tool with QSS assumption is performed. This simulation includes integration of the dynamic load models using the parameters in Table I. In the simulation, the generator at bus 32 is tripped at 1 [s] (contingency #1). Fig. 10 shows t-V curves of four buses after the simulation – these buses are arbitrarily selected. As shown in Fig. 10, the loading impedance of the line (16-15), monitored by the corresponding relay, crosses the zone 3 boundary. Assuming that t_{delay} is set to 1 [s], the relay may trip at 329 [s]. Thus, the determined control strategy should be applied before this time. Fig. 11 presents loci of the loading impedance. The starting and ending points of the loci are really similar to those in Fig. 9. Fig. 12 shows t-V curves of the case in which the relay trips the line at 329 [s]. After the trip, voltage levels of some buses dramatically decrease and the system seems to be collapsed at 349 [s].

Fig. 13 indicates the P-V curve of bus 15, obtained from the QSS simulation. Following 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] ($P_{o,total}$). During this process of load recovery, the monitored loading impedance meets the zone 3 boundary when total load is 6027.9 [MW] (P_{cross}). Then, the control amount of load shedding is determined using the procedure described in Fig. 8. The diameter (d_{relay}) of the zone 3 boundary is 0.1833635. Assume that the additional diameter (d_{add}) for maintaining a certain level of relay margin is 0.04, and that the tolerance ($d\varepsilon$) is 0.004. The initial control amount is 14 [MW] ($=P_{o,total}-P_{cross}$). The determined amount of load shedding is 28 [MW].

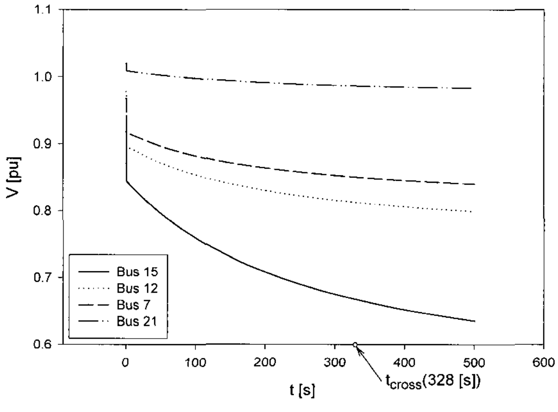

Fig. 10 t-V curves of the selected buses (contingency #1)

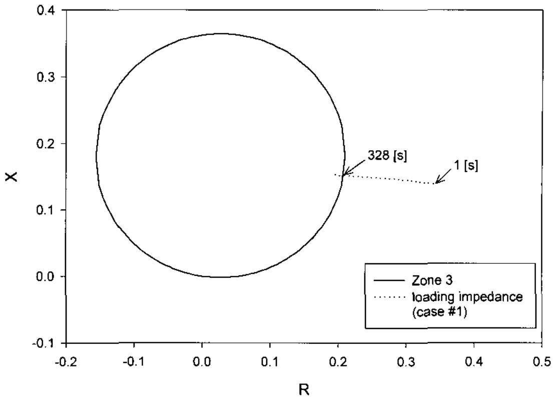

Fig. 11 Loci of the loading impedance at the sending end of line (16-15) (from QSS simulation)

Fig. 14 shows loci of the loading impedance in QSS simulation after applying the determined control strategy (bus 15, 28 [MW], before 329 [s]). In this simulation, the control is applied at 80 [s]. As indicated in Fig. 14, after applying the control strategy, the load impedance does not enter the zone 3 region during the simulation.

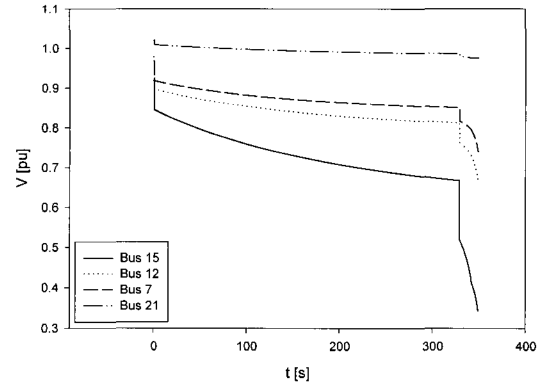

Fig. 12 t-V curves when allowing trip of line (15-16) at 329 [s]

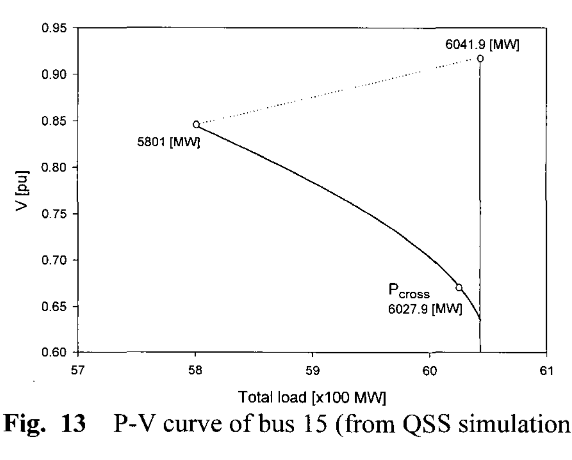

Fig. 13 P-V curve of bus 15 (from QSS simulation)

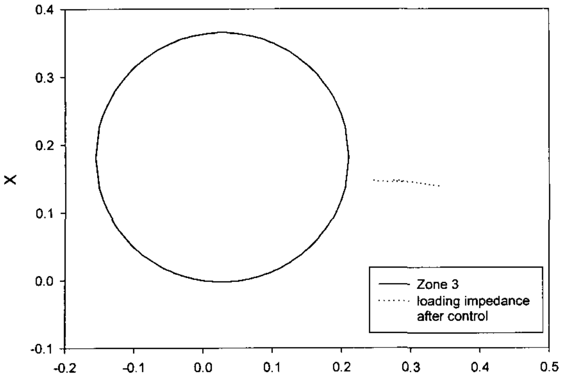

Fig. 14 Loci of the loading impedance after applying control (from QSS simulation)

5. Conclusion

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 for quick identification of possible zone 3 relay operations to screen severe relays in the given condition. For detail analysis, it performs QSS simulation to obtain time information that 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 possible additional trip by undesired relay operation.

Acknowledgement

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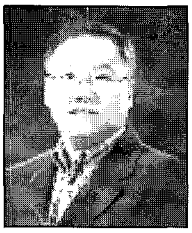

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