EMERGENCY CONTROL MEASURES AGAINST LONG TERM VOLTAGE INSTABILITY

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Abstract

System collapse may be caused by undesired protection relay operations during voltage instability. In this paper, the analysis of different emergency control measures is presented as means to prevent voltage collapse when long term voltage instability is evolving in the system. Being the first line of defence after such unexpected relay trip, the emergency control of load tap changers (LTC) of power transformers during undervoltage conditions is investigated. Alternatively, load shedding is applied to avoid undesired Zone 3 distance relay trips. Sensitivities of Zone 3 trip margin to load powers are calculated to determine the most efficient load shedding actions to prevent undesired operation of critical relays. The effectiveness of the proposed emergency control measures is demonstrated though simulation results for the Hellenic Interconnected System model.

1 Introduction

During voltage instability in a post contingency stage, timely emergency control measures are vital for the prevention of cascading outages and eventually system collapse. One of the root causes of major blackouts, according to [1], is the lack of efficient coordinated emergency control against imminent cascading events. Such emergency control strategies are studied in several research works that cope with voltage instability.

In [2] [3], centralized load tap changer (LTC) controls are proposed, where [2] addresses tap blocking after identifying long-term voltage instability based on a voltage sensitivity matrix and [3] adopts tap reversing to prevent Zone 3 trip of backup relays. A decentralized tap blocking technique upon low voltage detection at extra high voltage buses is also presented in [4]. In cases where load shedding is required due to insufficient loadability margin, research works [5] [6] implement load shedding schemes with local and wide-area measurements in order to mitigate cascading outages with the minimum amount of load shedding.

Such cascading outages can occur after an unexpected Zone 3 trip of distance relays which may be prevented by adjusting Zone 3 characteristic in ways proposed in [7] [8]. However, the modification settings of each relay cannot be easily optimized according to all possible instability scenarios.

When wide-area synchronized measurements are available, an early centralized emergency control strategy can be put into effect as means to prevent Zone 3 undesired trip and consequently possible system deterioration. In [1] [9] the sensitivity of relay operation margin with respect to load powers is calculated and utilized in a load shedding control strategy implemented by multi-agent technology.

The organization of this paper is as follows. Section 2 introduces LTC operation and Zone 3 trip margin of distance relays which form the basic principles for the proposed emergency control measures. The latter referring to LTC emergency control and sensitivity-based load shedding are described in Section 3. Section 4 addresses the case study examined and presents the results of the simulation analysis conducted. Section 5 concludes the paper.

2 Basic Principles

2.1 Load Tap Changers

One of the most important mechanisms for load and voltage restoration in power systems is the LTC of power transformers. Controlled by an automatic voltage regulator, the LTC alters the turns ratio of the transformer in order to maintain the voltage of the controlled bus within a preset deadband. Fig. 1 shows the typical equivalent circuit of a power transformer equipped with LTC.

During normal operation and while V_2 lies within the deadband, LTC takes no action. Whereas if the value of V_2 increases or decreases past the upper or lower bound, respectively, and remains there for longer than a preset time delay ΔT_k, then the ratio r_k of the transformer will be adjusted by Δr. It should be noted that the number of steps of each LTC is defined, thus when r_k reaches its limits (r_{min} or r_{max}) the controlled voltage will no longer be regulated.

In mathematical formulation, ratio r_{k+1} is calculated as follows:

$$r_{k+1} = \begin{cases} r_k + \Delta r, \ \{(V_2 > V_2^0 + d) \ \& \ [r_{k+1} \in (r_{min}, r_{max})]\} \\ r_k - \Delta r, \ \{(V_2 < V_2^0 + d) \ \& \ [r_{k+1} \in (r_{min}, r_{max})]\} \\ r_k, \ \{V_2 \in (V_2^0 - d, V_2^0 + d) \end{cases} \quad (1)$$

where, V_2^0 is the set target voltage (i.e. LTC's voltage setpoint), and d is half the value of deadband, as shown in Fig. 2.

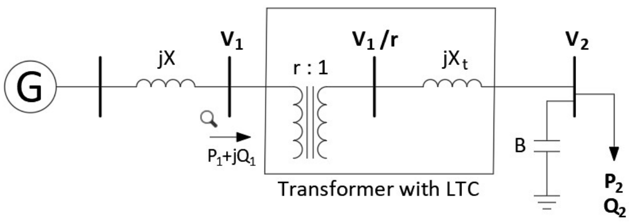

Fig. 1 Equivalent circuit of a power transformer with LTC

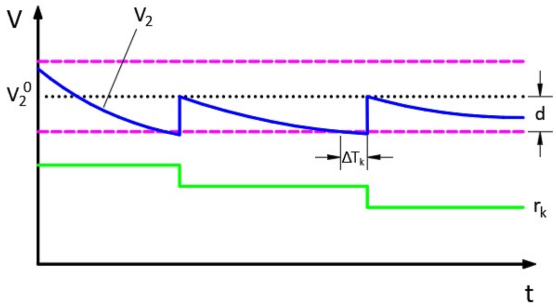

Fig. 2 Voltage regulation by LTC

2.2 Distance Relays

The operating principle of a distance relay is to calculate the complex apparent impedance through voltage and current measurements taken from the protected line and compare it against the preset zones. Typically, there are three zones and corresponding time delays set in a distance relay in the forward direction. Zone 3 refers to the element with the largest reach in the forward direction and the largest time delay. Zone 3 trip margin is defined as the shortest distance between Zone 3 characteristic and the apparent impedance.

Let us assume the short length transmission line of Fig. 3 protected by two distance relays DR_{ij} and DR_{ji} with a mho characteristic (Fig. 4). The apparent impedance seen by the distance relay DR_{ij} at line end *i* is given by:

$$Z_{ij} = \frac{V_S}{I_S} \tag{2}$$

where V_s and I_s are the voltage and current measurements, respectively, taken from line end *i*.

The trip margin M_{ij} of the relay DR_{ij} is given by the following equation:

$$M_{ij} = |Z_{ij} - \rho_3| - |\rho_3| \tag{3}$$

where ρ_3 is the center of Zone 3 mho characteristic in the complex impedance plane R-X and $|\rho_3|$ is the radius of the corresponding circle.

Fig. 4 also shows the typical load area on the R-X plane. Zone 3 characteristic, due to its size, may intersect the load area. Hence, Zone 3 element is susceptible to falsely trip under non-fault conditions, especially if the load is highly inductive which could cause the apparent impedance trajectory to exit the load area.

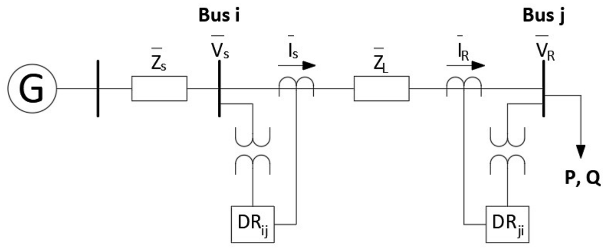

Fig. 3 Transmission line protected by distance relays

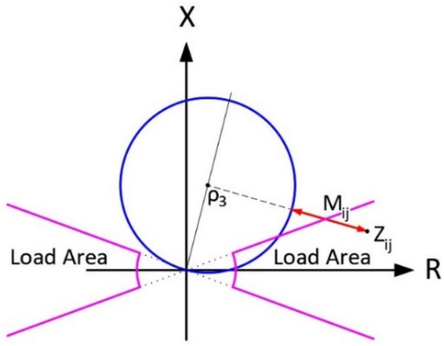

Fig. 4 Zone 3 characteristic of a mho relay with blinders

3 Proposed Emergency Control Strategy

3.1 LTC Emergency Control

As mentioned in the previous section, the main purpose of a LTC is to maintain the voltage of the secondary side of the transformer within a preset deadband in accordance with load variations. However, during stressed system conditions, the load restoration mechanism of LTCs may become unstable. This typically occurs when the system loadability limit has been reached, while the LTCs continue to operate in an attempt to restore load.

This undesired operation of the LTCs in an unstable power system may cause some generators to reach their overexcitation limits, further deteriorating system's operation. Several blackouts have been reported to occur due an undesired Zone 3 trip of a transmission line [1].

The following two decentralized LTC emergency control measures are addressed in this paper:

- *Tap Blocking:* This measure disables the LTC operation at certain unstable high voltage / medium voltage (HV/MV) bulk power distribution transformers before they reach the limits of their regulation range. Tap blocking is applied to the transformers when the primary side voltage drops below a predefine threshold V_{th}. This way, secondary side voltage reduces to lower levels slower.
- *Setpoint Reduction:* This measure reduces the LTC voltage setpoint at certain HV/MV bulk power distribution transformers when their primary side voltage drops below V_{th}. This control action allows the LTC to continue regulate the secondary voltage but at a lower voltage level. Hence, an indirect load rejection is applied.

3.2 Sensitivity Based Load Shedding

In a heavily loaded power system, an undesired Zone 3 trip of a transmission line can cause immediate voltage collapse, making the LTC emergency control measures inefficient. Load shedding is the most appropriate emergency control measure to prevent a potential blackout.

In this paper, the Zone 3 trip margin of all the distance relays is monitored. Load shedding actions are performed to prevent undesired Zone 3 trips of critical transmission lines. To find the most effective loads for applying shedding, the sensitivities $\boldsymbol{S_{M_{PQ}}}$ of the trip margin with respect to the active and reactive power loads are calculated, as shown below:

$$\boldsymbol{S_{M_{PQ}}} = \mathbf{C_M J^{-1}} \begin{bmatrix} \mathbf{\Delta P} \\ \mathbf{\Delta Q} \end{bmatrix} \quad (4)$$

where $\mathbf{J_{P\theta}}$, $\mathbf{J_{PV}}$, $\mathbf{J_{Q\theta}}$, $\mathbf{J_{QV}}$ are the submatrices of the Jacobian matrix $\mathbf{J}$:

$$\mathbf{J} = \begin{bmatrix} \mathbf{J_{P\theta}} & \mathbf{J_{PV}} \\ \mathbf{J_{Q\theta}} & \mathbf{J_{QV}} \end{bmatrix} \quad (5)$$

and $\mathbf{C_M}$ is the following matrix:

$$\mathbf{C_M} = \begin{bmatrix} \frac{\partial M}{\partial \theta_{ki}} & \frac{\partial M}{\partial \theta_{kj}} & \frac{\partial M}{\partial V_{ki}} & \frac{\partial M}{\partial V_{kj}} \end{bmatrix} \quad (6)$$

where M is the trip margin of interest and V_k, θ_k are the voltage magnitudes and angles of the line end buses.

The increase ΔM of trip margin after rejecting an amount ΔP_k of active power and an amount ΔQ_k of reactive power from bus k is calculated by:

$$\Delta M = \sum_k (S_{M_{Pk}} \Delta P_k + S_{M_{Qk}} \Delta Q_k) \quad (7)$$

Supposing that the loads have a constant power factor, the increase of trip margin is calculated as below:

$$\Delta M = \sum_k (S_{M_k} \Delta S_k) \quad (8)$$

where ΔS_k represents the amount of apparent load shed from bus k.

4 Simulation Analysis

The simulation runs are carried out by properly moderating the quasi-steady-state simulation software WPSTAB, developed at National Technical University of Athens (NTUA) [10].

4.1 Case Study

The proposed emergency control measures are tested on the Hellenic Interconnected System model (i.e., the Greek power system). The latter consists of 893 buses, whose grid nominal voltage varies from 20 kV to 400 kV. The snapshot under consideration assumes an initial system load equal to 9084 MW, whereas the total installed power capacity is 9300 MW. A stressed system operating condition is reflected.

The base case scenario applies a 0.2% p.u./s ramp increase in the total load demand for a duration of 1200 s. The simulation lasts for 1500 s.

As the scenario develops with no control against voltage instability, LTCs operate normally, and multiple generators reach their overexcitation limit. Subsequently, an undesired Zone 3 trip of line 397-402 occurs at time 909 s (Fig. 5). As a result, the loss of the 400 kV transmission line 939-404 due to Zone 3 trip occurred in a cascaded manner. It can be seen from Fig. 6 that the apparent impedance trajectory of the distance relay protecting the transmission line 939-404 line exits the load area causing the unwanted trip. Eventually voltage collapses at time 1310 s (Fig. 7).

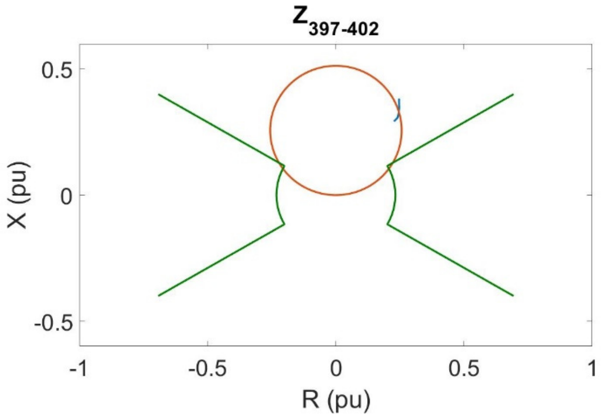

Fig. 5 Zone 3 trip of line 397-402

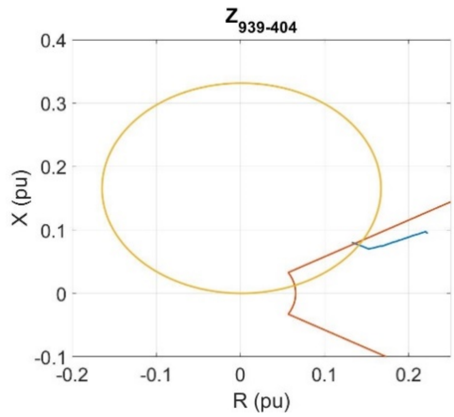

Fig. 6 Zone 3 trip of line 939-404

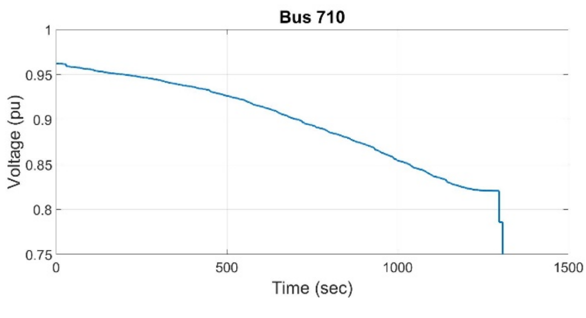

Fig. 7 Representative transmission bus voltage without emergency control

4.2 Applying LTC Emergency Control

The same scenario is simulated again by enabling the LTC emergency control measures.

First, tap blocking is tested. The primary voltage of the 150/20 kV power distribution transformers is constantly monitored and if it drops below V_{th} = 0.9 *p.u.*, the LTC of the respective transformer is disabled. Fig. 8 illustrates an example of tap blocking applied in distribution transformer 633-639.

Alternatively, the LTC voltage setpoint reduction measure is applied for the same scenario. The setpoint is reduced by 2% when the primary voltage drops below V_{th} = 0.9 *p.u.* Fig. 9 illustrates an example of setpoint reduction applied in distribution transformer 633-639.

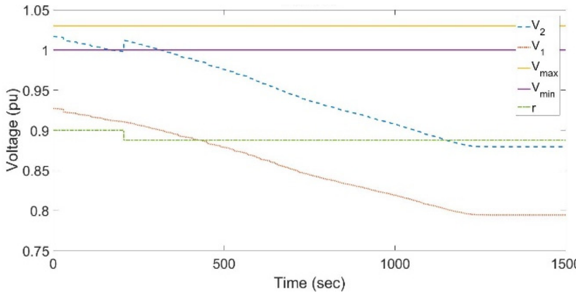

Fig. 8 Tap blocking applied in transformer 633-639

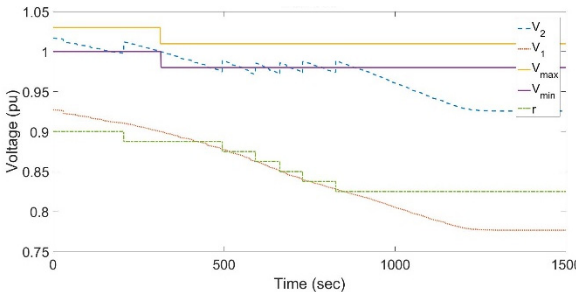

Fig. 9 Voltage setpoint reduction applied in transformer 633-639

As shown in Fig. 10, system voltage collapse is prevented with both measures. System voltages are stabilized at a higher point by applying tap blocking than with setpoint reduction. Fig. 11 gives the P-V curve for the two measures. It is interesting to observe the change of the P-V curve after the undesired Zone 3 trip of line 397-402.

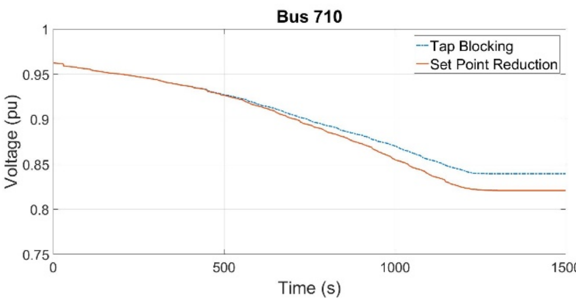

Fig. 10 Representative transmission bus voltage with LTC emergency control

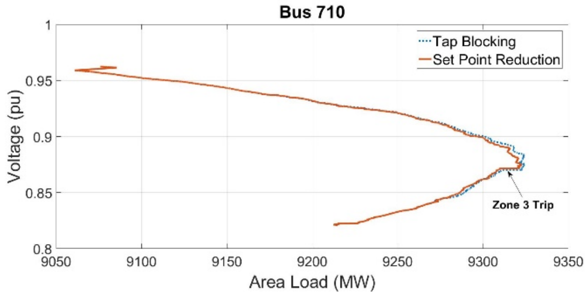

Fig. 11 P-V curve with LTC emergency control

4.3 Applying Emergency Load Shedding

The same scenario is now simulated by enabling the emergency load shedding measure. Based on this measure, load is shed from the most effective load buses. The latter are found by calculating the sensitivities $\boldsymbol{S_{M_{PQ}}}$. Shedding begins when the lowest (i.e., the most critical) distance relay trip margin approaches zero.

A closed-loop load shedding scheme is applied, meaning that each time the apparent impedance trajectory of the most vulnerable relay approaches Zone 3, while not being inside the load area, a 10% load is rejected from the load with the highest sensitivity $\boldsymbol{S_{M_{PQ}}}$. The latter is the most effective to increase the trip margin of the most vulnerable relay. The algorithm allows up to 4 shedding actions to be performed from the same load, that is a maximum of 40% rejection per load.

Eventually, a total of 24.5 *MW* and 32.7 *MVAr* has been rejected during 29 load shedding actions. In Fig. 12 and Fig.13, the voltage of 150 kV bus 710 and the system P-V curve is shown, respectively. While system voltages stabilize in a point lower than with tap blocking, the prevention of cascaded Zone 3 trips is obtained which is much more desirable. By increasing the load shedding percentage, the voltages would be increased.

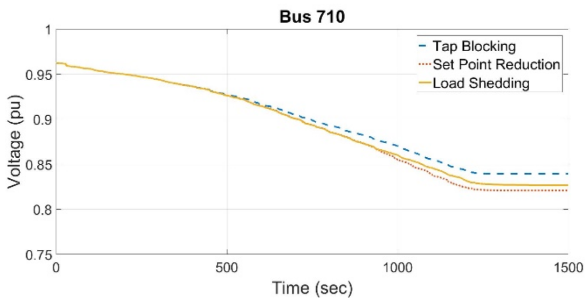

Fig. 12 Representative transmission bus voltage after load shedding

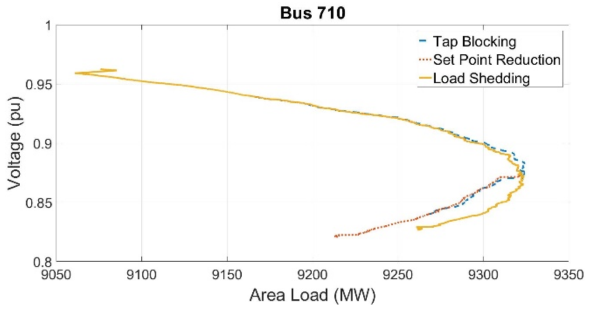

Fig. 13 P-V curve after load shedding

5 Conclusion

Two emergency control measures have been proposed for the prevention of system collapse during long term voltage instability: a decentralized LTC control of bulk power distribution transformers and a centralized sensitivity-based load shedding scheme. The primary objective of LTC emergency control is to delay voltage decrease and, secondarily, to avoid voltage collapse if possible. The load shedding measure is mainly focused on the prevention of undesired Zone 3 trip of distance relays that could lead to voltage collapse. Both methods eventually shed load, whether directly or indirectly, demonstrating through simulation results the effectiveness in obtaining the abovementioned goals.

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7 References

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