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# Emergency Load Shedding Strategy Based on Sensitivity Analysis of Relay Operation Margin against Cascading Events

Zhou Liu, Zhe Chen, *Senior Member, IEEE*, Haishun Sun, Chengxi Liu

***Abstract: In order to prevent long term voltage instability and induced cascading events, a load shedding strategy based on the sensitivity of relay operation margin to load powers is discussed and proposed in this paper. The operation margin of critical impedance backup relay is defined to identify the runtime emergent states of related system component. Based on sensitivity analysis between the relay operation margin and power system state variables, an optimal load shedding strategy is applied to adjust the emergent states timely before the unwanted relay operation. Load dynamics is also taken into account to compensate load shedding amount calculation. And the multi-agent technology is applied for the whole strategy implementation. A test system is built in real time digital simulator (RTDS) and has demonstrated the effectiveness of the proposed strategy.***

***Keywords: voltage instability, load shedding, sensitivity analysis, relay operation margin, multi agent, RTDS***

## I. INTRODUCTION

In the post fault stage, assuming the power system has survived the short term period following the initial fault, the loads attempt to restore their pre fault powers though actions of load tap changer (LTC) or other auto regulation actions [1], when the increasing load demand is beyond the supply capability of generation and transmission system, the equilibrium between them will lose, which is referred as long term voltage instability. When transmission lines get overloaded and excitation of generators hit the limits (OEL), the backup relays on them may operate to trip the line or generator, which are regarded as unwanted relay operation with the possibility to initiate cascading trips or blackouts, such as the northeast U.S./Canada blackout in 1965, the western U.S. blackout in 1996, the Brazil blackout in 1999, and the southern Sweden and eastern Denmark blackout in 2003 [2]. So the emergent system states in the post fault stage, which are featured by overload of transmission line and over excitation of generators, should be adjusted to avoid this kind of blackouts.

In recent years, many special system protection schemes (SPS) based on wide area measurements (WAMS) has been proposed and designed to prevent voltage instability and subsequent cascading trips. Such as adaptive backup relay system, LTC emergency control, reactive compensation, generator excitation emergency control, load shedding and etc [2-6]. Among the diverse countermeasures, load shedding is regarded as the last and fast resort when there is no other alternative to adjust the system emergent states and stop the progress approaching voltage collapse [4] [7] [8].

In this paper, a sensitivity based load shedding strategy is proposed in order to adjust the system emergent states and prevent unwanted relay operation and voltage instability during load restoration. The key issue of load shedding is to determine where to shed the load and how much should be shedding. A method based on sensitivity of relay operation margin to bus load of the system is presented to determine the optimal load shedding strategy with reasonable shedding location and less shedding amount. The steady and transient characteristics of load model are considered in load shedding strategy to ensure the system operating in a secure scope finally. The whole strategy is implemented by multi-agent technology, and demonstrated in a test system in RTDS.

The rest of the paper is organized as follows. The concepts and deduction of relay operation margin and related sensitivity will be presented in Section II briefly. Then the sensitivity based load shedding strategy will be described in Section III. In Section IV, validation of the strategy will be demonstrated based on the test system simulation in RTDS. Finally, the conclusion will be made in Section V.

## II. SENSITIVITY OF RELAY OPERATION MARGIN TO POWER SYSTEM STATE VARIABLES

### A.Definition of Relay operation margin

The relay operation margin is defined here as the difference between the measured impedance and the set value of backup relay (zone 3 relay) based on impedance principle. Take consideration of the characteristics of transmission line backup impedance relay in the X-R plane. As shown in Fig. 1, the circle area represents the operation area of the relay. $Z_{Tset}$ represents the set value of the relay which is along the circle in the plane. $Z_{aij}$ is the measured impedance by the backup relay. At current load angle, the relay operation margin can be expressed as:

$$\mathrm{M_{Tij}} = \mathrm{Z_{aij}} - \mathrm{Z_{Tsetij}} \quad (1)$$

where

$$\mathrm{Z_{Tsetij}} = \mathrm{Z_{Tset}}\cos(\Delta\varphi) \quad (2)$$

$$\Delta\varphi = \varphi_{\mathrm{line}} - \varphi_{\mathrm{ij}} \quad (3)$$

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$\varphi_{\mathrm{line}}, \varphi_{\mathrm{ij}}$ are line impedance angle and load angle respectively. The subscript i and j represent the bus numbers of line.

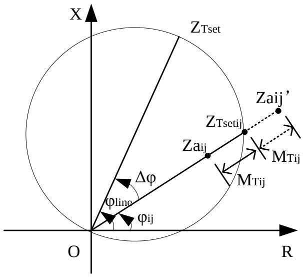


Fig. 1 Characteristics of transmission line backup impedance relay

Under normal system operation states, the measured apparent impedance $Z'_{aij}$ should be located outside the circle area and the relay operation margin $M'_{Tij}$ is positive as shown in Fig. 1. When the measured impedance $Z_{aij}$ enters into the circle area, the backup relay would be initiated to trip the line within a preset delay. At this time, the margin $M_{Tij}$ is negative. If the negative margin is caused by the post fault load restoration dynamics, the trip of line is not expected because it would weaken the stressed system futher more and might result cascaded events.

The set value of line backup relay is defined as [9]

$$\mathrm{Z_{Tset}} = \frac{\mathrm{V_{min}^2}}{\mathrm{S_{max}} \cos\left(\varphi_{\mathrm{line}} - \varphi_{\mathrm{max}}\right)} \tag{4}$$

Where $S_{max}, V_{min}, \varphi_{line}, \varphi_{max}$ represent the load capacity limit of the line, low voltage limit of the bus, impedance angle of the line and maximum load angle allowed respectively. While the measured impedances $Z_{aij}$ by the backup relay can be calculated by the terminal buses voltage of the line as [10]

$$\mathrm{Z_{aij}} = \frac{\mathrm{Z_{ij} V_i}}{\sqrt{\left(\mathrm{V_i} - \mathrm{V_j}\cos\theta_{\mathrm{ij}}\right)^2 + \left(\mathrm{V_j}\sin\theta_{\mathrm{ij}}\right)^2}} \tag{5}$$

Where $Z_{ij}, V_i, V_j, \theta_{ij}$ represent the impedance, terminal buses voltage magnitude and phase angle of the line respectively. By equation (4) and (5) the relay operation margin can be related to the operation state of the line power flow.

On the other hand, considering the backup relay of generator based on impedance principle, similar definition of relay operation margin can be defined and the margin can be related to the system state variables as well. The characteristics of generator backup relay in X-R plane are shown in Fig. 2.

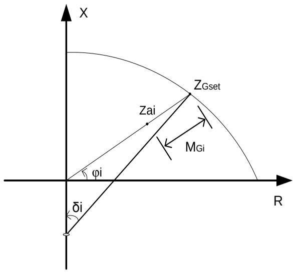


Fig. 2 Characteristics of generator backup impedance relay

The arc curve in the X-R plane represents the generator backup relay setting which can be transferred from the capacity capability curve of generator [11] and given by

$$\mathrm{Z_{Gset}} = \mathrm{Z_{oel}} = \frac{\mathrm{X_s V_{min}}}{\sqrt{\mathrm{E_{fdmax}}^2 + \mathrm{V_{min}}^2 - 2\mathrm{V_{min}}\mathrm{E_{fdmax}} \cos\delta_{\mathrm{s}}}} \tag{6}$$

where $Z_{Gset}$ is the backup relay settings on generator, $\mathrm{E_{fdmax}}$ is the maximum excitation voltage , $\mathrm{E_{fdmax}} = \mathrm{X_{ad}} \mathrm{i_{fdmax}}$, $X_s$ is synchronous impedance of generator, $\delta_s$ is the load angle of generator when active power of generator $P_{Gsp}$ , low limit voltage $V_{min}$ and $E_{fdmax}$ are defined.

The measured impedance $Z_{ai}$ is given by (7) and the relay operation margin is defined by (8). The subscript *i* denotes the number of the generator.

$$\mathrm{Z_{ai}} = \frac{\mathrm{X_{si} V_i}}{\sqrt{\mathrm{E_{fdi}}^2 + \mathrm{V_i}^2 - 2\mathrm{V_i}\mathrm{E_{fdi}} \cos\delta_{\mathrm{i}}}} \tag{7}$$

$$\mathrm{M_{Gi}} = \mathrm{Z_{ai}} - \mathrm{Z_{Gseti}} \tag{8}$$

When the measured margin is negative, it means that the generator is probably in an overexcited state. If this is the case, the trip of generator by the backup relay might deteriorate the system operation.

### *B.Sensitivity of relay operation margin to bus voltages*

By definition, the relay operation margin can be used to identify the system emergent states. Since the margin is related to the power flow state of system, it is possible to obtain secure positive margin by adjusting the power flow. Following this idea, the load shedding strategy (LS) under emergent state, such as the post fault process with long term voltage instability due to the slow load restoration dynamics, can be formed based on sensitivity analysis of the relay operation margin to the bus load.

From equation (1)-(8), the sensitivity of relay operation margin to related state variables can be defined as follow [1]

$$\mathrm{Sen_{xj}} = \frac{\Delta \mathrm{M_x}}{\Delta \mathrm{u_j}} \qquad \mathrm{j} = 1, 2, \dots, \mathrm{n} \tag{9}$$

where $\Delta u_j$ is the adjusting amount of state variables at bus j, including $\Delta V_j$, $\Delta\theta_j$, $\Delta P_j$, $\Delta Q_j$ and $\Delta S_j$; $\Delta M_x$ is the operation margin increment of critical relay *x* after adjusting state variables, and *n* is the number of controllable buses.

By linearization method, the sensitivity of transmission line relay operation margin to bus voltages can be given by (10) and (11) based on line power flow of the current operation state, where $C_{Tij}$ is the sensitivity vector including the sensitivities of the relay margin $M_{Tij}$ to related bus voltages $(\theta_i, \theta_j, V_i, V_j)$.

$$\Delta\mathrm{M_{Tij}} = \mathrm{C_{T\theta i}}\Delta\theta_{\mathrm{i}} + \mathrm{C_{T\theta j}}\Delta\theta_{\mathrm{j}} + \mathrm{C_{Tvi}}\Delta\mathrm{V_i} + \mathrm{C_{Tvj}}\Delta\mathrm{V_j} \tag{10}$$

$$\begin{aligned}\mathrm{C_{Tij}} &= \begin{bmatrix}\mathrm{C_{T\theta i}} & \mathrm{C_{T\theta j}} & \mathrm{C_{Tvi}} & \mathrm{C_{Tvj}}\end{bmatrix} \\ &= \begin{bmatrix}\dfrac{\partial \mathrm{M_{Tij}}}{\partial\theta_{\mathrm{i}}} & \dfrac{\partial \mathrm{M_{Tij}}}{\partial\theta_{\mathrm{j}}} & \dfrac{\partial \mathrm{M_{Tij}}}{\partial \mathrm{V_i}} & \dfrac{\partial \mathrm{M_{Tij}}}{\partial \mathrm{V_j}}\end{bmatrix}\end{aligned} \tag{11}$$

Similarly, sensitivity analysis can be taken on generator relay operation margin as given by (12) and (13), where $C_{Gi}$ is the sensitivity vector including the sensitivities of $M_{Gi}$ to the related variables *(*$V_i$, $I_{fdi}$, $\delta_i$*)* at a generator bus *i*.

$$\Delta\mathrm{M_{Gi}} = \mathrm{C_{GVi}}\Delta\mathrm{V_i} + \mathrm{C_{Ifd}}\Delta\mathrm{I_{fdi}} + \mathrm{C_{G\delta_i}}\Delta\delta_{\mathrm{i}} \tag{12}$$

$$\mathrm{C_{Gi}} = \begin{bmatrix}\mathrm{C_{GVi}} & \mathrm{C_{Ifd}} & \mathrm{C_{G\delta_i}}\end{bmatrix} = \begin{bmatrix}\dfrac{\partial \mathrm{M_{Gi}}}{\partial \mathrm{V_i}} & \dfrac{\partial \mathrm{M_{Gi}}}{\partial \mathrm{I_{fdi}}} & \dfrac{\partial \mathrm{M_{Gi}}}{\partial\delta_{\mathrm{i}}}\end{bmatrix} \tag{13}$$

Taking all the relays of concern into consideration, the sensitivity of relay operation margin can be expressed in matrix form as (14) and (15).

$$\mathbf{\Delta M_T} = \mathbf{C_T}\begin{bmatrix}\mathbf{\Delta\theta} \\ \mathbf{\Delta V}\end{bmatrix} = \begin{bmatrix}\mathbf{C_{T\theta}} & \mathbf{C_{TV}}\end{bmatrix}\begin{bmatrix}\mathbf{\Delta\theta} \\ \mathbf{\Delta V}\end{bmatrix} \tag{14}$$

$$\Delta\mathbf{M_G} = \mathbf{C_G}\begin{bmatrix}\Delta\mathbf{V}\\ \Delta\mathbf{I_{fd}}\\ \Delta\boldsymbol{\delta}\end{bmatrix} = [\mathbf{C_{GV}}\quad \mathbf{C_{GIfd}}\quad \mathbf{C_{G\delta}}]\begin{bmatrix}\Delta\mathbf{V}\\ \Delta\mathbf{I_{fd}}\\ \Delta\boldsymbol{\delta}\end{bmatrix} \tag{15}$$

where $\boldsymbol{C_{T\theta}}$ and $\boldsymbol{C_{TV}}$ are submatrices of sensitivity matrix $\boldsymbol{C_T}$ which is composed by sensitivity vector $\boldsymbol{C_{Tij}}$; $\boldsymbol{C_{GV}}$, $\boldsymbol{C_{GIfd}}$, $\boldsymbol{C_{G\delta}}$ are submatrices of sensitivity matrix $\boldsymbol{C_G}$ composed by sensitivity vector $\boldsymbol{C_{Gi}}$.

Under over excitation limit condition, the generator active and reactive power output can be calculated by

$$P_{Gspi} = \frac{V_i E_{qimax}}{X_{si}}\sin\delta_i \tag{16}$$

$$Q_G = \frac{V_i E_{qimax}}{X_{si}}\cos\delta_i - \frac{{V_i}^2}{X_{si}} \tag{17}$$

Supposing the active power $P_{Gspi}$ is constant from (16), the power angle $\delta_i$ is a function of $V_i$ when the generator $i$ hits the overexcited limit. Also from (17), the $Q_G$ will change with $V_i$, so the type of bus $i$ can be regarded as so called $PI_f$ node with constant $P$ and $I_f$ [12]. The equation (12) can be accordingly rewritten to (18) at this situation and the sensitivity $C'_{GVi}$ can be calculated by (19).

$$\Delta M'_{Gi} = (C_{GVi}+C_{G\delta_i} * C_{G\delta_i Vi})\Delta V_i = C'_{GVi}\Delta V_i \tag{18}$$

$$C'_{GVi} = C_{GVi} + C_{G\delta_i} * C_{G\delta_i Vi} = \frac{\partial M_{Gi}}{\partial V_i} + \frac{\partial M_{Gi}}{\partial \delta_i} * \frac{\partial \delta_i}{\partial V_i} \tag{19}$$

### C.Sensitivity of relay operation margin to bus powers

The bus voltages are related to bus powers by the system load flow equations, implying the sensitivity of relay margin to bus powers can be derived from (20) and (21) at current operation point, where $\mathbf{H_{TP}}$ and $\mathbf{H_{TQ}}$ are the submatrices of $\mathbf{H_T}$; $\mathbf{H_{GP}}$ and $\mathbf{H_{GQ}}$ are submatrices of $\mathbf{H_G}$; $\Delta\mathbf{P}$ and $\Delta\mathbf{Q}$ are the variations of active and reactive powers; $\mathbf{J_{P\theta}}$, $\mathbf{J_{PV}}$, $\mathbf{J_{Q\theta}}$ and $\mathbf{J_{QV}}$ are submartices of the Jacobian matrix $\mathbf{J}$; supposing that the bus power flowing into the bus is positive.

$$\Delta\mathbf{M_T} = \mathbf{H_T}\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} = \begin{bmatrix}\mathbf{H_{TP}} & \mathbf{H_{TQ}}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} \tag{20}$$

$$\Delta\mathbf{M_G} = \mathbf{H_G}\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} = \begin{bmatrix}\mathbf{H_{GP}} & \mathbf{H_{GQ}}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} \tag{21}$$

where

$$\mathbf{H_T} = \mathbf{C_T}\mathbf{J^{-1}} \tag{22}$$

$$\mathbf{H_G} = \mathbf{C'_G}\mathbf{J^{-1}} \tag{23}$$

$$\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix} = \mathbf{J}\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \Delta\mathbf{V}\end{bmatrix} = \begin{bmatrix}\mathbf{J_{P\theta}} & \mathbf{J_{PV}}\\ \mathbf{J_{Q\theta}} & \mathbf{J_{QV}}\end{bmatrix}\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \Delta\mathbf{V}\end{bmatrix} = \begin{bmatrix}\frac{\boldsymbol{\partial}\Delta\mathbf{P}}{\boldsymbol{\partial\theta}} & \frac{\boldsymbol{\partial}\Delta\mathbf{P}}{\boldsymbol{\partial}\mathbf{V}}\\ \frac{\boldsymbol{\partial}\Delta\mathbf{Q}}{\boldsymbol{\partial\theta}} & \frac{\boldsymbol{\partial}\Delta\mathbf{Q}}{\boldsymbol{\partial}\mathbf{V}}\end{bmatrix}\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \Delta\mathbf{V}\end{bmatrix} \tag{24}$$

## III. EMERGENCY LOAD SHEDDING STRATEGY

### A.Sensitivity based LS strategy

When the emergency load shedding scheme is considered, supposing the load powers are with constant power factor, then the sensitivity relationship between the critical relay margin and load powers can be given by (28), where $\Delta M_x$ is the margin increment of critical relay $x$, $S_{Lj}$ and $\Delta S_{Lj}$ represent the apparent load power and load shedding amount at load bus $j$, $H_{x,j}$ is the sensitivity of operation margin of relay $x$ to apparent load powers.

$$\Delta M_x = \sum_j\left(\frac{H_{Px,j}P_j + H_{Qx,j}Q_j}{S_{Lj}}\Delta S_{Lj}\right) = \sum_j H_{x,j}\Delta S_{Lj} \tag{28}$$

By sensitivity analysis, the effective load shedding locations with the largest sensitivities will be selected. In order to obtain the secure positive margin, the required relay margin $M_x^{req}$ is equal to 5% of $Z_{set}$ outside the $Z_{set}$ circle to ensure that the loadability margin is no less than the required 5% [16], so the expected relay margin increment $\Delta M_x^{exp}$ can be given by (29). The achieved increment $\Delta M_x^*$ can be calculated by (30), where $\Delta S_{Lj} = \alpha_j \times S_{Lj}$, $\alpha_j$ is the shedding fraction of the selected load, *n* and *m* are the numbers of total loads and selected loads respectively. The $\Delta M_x^*$ must exceeds $\Delta M_x^{exp}$ which proves the emergent state has been prevented successfully.

$$\Delta M_x^{exp} = M_x^{req} - M_x = (1+5\%)Z_{set} - Z_a \tag{29}$$

$$\Delta M_x^* = \sum_{j=1}^{m} H_{x,j}\times\Delta S_{Lj} = \sum_{j=1}^{m} H_{x,j}\, S_{Lj}\times\alpha_j \qquad m \le n \tag{30}$$

If the load shedding amount on the *m* selected loads has the same step size, namely $\alpha_1 = \alpha_2 = \cdots = \alpha_j = \alpha$, then the amount of LS can be obtained by (31), which is applied in [11] as same percentage load shedding strategy.

$$\alpha = \frac{\Delta M_x^{exp}}{\sum_{j=1}^{m} H_{x,j}S_{Lj}} = \frac{M_x^{req} - M_x}{\sum_{j=1}^{m} H_{x,j}S_{Lj}} \tag{31}$$

In this paper, in order to further minimize the total shedding amount on selected loads, an optimal load shedding strategy will be applied with the following objective function (32).

$$\begin{aligned}&\min\ S_{shed} = \min\left\{\textstyle\sum_{j=1}^{m}\Delta S_{Lj}\right\},\\ &\text{s.t.}\quad \Delta M_x^* \ge \Delta M_x^{exp}\end{aligned} \tag{32}$$

If there are some limitations from power system components and load shedding providers, then specific conditions (e.g. $|\alpha_j|_{max} \ge |\alpha_j| \ge 0$) will be considered in the optimization problem.

It should be noted that when the power system is in a post fault long term voltage instability situation, there may be three kinds of cases with regard to the alarm signals from the relays.

Case 1: Backup relay on generator is triggered.

Case 2: Backup relay on transmission line is triggered.

Case 3: Backup relays on generators and transmission lines nearby are triggered together.

When case 3 happens, the expected relay operation margin increment $\Delta M_x^{exp}$ will choose the biggest one (which means the worse situation) to do sensitivity and load shedding related calculation and validation in this paper.

### B.Load restoration characteristics consideration

In this paper, load restoration dynamic for long term voltage stability study is modelled as follow [1]:

$$P_L = z_P\, P_{L0}\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{33}$$

$$Q_L = z_Q\, Q_{L0}\left(\frac{V}{V_0}\right)^{\beta_t} \tag{34}$$

$$T_P\dot{z}_P = \left(\frac{V}{V_0}\right)^{\alpha_s} - z_p\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{35}$$

$$T_Q\dot{z}_Q = \left(\frac{V}{V_0}\right)^{\beta_s} - z_Q\left(\frac{V}{V_0}\right)^{\beta_t} \tag{36}$$

where $P_L$, $Q_L$ are the active and reactive power of the specific load, respectively; $P_{L0}$, $Q_{L0}$ are the active and reactive power of this load at a voltage $v$ equal to reference voltage $v_0 (= 1)$; $z_P$, $z_Q$ are dimensionless state variables associated with load dynamics; $\alpha_t, \beta_t$ represent the transient load exponents and

$\alpha_s, \beta_s$ are the steady state ones; $T_P, T_Q$ are the load restoration time constant respectively. In steady state, the voltage characteristics of the load model are given by (37) and (38):

$$\mathrm{P_{Ls}} = \mathrm{P_{L0}}\left(\frac{\mathrm{V}}{\mathrm{V_0}}\right)^{\alpha_\mathrm{s}} \tag{37}$$

$$\mathrm{Q_{Ls}} = \mathrm{Q_{L0}}\left(\frac{\mathrm{V}}{\mathrm{V_0}}\right)^{\beta_\mathrm{s}} \tag{38}$$

Assuming$\alpha_s = \beta_s = 0$, $\alpha_t = \beta_t = 2$ and $T_P = T_Q = 100\mathrm{s}$ in this paper, before the LS on this kind of loads, the system is already in a voltage instability situation due to LTC actions; all the sensitivity based information is obtained based on current power flow state which is not in a steady state. Especially around the time of LS, a big voltage variation is experienced on the load bus, the load will mainly respond with its transient characteristics (33) (34) before and just after LS. So both shedding amount and expected relay margin increment are calculated by the load powers with transient characteristics when backup relay is triggered. Also according to (33) (34), there will be an inevitable load power increment ($\Delta\mathrm{P_{Lit}^{inc}}$for an example) when related bus voltage $\mathrm{V_{it}}$ recovers to a high level just after LS, as can be given by (39) (40), assuming the voltage can be recovered to low voltage limit $\mathrm{V_{min}}(= 0.9\mathrm{pu})$ as an expectation, $\mathrm{D_{Pi}}$ is the sensitivity of load active power to bus voltage based on transient characteristics, *t* is the shedding time.

$$\Delta\mathrm{P_{Lit}^{inc}} = \mathrm{D_{Pi}} * (\mathrm{V_{min}} - \mathrm{V_{it}}) = \mathrm{D_{Pi}}\Delta\mathrm{V} \tag{39}$$

where

$$\mathrm{D_{Pi}} = \frac{\partial \mathrm{P_{Li}}}{\partial \mathrm{V_i}} \tag{40}$$

Then the load amount just after LS can be given by (41). $\mathrm{P_{Lit}}$ is the load amount with transient characteristics before LS. $\Delta\mathrm{P_{Li}^{sen}}$ is the shedding amount given by former sensitivity based calculation.

$$\mathrm{P'_{Lit}} = \mathrm{P_{Lit}} + \Delta\mathrm{P_{Li}^{ses}} + \Delta\mathrm{P_{Lit}^{inc}} \tag{41}$$

If $\Delta\mathrm{M_x^*}$ exceeds $\Delta\mathrm{M_x^{exp}}$at this time, then LS strategy will stop, but after the LS, the load will start to reach its steady state characteristics (37) (38) in a long run, which may induce $\Delta\mathrm{M_x^*}$ smaller than $\Delta\mathrm{M_x^{exp}}$ again, even cause $\mathrm{M_x^*}$ become negative again to trigger the backup relay. In order to prevent this unwanted relay operation successfully at one time, the restoration amount due to load restoration to steady state characteristics should be added into shedding amount on this load in advance. The restoration amount ($\Delta\mathrm{P_{Li}^{res}}$ for an example) can be calculated by (42), then total shedding amount ($\Delta\mathrm{P_{Li}^{tot}}$) on load i can be given by (43). $\mathrm{P'_{Li0}}$ is steady state load power after LS, which will not changes with voltage variation due to $\alpha_s = \beta_s = 0$, and is given by (44).

$$\Delta\mathrm{P_{Li}^{res}} = \mathrm{P'_{Li0}} - \mathrm{P'_{Lit}} \tag{42}$$

$$\Delta\mathrm{P_{Li}^{tot}} = \Delta\mathrm{P_{Li}^{sen}} + \Delta\mathrm{P_{Li}^{res}} \tag{43}$$

where

$$\mathrm{P'_{Li0}} = \mathrm{P_{Li0}} + \Delta\mathrm{P_{Li}^{ses}} \tag{44}$$

Similarly, considering constant load power factor, the apparent load shedding amount can be also defined by (45).

$$\Delta\mathrm{S_{LI}^{tot}} = \Delta\mathrm{S_{Li}^{ses}} + \Delta\mathrm{S_{Li}^{res}} \tag{45}$$

### *C.The structure of control strategy*

According to the content discussed above, the procedure of the proposed LS strategy can be depicted by Fig. 3.

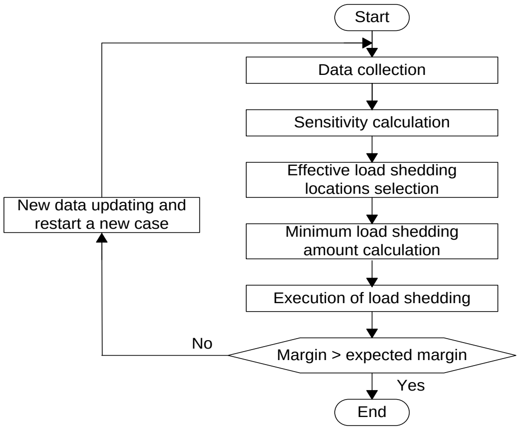
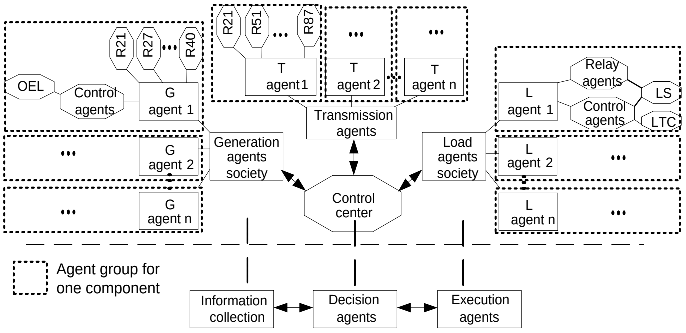


Fig. 3 Flowchart of proposed LS

In order to implement the proposed LS, some functions in Fig. 3 will be fulfilled by control center, such as the integrated information processing, the sensitivity based strategy defining and etc. But other functions in this whole protection strategy including the emergent state detection, data collection from WAMS, and LS execution, are finished by distributed relays and controllers or some groups of them. Owing to good environment for cooperation and communication, multi agent system (MAS) based structure is applied to implement the whole strategy, which is shown in Fig. 4 and already discussed in [11].



Gov—Generator governor; LS—Load Shedding controller; LTC—Under load tap changer controller; R21…R87—Different types of relay element

Fig. 4 Structure of MAS

## IV. SIMULATION AND VERIFICATION

### *A. Test system in RTDS and study case*

A 10-bus test system [15] shown in Fig.4 is selected as the test example and modeled in RTDS with details as follow:

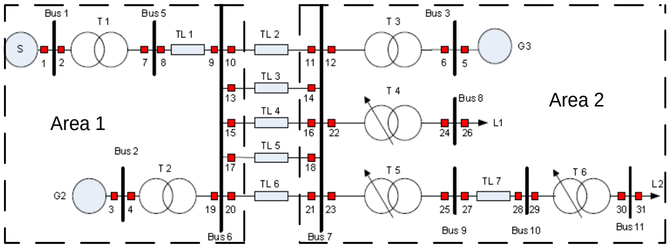


Fig. 4 Configuration of the test system

Bus 1 is designated as slack bus. Two generators, G2 and G3 are connected to bus 2 and bus 3 with OEL model [15]. Two loads $\mathrm{L_1}$ and $\mathrm{L_2}$ are connected to bus 8 and bus 11 respectively. The exponential model described above in section III is applied to express the load restoration dynamics which had been depicted with the parameters in Table I.

TABLE I
LOAD DATA

| Load | $P_{L10}$ (MW) | $Q_{L10}$ (MVar) | $\alpha_s = \beta_s$ | $\alpha_t = \beta_t$ | $T_P = T_Q(s)$ |
|---|---|---|---|---|---|
| L1 | -3250 | -1030 | 0 | 2 | 100 |
| L2 | -3320 | 0 | 0 | 2 | 100 |

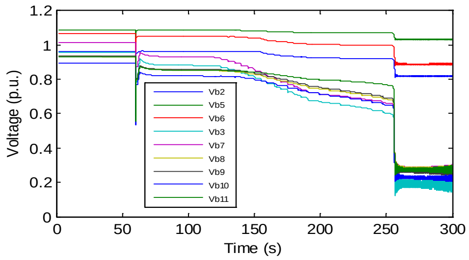
Under load tap changer controllers (LTC) are modeled with transformer T4, T5 and T6. As for the cluster connected transformers, such as T5 and T6, the faster upstream tapping will have the priority to be chosen as control output [1]. The LTC parameters are shown in Table II. They will be blocked when the LS strategy is initiated.

TABLE II
LTC DATA

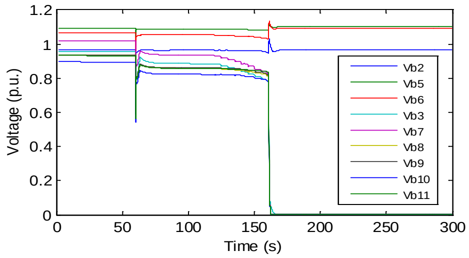
| LTC | Delay on first step (s) | Delay on next step (s) | Δr (pu) | r (pu) $[r_{min}, r_{max}]$ |
|---|---|---|---|---|
| T4 | 20 | 6 | 0.01 | [0.8, 1.09] |
| T5 | 20 | 6 | 0.01 | [0.8, 1.09] |
| T6 | 40 | 9 | 0.01 | [0.9, 1.19] |

All the backup relays of the generators and transmission lines are based on measured impedance and they are modeled with the standard distance relay model embedded in RTDS. The generators' OEL curves are modeled in R-X plot with the backup relay settings, which are used as criterion to initiate the alarm to CC. This new setting applies $I_{fd2max} = I_{fd2max} = 2.625$pu and $V_{min} = 0.9$pu. The relay settings on transmission lines are defined according to initial power flow condition.

A three phase short circuit fault is applied on line TL2, the relay 10 trips the line immediately to clear the fault within 0.1s. Before this fault occurred, the system states are stressed by the two transmission lines outages (TL5, TL6 between bus 6 and bus 7). In the post fault stage, the system survives in the transient period. But with the load restoring, the network cannot support the increasing load demand. The voltage collapse progress can be observed as in Fig. 5 with two situations. The backup relays on TL3 and TL4 are triggered at about 160s to cut these two lines, which is regard as unwanted relay operations. Then the network splits into two parts Area 1 and Area 2, the Area 1 survives, while the Area 2 including all the loads and one generator G3 collapses even faster due to bigger unbalance between generation and load.



(a) Voltage collapse with traditional relays blocked



(b) Unwanted traditional relay operation in voltage collapse

Fig. 5 voltage collapse progress in the post fault stage

## *B. Load shedding strategy verification*

In order to prevent these unwanted relay operation and voltage collapse, the proposed LS strategy will be taken into effect immediately when the backup relays agents on transmission line is triggered, such as relay 13 or 15 in Fig .4, the control center (CC) will identify that the system is now in an emergent state with risk of unwanted trip of the line TL3 and TL4. Based on the workflow in Fig. 2, once the LS strategy is started, the relay operation margins and sensitivity information at this operation point will be calculated in CC, which are shown in Table III. Based on the well developed data processing and communication technology, this emergent situation can be adjusted before the critical relay trips.

TABLE III
SYSTEM CONDITIONS UNDER EMERGENT STATE

| $M3$ | $M5$ | $M67$ | $\Delta M^{exp}$ |
|---|---|---|---|
| $-1.2E-4$ | $-8.62E-3$ | $-2.828E-3$ | $15.67E-3$ |

| *Sensitivity of relay13 on transmission line (M67)* | | | |
|---|---|---|---|
| $C_{T\theta6}$ | $C_{T\theta7}$ | $C_{Tv6}$ | $C_{Tv7}$ |
| $-0.0677$ | $0.0677$ | $-0.1046$ | $0.1294$ |
| $H_{TP8}$ | $H_{TQ8}$ | $H_{TP11}$ | $H_{TQ11}$ |
| $4.1E-3$ | $5.9E-3$ | $4.1E-3$ | $4.4E-3$ |

| *Sensitivity of relay3 on generator G2 (M3)* | | | | |
|---|---|---|---|---|
| $C_{Gv2}$ | $H_{GP8}$ | $H_{GQ8}$ | $H_{GP11}$ | $H_{GQ11}$ |
| $0.0757$ | $6E-4$ | $8E-4$ | $-6E-4$ | $-7E-4$ |

| *Sensitivity of relay5 on generator G3 (M5)* | | | | |
|---|---|---|---|---|
| $C_{Gv3}$ | $H_{GP8}$ | $H_{GQ8}$ | $H_{GP11}$ | $H_{GQ11}$ |
| $0.0912$ | $2.3E-3$ | $3.1E-3$ | $-1.7E-3$ | $-1.9E-3$ |

| *Sensitivity of load L1 to $V_8$* | *Sensitivity of load L2 to $V_{11}$* |
|---|---|
| $D_{L1} = 55.944$ | $D_{L2} = 55.6804$ |

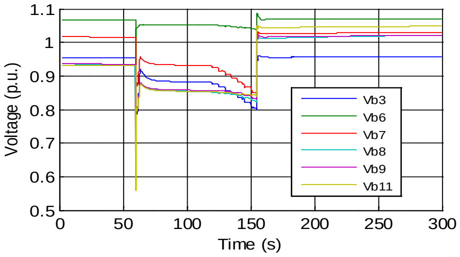
Supposing $M_{ij}^{exp} = 7.05E-3$ at current load angle to ensure that the loadability margin is no less than the required 5%, then $\Delta M^{exp} = M_{ij}^{exp} - M_5 = 15.67E-3$, namely at this moment, the expected relay operation margin increment is to recover the most emergent situation $M_5$. Thereafter the sensitivity based load shedding amount can be calculated, considering the load restoration characteristics, as shown in Table IV.

From Table IV, the optimal method is better for minimizing the shedding amount when considering the same expected relay operation margin increment. The simulation results are shown in Fig. 6 and Fig. 7

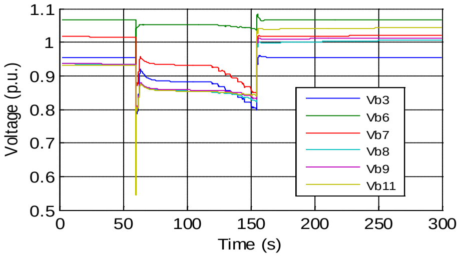
TABLE IV
LODE SHEDDING STRATEGY

| *Same percentage load shedding* | | | | | | |
|---|---|---|---|---|---|---|
| $\alpha_8 = \alpha_{11}$ | $\Delta S_8(MVA)$ | $\Delta P_{11}(MW)$ | $\Delta S_8^{res}$ | $\Delta S_{11}^{res}$ | $\Delta S_8^{fin}$ | $\Delta S_{11}^{fin}$ |
| $-14.53\%$ | 342 | 339.28 | 609.87 | 642.9 | 951.87 | 982.18 |

| *Optimal load shedding* | | | | | | |
|---|---|---|---|---|---|---|
| $\alpha_8$ | $\alpha_{11}$ | $\Delta P_{11}(MW)$ | $\Delta S_8^{res}$ | $\Delta S_{11}^{res}$ | $\Delta S_8^{fin}$ | $\Delta S_{11}^{fin}$ |
| 0 | $-21.65\%$ | 505.53 | 609.87 | 642.9 | 609.87 | 1148.43 |

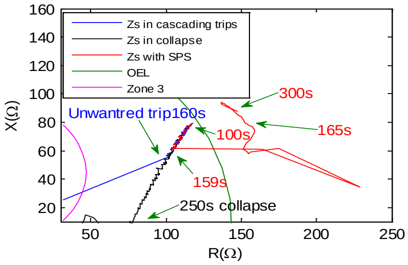


(a) Same percentage load shedding

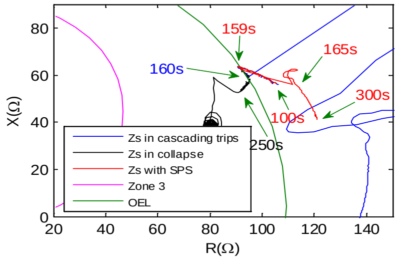


(b) Optimal load shedding

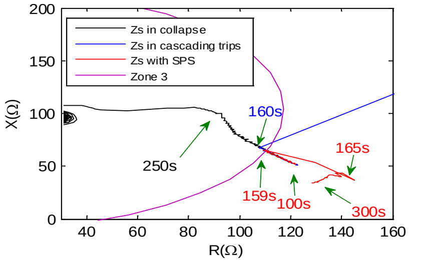
Fig. 6 Voltage variation in the post fault stage with proposed LS



(a) Impedance loci of relay 5 on G3



(b) Impedance loci of relay 3 on G2



(c) Impedance loci of relay 13 on TL3

Fig. 7 The impedance loci measured by relays with or without LS

It can be seen that after the LS execution of distributed load agents, the system voltage of all buses recovers to a normal level above 0.9pu in Fig. 6, while the measured impedances by relays on G2, G3 and TL3 are moved out of the backup setting area sooner after the LS control as shown in Fig. 7.

In Fig. 7, under different situation, the different loci of the critical relays are shown in different colors from 100s to 300s. When the loads start to restore, the unwanted backup relay operations will occurs on the transmission lines at 160s, then the system separates and collapse immediately, which are shown in blue loci in the figures. If the relays have been blocked, then the voltage collapse will still occur at about 250s, as shown in black loci. When the proposed optimal LS strategy is applied, this unwanted relay operations are prevented successfully at 159s before these relay trip. Thus, those emergent voltage states due to long term voltage instability are eliminated successfully.

## V. CONCLUSION

In this paper, with the targets to prevent the unwanted relay operations and post fault voltage instability due to long term load restoration, an optimal load shedding strategy based on sensitivity analysis is proposed to adjust the emergent system states immediately. The excitation capability (OEL) of generator and the power flow constraints of transmission line are considered as the set values of the backup impedance relays to identify the emergent voltage states. The sensitivity based algorithm is based on runtime power flow states to select the reasonable load shedding locations and define shedding amounts optimally, which is used to adjust the negative operation margins in the critical relays to expected positive values. Also, load dynamic characteristics have been considered in the calculation of load shedding amount to ensure the secure margin when loads reach their steady state characteristics. The case study and simulation results have successfully demonstrated the effectiveness of the proposed sensitivity based emergency LS strategy.

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