Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Control and Protection Cooperation Strategy for Voltage Instability

Liu, Zhou; Chen, Zhe; Sun, Haishun; Liu, Leo

Published in:
Proceedings of the 47th International Universities Power Engineering Conference (UPEC), 2012

DOI (link to publication from Publisher):
10.1109/UPEC.2012.6398558

Publication date:
2012

Document Version
Early version, also known as pre-print

Control and Protection Cooperation Strategy for Voltage Instability

Zhou Liu
Aalborg University
zli@et.aau.dk

Zhe Chen
Aalborg University
zch@et.aau.dk

Haishun Sun
Huazhong University of Science and Technology
Haishunsun@hust.edu.cn

Chengxi Liu
Aalborg University
cli@et.aau.dk

***Abstract*--Most cascaded blackouts are caused by unexpected backup relay operations due to low voltage or overload state caused by post fault load restoration dynamics. If such state can be sensed and adjusted appropriately prior to those relay actions, system stability might be sustained. This paper proposed a control and protection cooperation strategy to prevent post fault voltage instability. The multi-agent technology is applied for the strategy implementation; the criteria based on wide area measured apparent impedances are defined to choose the control strategy, such as tap changer adjusting or load shedding; and the sensitivity based load shedding has been adopted to save the system from severe states. A test system is built in real time digital simulator (RTDS) and has demonstrated the effectiveness of the proposed method.**

***Index Terms*—apparent impedance, cascaded blackout, cooperation strategy, multi agent, RTDS, unexpected relay operations, voltage instability**

I. Introduction

Voltage instability often stems from the load restoration dynamic with an attempt to restore power consumption that is beyond the capability of the transmission and generation system [1]. This may occur specially in the case of N-1 (or N-k) contingency, when the capability of generation and transmission system had been weakened greatly whereas the load may still attempt to recover to the pre-fault level. Such load restoration dynamic may lead the system state close to the critical voltage instability state inducing low voltage and over current since a large amount of active and reactive power is required to be transmitted in the weak linked system. On the other hand, the backup protection relays on the transmission lines and generators may identify the lower voltage and overcurrent as a remote short circuit and be activated to trip the lines or generators. These unexpected relay operations may lead the system into voltage instability, which would finally cause the whole system collapse.

Many of the past power system blackouts were due to unexpected lines or generators trips by zone 3 relay or other backup relay, 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] [3]. It can be inferred from these mentioned cascading events that voltage collapse may still occur in the post fault stage due to the load restoration dynamics with under load tap changer (LTC) and other auto regulation actions. This may take a long course of time and is usually referred as the long term voltage instability [4].

Also it can be inferred that if the unexpected relay actions could be prevented effectively somehow then the cascading events which might led to the blackout could be stopped reasonably. One idea is to adjust the settings of those involved relays to match power system conditions online. The information from wide area measurement system (WAMS) could be utilized for it [5-7]. But this scheme may fail to perform when the system is close to voltage collapse. Another idea is to design wide area protection and control strategy [8-11]. This scheme can detect the emergent system state which may result in the unexpected relay operations, prevent the abnormal state and keep the system operated in the stable region finally. However the difficulty is how to identify the emergent system state and how to coordinate the controllers.

A variety of indexes have been proposed for voltage stability. As for the study of long-term voltage stability, [12] used quasi-steady-state (QSS) time domain simulation to find if the network transmission power reaches the limit which was regarded as the static limit of voltage stability. Dynamic control strategies are also studied with excitation control, tap ratio of the LTC, shunt capacitor banks and load shedding to prevent voltage instability [13-17].

In this paper a control and protection cooperation strategy based on WAMS is proposed to prevent long term voltage instability and cascaded blackout due to the load restoration dynamics. The apparent impedance measured by each protective relay can be collected by WAMS and criteria based on the impedance are established to identify the post fault emergent state of the system. According to the identified states, control strategy with hybrid inverse tap changer control (ILTC) and sensitivity based load shedding (LS) would be combined and applied to prevent unexpected relay actions and the voltage instability due to LTC controlled load restoration. In order to implement the control strategy a multi-agent system (MAS) is designed to coordinate the protection relays and LTC that are distributed over the system wide. A test system is established in real time digital simulation (RTDS) system to verify the effectiveness of the proposed strategy. Basic concepts of long term voltage instability will be presented in Section II briefly. Then the multi-agent based control and protection cooperation strategy will be described in Section III including the apparent impedance based criteria and sensitivity based load shedding. In Section IV, validation of the strategy will be demonstrated based on the test system simulation. Finally, the conclusion will be made in Section V.

II. BASIC CONCEPTS OF LONG TERM VOLTAGE STABILITY

Load restoration dynamic for long term voltage stability study can be modeled as follow [1]:

$$P = z_P\, P_0 \left(\frac{v}{v_0}\right)^{\alpha_t} \quad (1)$$

$$Q = z_Q\, Q_0 (\frac{v}{v_0})^{\beta_t} \quad (2)$$

$$T_P \dot{z}_P = (\frac{v}{v_0})^{\alpha_s} - z_p (\frac{v}{v_0})^{\alpha_t} \quad (3)$$

$$T_Q \dot{z}_Q = \left(\frac{v}{v_0}\right)^{\beta_s} - z_Q \left(\frac{v}{v_0}\right)^{\beta_t} \quad (4)$$

where P and Q are the active and reactive power of the specific load, respectively; P_0 and Q_0 are the active and reactive power of this load at a voltage v equal to reference voltage v_0; z_P, z_Q are dimensionless state variables associated with load dynamics; α_t, β_t represent the transient load exponents and α_s, β_s are the steady state ones; T_P, T_Q are the load restoration time constant for the active and reactive load respectively. In steady state, the voltage characteristics of the generic load model are given by (5) and (6):

$$P = P_0 \left(\frac{v}{v_0}\right)^{\alpha_s} \quad (5)$$

$$Q = Q_0 (\frac{v}{v_0})^{\beta_s} \quad (6)$$

Usually the transient load exponents α_t, β_t have larger values than the steady state ones α_s, β_s [1].

The typical scenario for long term voltage instability due to the load restoration dynamics can be interpreted using P-V characteristic curves as shown in Fig. 1 [2].

Three of the curves which are labeled by “Normal”, “N-1” and “N-2” represent P-V curves of the generation and transmission system under normal, N-1 and N-2 system conditions respectively, while the other three curves labeled by “A”, “B”, “C” show how the P-V curves of the system load varies during the load restoration dynamics.

The system is initially operated at the point “a”. Assume that the system survived in the transient period with N-1 contingency. The P-V characteristics of the generation and transmission system changed from normal curve to the N-1 curve. Therefore the operation point moves from point “a” to “b” along the curve “A” to gain temporary equilibrium. After that the P-V characteristics of the system load will change due to load restoration dynamic by LTC and other system auto regulation actions, for example, from curve A to curve B and C with tap changer ratio changing from r1 to r2 and r3. This will lead the system operation point moving along the N-1 P-V characteristics from “b” to “t” and may finally settle down at “c”, where the system loads have restored to pre-fault level. It is obvious that the operation state at “c” is less stable than that at “a”.

However, if some generators reached the over excitation limits (OEL) during the load restoration, the P-V curves of generation and transmission system at N-1 state will be changed to the dashed line and the maximum possible load restoration is less than the pre-fault level. With further action of LTC, an unstable equilibrium point “c1” is obtained. Moreover, due to the decreasing voltage and increasing current, one or more of the backup relays in generation and transmission system may sense the apparent impedance entering its operation zones and be initiated to trip the un-fault components in preset time which is usually 500ms or so. The trip will make the P-V curves of generation and transmission system to be changed to N-2 or N-k (k>2) curve. As a consequence, voltage collapse and cascaded blackout will happen inevitably.

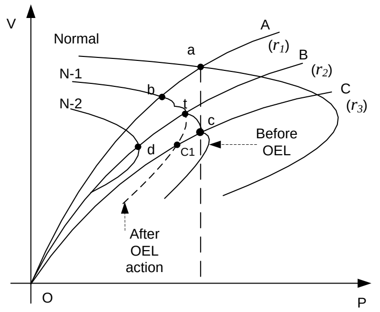


Fig. 1. P-V curves of the generation and transmission system and load

It can be inferred that identification of the system state and adjusting the state into secure scope with appropriate control in real time can effectively help to prevent long term voltage instability due to the load restoration dynamics. In this regard it is focused in this paper on the identification of the post fault system states with generators reaching their OEL and potential unexpected backup relay action, as well as the wide area control strategy applied to sustain the system stability.

III. MULTI-AGENT BASED CONTROL AND PROTECTION COOPERATION STRATEGY

A. *Identification of voltage stability scenarios with apparent impedance*

Using the measured apparent impedance from the backup relays, the emergent states of system could be identified. This can be explained using the R-X plane of measured apparent impedance as shown in Fig. 2.

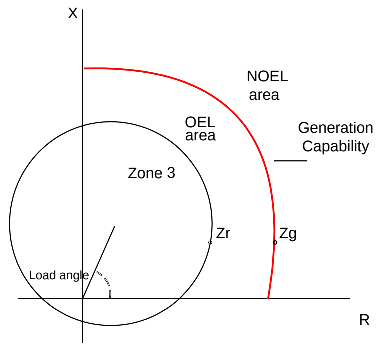


Fig. 2 Combination Impedance curves

For the generator backup relay, the R-X plane can be divided into three areas. One of the areas is the well-known Zone 3 area inside the circle shown in Fig. 2. When the measured impedance lies in this area the protective relay will be initiated to act after a preset delay. *Zr* represents the impedance of any point on the border of zone 3. Another area is labeled as NOEL in the R-X plane, which is intended to present the state that no OEL of the generator is reached with measured impedance in this area. The area between Zone 3 and the NOEL is OEL area. When measured impedance lies in this area, the generator should have reached its OEL implying the generation and transmission system P-V characteristics being changed to a weaker mode according to Section II. The border between the OEL area and NOEL area in R-X plane represents the apparent impedance when the generator is operating right on its capacity limits. It can be transformed from the P-Q limit curves easily and *Zg* is used to represent impedance of any point on this border [18].

By comparing the measured impedance *Zs* in real time with *Zr* and *Zg*, the backup relay of the generator will output two signals named S_{g1} and S_{g2} as follow:

1) If Zs is in the area of NOEL on the R-X plane, $S_{g1}=S_{g2}=0$.

2) If Zs is in the area of OEL, $S_{g1}=0$, $S_{g2}=1$.

3) If Zs is in the area of zone 3, $S_{g1}=S_{g2}=1$.

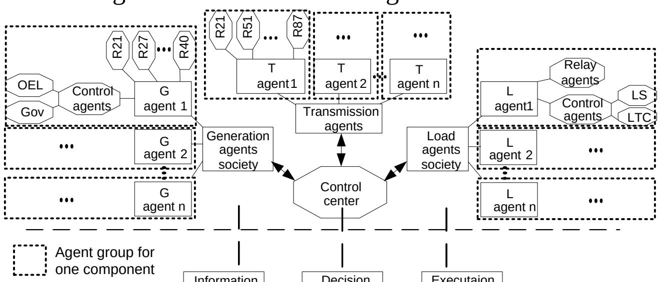
For zone 3 backup relay of transmission line, the R-X plane will include only two areas in this paper, i.e. zone 3 and non-zone 3. Only one signal named S_{L1} will be generated. When *Zs* lies in zone 3 area S_{L1} will be set to high level otherwise it will be kept to zero level.

By this way the emergent state of system might be identified with all these signals collected together and a wide area control strategy may be generated and applied to help maintaining system stability.

B. Design of multi-agent system

Traditional backup relays of system components are designed to act independently. However the proposed system state identification method needs inter-communication among all the relays. Then a multi-agent system (MAS) can be designed here for this application.

MAS is an extension of the agent technology where a group of loosely connected autonomous agents act in an environment to achieve a common goal [7][19]. The structure of the designed MAS is shown in Fig. 3.



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

Fig. 3 Structure of MAS

The MAS can be designed in three levels. The controller or relay of each equipment in the system is designed as the lowest level of the MAS, including the generator control and backup relay, transmission line backup relay, load shedding controller, load tap changer control, and so on. Apart from undertaking their normal control and protective function independently, these agents will send messages to and receive control orders from the corresponding higher level agents.

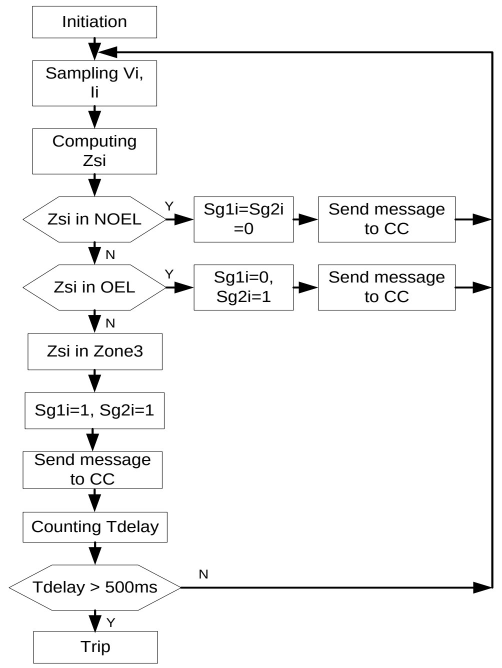
The control and protective agents in the lowest level can be grouped into agent society, such as generation agent society, transmission agent society, load agent society, and so on. This is the middle level of the designed MAS.

A control center (CC) agent is the highest level of the designed MAS and is designed to coordinate with all the lower level agents collecting information, identifying system state, generating wide area control strategy.

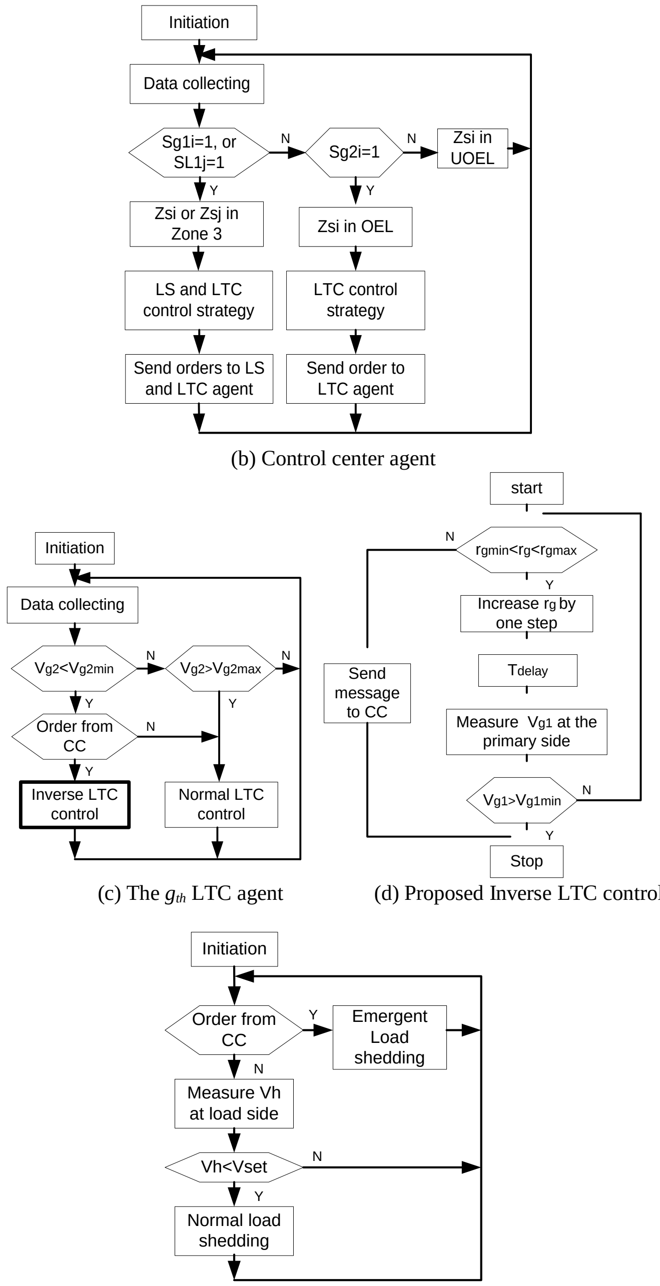
Every agent takes information collection, which might include local measurements of the current, voltage, and the status of related equipments, makes decisions according to the prevailing state, and produces output actions such as breaker trip signals, adjusting LTC settings, and LS signals. Moreover, agents can communicate with each other to help CC choose the suitable strategy dealing with the different system emergent states.

C. Control strategy based on MAS

With the designed MAS, cooperated control and protective strategy can be generated and applied in real time. The flow charts as shown in Fig. 4 demonstrate how each distributed agent and the CC agent work in a coordinated way. Assuming in a power system, the number of generators, transmission lines, distribution transformers with LTC and distributed loads are *m*, *n*, *p* and *q* respectively. The S_{g1i}, S_{g2i} are the output signals of backup relay of the i_{th} generator ($i=1,\ldots,m$); *Vi*, *Ii*, *Zsi* are the measured voltage, current, impedance by backup relay of the i_{th} generator; and the S_{L1j} is the output signal of relay of the j_{th} transmission line ($j=1,\ldots,n$). While, V_{g1}, V_{g2} are the voltage of primary side and second side of the g_{th} LTC transformer ($g=1,\ldots,p$), V_h is the bus voltage of the h_{th} load ($h=1,\ldots,q$). The tap ratio of LTC transformer is r:1. The primary side of LTC transformer is power supply side and the second side is distribution side. Then the work flowcharts of the agents are depicted in Fig. 4.



(a) The i_{th} generator backup impedance relay agent



(b) Control center agent

(c) The g_{th} LTC agent (d) Proposed Inverse LTC control

(e) The h_{th} LS agent

Fig. 4 The flow chart of the designed MAS

The work flow of generator backup impedance relay agent is shown in Fig. 4(a). This agent measures the apparent impedance and generates signals S_{g1i} and S_{g2i}, which represent that if this generator has reached its OEL or a remote fault. The signals are sent to the CC agent for control decision with wide area information.

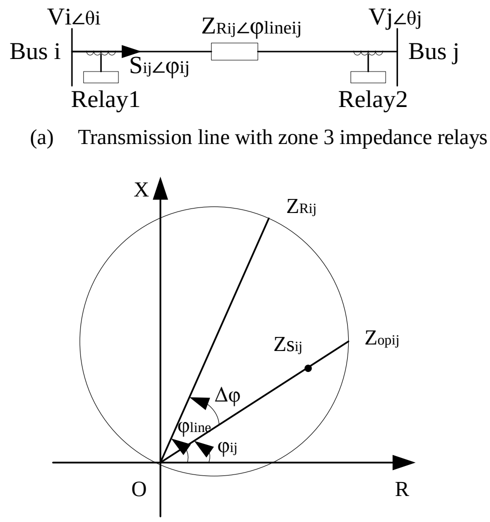
In Fig. 4(b), the CC agent is responsible to identify the emergent voltage state with the collected signals from all the lower level agents and make control strategy correspondingly. The main control purpose is to eliminate OEL state of generators and prevent unexpected trip of generators and transmission lines without fault. ILTC, which acts in the opposite way as auto voltage regulation control [14] [15], is started when only OEL state of generators is detected. This control strategy will be executed by LTC agent as shown in Fig. 4(c) and (d), the control orders from CC will interrupt the normal LTC control and change the LTC into inverse control in the ratio range ($r_{gmin}<r_g<r_{gmax}$). It will be stopped when bus voltage V_{g1i} at the primary side returns to normal level.

When the CC detects that some backup relays had been initiated, a hybrid ILTC and LS strategy is proposed to quickly change the system state to secure scope. A sensitivity based load shedding algorithm will be implemented to determine the location and amount of LS. Then the CC will send the final control orders to LS and LTC agents. Once receives the control order, the LS agent will initiate emergent load shedding immediately as shown in Fig. 4(e). Then the *Zs* would move out of zone 3 expectedly in case of no fault occurs thus preventing unexpected trip of normal components.

On the other hand, the relays can function independently from Fig. 4. If there is a fault in its protective region, the *Zs* would be kept in zone 3 no matter what kind of control is applied by MAS. In another words, the MAS will not affect traditional function of the backup relays.

D. Sensitivity based load shedding strategy

In this paper, the method proposed in [16] is adopted here to calculate the sensitivity of apparent impedance to the change of electrical parameters, such as bus voltages and bus powers. Based on sensitivity information, a load shedding algorithm is proposed here executed by the CC agent.



(a) Transmission line with zone 3 impedance relays

(b) R-X characteristic of zone 3 impedance relays

Fig. 5 Impedance relays on a transmission line

For transmission line *ij* in Fig. 5 (a), the relay1 will be initiated when $Z_{sij} < Z_{opij}$, then the operation margin (the difference between the apparent impedance and the operation impedance at current load angle φ_{ij}) can be expressed as functions of bus voltages, as given by (7).

$$\mathrm{M_{ij}} = \mathrm{Z_{sij}} - \mathrm{Z_{opij}} = \frac{\mathrm{Z_{ij}V_i - Z_{Rij}(V_i - V_j\cos\theta_{ij})}}{\sqrt{\mathrm{(V_i - V_j\cos\theta_{ij})^2 + (V_j\sin\theta_{ij})^2}}} \quad (7)$$

where Z_{ij} is the impedance of line *ij*, $V_i\angle\theta_i$ and $V_j\angle\theta_j$ are voltages at bus *i* and bus *j* respectively, $\theta_{ij} = \theta_i - \theta_j$.

So the linear form of operation margin (7) to bus voltages can be expressed by (8). For the zone 3 relay at the bus *i*, the linear form is given by (9), which means at this operation point the changes of voltages ($\Delta V_i, \Delta\theta_i$ and $\Delta V_j, \Delta\theta_j$) at bus *i* and bus *j* can quantify the change of operation margin ΔM_{ij} of this relay by specific sensitivity $C_{\theta i}$, $C_{\theta j}$, C_{vi} and C_{vj}.

$$\Delta M = C\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} = [C_\theta \;\; C_V]\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} \quad (8)$$

$$\Delta M_{ij} = C_{\theta i}\Delta\theta_i + C_{\theta j}\Delta\theta_j + C_{vi}\Delta V_i + C_{vj}\Delta V_j \quad (9)$$

Also, the linear form of operation margin to bus powers can be derived by (10), according to power flow sensitivity matrix (11), and the sensitivity matrix of operation margin to bus powers is calculated by (12).

$$\Delta M = T\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = [T_P \;\; T_Q]\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (10)$$

where

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = J\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} = \begin{bmatrix}J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} \quad (11)$$

$$T = CJ^{-1} \quad (12)$$

Based on (10), the equation (9) can be transformed to (13), in which the change of relay margin is determined by the active powers and reactive powers at bus *n*; also, it can be given by (14) if the load power factor is constant.

$$\Delta M_{ij} = \sum_n (T_{Pij,n}\Delta P_n + T_{Qij,n}\Delta Q_n) \quad (13)$$

$$\Delta M_{ij} = \sum_n \left(\frac{T_{Pij,n}P_n + T_{Qij,n}Q_n}{S_{Ln}}\Delta S_{Ln}\right) = \sum_n T_{ij,n}\Delta S_{Ln} \quad (14)$$

$T_{ij,n}$ is the sensitivity of relay operation margin to load power at bus n. So if we assume emergent load shedding on the loads in this paper have the same step size, which is represented by a percentage α ($|\alpha| < 1$), then the amount of LS at this moment will be obtained by (16).

$$\Delta M_{ij} = \sum_n T_{ij,n}\Delta S_{Ln} = \sum_n T_{ij,n}\alpha S_{Ln} = \alpha\sum_n T_{ij,n}S_{Ln} \quad (15)$$

$$\alpha = \frac{\Delta M_{ij}}{\sum_n T_{ij,n}S_{Ln}} = \frac{M_{ij}^{exp} - M_{ij}}{\sum_n T_{ij,n}S_{Ln}} \quad (16)$$

where M_{ij}^{exp} ($M_{ij}^{exp} \geq 0$) is the expected relay operation margin. Assume that the power flowing into the bus is positive, the shedding amount ΔS_{Ln} is positive, the load powers and α will be negative. Then based on validation of power flow calculation or all the relay margins in whole system, the final outcome with a reasonable load shedding amount will be determined. The work flow of this strategy is shown in Fig. 6.

This LS strategy is generated in real time and more sophisticated method may be applied to make it more effective. Meanwhile, the ILTC will provide a good compensation to LS after unexpected relay operation is prevented successfully. Besides, the wide area measurement system is required for this MAS design and the transmit delay of the communicated signals should be considered. With 5μs/km delay of multiplexer and repeater of modern optic fiber system, the load shedding control can be applied prior to the action of the backup relay which is normally set to delay for at least 500ms after start [7].

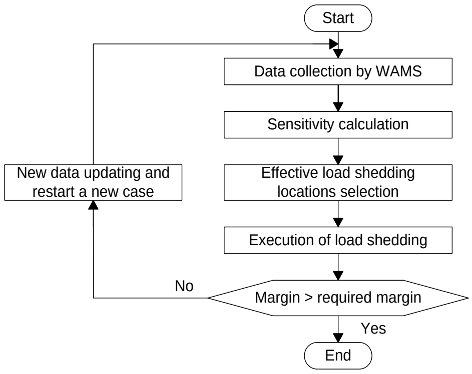


Fig. 6 The flow chart of LS control strategy in CC

IV. Simulation and Verification with RTDS

A. Test system and modeling with RTDS

A 10-bus test system shown in Fig.7 is selected as the test example and modeled in RTDS with details as follow:

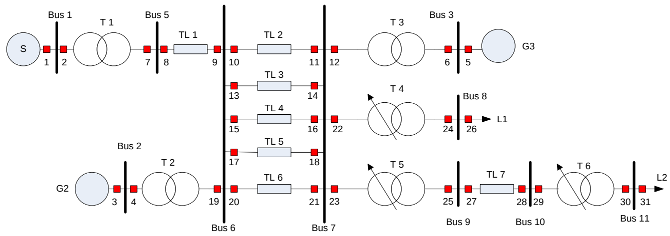


Fig. 7 Configuration of the test system

- Bus 1 is designated as slack bus. Two generators, G2 and G3 are connected to bus 2 and bus 3 respectively with OEL model [1].
- Two loads L_1 and L_2 are connected to bus 8 and bus 11 respectively. The load restoration dynamics is modeled as equations (1)-(4) which had been depicted with $\alpha_s = \beta_s = 0$, $\alpha_t = \beta_t = 2$ and $T_P = T_Q = 100s$. 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 I.

TABLE I
LTC DATA

LTC	Delay on first step (s)	Delay on next step (s)	Δr (pu)
T4	20	6	0.01
T5	20	6	0.01
T6	40	9	0.01

- The proposed MAS is implemented in RTDS with embedded intelligent electronic devices (IED) acting as control or protective agents. An IED is a hardware environment that has the necessary computational, communication, and other I/O capabilities needed to support a software agent [19].
- Assume all the backup protections of the generators and transmission lines are based on measured impedance and they are modeled with the standard

distance protective relay model embedded in RTDS. The generators' P-Q capability is also modeled in equivalent R-X plot with the backup relay settings.

- The control center is modeled with measured impedance from relays as input and predetermined control scheme composed of LTCs and load shedding would be chosen according to the principle established in section III.
- Each of the LTCs and backup protective relays acts as an agent with autonomous measuring and control function. All the distributed agents which can communicate each other send measuring impedance and receive control order.

B. *Cases study*

(1) Case 1

In this case, the scenario that generators reach OEL during the load restoration process will be simulated and the effectiveness of the proposed ILTC strategy would be validated.

The load at bus 8 and bus 11 are set as S_{L10} = *3564MW + j905MVar* and S_{L20} = *3416MW + j0MVar* respectively. The line TL6 is initially out of service. Line TL2 is disconnected due to a three phase short circuit fault with duration of 0.1s and the system survives in the transient period with all the bus voltages recover to an accepted level after tens of seconds.

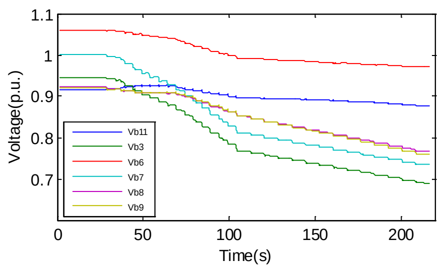
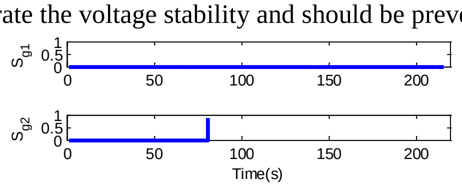
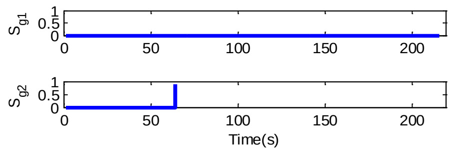


Fig. 8 Voltage variation due to the load restoration dynamics

With the MAS control output blocked intentionally at first, the load restoration dynamics following this transient is observed. The voltage variation of some buses, the output signal of the generator backup relay agents and the control center agent, and the impedance loci measured by the backup relays of generator G2 and G3, are depicted in Fig. 8, Fig. 9 and Fig. 10 respectively. It can be seen that at the first stage of load restoration the voltage sustained nearly constant for about 30s and begin to drop obviously. Fig. 9 shows that at about 60s the signal S_{g2} from G3 relay agent turned to high level whereas S_{g1} being kept zero level, demonstrating that generator G3 had reached OEL at this time, but no backup relay is started. G2 reached OEL at about 70s. As seen in Fig. 10, the apparent impedance entered the OEL area on the R-X plane. Since no control is applied, the voltage decreased progressively. In this case, further LTC actions would deteriorate the voltage stability and should be prevented.


(a) Output Signal S_{g1}, S_{g2} of protective agent of G2


(b) Output Signal of protective agent of G3

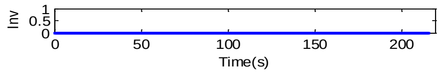
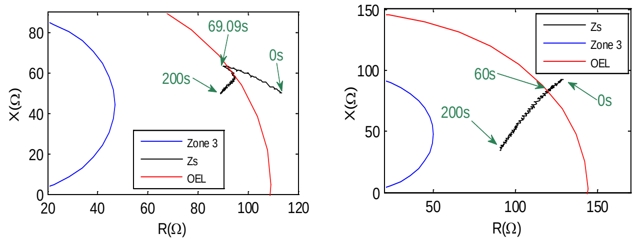

(c) Output control by CC agent (control is blocked)

Fig. 9 Output signals of the MAS



(a) Relay 3 of G2 (b) Relay 5 of G3

Fig.10 Impedance locus measured by generator backup relays of G2 and G3

The same case is simulated with the proposed combined protection and control strategy taken into effect. The state that generators had reached their OEL is identified with the observed signals $S_{g1}=0$ and $S_{g2}=1$ by the CC. A preset ILTC control is applied. The bus voltages, output signal of generator relay agent and the control center agent and the Z_s are presented in Fig. 11, Fig. 12 and Fig. 13 respectively. It can be seen that all the bus voltages start to recover once the control strategy is applied. Consequently, the signal S_{g2} returns to zero level and the Z_s return to NOEL area, which can be seen from Fig.12 and Fig. 13 respectively.

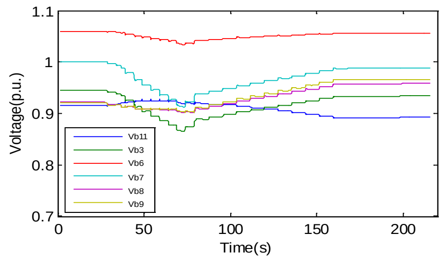
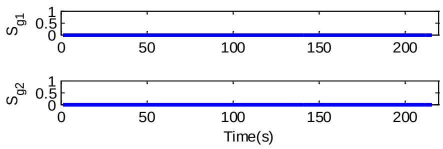
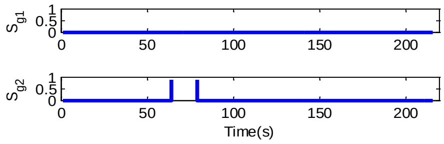


Fig. 11 Voltage variation with proposed control strategy


(a) Output of Signal S_{g1} of protective agent of G2


(b) Output Signal of S_{g2} of protective agent of G3

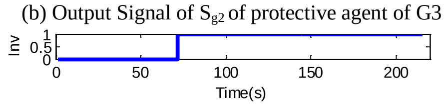
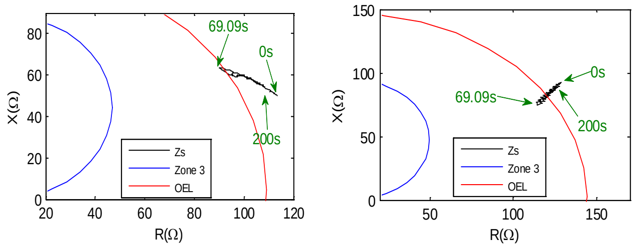

(c) Output LTC control by CC agent with proposed control

Fig. 12 Output signals of the MAS with proposed control



(a) Relay 3 of G2 (b) Relay 5 of G3

Fig. 13 The impedance locus measured by generator back up relay with proposed control strategy in effect

It can also be found that the inverse LTC control may cause further voltage drop of some bus, e.g. the voltage at the load bus 11 in this case. In this regards load shedding should be more effective.

(2) Case 2

In this case a more severe situation is simulated with both OEL of generators and backup relays initiated and the hybrid ILTC and LS control strategy should be validated.

The load at bus 8 and bus 11 are set as P_{L10}=*-3250MW*, Q_{L10}=*-1030MVar* and P_{L20}=*-3320MW* respectively. Line TL5 and TL6 between the bus 6 and bus 7 are out of service. The same fault as scenario 1 is applied on line TL2 and the post fault voltage variation of some buses due to load restoration dynamics is observed as in Fig.14 without control. The output of the MAS and the measured impedance by the backup relays of generators and lines are presented in Fig. 15 and Fig. 16 respectively.

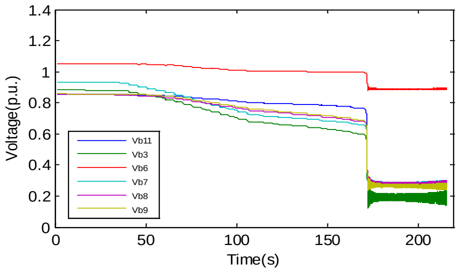
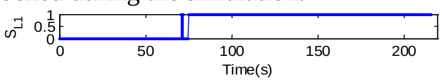
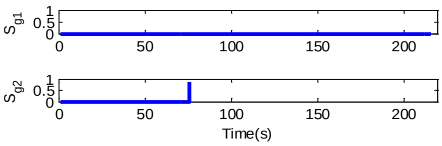


Fig.14 Post fault voltage variation due to load restoration dynamics without control

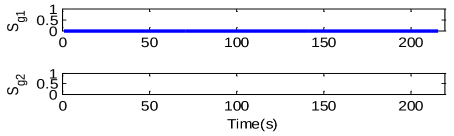
It can be seen that the measured impedances are in the OEL area of the R-X plane which inferred that generator G2 and G3 have reached their OEL. On the other hand, both backup protective relays of TL3 and TL4 have been initiated for the measured impedance has entered the Zone 3 area at about the time of 70s. If these two lines are disconnected the system might suffer collapse inevitably. This can be verified by the voltage collapse observed as in Fig. 14 even with those relays blocked during the simulation.



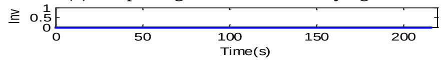
(a) Output signal S_{L1} of the lineTL3 relay agent



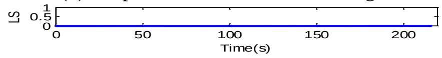
(b) Output signal of the G2 relay agent



(c) Output signal of the G3 relay agent

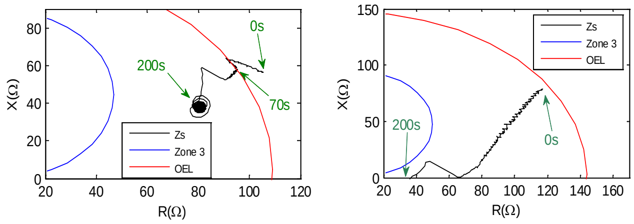


(d) Output LTC control of the CC agent

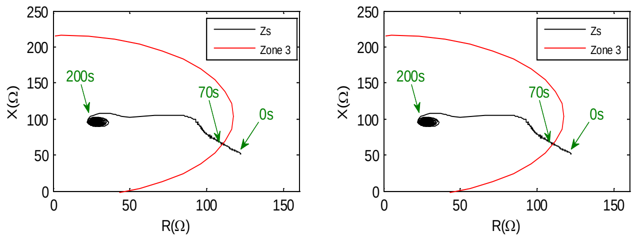


(e) Output load shedding control of the CC agent

Fig. 15 Output of the MAS without control



(a) Relay 3 of G2 (b) Relay 5 of G3



(c) Relay 13 of TL3 (d) Relay 15 of TL4

Fig.16 The impedance locus measured by relay agents of generators and transmission lines

Fig. 17, Fig. 18 and Fig. 19 present the results when the hybrid control strategy is taken into effect. With the signal S_{L1} from the backup relays agents of TL3 and TL4 at high level, the control center agent identified the system as in emergent state with risk of unexpected trip of the line TL3 and TL4 in 500ms. The online control strategy with load shedding is then applied prior to the action of the backup relays.

The operation margins of the relay 3, 5, 13 are calculated when S_{g2}, S_{L1} turn to high level: $M_3 = Z_{s2} - Z_{op3} = -1.2E-4$, $M_5 = Z_{s5} - Z_{op5} = -15.62E-3$, $M_{67} = Z_{s67} - Z_{op67} = -2.828E-3$. Supposing $M_{ij}^{exp} = 0$, then $\Delta M^{exp} = 0 - M_5 = 15.62E-3$, namely at this moment, the expected relay operation margin increment is to recover the most emergent situation M_5. Then based on the current system state, the sensitivity and load shedding amount are calculated, as shown in Table II.

TABLE II
SENSITIVITY AND LOAD SHEDDING AMOUNT

$C_{\theta 6}$	$C_{\theta 7}$	C_{v6}	C_{v7}
-0.0677	0.0677	-0.1046	0.1294
T_{P8}	T_{Q8}	T_{P11}	T_{Q11}
$4.1E-3$	$5.9E-3$	$4.1E-3$	$4.4E-3$
α	$\Delta P_7(MW)$	$\Delta P_{10}(MW)$	$\Delta Q_7(Mvar)$
-7.1%	155.35	165.79	61.54

Once the distributed LS agents execute the control strategy, the system voltage of all buses recovers to a normal level, while the measured impedance by relays on TL3 and TL4 are moved out of the Zone 3 area sooner after the control. So the relay margins have been corrected without any emergent S_{g1}

or S_{L1} signals. Meanwhile the ILTC control is applied to compensate the LS strategy moving the Z_s to NOEL area until the primary side voltage returns to be over the permitted minimum low level. The results are shown clearly in Fig. 17 and Fig. 19. Under this severe situation, the voltage collapse and unexpected relay operation has been prevented successfully based on proposed strategy.

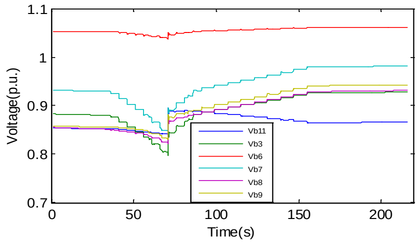
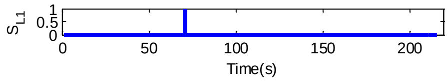
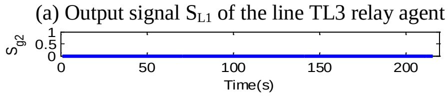


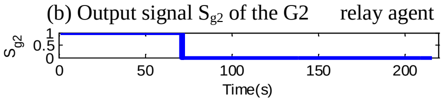
Fig. 17 Post fault voltage variation due to load restoration dynamics with proposed control



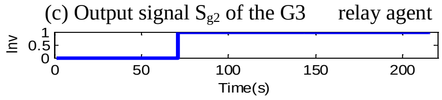
(a) Output signal S_{L1} of the line TL3 relay agent



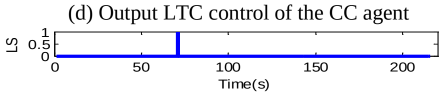
(b) Output signal S_{g2} of the G2 relay agent



(c) Output signal S_{g2} of the G3 relay agent

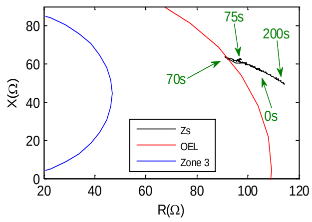


(d) Output LTC control of the CC agent

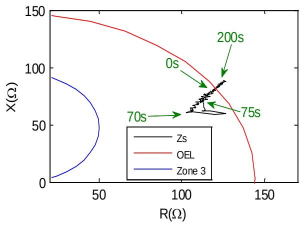


(e) Output load shedding control of the CC agent

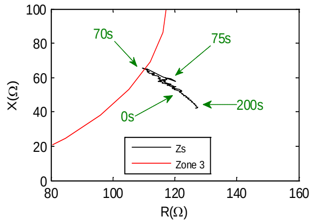
Fig. 18 Output of the MAS with proposed control



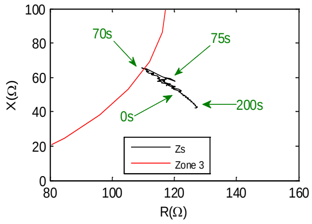
(a) Relay 4 of G2



(b) Relay 6 of G3



(c) Relay 13 of TL3



(d) Relay 15 of TL4

Fig.19 The impedance locus measured by relay agents of generators and transmission lines with proposed control

V. Conclusion

A multi agent based wide area control and protection cooperation strategy has been proposed to prevent the possible unexpected relay operation and post fault voltage instability. The measured apparent impedance is used to estimate the system emergent voltage states. The focus is on the identification of generators reaching their OEL and backup relays started to trip normal components unexpectedly. In order to prevent potential voltage instability due to the long term load restoration dynamics, the inverse tap changer control strategy is suggested to eliminating OEL of generators and a hybrid control strategy combined ILTC with load shedding is proposed to adjust system conditions to avoid unexpected backup protective relay actions. Simulation results have demonstrated the effectiveness of the proposed method in preventing the voltage instability due to the long term load restoration dynamics.

References

[1] T. Cutsem and C. Vournas, *Voltage stability of Electric Power System*, Springer, 2008.

[2] C. Taylor, *Power System Voltage Stability*, McGraw Hill Inc., 2004.

[3] S. Larsson, and E. Ek, "The black-out in southern Sweden and eastern Denmark," *IEEE PES General meeting*, Denver Colorado, USA, pp. 309-313, 2004.

[4] P. Kundur, "Definition and Classification of Power System Stability", *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 1387- 1401, May 2004.

[5] C. Kim, J. Heo and R. Aggarwal, "An Enhanced Zone 3 Algorithm of a Distance Relay Using Transient Components and State Diagram", *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 39-46, 2005.

[6] M. Yang, Y. Zhu, **"**Study on adaptive distance protection using multi-agent technology," *Power Engineering Conference, 2005. IPEC 2005. The 7th International*, vol. 2, pp. 618 -622, 2005.

[7] S. Sheng, D. Shi, X. Duan, "Adaptive Agent-Based Wide-Area Current Differential Protection System", *IEEE Transactions on Industry Applications*, vol. 46, no. 5, pp. 2111-2117, 2010.

[8] S. Corsi, "Wide area voltage protection", *IET Generation, Transmission & Distribution*, vol. 4, pp. 1164 – 1179, 2010.

[9] W. G., "Undervoltage load shedding protection," *IEEE PES*, System Protection Subcommittee, Power System Relaying Committee, Tech. Rep., 2010.

[10] M. Begovic, D. Novosel, D. Karlsson, C. Henville and G. Michel, "Wide-Area protection and emergency control," *Proc. Of the IEEE*, vol. 93, no. 5, pp. 1776-1777, May 2005.

[11] H. Song, B. Lee and V. Ajjarapu, "Control strategies against voltage collapse considering undesired relay operations", *IET Generation, Transmission & Distribution*, vol. 3, no. 2, pp. 164-172, 2009.

[12] T. Van Cutsem, "Voltage instability: phenomena, countermeasures, and analysis methods", *Proceedings of the IEEE*, vol. 88, no. 2, pp. 208-227, 2000.

[13] C. D. Vournas and T. Van Cutsem, "Local identification of voltage emergency situations;" *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1239-1248, Aug. 2008.

[14] P. Mandoulidis, C. Lanbrou and C. Vournas, "Effect of load restoration on an integrated autonomous protection system against voltage instability," *PowerTech, 2011 IEEE Trondheim*, pp. 1-8, 2011.

[15] C. Vournas, etc, "Comparison and combination of emergency control methods for voltage stability", in *Proc. IEEE Power Eng. Soc. General Meeting*, vol. 2, 2004, pp. 1799-1804.

[16] S. Li, etc, "Sensitivity Analysis to Operation Margin of Zone 3 Impedance Relays with Bus Power and Shunt Susceptance", *IEEE Transactions on Power Delivery*, vol. 23, no. 1, January 2008.

[17] B. Zhang, etc, "Strengthen the protection relay and urgency control system to improve the capability of security in the interconnected power network [J]," Proceedings of the CSEE, pp. 1-6, 2004.

[18] Z. Bukhala, etc, "Coordination of Generator Voltage Regulator Controls with Unit Capabilities and Protection", Draft Standard PRC-019-1, NERC Phase III-IV Draft Standards for Field Tests, Sep. 2006.

[19] W. Elmore, etc, "Protective Relaying Theory and Applications", ABB Power T&D Company Inc., 2003.

[20] S. McArthur, etc, "Multi-Agent systems for power engineering applications, part I: concepts, approaches, and technical challenges". *IEEE Trans. on Power Systems*, vol. 22, no. 4, pp. 1743-1752, 2007.