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Wide Area Protection Scheme Preventing Cascading Events based on Improved Impedance relay

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Abstract: In this paper, the role of impedance relay in cascading blackout has been discussed. Whether zone 3 impedance relay need to be replaced depends on whether the zone 3 function can be made to avoid the unexpected trips under overloading situations. Sensitivity based identification methods are presented to improve the traditional zone 3 relay functions, which can differentiate overloading situations from short circuits. A wide area protection scheme is proposed based on this improved impedance relay algorithm and multi agent system (MAS). Simulation results based on real time digital simulator (RTDS) indicate this strategy can successfully predict and prevent the unexpected relay operation caused by overloading conditions.

Keywords: Cascading blackout, impedance relay, sensitivity, multi agent system, wide area protection

1 Introduction

In many past blackouts, zone 3 impedance relay played an important role in the propagation progress of cascading events and overloading condition. Hereby, some researchers even suggested to completely eliminating the zone 3 relay, to remove the possibility of the unexpected zone 3 relay operation under heavily loading conditions forever [1].

However, as a backup to zone 1 and zone 2 protections, zone 3 impedance relay with higher setting and longer reach is an indispensible part of step-distance protection to protect transmission and distribution lines [2]. Whether it should be replaced by other relays needs to be carefully evaluated.

Also from the view point of cascading events prevention, the zone 3 relay can be a good detector for system stability under stressed operation conditions when its settings are designed considering the stability boundaries [3] [4]. Furthermore, if the zone 3 functions can be make immune to tripping under overloading situations, then zone 3 relay will not be an “accomplice” to cascading events any more, and it can be an good “assistant” to prevent cascading events.

In the paper [5], the identification algorithm based on impedance sensitivities is proposed to identify the load flow transferring induced overloading situation. In the paper, the under load tap changer (ULTC) operation induced overloading situation and related identification algorithm will be further discussed. The rest of paper is organized as follows: a brief introduction of the impedance relay’s behavior in the blackouts is presented in Section II; the improved impedance relay based on overload identification algorithms is described in Section III; then in Section IV, the MAS based wide area protection strategy is presented; case studies based on RTDS will be given in Section V; and finally, the conclusion is made in Section VI.

2 Impedance relay in cascading events

Based on the progresses of many voltage instability induced blackouts, such as the northeast U.S./Canada blackout in 1965, the western U.S. blackout in 1996, the Brazil blackout in 1999, and etc. [6], the general sequence of the blackout can be depicted in Figure. 1.

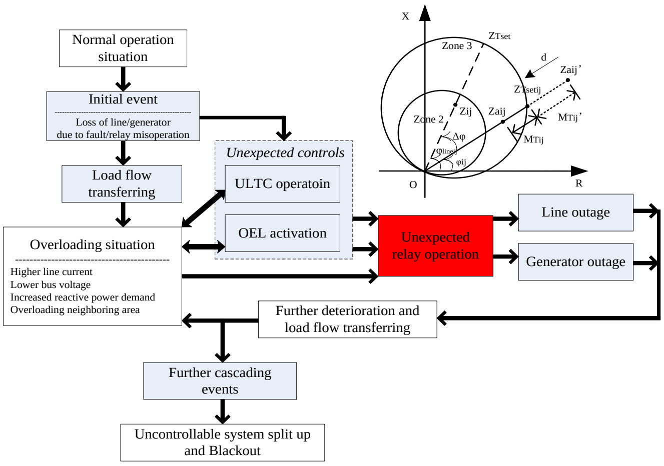


Figure 1 The flowchart of cascading blackouts

It can be easily found that the impedance relay played an importance role in the progress of blackout. The post contingency overloading situation, characterized by higher currents and lower voltages, induces the unexpected relay operations, together with some unexpected controls (e.g. ULTC operations), which further induces power components outages at the transmission side. Thus the remaining grid would suffer a further deterioration of overloading situation, which makes these events even worse until the whole system collapse. The impedance relays in the cascading trips performed their traditional functions to isolate the faults locally. But under heavily overloading situation, these trip operations are regarded as unexpected ones due to their severe and fast deteriorating effects on system structure and stability.

The traditional characteristics of impedance relay are depicted in the top right corner of Figure 1 [7]. At the power factor angle φ_{ij}, Z_{aij} and Z_{Tsetij} are the measured impedance and setting value of the zone 3 backup relay, the operation margin M_{Tij} of this relay can be expressed as

$$M_{Tij} = Z_{aij} - Z_{Tsetij} \tag{1}$$

Normally, the measured impedance (Z'_{aij}) should be located outside the zone 3 area and the operation margin is positive as expressed by M'_{Tij}. When measured impedance enters the zone 3 to Z_{aij} in the direction d, the backup relay will trip the breaker within a delay. Under overloading situations, the sign of M_{Tij} will be changed to negative.

So, if in the early stage of cascading events, the impedance relays could online differentiate those overloading situations from short circuits, then those unexpected relay operations can be blocked for a short period which will give time for execution of emergency controls. Meanwhile, according to identified different overloading situations, the corresponding emergency control strategies can be defined. In this way, the cascading events will not be triggered, and the total blackout can be effectively prevented.

3 Improved impedance relay algorithm

From the Figure 1, the normal ULTC operations under heavy loading situation are regarded as unexpected operations which could induce overloading situation and trigger the unexpected relay operations. In order to identify this kind of overload, the impedance sensitivity based prediction and identification method proposed in [5] is adopted here to further identify the ULTC induced overloading situation.

A. Impedance sensitivity

Based on paper [5], the mathematic model of the impedance sensitivity can be expressed as:

$$\boldsymbol{Z_a} = \boldsymbol{R_a} + j\boldsymbol{X_a} \tag{2}$$

$$\begin{bmatrix}\Delta \boldsymbol{R_a} \\ \Delta \boldsymbol{X_a}\end{bmatrix} = \boldsymbol{C}\begin{bmatrix}\Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V}\end{bmatrix} = \begin{bmatrix}\boldsymbol{C_{R\theta}} & \boldsymbol{C_{RV}} \\ \boldsymbol{C_{X\theta}} & \boldsymbol{C_{XV}}\end{bmatrix}\begin{bmatrix}\Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V}\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}\Delta \boldsymbol{R_a} \\ \Delta \boldsymbol{X_a}\end{bmatrix} = \boldsymbol{H}\begin{bmatrix}\Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q}\end{bmatrix} = \begin{bmatrix}\boldsymbol{H_{RP}} & \boldsymbol{H_{RQ}} \\ \boldsymbol{H_{XP}} & \boldsymbol{H_{XQ}}\end{bmatrix}\begin{bmatrix}\Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q}\end{bmatrix} \tag{4}$$

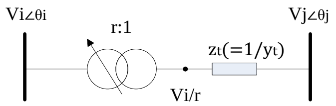
where

$$\boldsymbol{H} = \boldsymbol{C}\boldsymbol{J}^{-1} \tag{5}$$

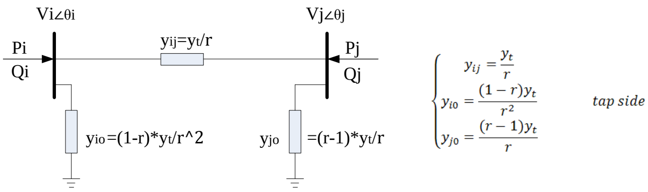
$\boldsymbol{Z_a}$ is the measured impedances seen by impedance relays, $\boldsymbol{C}$ is the sensitivity matrix of measured impedances to bus voltages, where $\boldsymbol{C_{R\theta}}$, $\boldsymbol{C_{RV}}$, $\boldsymbol{C_{X\theta}}$ and $\boldsymbol{C_{XV}}$ are submatrices of $\boldsymbol{C}$; $\boldsymbol{H}$ is the sensitivity matrix of measured impedances to bus powers, $\boldsymbol{H_{RP}}$, $\boldsymbol{H_{RQ}}$, $\boldsymbol{H_{XP}}$ and $\boldsymbol{H_{XQ}}$ are submatrices of $\boldsymbol{H}$. $\boldsymbol{J}$ is the classic load flow Jacobin.

B. ULTC operation identification

As for the branch *ij* with a tap changing transformer in Figure 2, when the tap ratio r is at the nominal value, the transformer is represented by a series impedance $z_t(=1/y_t)$. With off nominal ratio, the impedance on this branch is different due to the effect of the off nominal ratio. The Π model equivalent circuit considering the off nominal tap ratio is shown in Figure 2 (b).



(a) Transformer with tap ratio r:1



(b) Equivalent circuit for tap changing transformer

Figure 2 A transformer branch with tap changer

When the tap ratio is changed by Δr, the node admittance matrix Y will be changed, and power flow on this branch will be changed accordingly, which cause the change of the injection powers at related nodes. Assume $y_{ij}\angle\varphi_{ij} = g_{ij} + b_{ij}$, then based on basic power flow equations [8], the sensitivities $\boldsymbol{\mathcal{L}_{Sr}}$ of injection powers to tap ratio can be expressed as:

$$\boldsymbol{\mathcal{L}_{Sr}} = \begin{cases} \dfrac{\partial P_i}{\partial r} = \left(\dfrac{2}{r^3}\right)V_i^2 g_{ij} - \left(\dfrac{1}{r^2}\right)V_iV_j\left(g_{ij}cos\theta_{ij} + b_{ij}sin\theta_{ij}\right) \\ \dfrac{\partial Q_i}{\partial r} = -\left(\dfrac{2}{r^3}\right)V_i^2 g_{ij} + \left(\dfrac{1}{r^2}\right)V_iV_j\left(b_{ij}cos\theta_{ij} - g_{ij}sin\theta_{ij}\right) \\ \dfrac{\partial P_j}{\partial r} = -\left(\dfrac{1}{r^2}\right)V_iV_j\left(g_{ij}cos\theta_{ij} - b_{ij}sin\theta_{ij}\right) \\ \dfrac{\partial Q_j}{\partial r} = \left(\dfrac{1}{r^2}\right)V_iV_j\left(b_{ij}cos\theta_{ij} + g_{ij}sin\theta_{ij}\right) \\ \dfrac{\partial P_k}{\partial r} = \dfrac{\partial Q_k}{\partial r} = 0 \qquad (k \neq i, k \neq j) \end{cases} \tag{6}$$

where θ_{ij} is the angle difference between V_i and V_j, bus *i* is at the tap side.

If there are n tap changing transformer branches in the system, then the linearized form of power injections to tap ratios can be expressed as:

$$\begin{bmatrix}\Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q}\end{bmatrix} = \boldsymbol{\mathcal{L}_{Sr}}\Delta \boldsymbol{r} = \begin{bmatrix}\boldsymbol{\mathcal{L}_{Pr1}} & \cdots & \boldsymbol{\mathcal{L}_{Prn}} \\ \boldsymbol{\mathcal{L}_{Qr1}} & \cdots & \boldsymbol{\mathcal{L}_{Qrn}}\end{bmatrix}\begin{bmatrix}\Delta r_1 \\ \vdots \\ \Delta r_n\end{bmatrix} \tag{7}$$

where $\boldsymbol{\mathcal{L}_{Pr1}} \ldots \boldsymbol{\mathcal{L}_{Prn}}$ and $\boldsymbol{\mathcal{L}_{Qr1}} \ldots \boldsymbol{\mathcal{L}_{Qrn}}$ are the submatrices of $\boldsymbol{\mathcal{L}_{Sr}}$. From equations (6), the $\boldsymbol{S_{Sr}}$ is a sparse matrix, there are at most two non-zero elements in each column, which is related to the nodes of the related transformer branch.

Therefore, according to the equations (4), the linear form of impedances to tap ratios can be given by:

$$\begin{bmatrix}\Delta \boldsymbol{R}_a \\ \Delta \boldsymbol{X}_a\end{bmatrix} = \boldsymbol{H}\begin{bmatrix}\Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q}\end{bmatrix} = \boldsymbol{\mathcal{L}}_{Zr}\Delta \boldsymbol{r} \quad (8)$$

where $\boldsymbol{\mathcal{L}}_{Zr}$ is the sensitivity matrix between measured impedances and tap ratios, and given by:

$$\boldsymbol{\mathcal{L}}_{Zr} = \boldsymbol{H}\boldsymbol{\mathcal{L}}_{Sr} \quad (9)$$

1) Sensitivity based relay impedance prediction

Base on the mathematic model, the impedance seen by relays can be previously calculated before every next step of ULTC operations. Based on Equation (9), the predicted impedance variations (ΔR_{aij}^{Plt}, ΔX_{aij}^{Plt}) on any transmission line ij after next step of ULTC operations, can be expressed as:

$$\begin{bmatrix}\Delta R_{aij}^{Plt} \\ \Delta X_{aij}^{Plt}\end{bmatrix} = \boldsymbol{\mathcal{L}}_{Zr.ijk}\begin{bmatrix}\Delta r_1 \\ \vdots \\ \Delta r_k\end{bmatrix} \quad (10)$$

Here assume k ULTCs change their taps by one step at the same time, if all their operations are at the different time, then there could be only one element in matrix Δr. $\boldsymbol{\mathcal{L}}_{Zr.ijk}$ is the submatrix of $\boldsymbol{\mathcal{L}}_{Zr}$.

2) ULTC operation identification

Then, in order to identify the overloading situation induced by unexpected ULTC operation, the identification criterion based on measured data Z_{aij}^{M} and predicted data Z_{aij}^{P} can be given by:

$$|Z_{aij}^{M} - Z_{aij}^{P}| < \varepsilon|Z_{aij}^{P}| \quad (11)$$

where

$$Z_{aij}^{M} = R_{aij}^{M} + jX_{aij}^{M} \quad (12)$$

$$Z_{aij}^{P} = R_{aij}^{Plt} + jX_{aij}^{Plt} = R_{aij}^{0} + \Delta R_{aij}^{Plt} + j(X_{aij}^{0} + \Delta X_{aij}^{Plt}) \quad (13)$$

R_{aij}^{0} and X_{aij}^{0} are measured impedance before every next step of tap operation; ΔR_{aij}^{Plt} and ΔX_{aij}^{Plt} are predicted variation of the impedance after every next step; ε is the threshold of errors.

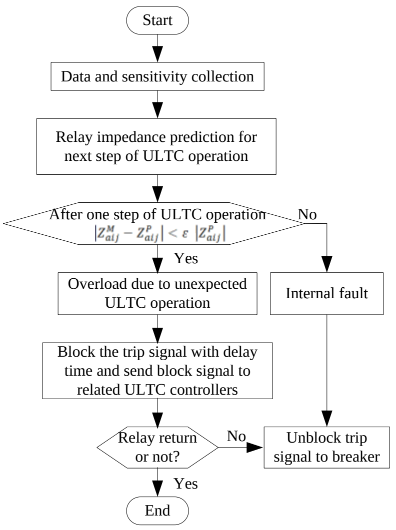


Figure 3 Flowchart of ULTC operation induced overload identification

The identification rules are almost the same as the case of load flow transferring induced overload [5], except the block signal will be sent to related ULTC controllers to stop their unexpected operation. The flowchart of this identification method is shown in Figure 3.

C. Transient period consideration

So far, it has been assumed that all other power injections are unchanged. However, during transient period in the post contingency stage, node injection powers cannot be kept constant, especially the reactive power outputs of generators under overloading situation, which is the main reason of calculation errors. So based on superposition principle, the final ($\Delta R_{aij}^{P}, \Delta X_{aij}^{P}$) on line *ij*, can be expressed as:

$$\begin{bmatrix}\Delta R_{aij}^{P} \\ \Delta X_{aij}^{P}\end{bmatrix} = \begin{bmatrix}\Delta R_{aij}^{Plt} \\ \Delta X_{aij}^{Plt}\end{bmatrix} + \begin{bmatrix}\Delta R_{aij}^{PJ} \\ \Delta X_{aij}^{PJ}\end{bmatrix} \quad (14)$$

where

$$\begin{bmatrix}\Delta R_{aij}^{PJ} \\ \Delta X_{aij}^{PJ}\end{bmatrix} = C_{ij}J_{ijJ}{}^{-1}\begin{bmatrix}\Delta P_{J1} \\ \vdots \\ \Delta P_{Jn} \\ \Delta Q_{J1} \\ \vdots \\ \Delta Q_{Jn}\end{bmatrix} = H_{ijJ}\begin{bmatrix}\Delta P_{J1} \\ \vdots \\ \Delta P_{Jn} \\ \Delta Q_{J1} \\ \vdots \\ \Delta Q_{Jn}\end{bmatrix} \quad (15)$$

J_{ijJ} and H_{ijJ} are the submatrices of $\boldsymbol{J}$ and $\boldsymbol{H}$ respectively, which represent the relationship of node voltages and relay impedances to node injections; ΔP_{J1}, $\Delta Q_{J1} \cdots \Delta P_{Jn}$, ΔQ_{Jn} represent the variations of n node injections.

4 Strategy implementation

In order to implement the proposed wide area protection strategy based on the improved relay algorithms, multi agent system (MAS) based structure is adopted, as shown in Figure 4. A three-level control structure is adopted in this MAS based control system, which is comprised of distributed agent level, cooperation society level and central processing level. Moreover, every agent in this system has three basic functions: information collection, decision making and decision execution [9].

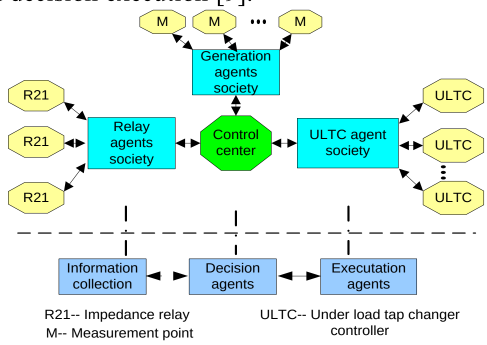


Figure 4 The structure of MAS based control system

In the distributed agent level, the relay agents all over the system will collect and send the information of breakers and relays to other agents. The generator agents and the ULTC agents will monitor the states of related components and share the information with other agents. The agents in the lowest level can be grouped into agent societies according to the similarity of their features, such as relay agent society, ULTC agent society, generator agent society and etc. These agent societies compose the middle level of MAS to builds an effective cooperation environment between agents. A control center (CC) agent is the highest level of the MAS and is designed to coordinate with all the lower level agents executing wide area protection strategy.

In this paper, since the delay time of zone 3 impedance relay is typical 500ms or longer, so there is enough time for relay agent to collect the information about network states and sensitivity. Then the predicted post fault impedance Z_{aij}^{P} can be calculated timely. Based on the identification criteria and MAS system, whether this relay is triggered by load flow transferring [5] or ULTC operations can be identified quickly. Then the unexpected relay and ULTC operations will be blocked. In the next stage, the related emergency control strategies will be defined in CC and executed by other control agents to make the different overloading states recover to normal states (which will be discussed in another paper).

5 Case study

The test system model simplified from eastern Denmark power system is built by RSCAD/RTDS with two racks and depicted in Runtime/RTDS, as shown in Figure 5. The detailed network data can be found in [10].

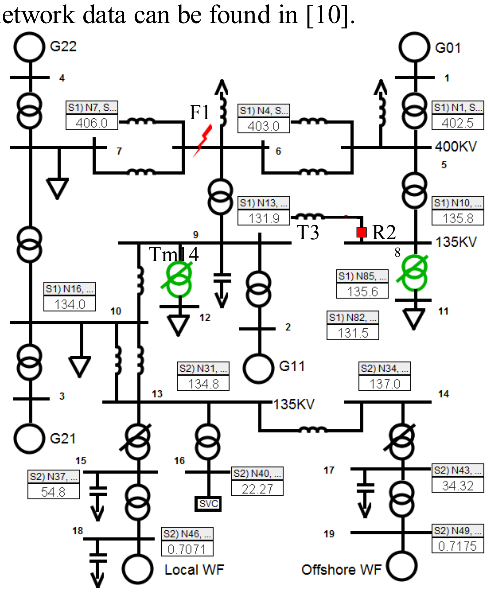
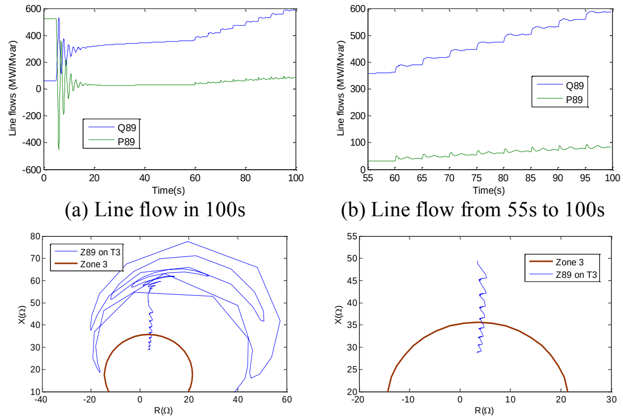


Figure 5 Test system model in Runtime/RTDS

Assume a three phase permanent short circuit fault (F1) occurred on the Bus 6 at 5s, then all the equipments connected to this bus were tripped 0.1s later. Load 1 and Load 2 are modeled by restoration load described in [4]. The system recovered after an oscillation period. Due to the tap changer of Tm14 operations, the zone 3 relay R2 on T3 was triggered firstly. Within the 75s after the fault, the system still be kept stable, but after the trip of R2, the system would experience cascading events and collapse finally. The relay R2 on T3 is chosen as a studied example; assume all the tripping signals are blocked, the line flow and impedance seen by R2 are shown in Figure 6.



(a) Line flow in 100s (b) Line flow from 55s to 100s

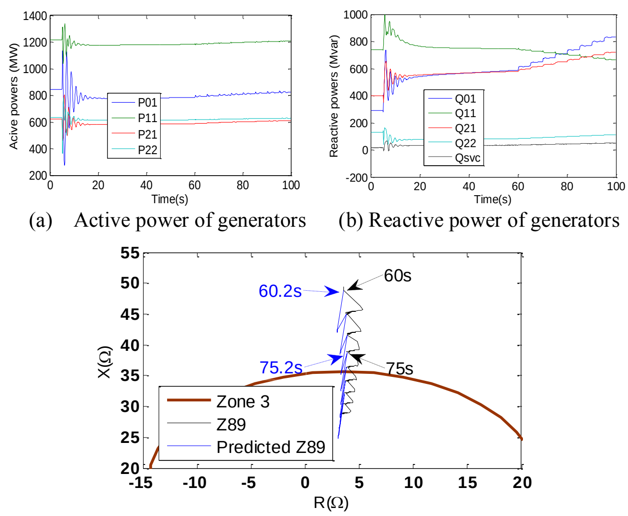
(c) Impedance locus of R2 (d) Impedance locus from 55s to 100s

Figure 6 Line flow and impedance seen by R1 on line T3

The impedance loci from 55s to 100s will be focused. When the proposed identification method is applied, assume $r^0 = 1$and $\Delta r = 0.01$, the related sensitivities and predicted impedance of R2 at the first step are shown in Table 1. Similarly, the predicting calculation can be started at 0.2s after every step of ULTC operation. The injection variations and impedance curves are shown in Figure 7.

Table 1 Experiment data at a flow rate of 0.45 m³/h

$\mathcal{L}_{Sr129}$ of powers to tap ratio	$\begin{bmatrix} 0.5025 & -0.5025 & 91.9816 & 91.9816 \end{bmatrix}$
Sensitivity matrix C_{89} of impedanc of R2 to local voltages	$\begin{bmatrix} -3.1630 & 3.1630 & -0.1787 & 0.1928 \\ -0.1765 & 0.1765 & 3.2034 & -3.4546 \end{bmatrix}$
Sensitivity matrix H_{89129} of impedance of R2 to powers on tap changing transformer Tm14	$\begin{bmatrix} 0.0637 & 0.0637 & -0.0064 & 0.0003 \\ -0.0073 & -0.0067 & 0.0567 & 0.0015 \end{bmatrix}$
Predicted impedance (ohm)	$\begin{bmatrix} R_{a109}^{0} \\ X_{a109}^{0} \end{bmatrix} = \begin{bmatrix} 3.56 \\ 48.81 \end{bmatrix}$ $\begin{bmatrix} \Delta R_{aij}^{Plt} \\ \Delta X_{aij}^{Plt} \end{bmatrix} = \begin{bmatrix} -1.0264 \\ -9.2497 \end{bmatrix}$



(a) Active power of generators (b) Reactive power of generators

(c) Impedance loci of relay R2

Figure 7 Generator powers and impedance seen by R1 on line T3

It can be seen from Figure 7, the biggest error is about 4Ω between predicted impedance (blue) and measured impedance (black). So the threshold of identification criterion can be set as 4 Ω, and ε applies 0.8. It should be noted that, the variations of load powers was not considered in this case, that is why the predicted error here is a little bigger. Also, it can be seen that the predicted impedance violates the zone 3 before it happens which may give an early alarm to control center. Then emergency control strategies, such as the ULTC blocking or inverse controlling, can be applied timely and effectively to adjust the overloading situation.

6 Conclusion

In this paper, sensitivity based identification algorithms are proposed to online identify the overloading conditions caused by unexpected ULTC operations, which aims to improve the traditional zone 3 impedance relay function under the overloading situations,. Moreover, a MAS based wide protection strategy is built up, which not only help dispersed relay to share the system information for identifying specific overloading situations, but also can define suitable emergency control strategy according to those identified states. In this way, the impedance relay agents, as an importance detector for emergent loading conditions, help to perform the most effective controls in the environment of MAS. The RTDS based case study has demonstrated the proposed algorithms can effectively predict the measured impedance and prevent the unexpected relay trips under overloading situations caused by ULTC operations.

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