ADAPTIVE LINE DIFFERENTIAL PROTECTION ENHANCED BY PHASE ANGLE INFORMATION

Youyi LI, ABB – Sweden, youyi.li@se.abb.com
Jianping WANG, ABB – Sweden, jianping.wang@se.abb.com
Kai LIU, ABB – China, aken-kai.liu@cn.abb.com
Ivo BRNCIC, ABB – Sweden, ivo.brncic@se.abb.com
Zhanpeng SHI, ABB - Sweden, zhanpeng.shi@se.abb.com

ABSTRACT

Good balance among speed, sensitivity and security at the same time is a big challenge for line differential protection. Its security may be influenced seriously by CT saturation. Meanwhile its speed and sensitivity may be influenced seriously by high resistance faults and heavy load conditions. To meet these challenges, a new line differential is described in this paper. By using adaptive characteristic from incremental currents, proposed protection can achieve high security, speed and sensitivity simultaneously.

INTRODUCTION

Classical line differential protection with percentage restrained characteristics is widely used in power systems as the main protection, because it can achieve fast operation for the whole line with high sensitivity and phase-segmented operation and clear selectivity inherently [1]. Despite the great advantages mentioned above, there are some problems of sensitivity and security with line differential protection. The criterion of a typical line differential protection is shown as below.

$$\begin{cases} |\dot{I}_L + \dot{I}_R| > k \cdot |\dot{I}_L - \dot{I}_R| \\ |\dot{I}_L + \dot{I}_R| > I_{d\min} \end{cases} \quad (1)$$

As shown in Fig.1a, $\dot{I}_L$ and $\dot{I}_R$ are the measured currents at local and remote sides respectively. $I_{d\min}$ is the threshold of differential current and k is the slope ratio in operation characteristic.

Generally, this classical line differential protection works well for normal operation conditions. It may have low sensitivity and speed for the faults with heavy load condition and high resistance. In such cases, the restrain current may become too large and operate (differential) current may become too small. It may even lead to failure of operation for internal faults.

Current transformer (CT) saturation is an additional challenge for differential protections. The measurement error by CT saturation may bring big ´false´ differential current even for external fault cases, which may lead to mal-trip. Some additional methods such as harmonics blocking function could be used to block such potential mal-trips, but it makes the solution complex and slows down the speed obviously.

Another problem of classical line differential protection is balance of security, sensitivity and speed. For classical line differential protection, its operating characteristic is fixed after the settings are made. High threshold means high security, low sensitivity and slow speed. Low threshold means low security, high sensitivity and fast speed. It's difficult to get good security, sensitivity and speed at the same time with the same group of settings.

Fault component based differential protection has been proposed to improve the performance [2][3], which may be described by the criterion as shown below.

$$\begin{cases} |\Delta\dot{I}_L + \Delta\dot{I}_R| > k \cdot |\Delta\dot{I}_L - \Delta\dot{I}_R| \\ |\Delta\dot{I}_L + \Delta\dot{I}_R| > I_{d\min} \end{cases} \quad (2)$$

Compared with classical differential protection, the main change in the criterion in equation (2) is that the fault component currents (incremental currents or sudden change currents) $\Delta\dot{I}_L$ and $\Delta\dot{I}_R$ are used instead of full component currents $\dot{I}_L$ and $\dot{I}_R$. It has better sensitivity and speed especially for the cases with heavy load condition and high resistance, because the load currents are removed in this method. On the other hand, the problem of CT saturation remains in this fault component based line differential protection. In addition, the difficulty of balance for sensitivity, speed and reliability also remains.

Thereby, it is clear that performance improvement of line differential protection is still very attractive. Lots of studies have been done to improve the performance for both sensitivity of internal faults and security of external faults by employing directional information of fault components [4][5], which shows the possibility to get good balance of sensitivity and security at the same time.

Our research shows that the line differential protection can get even better performance by using the adaptive operating characteristic based on the change of phase angle between fault component currents. The proposed new protection can achieve some very attractive features:

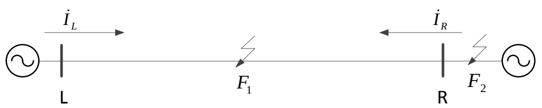
- Good sensitivity and speed for high resistance faults and heavy load conditions.
- Be immune to CT saturation inherently.
- Good balance of security, sensitivity and speed.

BASIC PRINCIPLE

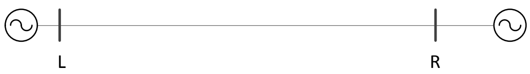
Proposed solution is based on the additional information of fault component currents. It will calculate the phase angle difference between the incremental currents from both ends of the protected line. If it is close to 0˚, a preliminary internal fault will be indicated. Then the sensitivity of the protection will be increased. Otherwise, if the angle is close to 180˚, a preliminary external fault will be indicated. Then the operate threshold will be increased to enhance the security. Based on the adjusted characteristic, the protection can achieve better sensitivity for internal faults and better security for external faults.

Basic theory

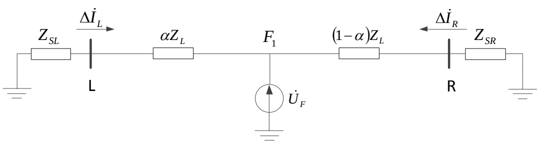
Fault component theory has already been widely used in different kinds of protections. In these protections, the sensitivity and speed is improved by removing the load components. The general idea of fault component theory can be described in Fig.1 as shown below.



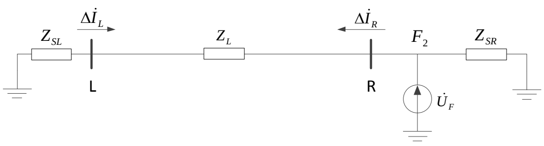
(a) System with faults



(b) System in normal operation



(c) Fault component network (internal fault)



(d) Fault component network (external fault)

Fig.1 Fault component network

In Fig.1 above and other parts in this paper, F_1 and F_2 are the internal fault and external fault respectively. $\dot{I}_L$ and $\dot{I}_R$ are the measured currents on terminal L and R respectively. $\Delta\dot{I}_L$ and $\Delta\dot{I}_R$ are the corresponding fault component currents. $\dot{U}_F$ is the voltage of the additional source at the fault point in fault component networks. Z_{SL}, Z_{SR} and Z_L are the equivalent source impedances and line impedance. θ_L and θ_R are the phase angles of the fault component currents of terminal L and R respectively.

As shown in Fig.1, the network with a fault (Fig.1a) can be divided into two networks, one is the network in normal operation (Fig.1b) and the other one is fault component network (Fig.1c or Fig.1d).

When an internal fault occurs, the phase angle difference between the fault component currents is:

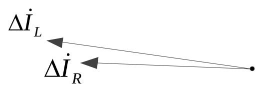
$$\begin{aligned}\theta_L-\theta_R &= \arg\Delta\dot{I}_L-\arg\Delta\dot{I}_R=\arg\frac{\Delta\dot{I}_L}{\Delta\dot{I}_R}\\ &=\arg\frac{\dot{U}_F/(Z_{SL}+\alpha Z_L)}{\dot{U}_F/[Z_{SR}+(1-\alpha)Z_L]}\\ &=\arg\frac{Z_{SR}+(1-\alpha)Z_L}{Z_{SL}+\alpha Z_L}\end{aligned} \tag{3}$$

In EHV/UHV power systems, the phase angle of equivalent source impedances Z_{SL} , Z_{SR} and line impedance Z_L have relatively similar phase angles. The phase difference calculated by formula (3) is a small value and is close to 0˚ normally.

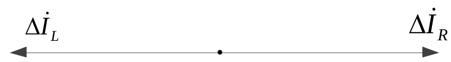
When an external fault occurs, the phase angle difference between the fault component currents on both terminals is:

$$\begin{aligned}\theta_L-\theta_R &= \arg\Delta\dot{I}_L-\arg\Delta\dot{I}_R=\arg\frac{\Delta\dot{I}_L}{\Delta\dot{I}_R}\\ &=\arg\frac{\Delta\dot{I}_L}{-\Delta\dot{I}_L}\\ &=180^\circ\end{aligned} \tag{4}$$

Obviously, the phase differences are different for internal fault cases and external fault cases. The corresponding vector diagram is shown below.



(a) Internal fault cases



(b) External fault cases

Fig. 2 Vector diagram of incremental currents

Such obvious difference of phase angles between internal fault and external fault (the gap is almost 180˚) can be employed in line differential protection to enhance the protection performance for both sensitivity and security. In practical applications, there may be lots of errors from different factors, such as CT saturation, measurement error, digital filter error, charging current etc., especially during the fault transient period. Fortunately, the big gap of phase difference between internal fault and external fault can ensure enough security even with all these errors in practical applications.

Main algorithm

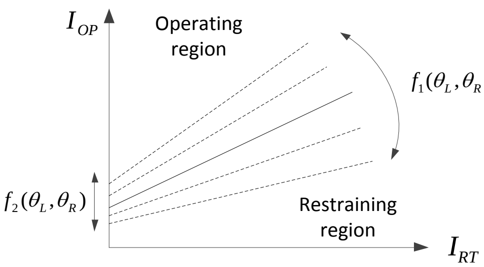
Proposed protection can be described by different mathematical forms, two of them are shown as below by general equation (5) or (6).

$$\begin{cases} I_{OP} > f_1(\theta_L,\theta_R)\cdot I_{RT} + f_2(\theta_L,\theta_R) \\ \theta_L = \arg(\Delta\dot{I}_L) \\ \theta_R = \arg(\Delta\dot{I}_R) \end{cases} \quad (5)$$

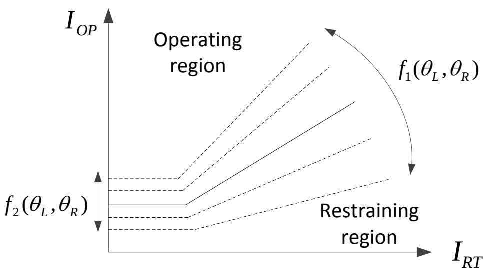
$$\begin{cases} I_{OP} > f_1(\theta_L,\theta_R)\cdot I_{RT} \\ I_{OP} > f_2(\theta_L,\theta_R) \\ \theta_L = \arg(\Delta\dot{I}_L) \\ \theta_R = \arg(\Delta\dot{I}_R) \end{cases} \quad (6)$$

Here, I_{OP} is the operate current (differential current) and I_{RT} is restrain current. They may be based on full component values or fault component values with different mathematical forms. For example, I_{OP} may be $|\dot{I}_L+\dot{I}_R|$ or $|\Delta\dot{I}_L+\Delta\dot{I}_R|$, etc. I_{RT} may be $|\dot{I}_L-\dot{I}_R|$ or $\max(|\Delta\dot{I}_L|,|\Delta\dot{I}_R|)$, etc.

The adaptive feature of proposed method is mainly controlled by the two general functions $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$. $f_1(\theta_L,\theta_R)$ is used to control the slope ratio of the percentage restraint characteristic and $f_2(\theta_L,\theta_R)$ is used to control the value of minimum operating value or the offset of total operating threshold. The diagram of the characteristic in equation (5) and (6) are shown in Fig.3(a) and Fig.3(b) respectively as below.



(a) Characteristic 1



(b) Characteristic 2

Fig. 3 Adaptive operating characteristic

When $|\theta_L-\theta_R|$ is close to 0°, it means a possible internal fault generally. The function values of $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$ will be decreased automatically to reduce the operate threshold. Otherwise, when $|\theta_L-\theta_R|$ is close to 180°, it means a possible external fault. The function values of $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$ will be increased to amplify the operate threshold.

As shown in Fig.3, the characteristic of this protection is, to a great extent, determined by the function values of $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$. And the two adaptive feature functions are based on fault component values. Thereby, the influence of load current is reduced greatly.

It is well-known that CT saturation will cause large measurement error of currents for both amplitude and phase angle, which might lead to mal-trip in some cases. Fortunately, its influence on current phase is limited in some sense. During the external faults with CT saturation, the phase angle difference of $|\theta_L-\theta_R|$ is no more 180°, but the angle offset is not too much normally. Even for the external faults with serious CT saturation, $|\theta_L-\theta_R|$ is more close to 180° instead of 0°. The adaptive feature based on $|\theta_L-\theta_R|$ still works well with proper design of functions $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$. Proposed method is immune to CT saturation.

Here, the detailed algorithm designs of $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$ may be linear function, nonlinear function or piecewise linear (nonlinear) function depending on the detailed requirements. Furthermore, $f_1(\theta_L,\theta_R)$ and (or) $f_2(\theta_L,\theta_R)$ may be predefined fixed value(s) instead adaptive function(s) if it is needed. If both adaptive functions are fixed values, the algorithms in equation (5) and (6) become the classical differential protections.

Our study also shows that after the fault occurs, it will get a stable calculation result of $|\theta_L-\theta_R|$ within very short time period. It means that the adaptive operating characteristic based on $|\theta_L-\theta_R|$ is ready in a very short time after the fault occurs and it will not delay the fault detection.

As mentioned before, there are lots of choices for adaptive feature functions of $f_1(\theta_L,\theta_R)$ and $f_2(\theta_L,\theta_R)$. One of the possible detailed designs for equation (5) is shown as below.

$$\begin{cases} \left|\Delta\dot{I}_L+\Delta\dot{I}_R\right| > [k_1 - k_2\cdot\cos(\theta_L-\theta_R)]\cdot\max(\left|\Delta\dot{I}_L\right|,\left|\Delta\dot{I}_R\right|) + I_{d\min} \\ \theta_L = \arg(\Delta\dot{I}_L) \\ \theta_R = \arg(\Delta\dot{I}_R) \end{cases} \quad (7)$$

Here, $f_1(\theta_L,\theta_R)$ is an adaptive function based on $\cos(\theta_L-\theta_R)$ as shown in equation (8) and $f_2(\theta_L,\theta_R)$ is a fixed value as shown in equation (9). k_1 and k_2 are used to control the adaptive feature.

$$f_1(\theta_L,\theta_R)=[k_1-k_2\cdot\cos(\theta_L-\theta_R)] \tag{8}$$
$$f_2(\theta_L,\theta_R)=I_{d\min} \tag{9}$$

Here, $f_2(\theta_L,\theta_R)$ is a fixed value $I_{d\min}$ in equation (7) only for simplicity in design. If an adaptive function like equation (10) is used instead of fixed value, it may result in an even better adaptive feature.

$$f_2(\theta_L,\theta_R)=I_{d\min}\cdot[k_3-k_4\cdot\cos(\theta_L-\theta_R)] \tag{10}$$

SIMULATION VERIFICATION

Proposed solution is verified by both simulation and prototype. Lots of simulation analysis with PSCAD /Matlab have been done to verify the performance of the proposed method. The structure of the simulation system is shown in Fig.4.

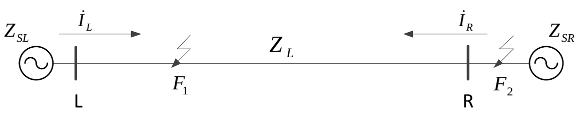


Fig. 4 Simulation system model

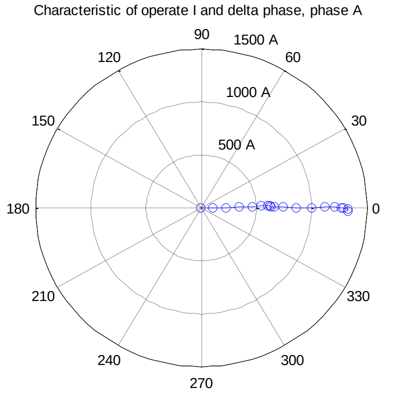
This is a 150km length 500kV transmission line system. F_1 is an internal fault located at 50 km from terminal L. And F_2 is in an external fault on the busbar of terminal R. The main parameters of the simulation system are shown as below:

$$Z_{SL1}=10e^{j85}\Omega,\ Z_{SL0}=15e^{j84}\Omega$$
$$Z_{SR1}=20e^{j85}\Omega,\ Z_{SL0}=25e^{j84}\Omega$$
$$Z_{L1}=(0.195+j2.8)\times10^{-4}\Omega/m$$
$$Z_{L0}=(1.628+j8.6)\times10^{-4}\Omega/m$$
$$X_{C1}=2.359\times10^{8}\Omega/m$$
$$X_{C0}=3.462\times10^{8}\Omega/m$$

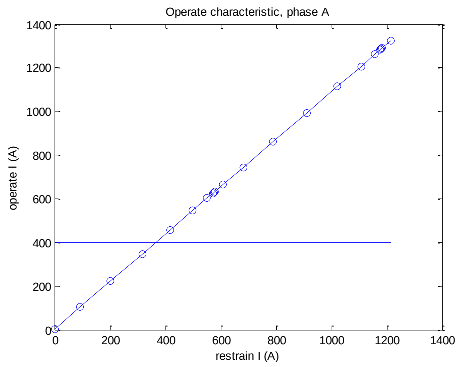
In the simulation cases of this paper, the algorithm in equation (7) is used. The setting are given below:
$I_{d\min}=400A$, $k_1=k_2=0.8$.
The sampling frequency is 1 kHz and calculating cycle of the protection algorithm is 1 ms. Proposed method will update the adaptive threshold and calculate the algorithm in equation (7) in every calculating cycle.

Internal fault

An internal A-G fault occurs at F_1 in Fig.4 with 300Ω resistance. The load current is 3 kA. Because of high resistance and heavy load, it may be difficult for classical line differential protection to operate quickly in this case. But proposed method can operate within 6 ms. The characteristic of proposed protection for this case is described in both polar coordinate and classical Cartesian coordinates as shown in Fig.5 (a) and Fig.5 (b).



(a) Characteristic in polar coordinate



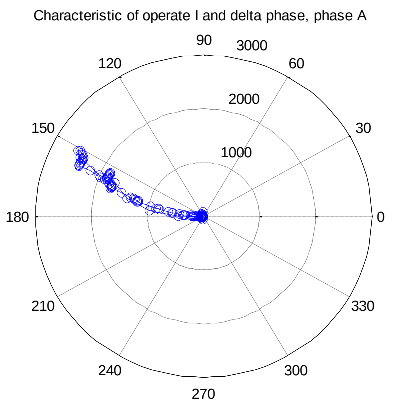
(b) Characteristic in classical coordinate

Fig. 5 Characteristic for internal fault

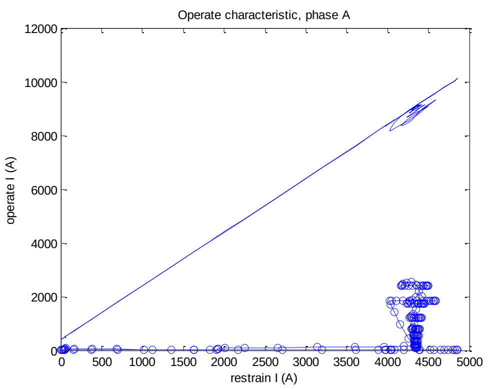
In Fig.5 (a), the radial coordinate is operate current $|\Delta\dot{I}_L+\Delta\dot{I}_R|$ and the angular coordinate is differential phase angle $(\theta_L-\theta_R)$. After fault occurs, $(\theta_L-\theta_R)$ becomes 0° rapidly and steadily together with big incremental of differential current $|\Delta\dot{I}_L+\Delta\dot{I}_R|$. Based on the two obvious features, an internal fault can be detected. Fig.5 (b) shows the characteristic of the protection in equation (7) in classical I_{OP}/I_{RT} coordinate. After the fault occurs, $(\theta_L-\theta_R)$ becomes 0°. This method can detect the change of phase angle rapidly, and modify the characteristic dynamically and automatically. Thereby, the slope in characteristic described in equation (8) could be calculated as: $[0.8-0.8\cdot\cos(\theta_L-\theta_R)]=0$. As a result, the required operate threshold for trip becomes much smaller than that of classical percentage differential characteristic. By this means, the speed and sensitivity is improved. More simulation cases on this 500 kV system show that proposed method can operate within one cycle for high resistance fault even up to 1 kΩ with proper settings.

External fault

An external A-G solid fault occurs at F_2 in Fig.4 with serious CT saturation of $\dot{I}_R$. The characteristic of proposed protection is shown in Fig.6.



(a) Characteristic in polar coordinate



(b) Characteristic in classical coordinate

Fig. 6 Characteristic for external fault

It is clear in Fig.6 (a) that there is a big differential current up to more than 2 kA for this external fault because of CT saturation. Meanwhile, the differential phase of incremental currents is no more 180˚ because of CT saturation. It reaches 150˚ during the external fault period. But it is still in the second quadrant as expected and far away from 0˚. For the worst condition in this case, when the differential phase reaches 150˚, the slope in characteristic is,

$$\left[0.8 - 0.8\cdot\cos(\theta_L - \theta_R)\right] = 0.8 - 0.8\cdot\cos(150^\circ) = 1.49$$

This high slope can ensure good security of proposed protection from mal-trip. Fig.6 (b) also shows the characteristic in a classical way. Although there is a big differential current after fault occurs, the required trip threshold also become very large thanks to the adaptive feature, which is much more than the operate value.

CONCLUSION

The differential phase angle of incremental currents can indicate internal/external fault rapidly and reliably. This feature can be employed to change the characteristic dynamically. By this means, adaptive differential characteristic is achieved, which improves the speed and sensitivity for internal faults and improves the security for external fault even with heavy CT saturation. Some general mathematical equations of the new idea are described in this paper. Finally, simulation tests demonstrate that the principle has not only very good dependability for internal faults but also high security for external faults.

REFERENCES

[1] S. C. Sun, R. E. Ray, 1983, "A current differential relay system using fiber optics communications ", *IEEE Transactions on Power Apparatus and Systems*. vol. PAS-102, 410-419.

[2] Wu Yekai, Yuan Baoji, 1996, "Split-phase current differential protection using fault components", *Electric Power*. vol. 24, 4-9, 29.

[3] Yi Xianggen, Chen Deshu, Zhang Zhe, 1996, "Fault component based digital differential protection", *Automation of Electric Power Systems*. vol. 22, 13-17.

[4] Zhang Zhen-yu, He Jiali, Wang Guoxin, Guo zheng, 2005, "Directional current differential protection based on fault components", *Electric Power*. vol. 38, 1-6.

[5] B. Kasztenny, G. Brunello, and L. Servov, 2001, "Digital low-impedance bus differential protection with reduced requirements for CTs", *Proc. 2001 IEEE/PES Transmission Distribution Conf.*, vol.2, 703-708