A WAMS based Novel Voltage Relaying Adaptive Protection Scheme for Distribution System Installed with Distributed Generation

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Abstract

For potential distributed generation (DG) installed distribution system, a new protection scheme based on adaptive voltage relaying technique is proposed in this paper. The limited-area centralized wide-area protection system is utilized to store relevant line parameters, get the data of online voltage and current and facilitate communication among the Intelligent Electronic Device (IED)s. Based on this, a primary and backup protective relaying scheme with voltage adaptive feature are put forward according to the relationship between pre-and-post fault phase voltage difference and corresponding phase current. The proposed method was simulated on a radial distributed system with DG installed using PSCAD/MATLAB under various operating conditions of the system and fault types and verified the immunity of the proposed method to the insertion and output variation of DG. As an extension, it was compared with traditional low voltage protection; the proposed protective relaying the range of protection was extended to a considerable degree.

***Keywords**: Adaptive voltage protection, Intelligent Electronic Device (IED), distributed generation (DG), primary and backup protective relaying*

INTRODUCTION

In recent years, with the introduction of DGs, the operation modes of the grid have become more flexible, and the contradiction among those requirements of selectivity, sensibility and reliability for adaptive relaying has been ever prominent. In common/conventional/classic protective relaying, to calculate the setting value the maximum operation mode of the system at off line, where as minimum operation mode of system to check sensitivity and the setting value does not change during the real/normal operation [1-2]. In such case, it is difficult to achieve optimal protection because when the system is not operating in the maximum mode corresponding setting value is not the optimal one. Since the concept of adaptive relaying was first introduced in 1980s [3-5], which highlights that when the system is subjected to different operating mode and different faults then there should be corresponding change in the operating characteristics or setting value in the protecting relaying.

In the study and research on adaptive relaying noticeable/reasonable/substantial performances have been made such as adaptive current relaying [6-9], adaptive distance relaying [10-13], adaptive differential protection [14-15], etc. Consider the study on adaptive current relaying. Reference [6] comes up with a real-time setting calculation according to the current operating state of the system, realizing adaptive current fast relaying and adaptive voltage fast relaying based on local data only. On this basis, reference [7] introduces an adaptive current fast relaying suitable for double lines. In reference [8] an adaptive current backup relaying is achieved using the multi-Agent system. A new adaptive current relaying method is introduce in reference [9] which is convenient for distribution networks with DG connections, and which can adequately solve the problem of cooperative setting between the primary and backup relaying. As for the study on adaptive distance relaying, reference [10] proposes an adaptive relaying scheme based on the phase-to-phase current difference and line voltage. A novel adaptive distance II-section relaying is put forth in reference [11] with an extension of the protection range compared to traditional distance II-section relaying. In reference [12] an adaptive ground distance relaying is proposed, which can effectively avoid the problem of transient overreach, extend the protection range and improve the protection performance. Reference [13] modifies the operation characteristic of the adaptive ground distance relaying to better counteract the influence of transition resistance and transient overreach. As for the research on adaptive differential protection, a ratio differential adaptive relaying is proposed in reference [14], which regulates the parameters of the ratio-restrained characteristic according to the differential current, and is highly sensible to both in-zone and out-of-zone faults. In reference [15] a differential current adaptive relaying is put forward, which achieves the adaptive feature by increasing and decreasing the restraint coefficient respectively for out of zone and in zone faults.

In this context, A WAMS based Novel Adaptive Protection Scheme is proposed in this paper, where the limited-area centralized wide-area protection system [17-18] is utilized to store relevant line parameters, achieve real-time voltage and current data, and helps in communication among the IEDs. Based on this, the adaptive voltage primary and backup protective relaying are introduced according to the relationship between the pre-and-post fault phase voltage difference and the phase current. Based on simulation results show the of proposed protection scheme under different system operation conditions and fault types, it shows automatically relaying is adaptive and verify the immunity of the proposed method to the introduction and output variation of DG. Moreover, compared with conventional low voltage protection, the proposed protective relaying shows the protection range to a considerable degree.

PRINCIPLE AND SETTINGS

One line diagram with IEDs for a power system is shown in Figure 1, the generators connected to Bus A, B and C all represent equivalent power supply networks. F is the fault location. The impedances of line BC and line AB are Z $_{BC}$ and Z $_{AB}$ respectively, and that of line BF is αZ_{BC}. In addition, the directional device is needed for the proposed method so as to making the correct function of the adaptive voltage protective relaying.

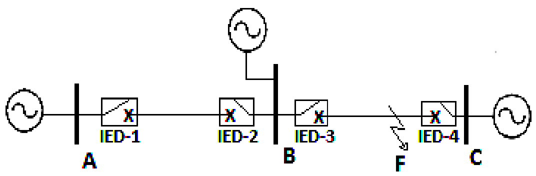

Fig-1: one line diagram of Power system with IEDs

Principle and Setting Schemes of Primary Relaying

When a three-phase fault occurs at F, the phase voltages V_{a3}^{B}, V_{b3}^{B} and V_{c3}^{B} measured at IED3 have the following relationship.

$\left|V_{a3}^{B}-V_{b3}^{B}\right|=\left|V_{b3}^{B}-V_{c3}^{B}\right|=\left|V_{c3}^{B}-V_{a3}^{B}\right|$ ….1

Take phases *b and c* as an example, (1) can be further illustrated as:

$\left|V_{b3}^{B}-V_{c3}^{B}\right|=\left|i_{b3}^{B}\alpha Z^{BC}-i_{c3}^{B}\alpha Z^{BC}\right|=\sqrt{3}\alpha\left|i_{b3}^{B}\ Z^{BC}\right|$…2

where i_{b3}^{B} and i_{c3}^{B} are expressed the phase currents of phase-*b* and phase-*c* measured at IED3.

When a fault phase-to-phase *b-c* occurs at F, the phase voltages V_{b2}^{B} and V_{c2}^{B} are measured at IED3 always achieves the expression:

$\left|V_{b2}^{B}-V_{c2}^{B}\right|=\left|(i_{b2}^{B}-i_{c3}^{B})\alpha Z^{BC}\right|=\sqrt{3}\alpha\left|i_{b3}^{B}\ Z^{BC}\right|$ ……3

where i_{b2}^{B} and i_{c3}^{B} are the phase currents measured at IED3.

Generally, the current distribution factor in the negative sequence is the same with that in the positive sequence. Thus (3) can be written as:

$\left|V_{b2}^{B}-V_{c2}^{B}\right|=\left|(i_{b2}^{B}-i_{c3}^{B})\alpha Z^{BC}\right|=2\alpha\left|i_{b3}^{B}\ Z^{BC}\right|$ ….4

Define the measured value for the adaptive voltage primary relaying of line BC to be V_{B1}.$V_{B1}=\left|V_{1\phi}^{B}-V_{2\phi}^{B}\right|$ ---(5)

where $V_{1\phi}^{B}$ and $V_{2\phi}^{B}$ are the phase voltages of any two faulted phases measured at IED3.

Define the setting value for the adaptive voltage primary relaying of line BC to be V_{set1}

$V_{set1}=k_{ft}i_{\phi}^{B}Z^{BC}$ ---(6)

where k_{RC1} is the reliability coefficient of the adaptive voltage primary relaying, set to be 0.9.

i_{ϕ}^{B} is the phase current of any fault phase measured at IED3.

k_{ft} refers the type of fault information, which can be obtained by the fault phase selector, and k_{ft} is set to be 3 for three-phase faults, 2 for phase-to-phase faults, and 1 for no faults at all (i.e. normal operation).

Now the cases of three-phase and phase-to-phase (taking *b-c* as an example) faults are studied.

At the normal state, the value for the primary relaying is measured as

$V_{B1}=\left|V_{b}^{B}-V_{c}^{B}\right|=\sqrt{3}\left|V_{b}^{B}\right|$

Whereas the setting value is

$V_{set1} = 0.9 i_b^B Z^{BC}$

where $\left| i_b^B Z^{BC} \right|$ is the voltage difference between bus B and C, which can also be written as $\left| V_b^B - V_c^B \right|$. Consider that in normal operation state, stability of the system is a main concern, so the terminal voltage of a line does not differ much in amplitude and usually maintain a phase angle difference within 90^0 results in $\left| V_b^B - V_c^B \right| \leq \sqrt{3} \left| V_b^B \right|$. Therefore, before the fault occurs, the setting value of the adaptive voltage primary relaying is smaller than the measured value, the relay performs correctly with an inaction.

After the fault occurs, $\left| i_b^B \right|$ in (6) changes from the load current to fault current, shows a significant increase in its own value and in the setting value of the primary relaying. Comparing (6), (2) and (4), the conclusion can be drawn that: in both cases of three-phase and phase-to-phase faults, when $\alpha < k_{RC1}$ implies $V_{set1} > V_{B1}$, and the primary relaying acts; when $\alpha > k_{RC1}$ represents $V_{set1} < V_{B1}$, and the primary relaying does not act; when $\alpha = k_{RC1}$ indicates $V_{set1} = V_{B1}$. Thus, the protection range of the primary relaying can be settled as $\alpha = k_{RC1} = 90\%$. The adaptive voltage primary relaying is based on voltage and current data acquired at the relaying point, without any communication delay of the wide-area protection system, thus the speed demand of primary relaying is met.

Principle and Setting Schemes of Back up Relaying

Through the wide-area protection system, the real-time measured current from IED1 and IED2 can be gained, and then by applying the wide-area differential protection method, the relay at Bus A can be set to act as a short-range backup relaying for line AB. If the fault occurs on line AB, and the primary relaying at IED1 does not act, the wide-area differential protection will act without delaying, the action time being the wide-area communication time only. Besides, in order to avoid miss-trip of the breaker or relaying at IED3, such method as follows is used to accomplish adaptive backup relaying for line BC.

When a three-phase fault occurs at F, the phase voltages V_{a3}^A, V_{b3}^A and V_{c3}^A measured at IED1 meet the following equations.

$$\left| V_{a3}^A - V_{b3}^A \right| = \left| V_{b3}^A - V_{c3}^A \right| = \left| V_{c3}^A - V_{a3}^A \right| \text{--- (7)}$$

Take phase b, c as an example, (7) can be further illustrated as:

$$\left|V_{b3}^{B}-V_{c3}^{B}\right|+\left|V_{b3}^{A}-V_{c3}^{A}\right|=\sqrt{3}\left(\alpha\left|i_{b3}^{B}\ Z^{BC}\right|+\left|i_{c3}^{A}\ Z^{AB}\right|\right) \quad \text{--(8)}$$

where $\left|i_{b3}^{B}\right|$ and $\left|i_{c3}^{A}\right|$ are expressed as the phase currents of phase-*b* and phase-*c* measured at IED1.

When a *b-c* phase-to-phase/line fault occurs at F, we have the following expression:

$$\left|V_{b2}^{B}-V_{c2}^{B}\right|+\left|\left(V_{b2}^{A}-V_{c2}^{A}\right)-\left(V_{b2}^{B}-V_{c2}^{B}\right)\right|=2\left(\alpha\left|i_{b2}^{B}\ Z^{BC}\right|+\left|i_{b2}^{A}\ Z^{AB}\right|\right)$$

---(9)

where i_{b2}^{A} and i_{c2}^{A} are the phase currents measured at IED1.

The measured value for the adaptive voltage backup relaying of line BC to be V_{B2}.

$$V_{B2}=\left|V_{1\phi}^{B}-V_{2\phi}^{B}\right|+\left|V_{1\phi}^{A}-V_{2\phi}^{A}\right| \quad \text{--- (10)}$$

where $V_{1\phi}^{B}$ and $V_{2\phi}^{B}$ are the phase voltages of any two fault phases measured at IED3 and transmitted to IED1, while $V_{1\phi}^{A}$ and $V_{2\phi}^{A}$ are the corresponding voltages measured at IED1.

Define the setting value for the adaptive voltage backup relaying of line BC to be V_{set2}.

$$V_{set2}=k_{ft}\left(k_{RC2}\left|i_{B\phi}\ Z^{BC}\right|+\left|i_{A\phi}\ Z^{AB}\right|\right) \quad \text{--- (11)}$$

where k_{RC2} is the reliability coefficient of the adaptive backup relaying, set to be 0.8. $i_{A\phi}$ is the phase current of any fault phase measured at IED1.

Similar to the primary relaying issue, the cases of three-phase and phase-to-phase (taking *b-c* as an example) faults are studied for the backup relaying.

When the system operates in the normal state, the measured value for the backup relaying is $V_{B2}=\sqrt{3}\left(\left|V_{b}^{B}+V_{b}^{A}\right|\right)$.Whereas the setting value is $V_{set2}<\sqrt{3}\left|V_{b}^{A}\right|+\sqrt{3}\left|V_{b}^{B}\right|$. Therefore, before the fault occurs, the setting value of the adaptive backup relaying is smaller than the measured value, the relay performs correctly with an inaction. After the fault occurs, $\left|i_{b}^{B}\right|$ and $\left|i_{b}^{A}\right|$ in (11) both change from the load current to fault current, inciting a significant increase in their own values and in the setting value of the backup relaying. Comparing (11), (8) and (9), the conclusion can be drawn that: in both cases of three-phase and phase-to-phase faults, when $\alpha<k_{RC2}$ implies $V_{set2}>V_{B2}$, and the backup relaying acts; when $\alpha>k_{RC2}$ represents $V_{set2}<V_{B2}$, and the backup relaying does not act; when $\alpha=k_{RC2}$ indicates $V_{set2}=V_{B2}$. Thus, the

percentage of the downstream line which the backup relaying is able to cover can be settled as $\alpha = k_{RC2} = 80\%$. Besides, the protection range covered by the backup relaying is shorter than that by the primary relaying, thus selectivity for protective relaying is satisfied.

SIMULATION VERIFICATION

A 11 kV distribution system with isolated neutral shown in Figure 2 is considered for verification of proposed technique in aid with PSCAD/EMTDC software. The reference capacity of the distribution system is 750MVA, and reference voltage 11kV. Line AB, BC and AF are overhead lines, and line CD, DE and FG are cables. The parameters of the lines are shown in Table 1. The rated power of the load is 7 MVA, the power factor being 0.85. The distributed generation (DG) with a rated power of 11MVA, which applies the PQ control strategy, is introduced through Bus C.

The relaying performance of R_3 and R_2 is studied in this paper to highlight the cooperative setting of the proposed adaptive voltage relaying scheme. The setting and measured values for R_3 as the primary relaying (for line CD) are Vps3 and Vpm3 respectively. The setting and measured values for R_2 as the backup relaying (for line CD) are Vbs2 and Vbm2 respectively.

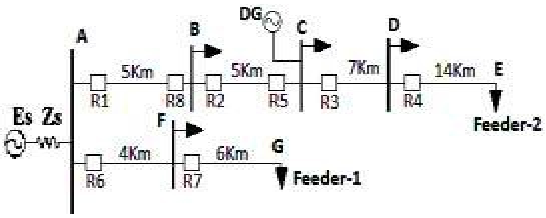

Fig-2: 11KV distribution system

TABLE-1
11KV Distribution system test data

Line (From Bus-To Bus)	Impedance (Ω/Km)
AB	0.0282+j0.3635
BC	0.0282+j0.3635
CD	0.2713+j0.0812
DE	0.2713+j0.0812
AF	0.0282+j0.3635
FG	0.2713+j0.0812

Evaluation of Primary Relaying performance

Set the system in the maximum operation mode, and the output of DG to be 5 MVA. The fault occurs at T=0.30s and disappears at T=0.80 s. When a three-phase fault occurs in the middle of line CD (which is within the primary relaying protection range), the adaptive operation characteristic curve of R_3 as the primary relaying is shown in Figure 3. While in the case of a phase-to-phase fault, the adaptive operation characteristic is shown in Figure 4.

Fault Location From Bus C (% distance)	Setting Value (KV)	Measured Value (KV)
0	5.2745	0.0014
20	4.87696	1.1029
40	4.5292	2.0433
60	4.22411	2.8523
80	3.9551	3.55322
100	3.7169	4.1649

As shown in Figure 3 and Figure 4, when the fault occurs within the protection range of R_3 as the primary relaying, the measured value Vpm3 decreases rapidly, while in the meantime the setting value Vps3 increases greatly. When the measured value falls below the setting value, the primary relaying acts promptly

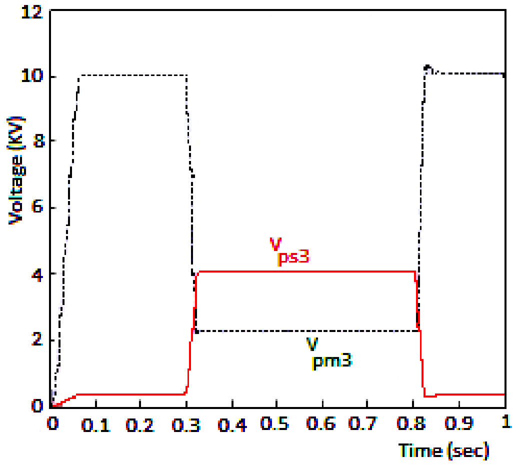

Fig-3: Relay R3 adaptive primary protection response for three phase fault in line CD

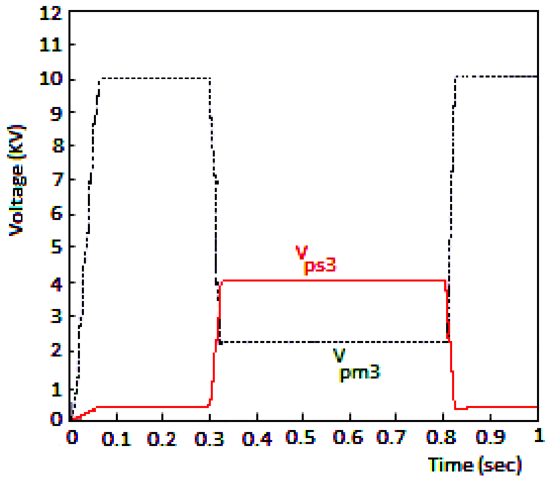

Fig-4: Relay R3 adaptive primary protection response for phase to phase fault in line CD

Table 2 shows the simulation results of R_3 as the primary relaying for different fault locations on line CD. It can be seen that even in the unfavorable case of phase-to-phase faults, the proposed adaptive voltage primary relaying is able to cover a protection range of 90% of the protected line length.

TABLE-2

Adaptive Primary protection of relay R_3 test results

Case-I: *Phase to Phase Fault*

Fault Location From Bus C (% distance)	Setting Value (KV)	Measured Value (KV)
0	5.2745	0.0014
20	4.87696	1.1029
40	4.5292	2.0433
60	4.22411	2.8523
80	3.9551	3.55322
100	3.7169	4.1649

Case-II: *Three Phase Fault*

Fault Location From Bus C (% distance)	Setting Value (KV)	Measured Value (KV)
0	5.3721	0.00009
20	4.9576	1.10253
40	4.5950	2.0430
60	4.2768	2.8519
80	3.9961	3.55289
100	3.7475	4.1647

Evaluation of Backup Relaying performance

When the fault occurs at a location close to Bus C on line CD (which belongs to the backup relaying operation zone), if R_3 as the primary relaying doesn't act, then R_2 as the backup relaying for line CD will provide backup protection. The adaptive operation characteristic curves of R_2 in the cases of three-phase and phase-to-phase faults are shown in Figure 5 and Figure 6, respectively.

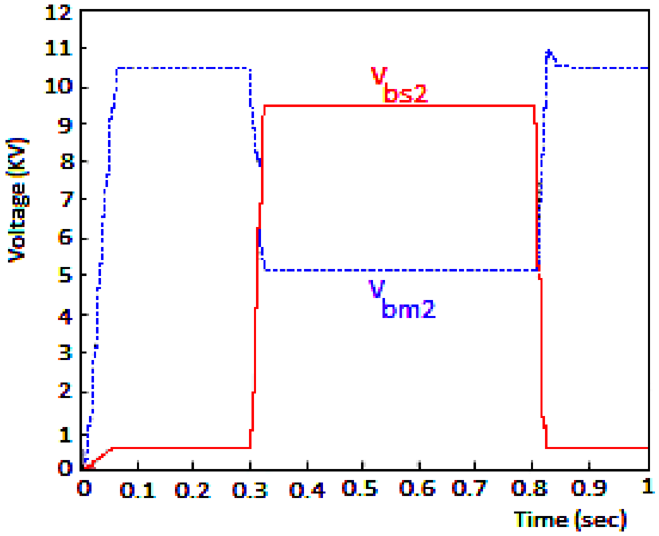

Fig-5: Relay R_2 adaptive back up protection response for three phase close -in fault in line CD

Table 3 shows the simulation results of R_2 as the backup relaying for different fault locations on line CD. It can be seen that even in the unfavorable case of phase-to-phase faults, the proposed adaptive voltage backup relaying is able to cover 80% of the protected downstream line length. Furthermore, the backup relaying fits in well with the primary relaying, thus selectivity for protective relaying can be satisfied.

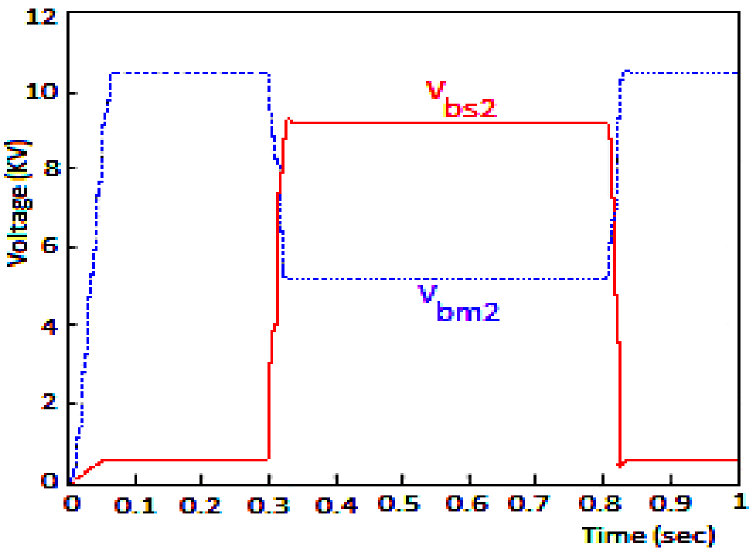

Fig-6: Relay R_2 adaptive back up protection response for phase- phase close-in fault in line CD

Evaluation of Impact of System Operation Mode and DG Output variations

Many simulation tests are carried out to analyze the impact of such factors as variation of the system operation mode, introduction of DG and the variation of DG output on the proposed adaptive relaying method. Among them, In Table 4 the simulation results of R3 as the primary relaying for faults at 90% line length from bus C (i.e. the end of the primary relaying protection range) on line CD are shown; and in table 5 the simulation results of R2 as the backup relaying for faults at 80% line length from bus C (i.e. the end of the backup relaying protection range) on line CD are shown

TABLE-3

Adaptive Back up protection of relay R_2 test results

Case-I: *Phase to Phase Fault*

Fault Location From Bus C (% distance)	**Setting Value (KV)**	**Measured Value (KV)**
0	10.0755	5.66984
20	9.24979	6.29574
40	8.52984	6.8243
60	7.89965	7.27012
80	7.34577	7.65259
100	6.85575	7.98292

Case-II: Three Phase Fault

Fault Location From Bus C (% distance)	**Setting Value (KV)**	**Measured Value (KV)**
0	10.44274	5.66951
20	9.60058	6.29651
40	8.86446	6.82319
60	8.21942	7.2699
80	7.6516	7.6523
100	7.14912	7.9827

TABLE-4

Relay R_3 adaptive primary protection results under various DG conditions

Operation Mode	Setting Value (KV)	Measured Value (KV)
System Max DG out of Service	5.2944	5.2975
System Min DG out of Service	5.2721	5.2743
System Max DG in Service	9.5788	9.5826
System Min DG in Service	9.5643	9.5690

Case-I: Phase to Phase Fault

Operation Mode	Setting Value (KV)	Measured Value (KV)
System Max DG out of Service	5.2944	5.2975
System Min DG out of Service	5.2721	5.2743
System Max DG in Service	9.5788	9.5826
System Min DG in Service	9.5643	9.5690

Case-II: *Three Phase Fault*

Operation Mode	Setting Value (KV)	Measured Value (KV)
System Max DG out of Service	5.2946	5.2975
System Min DG out of Service	5.2732	5.2734
System Max DG in Service	9.5808	9.5826
System Min DG in Service	9.5674	9.5368

All the simulation tests have verified the adaptive setting of the proposed relaying method in response to variation of the system operating mode and DG output. therefore the adaptive primary and back up relaying scheme is proved immune to the change of system operating mode as well as the introduction and output fluctuations of DG in either symmetrical or asymmetrical faults.

TABLE-5

Relay R_2 adaptive back up protection results under various DG conditions

Case-I: Phase to Phase Fault

Operation Mode	**Setting Value (KV)**	**Measured Value (KV)**
System Max DG out of Service	11.9894	11.9930
System Min DG out of Service	11.93604	11.9385
System Max DG in Service	14.5062	14.5104
System Min DG in Service	14.4640	14.4676

Case-II: Three Phase Fault

Operation Mode	**Setting Value (KV)**	**Measured Value (KV)**
System Max DG out of Service	11.9917	11.9930
System Min DG out of Service	11.9373	11.9385
System Max DG in Service	14.5085	14.5104
System Min DG in Service	14.4657	14.4676

CONCLUSIONS

A novel adaptive voltage protective relaying method is proposed in this paper, which has so many features. The setting value of the relaying is able to adapt to the change of system operation mode and fault type, so that reliable performance of the relay is guaranteed in either symmetrical or asymmetric faults. Thus the adaptability of the proposed voltage relaying is realized. Compared with traditional voltage relaying, the adaptive voltage primary relaying achieves a considerable extension of the protection range. The latter can cover nearly 90% of the protected line length even in the unfavorable case of the phase-to-phase faults. The adaptive voltage backup relaying can cover as much as 80% of the downstream line length in cooperation with the adaptive primary relaying, by which selectivity for protective relaying is satisfied. The impact of DG on the protective relaying of the grid is eliminated. The cooperative setting issue of the smart grid with DG inserts is thus resolved.

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