Toward Smarter Current Relays for Power Grids

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Abstract— **As the power systems in the United States become increasingly large, complex, and interconnected, the traditional relays are proving to be inadequate against blackouts. More "intelligent" relays are therefore needed to meet the security and reliability needs of the future power grid. In this paper, we propose a new logic for decision making and over-current relay setting. The proposed "smart" over-current relays can: 1) decide current settings with a new and more comprehensive logic; 2) use new technologies such as Phasor Measurement Unit (PMU) and/or Global Positioning System (GPS) to improve decision making; and 3) establish communications between relays to get real-time information.**

I. INTRODUCTION

Today's power systems are very large, complex, and interconnected systems. Because of the increased dependence on the power system, the requirements to meet an acceptable security and reliability level have become more and more important to both customers and suppliers. The traditional relays are not sophisticated enough to satisfy today's needs. In some situations, they are not adaptive enough to discriminate between fault and normal conditions, or to react correctly to faults. To reduce the damage on power systems hardware and the system as a whole, more "intelligent" relays are therefore needed.

Every four months, the United States experience a blackout large enough to leave half a million homes in dark [1]. According to the historical data, relay malfunctioning is one of the major contributing factors to 70% of the major disturbances in the United States [2]. The investigation team studying this problem concluded that in the blackout that happened in August 2003, relays tripped after each transmission line got overloaded. Relays were responding to overloads although there were not faults on the protected lines. These relays are the common mode of failure that accelerated the geographic spread of the cascade of faults [3]. To enhance the stability and security of protection systems, a lot of work has been done on improving relays' coordination and on building stronger back-up systems.

Real-time analysis and computer technologies are not new in protection systems. Computer control is applied to improve the selectivity of the relays [4]; while real-time tools that combine neural network based fault detection and classification algorithms and synchronized sampling based fault location algorithm were used in protection systems for fault analysis [2]. Thus, the adaptivity of the protection systems as a whole has been improved with the help of these technologies. However, to date, little research has been done or reported on improving the *inherent logic of individual relays*. This paper attempts to bridge this gap by introducing new methods for improving the relay's logic on making decisions and for providing rapid reactions. Computer control, communications, probability estimation, and real-time analysis are four components applied in our work to give each relay global and real-time information. These can improve the adaptivity of individual relays, thus enhancing the reliability and stability of the whole protection system [5].

In this paper, a more comprehensive functional setup and enhanced logic for decision making and over-current relay settings are proposed. The proposed "smart" over-current relays can: 1) make decisions during a fault by receiving real-time information from Supervisory Control And Data Acquisition (SCADA) system; 2) build communication between relays; and 3) use new technologies such as Phasor Measurement Unit (PMU) and/or Global Positioning System (GPS) to improve decision making.

The new logic of decision making of the "smart" relays is based on hypothesis testing and decision theory. This theory is widely used in communication systems, but it will be shown in this paper that it can be used in power systems as well.

The "smart" relays could have more than one threshold for their settings. Multiple thresholds may give more accurate information, including the occurrence and the location of the fault.

The remainder of this paper is organized as follows. In section II, an overview of traditional over-current relays is presented. In section III, we propose a new concept for "smart" over-current relays. In section IV, simulation results are presented to illustrate the validity of the proposed approach and concepts. In section V, the implications of the main findings of this paper are discussed and possible directions for future work are outlined. In section VI, related works are presented. Finally, conclusions are drawn in section VII.

II. OVERVIEW OF TRADITIONAL OVER-CURRENT RELAYS

With the increasing dependence of US population on electricity supplies, the requirements on having an acceptable level of reliability and security has become more and more important to both the suppliers and the customers. Hence, the protection system has become a critical part in the whole power system.

Over-current relays are widely used in the protection of power systems. Typically, three protection zones in the direction of the fault are used in order to cover a section of line and to provide back-up protection to remote sections. Along a transmission line, each protection zone covers the area between two adjacent relays. Zones are numbered as 1, 2, and 3 from the closest one to the farthest one relative to the location of fault against which relaying is desired (see Fig. 1). For example, relay 1 works as the primary one for faults in Zone 1, while it works as a back-up one for faults in Zone 2 and Zone 3.

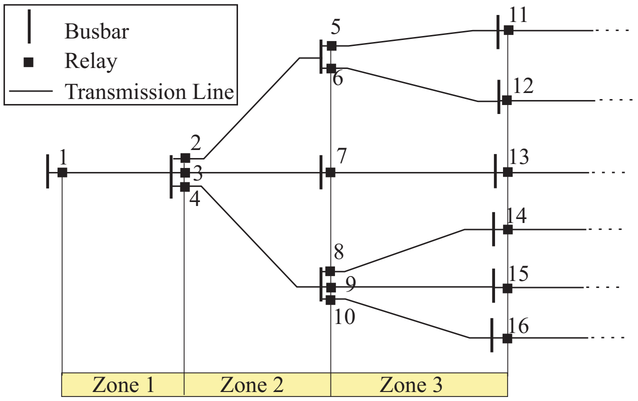

Fig. 1. Relay Protection Zones for Power Systems

There are several important assumptions made while setting traditional over-current relays:

1) Normal current is always lower than short-circuit current;
2) Zone 1 short-circuit current is always the highest one among the entire possible fault currents. Zone 2 short-circuit current is second highest, and Zone 3 short-circuit current is third highest;
3) Protections only respond the magnitude of the current, and not to the phase of the current;
4) The setting of the protection is based on the minimum value of thermal limit and the maximum operating current.

Based on the assumptions above, traditional over-current relay has only one threshold, which is called trip setting. The single threshold works well and is adequate in a situation where a fault is followed with the highest current, however, it will be shown in section IV of this paper that assumptions 1) and 2) are not always valid and can lead to malfunctioning of the relays.

III. “SMART” OVER-CURRENT RELAYS: A NEW CONCEPT

To avoid malfunctioning of the relay, an enhanced logic for relay settings should be adopted. In this paper, the new concept proposed toward such enhancement is based on hypothesis testing and decision theory.

A. Hypothesis Testing in Protection System

Hypothesis testing is widely used in statistical communication theory [7] [8]. It is a general method for making decisions about accepting or rejecting a hypothesis. The hypothesis being tested is referred to as the null hypothesis and denoted by H_0. Rejection of the null hypothesis implies acceptance of its complement, which is referred to as the alternative hypothesis and denoted by H_1 [9].

In the power protection system under investigation, we take the viewpoint that the normal condition of the power system can be presented by hypothesis H_0, and condition with fault by hypothesis H_1.

The distributions of normal and fault current that will be used in the hypothesis testing conducted in this paper is shown in Fig. 2.

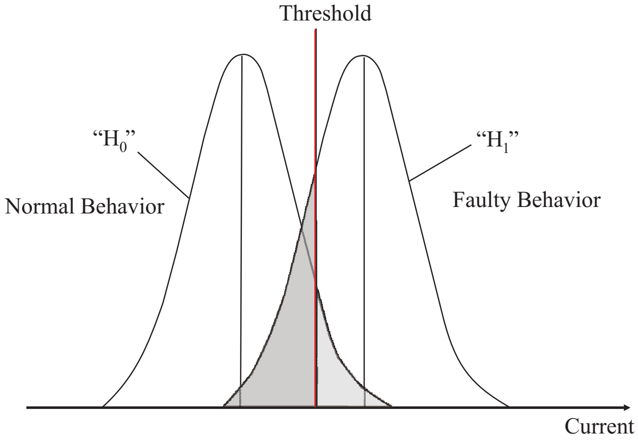

Fig. 2. Probability Density Functions (pdf) of Normal Current and Fault Current.

Usually, a threshold is used to discriminate H_0 and H_1. Where to place the threshold is decided by the performance criteria used for the discrimination. It can be seen that the main challenge in defining a threshold is in a situation where distribution of normal current overlaps with the distribution of fault current. In such a case, there are two types of errors.

Type I error occurs when the system judges the observed current to indicate a fault when it is, in fact, normal, which is denoted by $H_1|H_0$. This kind of error causes false alarms. It is documented that such an occurrence contributed to the cascading event during August 2003 US blackout. The probability for the type I error, which is denoted as $P(H_1|H_0)$, can be calculated as

$$P\left(H_1|H_0\right) = \int_{Threshold}^{\infty} f(H_0) \cdot dH_0 \qquad (1)$$

where $f(H_0)$ is the probability density function (pdf) of H_0. Type II error occurs when the decision making judges the observed current to be normal when it is, in fact, a fault, which is denoted by $H_0|H_1$. This kind of error causes the relays not to be able to detect faults. The probability for the type II error, which is denoted as $P(H_0|H_1)$, can be calculated as

$$P\left(H_0|H_1\right)=\int_{-\infty}^{Threshold} f(H_1)\cdot dH_1 \qquad (2)$$

where $f(H_1)$ is the probability density function (pdf) of H_1.

Both of these two errors are important and cause malfunctioning of relays. So the total probability of error is

$$P\left(error\right)=P\left(H_0|H_1\right)\cdot P\left(H_1\right)+P\left(H_1|H_0\right)\cdot P\left(H_0\right) \qquad (3)$$

Our goal is to minimize the probability of malfunctions (errors), so the threshold should be placed to minimize the result of equation (3).

B. Distribution of Normal and Fault Currents

To obtain distributions (i.e., probability density functions) of normal and fault currents, power flow and short-circuit analysis should be run for different conditions in the power system. To obtain the two conditional pdfs, the following assumptions are made in this paper:

1) Loads are random variables, which have a uniform distribution in the range from P_{load}^{min} to P_{load}^{max}.
2) Loads are modelled as constant power sinks ;
3) There is sufficient generation to meet demand.

C. "Smart" Over-Current Relay

"Smart" relays differ from traditional ones in two aspects:

- They keep database/thresholds which is determined via hypothesis testing;
- They apply new technologies such as PMUs and/or GPS.

Until recently, all the available measurement sets in power systems did not include phase angle measurements due to the technical difficulties associated with the synchronization of measurements at remote locations. Global positioning system (GPS) technology alleviated these difficulties and led to the development of Phasor Measurement Units (PMU). Synchronized Phase Measurement Unit (PMU),which was first introduced in mid-1980s, is a monitoring device, which uses synchronization signals from the global positioning system (GPS) satellites and provides the phasors of voltage and currents measured at a given substation [10].

The SMART relays determine the following (see Fig. 3):

- Judge if faults have happened;
- Determine the fault locations;
- Decide which protections should open;
- Decide when to try to reclose.

IV. SIMULATION RESULTS

To illustrate this concept, we consider a modified IEEE14 bus test network [1] [11] that is shown in Fig. 4.

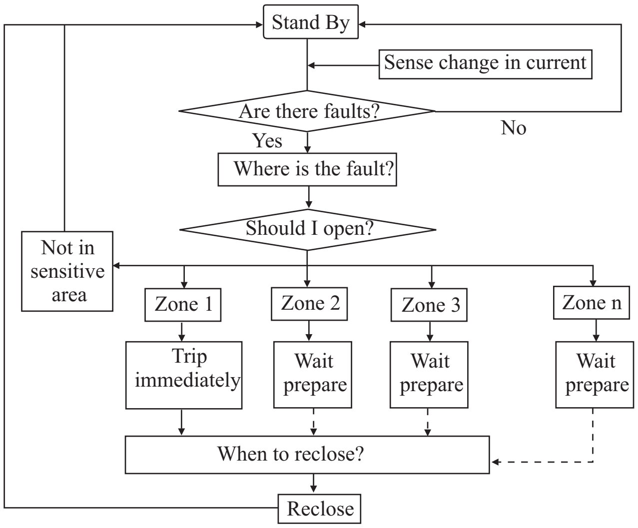

Fig. 3. Working Process (Principle of Operation) of Smart Relays

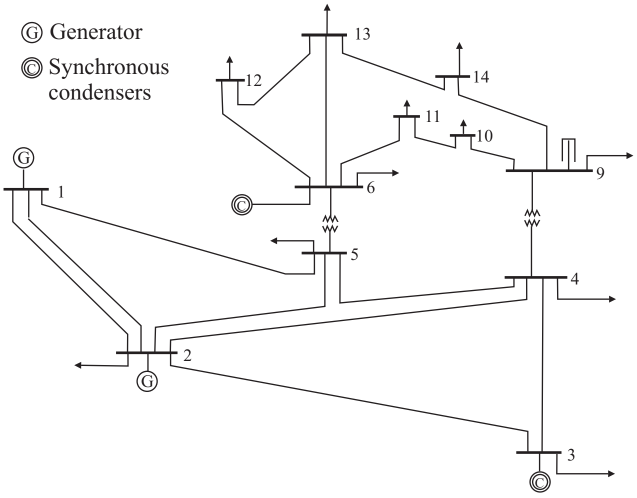

Fig. 4. Modified IEEE 14 Bus Network

A. Distribution of Single Fault Currents

To generate the distributions of normal and fault currents, the following assumptions are made:

1) The loads are random variables, which have a uniform distribution in the range from 80% to 120% of peak value;
2) Loads are modelled as constant power customers;
3) The generators always meet the loads.

Based on the simulation results, the 17 transmission lines can be classified into 4 classes:

- *Class 1*: Transformer: line 4-9, and line 5-6 ;
- *Class 2*: Heavy transmission lines: line 1-2, line 1-5, line 6-13, line 2-5, and line 2-3 ;
- *Class 3*: Weak transmission lines: line 9-10, line 9-14, line 10-11, line 13-14, line 12-13, line 6-12, and line 6-11 ;
- *Class 4*: Others.

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[1] Matlab and PowerWorld are used in simulation. Because of the constraint on the number of nodes in PowerWorld, the three-wing transformer between bus 4 and bus 9 is deleted to build a 12 bus network.

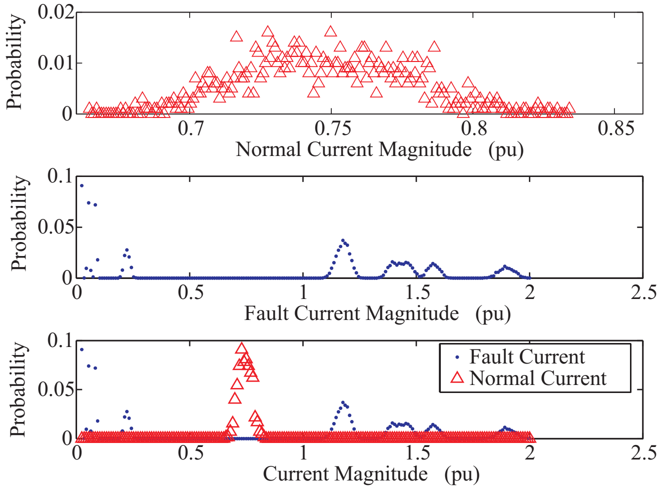

Fig. 5. Distribution of Current on Transmission Line 5-6

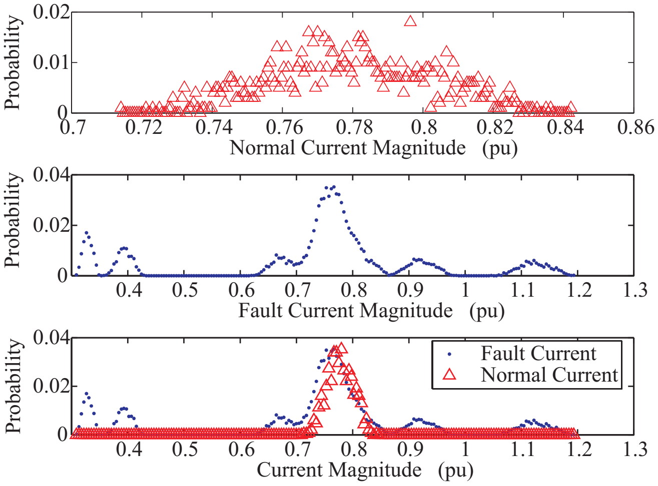

Fig. 6. Distribution of Current on Transmission Line 1-5

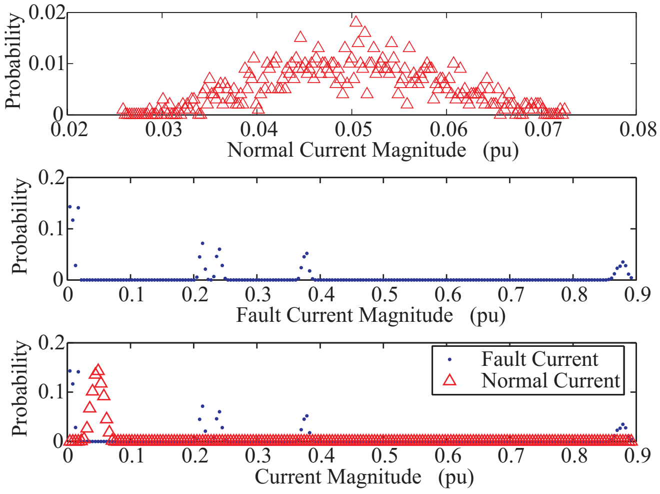

Fig. 7. Distribution of Current on Transmission Line 9-14

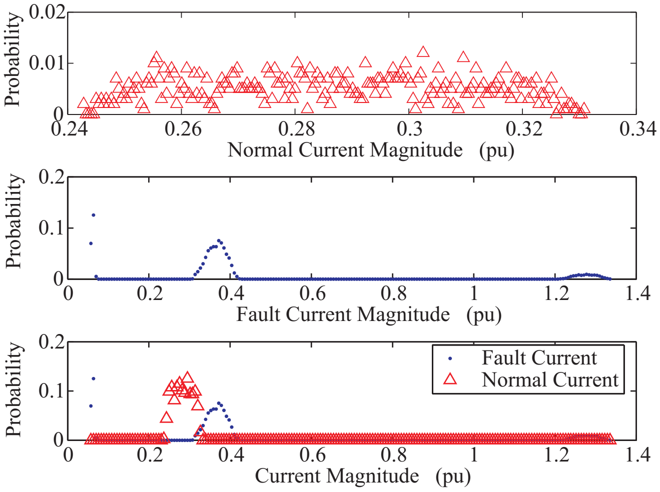

Fig. 8. Distribution of Current on Transmission Line 3-4

Distribution of Class 1 (see Fig. 5):

- Normal current has a Gaussian distribution;
- There are several peaks on the distribution of fault current, which are similar in size;
- The peak of normal current is very far from the peaks of fault current distribution, which makes the discrimination between normal and fault conditions easy.

Distribution of Class 2 (see Fig. 6):

- Normal current has a Gaussian distribution;
- There are several peaks on the distribution of fault current, one of which is much bigger than the others;
- The peak of normal current is very close to the main peak of fault current distribution, which makes the discrimination between normal and fault conditions hard.

Distribution of Class 3 (see Fig. 7):

- Normal current has a Gaussian distribution;
- There are several peaks on the distribution of fault current, which are similar in size and very scattered;
- The peak of normal current, which is located close to the left boundary, is very far from the peaks in fault current distribution, which makes the discrimination between normal and fault conditions relatively easy.

Distribution of Class 4 (see Fig. 8):

- Normal current does not have a Gaussian distribution;
- There are several peaks on the distribution of fault current, which are not always similar in size;
- The peak of normal current has an overlap with fault current, but not as close as the condition in Class 2.

Because of the characteristics of their distributions the threshold placement is relatively easy for the transmission lines in Class 1 and Class 3. However, further research is needed to determine the proper thresholds for the transmission lines in Class 2 and Class 4.

There is an obvious difference between the distributions of fault current and normal current. There is only one peak in normal current distribution while there are several peaks in fault current distribution. Because of these multiple peaks, a standard Gaussian distribution cannot be used to express the

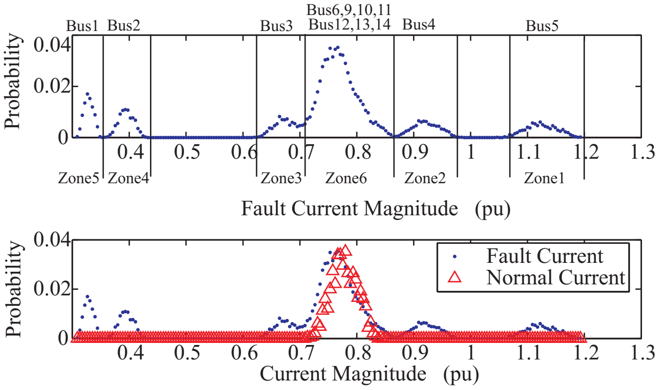

Fig. 9. Relationship between Peaks and Fault Locations (Distribution of Current in Transmission Line 1-5)

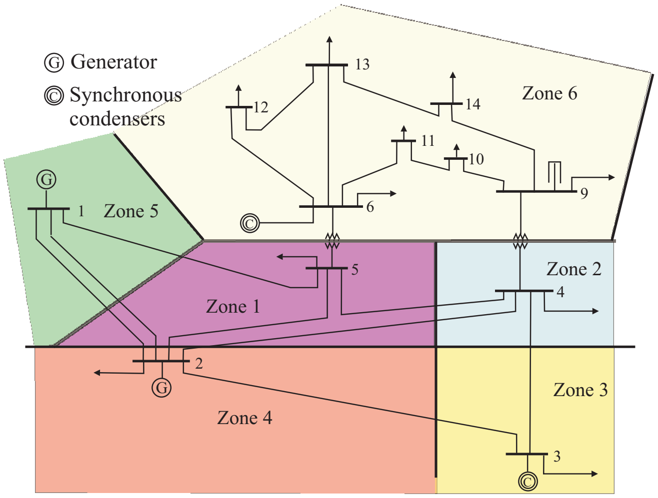

Fig. 10. Fault Locations and their Corresponding Zones (each area presents a set of nodes that belong to one zone)

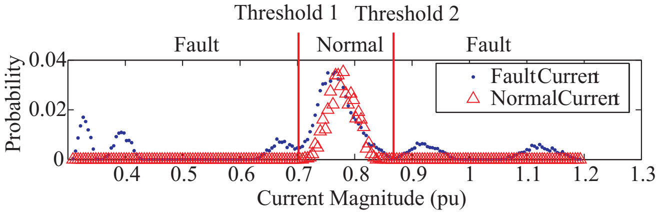

Fig. 11. Dual-Threshold Settings

distribution of fault current. It can be proved, however, that each peak separately has a Gaussian distribution.

To explain why there are more than one peak in the fault current distribution, transmission line 1-5 is analyzed in more detail. Based on the results in Fig. 9, one can conclude that there is a well-defined relationship between fault locations and peaks. In particular, the following observations can be made:

1) Different peaks indicate different fault locations;
2) The peak which is *closest* to normal current is caused by faults that happen in *far away* buses;
3) The highest current is caused by the fault in zone 1;
4) The lowest current is caused by the fault in generators' buses.

The faults located in generators' buses bring the lowest current (see Fig. 9). Because during these faults, generators are connect to ground directly. Supplies go to ground instead of being distributed into systems. So the lowest current appears because of loss of supplies. The fault current located in the main peak of the fault curve (see Fig. 9), which is caused by far away faults, can be treated as the normal current. This current is very close to the normal one, which means that this current at least won't harm the transmission line 1-5 (of course, this doesn't mean that it won't damage other parts of the system). Also, the relays in transmission line 1-5 are too far from the fault, so the relays should just take this condition as normal.

To locate the fault peaks on both the left and the right hand side of the peak of the normal current, two thresholds should be used. As shown in Fig. 11, only the current located between two thresholds is treated as normal, which means either higher or lower current indicate faults.

One can improve these results further: Instead of putting dual-threshold, multi-threshold settings can be used (see Fig. 12). When multi-threshold settings are used, not only the normal and the fault condition can be discriminated, but also the locations of the faults can be detected. For example, if the current is located between threshold 3 and 4, this implies that bus 2 has failed (see Fig. 12).

For the heavy load lines there is always overlap between the main peaks in the normal current distribution and the fault current distribution. Such transmission lines have large admittance and they are connected to heavy loads or generators, so that there are always high currents flowing through. Thus, we observe that the change in current magnitude caused by distant faults is too small compared with the normal current. The most critical situation is shown in Fig. 13, where there are only two peaks in the distribution of fault current. As the hypothesis testing performed indicates, the threshold should be placed around 1.61 pu. This threshold will cause an unacceptable probability of error. To discriminate the fault current from normal one more precisely, Phasor Measurement Units (PMU) can be applied in this transmission line.

As shown in Fig. 14, the phases of the fault current are distributed from -20° to 90°, while the normal current's phase is located around 15.29°. So, although there is a heavy overlap between distributions of normal and fault currents and it is hard to discriminate them by using only the magnitude of current, it is easy to do so when the phases of the currents are also considered.

B. *Threshold Adjustment after Parts of the System are Lost*

In this section, we propose threshold adjustment for cases, where parts of the power systems (e.g., transmission lines, buses) are lost because several switches stay open after previous faults.

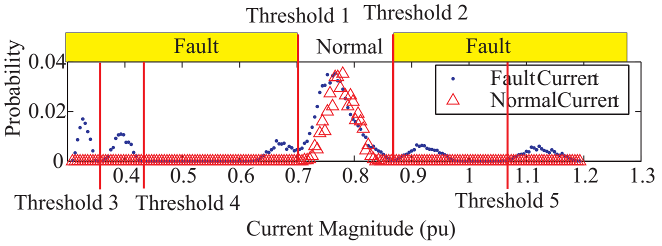

Fig. 12. Multi-Threshold Settings

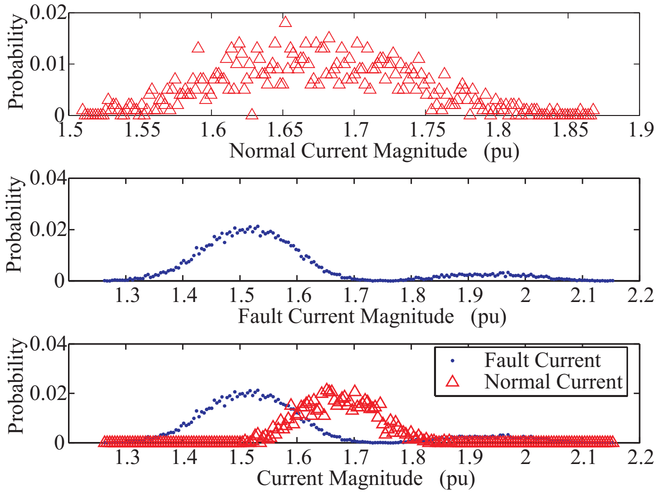

Fig. 13. Distribution of Current in Transmission Line 1-2

It should be pointed out that the malfunctioning of traditional over-current relays in these cases is one of the critical factors which caused the black out in August, 2003. Because traditional over-current relays are not adaptive enough, they don't change their settings after parts of the system fails, which means they always keep the same threshold, without applying PMUs and communications.

From Figures 15-18 one can observe that the failure of a weak bus, which connects no generators, causes the peak of the normal current to shift to the left or change the shape slightly.

For transmission lines in class 1, such a shift causes no problems for the threshold, because the peak of normal current

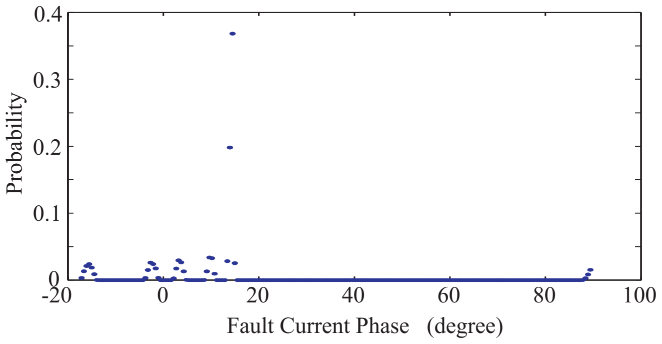

Fig. 14. Phase Distribution of Fault Current

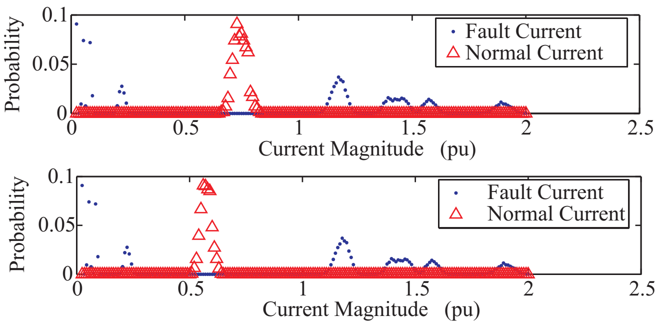

Fig. 15. Distribution of Current in Transmission Line 5-6 (upper) and Distribution of Current in Transmission Line 5-6 when bus 12 failed (lower)

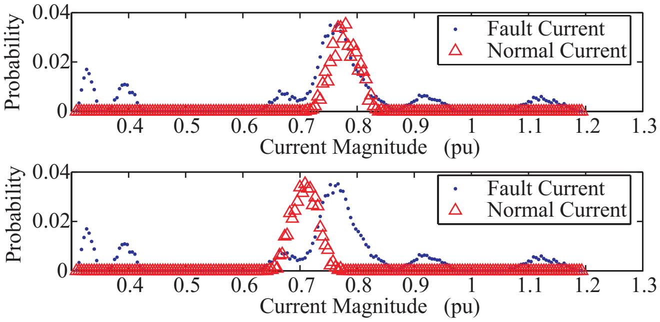

Fig. 16. Distribution of Current in Transmission Line 1-5 (upper) and Distribution of Current in Transmission Line 1-5 when bus 12 failed (lower)

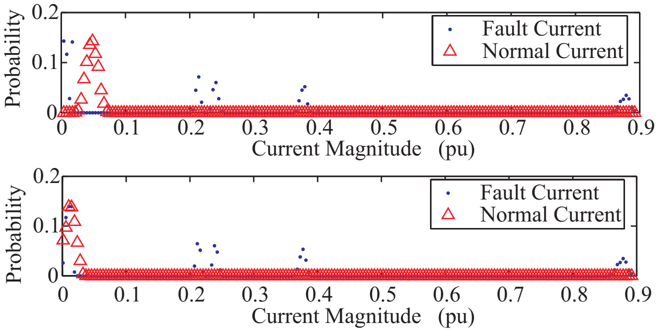

Fig. 17. Distribution of Current in Transmission Line 9-14 (upper) and Distribution of Current in Transmission Line 9-14 when bus 12 failed (lower)

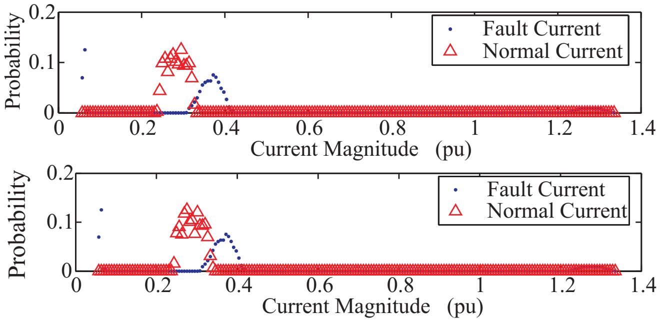

Fig. 18. Distribution of Current in Transmission Line 3-4 (upper) and Distribution of Current in Transmission Line 3-4 when bus 12 failed (lower)

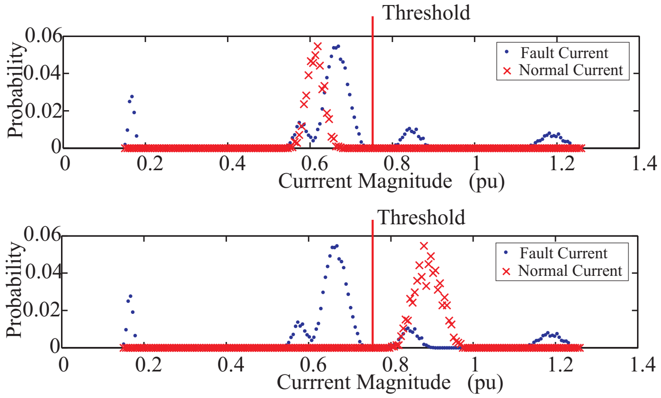

Fig. 19. Distribution of Current in Transmission Line 2-4 (upper), and Distribution of Current in Transmission Line 2-4 when transmission line 4-5 failed (lower) with single threshold in traditional relay

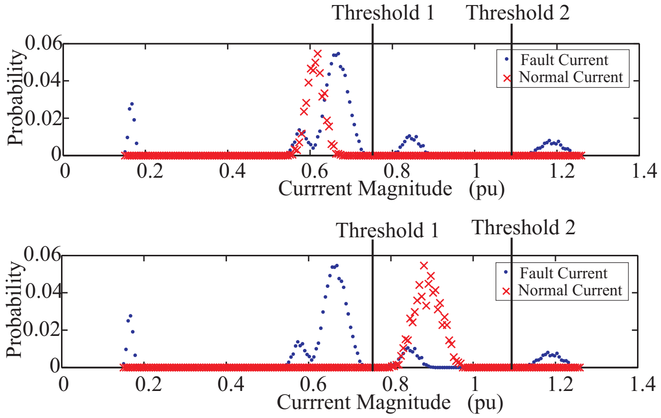

Fig. 20. Distribution of Current in Transmission Line 2-4 (upper) and Distribution of Current in Transmission Line 2-4 when transmission line 4-5 failed (lower) with multi-threshold in the new approach

is far from the ones in fault current distribution. This means that, the same threshold can be used both before and after a weak bus fails. For transmission lines in class 4, the same threshold can be used because the shift is very minor.

For transmission lines in class 2 and class 3, problems could arise because of such a shift. The peak of the normal current curve for class 3 transmission line overlaps with the first two peaks in fault current curve after the multiple fault. For transmission lines in class 2, the overlap turned out to be more profound after shifting. To make a sufficiently good discrimination in class 2 and class 3 transmission lines, PMU should be placed in these transmission lines and buses should gather the phase information.

It can also be shown that the peak of the normal current shift to the right when the fault is on the transmission line. It is a more critical situation due to the fact that the same demand should be satisfied by using reduced power grid. Let us assume that a fault on the line 4-5. Simulation results indicate that, the isolation of transmission line 4-5 did not have a serious effect on the transmission lines 3-4, 2-3, and 2-5, while it produced significant increase of the current in transmission line 2-4.

The distributions of current in transmission line 2-4 before and after transmission line 4-5 failed are shown in Fig. 19 for traditional relays and Fig. 20 for the new approach. One can observe that the current in transmission line 2-4 shifted to right after transmission line 4-5 failed. Traditional relays make decision based on the single threshold shown in Fig. 19. Because the normal current shown in the lower part of Fig. 19 is higher than the fault current caused by faults in Zone 2, traditional relays judge the observed current to indicate Zone 1 fault and trip immediately. If multi-threshold applied, which is shown in the upper part of Fig. 20, relays will not judge the observed current to indicate Zone 1 fault. However, the relays still cannot discrimine this normal condition from Zone 2 fault even when multi-threshold applied. In this condition, besides applying PMUs, communications play a critical role in decision making. Communications make the exchange of decisions possible among relays in transmission line 2-4 and nearby lines. Correct decisions for relay in tranmission line 2-4 could be made by also considering the decisions from its neighbors.

V. DISCUSSION

In this paper, we take a step forward in preparing the power grid against future blackouts. To that end, we make the important observation that the relays used in the protection system of power grid have been critical in sequences of cascading failures. To ensure that they do not malfunction, we argue that more “intelligent” relays can cope with catastrophic failures of future power grids.

The proposed “smart” over-current relays can: 1) decide current settings with a new and more comprehensive logic that utilizes statistical decision theory; 2) use new technologies such as Phasor Measurement Unit (PMU) and/or GPS to improve decision makings; and 3) establish communication between relays to get real-time information.

It is worth mentioning here that the approach outlined in this paper employs a “static” method of determining the normal and fault currents (one could also call this an off-line method). In other words, the normal and fault currents are determined in an “off-line” manner and then stored in a database in the relays. Further research is needed to understand and determine whether such an off-line technique is scalable to the power grid in US which is a very large and complex network. The alternative approach to the one outlined in this paper will be “on-line” approaches whereby the distributions of normal and fault currents are determined in real-time and hypothesis testing is done accordingly. Hybrid approaches might also be viable where the normal current distribution is determined in an “off-line” manner whereas the fault distribution is determined in real-time and in an “on-line” manner. On-line approaches will presumably involve machine learning techniques [12]. Further research is needed to understand the capabilities and limitations of these alternatives.

VI. RELATED WORK

Communications, computer control, and probability estimation are not new in protection systems. Similar studies have been done in [2], [4], [13], and [14]. In [2], the combination of Neural Network based Fault Detection and Classification (NNFDC) algorithm and Synchronized Sampling based Fault Location (SSFL) algorithm are used to provide a more accurate fault analysis for relays. Event tree analysis is applied to understand the event sequences happening at local power systems. Computer control is proposed as a means to solve the selective protection problem in large systems in [4]. During faults, the minimal nested selective protection unit is decided by tracking the evolution of the power system on the computer. In [13] the authors propose that Hidden Faults (HF), which are defined as “a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element as a direct consequence of another switching event”, can be analyzed more accurately in protection systems by making use of the Internet for slow-speed communications and proprietary high-speed networks for real-time critical data. Probability setup, which is proposed in [14], has been applied in determining the Relay Protection and Automatics (RPA) setup channel.

While computer control, communications, real-time tools, and probability estimation have been previously used to improve relay coordination [2] [4] [13] [14], little effort has been reported on their application to individual relays. In this paper, we take the viewpoint that these technologies, which include computer control, communications, real-time analysis, and probability estimation can also be used to improve the functionalities and capabilities of individual relays as well as the protection system as a whole. Thus, it is shown that the reliability, stability, and selectivity of the protection systems can be improved with the improvements in the inherent logic of individual relays.

VII. CONCLUSION

Malfunctioning of traditional relays in current power systems is unavoidable because of the limitations of the logic and some invalid assumptions for relay settings.

In this paper we have proposed a new concept of “smart” relays. “Smart” relays differ from the traditional ones in two aspects:

- They keep database/thresholds determined by hypothesis testing;
- They involve new technologies such as PMU and/or GPS.

It is shown that hypothesis testing is a viable method to help the relays to be more “intelligent” and adaptive. Furthermore, new techniques such as PMU also can be applied to help the relays to make more precise decisions during faults. In future work, communication between relays and updating database/thresholds with real-time information from SCADA will also be considered to make the relays more adaptive.

REFERENCES

[1] J. Apt, L. B. Lave, S. Talukdar, M. G. Morgan, and M. D. Ilic, ”Electrical Blackouts: A Systemic Problem”, *Issues in Science and Technology*, vol. 20, no 4, pp. 55-61, 2004.

[2] J. Zhang, and M. Kezunovic, “Improving Real-time Fault Analysis and Validating Relay Operations to Prevent of Mitigate Cascading Blackouts”, *IEEE 2005 PES Transmission & Distribution Conference & Exposition*, New Orleans, Louisiana, October 2005.

[3] U.S.-Canada Power System Outage Task Force, “Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations”, April 2004.

[4] J. Zaborszky, M. Ilic-Spong, G. Huang, and F. Dobraca, “Computer Control of the Large Power System During Faults For Inherently Adaptive Selective Protection”, *IEEE Transactions on Power Systems*, Vol. PWRS-2, No. 2, pp. 494-504, May 1987.

[5] S. Dixit, E. Yanmaz, and O. K. Tonguz, “On the Design of Self-Organized Cellular Wireless Networks”, *IEEE Communication Magazine*, Vol. 43, No. 7, pp 76-83, July 2005.

[6] J. M. Gers, and E. J. Holmes, *Protection of Electricity Distribution Networks*, 2nd ed. The Institution of Electrical Engineers, 2004. .

[7] H. L. Van Trees, *Detection, Estimation, and Modulation Theory-Part I*. John Wiley & Sons, 1968.

[8] A.D. Whalen, *Detection of Signals in Noise*. Academic Press, 1971.

[9] A. Abur, and A. G. Exposito, *Power System State Estimation, Theory and Implementation*. Harlow, England, Addison-Wesley, 1999.

[10] B. Xu, and A. Abur, “Optimal Placement of Phasor Measurement Units for State Estimation”, Final Project Report, Texas A&M University, October 2005.

[11] Power Systems Test Case Archive http://www.ee.washington.edu/research/pstca/

[12] T. M. Mitchell, *Machine Learning*. McGraw Hill, 1997.

[13] J. De La Ree, Y. Liu, L. Mili, A. G. Phadke, and L .Dasilva, “Catastrophic Failures in Power Systems: Causes, Analyses, and Countermeasures”, *Proceedings of the IEEE*, Volume 93, Issue 5, pp.965-964, May 2005.

[14] A. V. Shmojlov, “Probability setup and technical efficiency of relay protection and automatics”, *KORUS 2005 - The 9th Russian-Korean International Symposium*, pp. 382 - 386, 2005.