Hierarchical Coordinated Protection with High Penetration of Smart Grid Renewable Resources (2.3)

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***Abstract*-- In this paper, new Hierarchically Coordinated Protection (HCP) concept that mitigates and manages the effects of increased grid complexity on the protection of the power system is proposed. The concept is based on predicting protection circumstances in real-time, adapting protection actions to the power system's prevailing conditions, and executing corrective actions when an undesirable outcome of protection operation is verified. Depending on an application, HCP concept may utilize local and wide area measurements of the power system parameters, as well as non-power system data, such as meteorological, detection of lightning strikes, outage data and geographic information. Since HCP introduces intelligence, flexibility and self-correction in protection operation, it is well suited for the systems with increased penetration of renewables where legacy solutions may be prone to mis-operate. Such instances are unintended distance relay tripping for overloaded lines, insensitive anti-islanding scheme operation, and inability to mitigate cascading events, among other system conditions caused by renewable generation prevailing in future grids.**

I. INTRODUCTION

With the increasing energy demand, deregulated power market, environmental concerns and favorable government policies on integration of the renewable generation into the power grid, new challenges and needs in the power grid protection are introduced. The structure of the conventional grid with a few large, centralized generation sources at the transmission system that supply passive load at distribution system is changing towards the network with many renewable distributed generation (DG) sources connected at all voltage levels. In the last decade, due to significant development in the power electronics and digital control technology, a number of large scale, offshore and onshore wind generation units have been installed in the transmission system. Over the time, the transmission system structure becomes more complex and operation scenarios are changed now due deferral of the grid infrastructure upgrade. The system is planned to operate with tighter margins, less redundancy, reduced system inertia and fault levels, and under exemplified dynamic grid operating phenomena such as power and voltage oscillations, as well as voltage, frequency and angular instability. These phenomena may cause new dynamic behavior in the typical protection measurements such as voltage, current, frequency, power, etc. Such changes in the measurement properties may deteriorate protection system performance leading to unintended operation or mis-operation.

Many methods aiming at finding ways for detecting, preventing, and mitigating the cascading events are proposed in the literature. Considering that the cascading phenomena are very complex due to the diversity of failures and interactions, it is not possible to accomplish an exhaustive simulation of all possible combinations of N-m failures in a power system. Thus, different researchers have made various assumptions to reduce complexity in modeling and simulating the cascading outages [1-4]. Some researchers have studied the statistical properties of the power system network [5, 6], other used dynamic event tree analysis [7], expert system [8], pattern recognition [9] etc. to detect cascading events. These methods are either complex to implement and use in the real time applications or simply reduced to assessing the risk of cascading outages and may be used in the system planning stage only.

In addition, installation of DG at the distribution level changes the distribution system behavior from passive network that transfers power from substation to the customers in a radial fashion to an active network with generation sources causing bidirectional flows. This change may affect protection coordination and selectivity, may introduce power quality disturbances and may cause unintentional islanding. Since the island is unregulated, its behavior is unpredictable and voltage, frequency and other power quality parameters may have unacceptable limits. The out-of-phase reclosing is possible and safety of the public or utility workers may be threatened. Thus, the islanded systems should be de-energized promptly.

At the transmission levels, transfer trip is used to prevent islands in the network, while at the medium and low voltage levels active or passive islanding detection scheme are utilized. The passive methods [10-15] discriminate islanding from normal condition based on the measurements of system parameters at the point of common coupling (PCC) with the grid. Those measurements or some features extracted from

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them are compared to the predefined thresholds and are characterized by large non detection zone (NDZ) [16, 17]. Threshold settings for those relays are difficult to calculate because some other events in the grid may cause transients that trigger these relays. On the other head, active methods [18-22] are categorized by smaller NDZ than passive, but those methods inject small disturbances and may cause power quality and stability problems during normal power grid operation. The active methods are embedded into a control circuit of the power inverter and they are designed to inject small disturbances into the DG output. The active methods have small NDZ but they may deteriorate power quality during normal power system operation [23]. Besides, active methods may mis-operate in the system with multiple DGs due to mutual interference and cancelation of the injected disturbances [24] or they may have an effect on the system stability [25].

The paper is organized as follow. In Section II conceptual solution based on the HCP paradigm is described. Section III provides simulation details and illustrates benefits comparing to the existing approaches. The conclusions are summarized in Section IV followed by suggestions for the future work. At the end of the paper an elaborate list of relevant references is given.

II. HIERARCHICAL COORDINATED PROTECTION APPROACH

The aim of this study is to propose conceptual solution that will improve legacy protection operation and mitigate negative effects of the increased grid complexity on the system reliability and power quality. The key questions being faced relates to whether protection schemes should provide more flexibility in their behavior, how flexibility may be justified and how potential uncertainty in protection behavior may be assessed and corrected. As a response to this need the Hierarchically Coordinated Protection (HPC) concept is defined. The proposed approach relies on the three protection layers, shown in Figure 1: predictive protection, adaptive/settingless protection, and relay operation correction in case of unintended tripping. Each layer utilizes new data to perform an analysis, and only the right combination of the analysis at each layer will provide full benefits of the approach. The selection of analysis per each layer is highly dependent on the protection application. The main idea behind each layer is listed next.

The Predictive Protection layer recognizes conditions that lead to the major disturbance using statistics from the systems' earlier contingencies such as weather patterns, lightning, strikes, animal and bird migration patterns, component outage history, etc. This layer compares the unfolding conditions to the ones that lead to the major disturbance in the past and may trigger high intensity computational methods to verify whether the prevailing conditions resemble any previous system conditions. Since this layer may anticipate disturbance it may provide necessary "breathing time" for protection system to adjust bias between dependability and security, which may be implemented through triggering selectable relay setting groups.

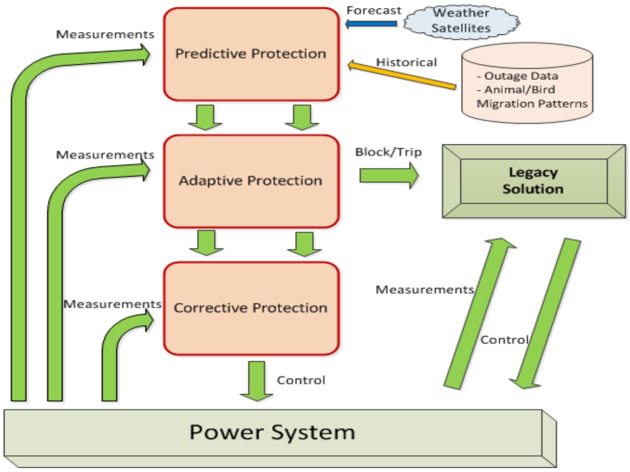

Fig. 1. Hierarchically Coordinated Protection Concept

The next is the Inherently Adaptive Protection layer that adjusts its tripping logic based on feature patterns of waveform measurements extracted in real-time. Such data patterns are matched to the patterns obtained during learning process that includes thousands of potential system conditions. This approach enables flexibility and robustness in protection behavior. Using this approach it is feasible to design a protection scheme that gives equal importance to dependability and security of protective relay operations. This was hard to achieve simultaneously with legacy protection schemes since designing protection systems for trade-offs between dependability and security was common in the past.

The third layer or Corrective Protection acts as a verification tool capable of assessing correctness of relay operation. This tool is characterized by high accuracy, but it has high computational burden, and may have unacceptable operational latency if used in real-time system operation. Thus, this tool should be triggered when a legacy protection scheme operates, and should be active immediately after to correct the original relay action if needed.

Further, two examples that utilize HCP will be presented. In the first example, HCP concept is used to enhance distance protection practice in transmission system that may be prone to misoperation in the overload and power swing condition. This relay misoperation may further lead to unfolding cascading events and system blackout. In the second example, HCP concept is used to detect islanding condition and reduce the negative effect of the active anti-islanding scheme on power quality in the distribution system.

A. Cascading Event Detection and Mitigation

An example of the novel transmission system protection philosophy that relies on HPC design concept is shown in Figure 2. This approach provides enhancements in system-wide monitoring of power system component condition, reliable protective relay operation and capability for corrective actions. The scope of the each HPC layer is described next.

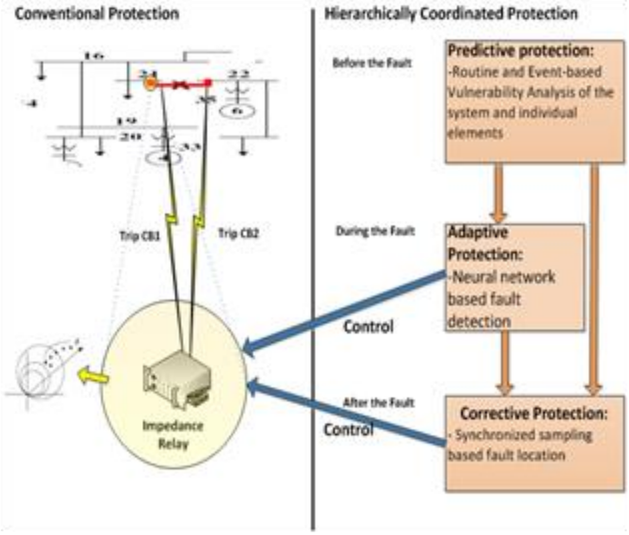

Fig.2 Hierarchically Coordinated Protection Concept for Cascading Event Detection and Mitigation

Predictive Protection: The system monitoring and control tool that performs routine vulnerability analysis of operating condition of the whole system and individual elements is deployed at the control center level and alert signals are sent to the substation level to closely monitor relays placed at the most vulnerable components [26]. The prediction of where the protection mis-operation may occur gives an early warning of how the contingencies may unfold. In addition, the statistical data and information from weather related tracking systems, history of the component outages, and power system operating conditions that may lead to the major disturbances, etc are used to anticipate occurrence of a fault condition may be utilized as well. At this point, due to lack of non-power system data only the vulnerability analysis tool is used.

Inherently adaptive protection: At the substation level, neural network based fault detection and classification algorithm is employed [27]. Its tripping logic is based on feature patterns of waveform measurements that are recognized on line and matched to the patterns obtained during learning process that includes thousands of potential fault conditions. This approach does not have settings and hence avoids mis-operation due to inadequate settings allowing for an inherently adaptive action to optimize the balance between dependability and security.

Corrective protection: At the substation level, fast and accurate synchronized sampling based fault location and event tree analysis are used to detect incorrect line tripping sequence and incorrect relay logic operation respectively [28]. Upon transmission line tripping, fault location algorithm will immediately validate correctness of relay's operation and in case of unconfirmed fault condition; the system component (transmission line) will be quickly restored. The relay logic will be checked as it executes and if an incorrect sequence is detected, the relay action will be corrected.

As an additional example of corrective action, highly accurate distribution system fault location is possible by combining lightning location data form the U.S. National Lightning Detection Network with fault monitor disturbance data and distribution feeder location (GIS) data [29]. The data latency is several seconds and may be used in the corrective protection to verify the fault location determination in the system. Moreover, animals and birds cause large number of outages in overhead distribution systems. The frequency of animal and bird related outages depend on the area, season and time of the day. The historically obtained outage patterns and animal/bird migration patterns may be used to verify the fault location determination in the distribution systems [30].

B. *Anti-islanding Protection*

The new protection approach to reduce negative effect of the active anti-islanding schemes on the power quality in the distribution system is presented next. The framework of the proposed approach consists of the following:

Predictive Protection: For this purpose, non-conventional power system data, the statistical historical event data and information from weather related tracking systems, history of the component outages, etc. may be used to calculate predictive indices. These indices are used to trigger corrective part of the approach. In this study due to lack of non-conventional power system data prediction indices are generated randomly.

Inherently Adaptive Protection: Using measurements at the PCC, Support Vector Machine (SVM) based islanding detection method is utilized [33]. The features from current and voltage signals are constantly extracted and fed to the SV models obtained in the offline training. This approach does not have NDZ and operates independently of generation/load mismatch. It shows great robustness to the external grid events, such as faults and component switching.

Corrective Protection: At the corrective layer, an active anti-islanding method is used. The active methods are characterized by high accuracy; however they may have negative impact on the system power quality during normal system operation. Thus, this method will be normally inactive and prediction indices will be used to trigger the method for short period of time. The corrective layer will sent block/trip signal to the circuit breaker at PCC.

III. MODELING AND SIMULATION RESULTS AND DISCUSSIONS

In this section HPC solution is presented using modeling and simulation examples for two applications and major benefits are assessed when compared to the legacy solutions.

A. *Cascading Events Detection and Mitigation*

In order to illustrate the use and operational efficiency of the proposed Hierarchically Coordinated Protection concept for the transmission applications, the IEEE 39-bus New England test system shown in Figure 4 is utilized [31]. The two most vulnerable lines according to their vulnerable indices are: Line 21-22, 28-29. The outage of those lines will have a large impact on the system stability since the original loads in those two lines will be redistributed to the neighboring lines causing more overloading issues. The system monitoring tool will inform the local relay monitoring tool on those lines to start monitoring relay operations closely. A series of disturbances occur in the system, with the event sequence shown in Figure 5. The related system components are marked in Figure 4.

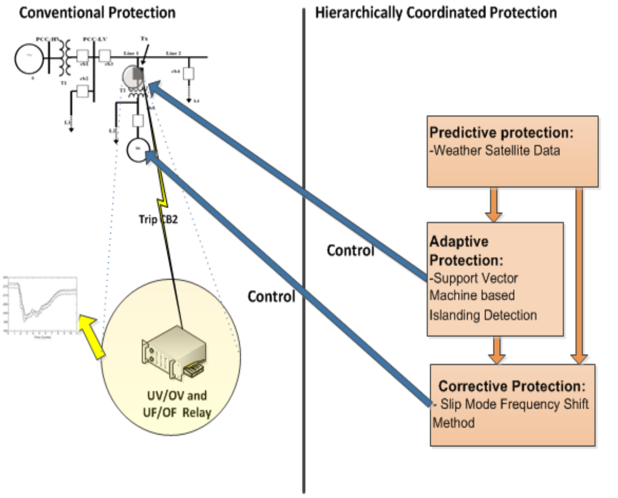

Fig.3. Hierarchically Coordinated Protection Concept for Islanding Detection

These two faults are permanent faults and thus isolated by the relay actions. After the line 21-22 is removed due to the first fault, the top 2 most vulnerable lines are changed to: Line 28-29, 2-3. After the line 28-29 is removed due to the second fault, the top 2 most vulnerable lines are changed to: Line 23-24, 26-29. This contingency may cause relay at Bus 26 of Line 26-29 to mis-operate. The trajectory of impedance seen by that relay is shown in Figure 6 with the event sequence labeled. Although the two faults are not related to the healthy line 26-29, the power swing caused by the two faults will have an impact on the distance relay. It observes Zone 3 fault at 1.627s after the second fault clearing until the trajectory leaves Zone 3 circle at 1.998s. The distance relay may trip Line 26-29 when its Zone 3 timer expires. As a result, buses 29, 38 will be isolated from the system, including the G9 and loads at bus 29. This will results in the oscillation in the rest of the system and further cascading outage may happen.

The mentioned situation can be prevented by the proposed solution and local monitoring and protection tool. When the first fault occurs, the faulted line 21-22 is removed and no other operation happens. The relay monitoring tool for the relay at Line 21-22 will inform the system monitoring tool about the relay operation for the three-phase fault. The system security analysis is activated after the first fault. An alert signal will be sent to the local relay monitoring tool at vulnerable lines at this stage. Since the first fault will not degrade the system stability very much, the local relay monitoring tool will not be authorized to intervene with relay operations at this stage. When the second fault happens and Line 28-29 is removed, the local relay monitoring tools for the most vulnerable lines 23-24 and 26-29 will be authorized to correct the potential relay mis-operation or unintended operation in real time since the mis-operation of those relays will directly separate the system. After the second fault, the local relay monitoring tool at Line 26-29 will draw a conclusion to block the relay from tripping for Zone 3 fault. That information will be sent back to the system level. The system level will issue appropriate control means to mitigate the disturbances. In an actual large scale system, it is impossible that one or two contingencies like the ones discussed in this scenario can cause large scale system oscillation. Usually there is enough time to coordinate the system-wide and local analysis in the initial stages of the disturbances to mitigate the impact of the disturbances before they unfold into the large one. An interactive system-wide and local monitoring and control means can help reduce the probability of a cascading blackout since the disturbances can be fully analyzed at both the local and system level.

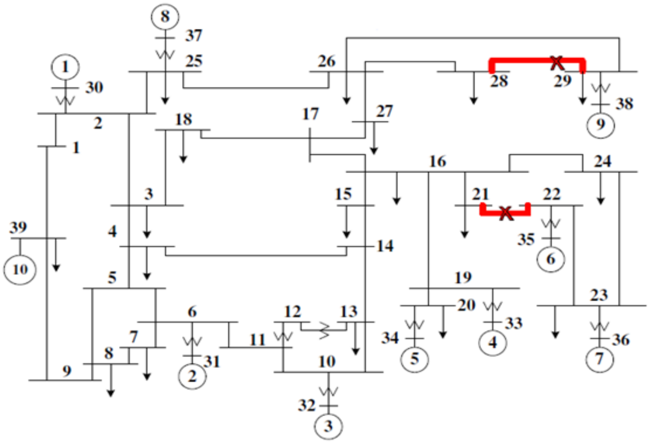

Fig. 4: IEEE 39-bus system

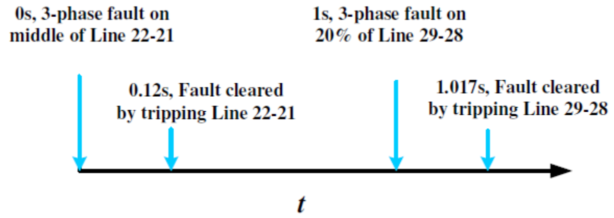

Fig. 5: Event Sequence

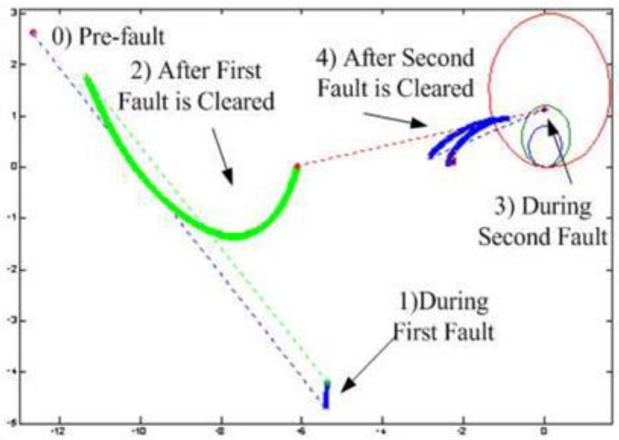

Fig. 6: Trajectory of Impedance

B. Anti-islanding Protection

In order to demonstrate the proposed concept, a study case using IEEE 13-bus test system shown in Figure 7 and modeled using PSCAD/EMTDC is presented [32]. A 5 kVA single phase 120V DG is connected to A phase of the node 692. The

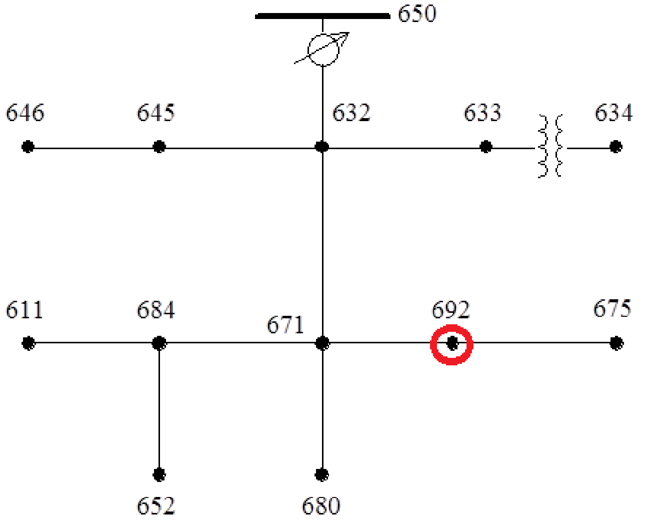

Fig. 7. Diagram of the IEEE 13 distribution test system

decoupled current control interface presented in [22] is used in the study. The inverter control is adjusted so that DG operates at unity power factor. In this arrangement DG supplies maximum active and zero reactive power to the grid. More details about proposed method may be found in [33].

The prediction trigger signal is artificially generated and sliding mode frequency shift method [19] is activated. Twenty cases seen in Table I, ten islanding and ten non-islanding are randomly simulated and all islanding cases were detected by the adaptive layer of the proposed framework. This is obvious sequence of events since active anti-islanding method injects disturbances into the signal and it takes time for the system to respond to the disturbance. To detect islanding condition using adaptive layer it takes 0.1s while the detection time for the sliding mode frequency shift is more than 0.15 s.

IV. CONCLUSIONS

The new proposed approach:

- has superior performance when compared to the existing solutions
- co-exists with the legacy solutions and only supplements its normal operation
- has self-corrections and verification tools
- makes a way for adaptive protection to be accepted as an alternative to conventional protection principle

V. FUTURE WORK

The future work involve exploring and assessing benefits of the proposed paradigm to the proposed power system applications in the protection area taking into account further implementation details.

VI. ACCESS TO PRODUCTS

The findings of the research may be found in the research papers and reports published by PSERC. Details related to implementation are contained in the related Ph.D. Dissertations, as well as in the Dissertation of the co-author.

TABLE I
GENERATED TEST CASES

Cases	**No. of Events**
Fault Event	4
Capacitor Stitching	2
Static Load Switching	2
Motor Load Switching	2
Islanding	10 (±20 % active power and ±3% reactive power mismatch)

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

[1] B. A. Carreras, V. E. Lynch, I. Dobson, and D. E. Newman, “Complex dynamics of blackouts in power transmission systems,” Chaos, vol.14, pp. 643–652, 2004.

[2] I. Dobson, B. A. Carreras, and D. E. Newman, “A branching process approximation to cascading load-dependent system failure,” 37th Hawaii International Conference on System Sciences, Hawaii, January 2004.

[3] H. Ren, I. Dobson, “Using transmission line outage data to estimate cascading failure propagation in an electric power system,” IEEE Trans. Circuits and Systems Part II, 2008, vol. 55, no. 9, pp. 927-931.

[4] X. Yu and C. Singh, “A practical approach for integrated power system vulnerability analysis with protection failures,” *IEEE Trans. on Power Systems*, vol. 19, no. 4, pp. 1811-1820, 2004.

[5] D. J. Watts, Small worlds, The dynamics of networks between order and randomness, Princeton University Press, Princeton, NJ, USA 2003

[6] P. Hines, S. Blumsack, “A centrality measure for electrical networks,” 41st Hawaii International Conference on System Sciences, Hawaii, Jan. 2008.

[7] Q. Chen, K. Zhu, and J.D. McCalley, "Dynamic decision-event trees for rapid response to unfolding events in bulk transmission systems," in IEEE 2001 Power Tech Proceedings, vol. 2 , Porto, Portugal, Sept. 2001.

[8] J.C. Tan, P.A. Crossley, and P.G. McLaren, "Application of a wide area backup protection expert system to prevent cascading outages," IEEE Transactions on Power Delivery, vol. 17, no. 2, pp. 375 – 380, April 2002.

[9] C. C. Liu, Learning to recognize the vulnerable patterns of cascaded events, EPRI Technical Report, 2007.

[10] W. Bower and M Ropp, “Evaluation of islanding detection methods for photovoltaic utility-interactive power systems”, IEA Task V Report IEA-PVPS T5-09, March 2002.

[11] A. Samui and S. R. Samantaray, “Assessment of ROCPAD relay for islanding detection in distributed generation,” IEEE Trans. Smart Grid, vol. 2, no. 2, pp. 391–398, Jun. 2011.

[12] J. Stevens, R. Bonn, J. Ginn, S. Gonzalez, G. Kern, “Development and Testing of an Approach to Anti-Islanding in Utility-Interconnected Photovoltaic Systems,” Tech Rep., Sandia National Laboratories, Albuquerque, NM, August 2000.

[13] Shyh-Jiler H., Fu-Sheng P. ‘A new approach to islanding detection of dispersed generators with self-commutated static power converters’, IEEE Trans. Power Deliv., 2000, 15, (2), pp. 500–507.

[14] Sung-Il Jang; Kwang-Ho Kim; , "An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current," Power Delivery, IEEE Transactions on , vol.19, no.2, pp. 745- 752, April 2004.

[15] S. K. Salman, D. J. King, and G. Weller, “Detection of loss of mains based on using rate of change of voltage and changes in power factor,” in Universities Power engineering conf.(UPEC 2000), Belfast, 2000.

[16] L. A. C. Lopes and H. Sun, “Performance assessment of active frequency drifting islanding detection methods,” IEEE Trans. Energy Convers., vol. 21, no. 1, pp. 171–180, Mar. 2006.

[17] M. E. Ropp, M. Begovic, A. Rohatgi, G. A. Kern, R. H. Bonn, and S. Gonzalez, “Determining the relative effectiveness of islanding detection methods using phase criteria and non detection zones,” IEEE Trans. Energy Convers., vol. 15, no. 3, pp. 290–296, Sep. 2000.

[18] G. Hung, C. Chang, and C. Chen, “Automatic phase-shift method for islanding detection of grid-connected photovoltaic inverter,” IEEE Trans. Energy Conversion, vol. 18, no. 1, pp. 169-173, Mar. 2003.

[19] S. Yuyuma, T. Ichinose, K. Kimoto, T. Itami, T. Ambo, C. Okado, K. Nakajima, S. Hojo, S. Shinohara, S. Ioka, M. Kuniyoshi, “A High Speed Frequency Shift Method as a Protection for Islanding Phenomena of Utility Interactive PV Systems”, Sol. Energy Materials, Sol. Cells, Vol. 35, Issue 1-4, 1994, pp. 477-486.

[20] M. C.Wrinch, “Negative sequence impedance measurement for distributed generator islanding detection,” Ph.D. dissertation, niversity of British Columbia, 2008

[21] G. Hernandez-Gonzalez and R. Iravani, “Current injection for active islanding detection of electronically-interfaced distributed resources,” IEEE Trans. Power Del., vol. 21, no. 3, pp. 1698–1705, Jul. 2006

[22] Jeraputra, C.; Enjeti, P.N.; , "Development of a robust anti-islanding algorithm for utility interconnection of distributed fuel cell powered generation," *Power Electronics, IEEE Transactions on* , vol.19, no.5, pp. 1163- 1170, Sept. 2004.

[23] Bower, Ward I., and Michael Ropp. Evaluation of Islanding Detection Methods for Utility-Interactive Inverters in Photovoltaic Systems. No. SAND2002-3591. Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US), 2002.

[24] Lopes, L.A.C.; Yongzheng Zhang; , "Islanding Detection Assessment of Multi-Inverter Systems With Active Frequency Drifting Methods," Power Delivery, IEEE Transactions on , vol.23, no.1, pp.480-486, Jan. 2008.

[25] Xiaoyu Wang; Freitas, W.; Dinavahi, V.; Xu, W.; , "Investigation of Positive Feedback Anti-Islanding Control for Multiple Inverter-Based Distributed Generators," *Power Systems, IEEE Transactions on* , vol.24, no.2, pp.785-795, May 2009.

[26] Song, H., “The Detection, Prevention and Mitigation of Cascading Outages in the Power System,” Ph.D. dissertation, Dept. Electrical Eng, Texas A&M University, 2006.

[27] S. Vasilić, M. Kezunović, “Fuzzy ART Neural Network Algorithm for Classifying the Power System Faults,” IEEE Transactions on Power Delivery, Vol. 20, No. 2, pp 1306-1314, April 2005.

[28] Zhang, N. “Advanced fault diagnosis techniques and their role in preventing cascading blackouts” Ph.D. dissertation, Dept. Electrical Eng, Texas A&M University, 2006.

[29] Kappenman, J.G.; Gordon, M.E.; Guttormson, T.W.; , "High-precision location of lightning-caused distribution faults," Transmission and Distribution Conference and Exposition, 2001 IEEE/PES , vol.2, no., pp.1036-1040 vol.2, 2001.

[30] Min Gui; Pahwa, A.; Das, S.; , "Analysis of Animal-Related Outages in Overhead Distribution Systems With Wavelet Decomposition and Immune Systems-Based Neural Networks," Power Systems, IEEE Transactions on , vol.24, no.4, pp.1765-1771, Nov. 2009.

[31] M. A. Pai, Energy Function Analysis for Power System Stability, Boston: Kluwer Academic Publishers, 1989, pp. 223-227.

[32] Kersting, W.H. “Radial Distribution Test Feeders”, Transaction on PowerSystem, August 1991, pp. 975-985.

[33] Matic-Cuka, B., Kezunovic M. “Machine Learning Approach to Islanding Detection for Inverter-based Distributed Generation” submitted to IEEE Transactions on Smart grid.

IX. BIOGRAPHIES

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