ENHANCEMENT OF A FAULT ANALYSIS METHOD USING ARC RESISTAANCE FORMULA

HOUMAN OMIDI

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Specially dedicated:

To my beloved family

My mother, father

And

Dearest sister

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ABSTRACT

Generally there are two different methods in calculation short-circuit currents in power system networks in terms of considering arc resistance in calculations, first method is based on considering the value of the arc resistance as a constant value (usually 0.5Ω) or neglecting this value. By introducing some formulae for the arc resistance like the Warrington formula which is one of the most well-known formulae second method could be applied. Second method is based on considering the value of the arc resistance in short-circuit calculation. To calculate the short-circuit current in power system networks our model should be accurate enough, to have an accurate model in theses studies the value of the arc resistance should be considered. The problem here is the non-linear relationship between fault current and arc resistance. By using more accurate formula like Terzija has been proposed in one of the recent studies values of short-circuit current and arc resistance can be identified more accurate but still there are some problems relates to the high fault currents. In this study by using ETAP software for fault analysis, Microsoft visual studio 2010 (C++ programming) for the related iteration and one the most recent formula for the arc resistance, short-circuit studies based on symmetrical components has been investigated on two different IEEE networks; IEEE 30-bus and IEEE 34-bus test feeders. Results have been compared with fault analysis based on phase coordination in the same network and shows the efficiency of the arc resistance formula which has been used in this study in special range of fault currents in balanced and unbalanced networks.

ABSTRAK

Secara umumnya, terdapat dua kaedah yang berbeza dalam pengiraan litar pintas arus dalam rangkaian sistem kuasa dari segi mengingati rintangan arka dalam pengiraan, kaedah pertama adalah berdasarkan mempertimbangkan nilai rintangan arka sebagai nilai malar (biasanya 0.5Ω) atau mengabaikan nilai ini. Dengan memperkenalkan beberapa formula untuk rintangan arka seperti formula Warrington yang merupakan salah satu kaedah yang paling terkenal kedua formula boleh digunakan. Kaedah yang kedua ialah berdasarkan menimbangkan nilai rintangan arka dalam pengiraan litar pintas. Untuk mengira arus litar pintas dalam rangkaian sistem kuasa model kita harus cukup tepat, untuk mempunyai model yang tepat dalam kajian tesis nilai rintangan arka perlu dipertimbangkan. Masalah di sini adalah hubungan bukan linear antara arus kerosakan dan rintangan arka. Dengan menggunakan formula yang lebih tepat seperti Terzija telah dicadangkan dalam salah satu nilai kajian terkini litar pintas semasa dan arka rintangan boleh dikenal pasti yang lebih tepat tetapi masih terdapat beberapa masalah yang berkaitan dengan arus kerosakan yang tinggi. Dalam kajian ini dengan menggunakan perisian ETAP untuk analisis kesalahan, Microsoft visual studio 2010 (C++ pengaturcaraan +) bagi lelaran yang berkaitan dan 1-formula paling terkini untuk rintangan arka itu, litar pintas kajian berdasarkan komponen simetri telah telah disiasat pada 2 IEEE rangkaian yang berbeza IEEE 30-bas dan IEEE ujian pemakan 34-bas. Keputusan telah dibandingkan dengan analisis kesalahan berdasarkan penyelarasan fasa dalam rangkaian yang sama dan menunjukkan kecekapan formula rintangan arka yang telah digunakan dalam kajian ini dalam julat khas arus kerosakan dalam rangkaian yang seimbang dan tidak seimbang.

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CHAPTER 1

INTRODUCTION

1.1 Background

This chapter discuses about the objectives, scope, significant and a short background of this study and this dissertation. This study focuses on fault analysis methods in both balanced and unbalanced systems and enhancement of these methods by using arc resistance formula which has been got from one the recent studies [1] and test this formula in two different IEEE test networks and compare the obtained values with the values which obtained based on previous methods.

Short-Circuit current calculation in power system networks is necessary for different reasons like network planning, operation purposes and also for network designs and expansions. Design of switchgears and protection devices needs accurate calculation of short-circuit current which protection coordination is so sensitive to these calculations. By introduction of distribution generators (DG) and other renewable sources these studies become more important than ever. In order to calculate the accurate value of the short-circuit current we should have an accurate model of our system.

In fault calculation both maximum and minimum fault currents are calculate for the related network. To calculate the maximum short-circuit current we should assume that all generators are connected and the load is maximum load and also the fault is bolted which the fault impedance equals to zero.

To calculate the minimum current we assume that the number of connected generators has the minimum value and the load is at a minimum, also the fault is not a bolted fault which means that the fault impedance is consists of tower footing resistance and the arc resistance. It means to calculate the minimum current the arc resistance should be taken into account. The point here is that the practical value which often use for the fault resistance introduces a large error into our final results of calculation because these values are far away from the actual values.

The networks in the power system that we are going to analyze may be radial or meshed, balanced or unbalanced and also may be single-phase, two-phase or three-phase which need different calculation methods.

For example distribution system which is one of the most complex systems to analyse is generally unbalanced, there are many different methods to analyze a distribution network which some of them are based on symmetrical components and others are not. The main advantage of the symmetrical component method is that the three sequence matrices are treated separately but the problem relates to this method is that this method does not enable the exact modeling of the four-wire distribution networks.

Arc resistance which is an important macroscopic parameter describes the complex nature of arcs. Arc discharge is occurred in everyday use of power system equipment [2].

Permanent faults in power system equipment like machines, transformers, cables and transmission line always involve an arc. Every time which a circuit breaker is opened when carrying a current an arc strikes between its separating contacts.

All arcs in nature possess a highly complex nonlinear nature which is influenced by a number of factors. This phenomenon can be considered as an element of an electrical power system which has a resistive nature, for example as a pure resistance. One of the important factors in describing the arc behavior and arc resistance is the length variation.

Warrington formula is one of the formulas which the fault arc resistance can be calculated by use of this formula. He (Warrington) derived a relationship by using the measured arc voltage gradient and arc current for arc voltage. Recent studies shows that his measurements and the results according to his measurements are not accurate [2], in this study one of these new studies which has been done by Terzija (2011) [1] has been used.

To calculate the fault current in power system networks accurately we need an accurate model of fault which must include the electrical arc existing at the fault point which is so important in fault current calculation. In this study the value of the arc resistance at the fault point must be known in advance. But the question is how to calculate the arc resistance and fault current at the fault location when these two values are related to each other.

In this study the goal is to introduce some of most applicable short-circuit analysis for balanced and unbalanced networks and enhance these methods by using the arc resistance formula to achieve more accurate values of short-circuit current and arc resistance.

1.2 Problem Statement

Statistically in more than 80% of all faults arcing faults occur [3] which makes the consideration of arc resistance in fault analysis essential. To calculate the arc resistance value the problem is that the fault current depends on arc resistance which itself a nonlinear function of fault current so, the question here is how to calculate the unknown arc resistance and fault current consequently and also accurately.

Previously in calculating the short-circuit the value of the arc resistance has been assumed to be constant (e.g. 0.5Ω) or has been neglected at the fault location. But the problem relates to these calculations is that the currents obtained by this are larger than those which would be obtained if the value of the arc resistance had been included in the calculation procedure. On the other hand, the actual value of the arc resistance which exists on the fault location would affect the real value of the fault current.

The arc resistance physically is determined by the arc current and the arc length which is proportional to the arc length and inversely proportional to the arc current. Compare to the existing methods of short-circuit calculation which the arc resistance has been totally neglected or assumed to have a constant value the method which is used in this study offers a more accurate short-circuit current calculation which can be useful in protection coordination and also power system design and planning. Because based on these studies the components of switchgears are designed, constructed, manufactured and installed and protective devices are so sensitive in changing of these values.

If the arc resistance is neglected the value of the impedance would be 25% smaller compare to the real value [1] which affects the fault current and can cause calculating wrong values of fault current. Therefore this method offers a more realistic approach and calculations of short-circuit currents and voltage profile is more accurate.

So one of the significant achievements of this study is that this method calculate short-circuit current and arc resistance consecutively which improves the accuracy of this computation.

One of the objectives of any short-circuit analysis is to calculate the fault current and the voltages. Short-circuit studies is needed for many power system studies such as transient stability and voltage sag analyses.

Distribution system in power system domain is one of the most complex systems. Analysis of distribution system becomes more important in recent days because of expansion of these networks and also the automation of its operation. To determine the rating of the protective devices in the distribution and design of the switchgears short-circuit analysis is an important tool. Distribution systems are generally unbalanced so, the analysis of short-circuit current in unbalanced networks becomes more important.

Symmetrical components method is one of the traditional fault analyses [4]which is implemented in the majority of software packages which are used today in industries. The reason lies on the computational efficiency and the simplicity of modeling power system elements such as generators and transformers but the existence of single-phase and two-phase lines in three-phase system made the application of symmetrical components complicated for fault analysis.

The other issue which will be discussed in this study is analyzing the different methods of short-circuit calculation for both balanced and unbalanced networks. There are different methods to solve an unbalanced network, in this study some of the methods which are used to solve balance and unbalanced networks will be discussed and these methods are also has been compared to each other and advantages and disadvantages of each method has been discussed.

1.3 Objectives

The aim of this study is to investigate the applicable methods of short-circuit analysis in both balanced and unbalanced power system networks and compare these methods to each other.

In analyzing the short-circuit methods the effects of considering the arc resistance in calculating the fault current is also investigated which need to analyse the iterative method to calculate the accurate value of the arc resistance.

In this study the effects of considering arc resistance in two different IEEE test networks has been investigated and has been compared to the previous methods which do not consider this value into their calculations.

So the objectives could be specified as:

i. To analyze the importance and effects of considering the arc resistance in calculation of short-circuit current in balanced and unbalanced networks.
ii. To analyze the iterative method of finding the short-circuit current and the value of the arc resistance consequently which is based on an arc resistance formula.
iii. To evaluate the fault analysis methods which are used to calculate short-circuit currents in both balanced and unbalanced networks
iv. To test a fault analysis method in balanced and unbalanced networks using ETAP software on two IEEE test networks.
v. To compare the method of considering arc resistance in fault analysis and methods which do not consider this value in both balanced and unbalanced networks.

According to the objectives which has been shown above two simulations has been done in this study in one balanced and one unbalanced networks in two different cases:

i. Case a: Considering the value of the arc resistance.
ii. Case b: Ignoring the value of the arc resistance.

1.4 Scope

The scope of this study is based on distribution networks due to existence of unbalanced loads in this network but the results can be extended to any other balanced or unbalanced networks.

To show the efficiency of this method result of short-circuit current simulation with and without considering arc resistance has been analysed.

As it considered before, our calculation according to the iterative method has been done on two different IEEE networks:

i. IEEE 34 Distribution Network
ii. IEEE 30 Bus Power System Test Case

Which the case a represent the unbalanced network and case b has been used as the balanced network.

1.5 Significance

By calculating the accurate value of the arc resistance according to the formula which is based on one of the recent studies [1] the accurate value of the current and impedance can be obtained.

This process will help us to improve the efficiency of the protection system which is so sensitive to the changes of these values. Also using these new and accurate values of current and impedance in procedure of sizing switchgears and components like CBs and bus bars is so useful.

Another application which can be considered using these new values is based on use of artificial intelligence of distribution system protection. For example this method will increase the learning ability and efficiency of neural networks.

On the other hand studying different fault analysis methods will help us to choose between these methods the appropriate model for our case. Traditional fault analysis is based on the symmetrical components which for any unbalanced fault the three sequence networks should be modified and they should connected together appropriately to model the fault conditions.

Several new methods have been proposed base on the Symmetrical component method. If the system contains the elements of unbalanced parameters which include mutual couplings between the sequence networks, in this case the symmetrical components will lose its advantages.

One of the recent methods which has been discussed in this study is named by Hybrid Compensation Method which capable of handling features of distribution system with different configurations.

The hybrid compensation method is basically a distribution power flow which has been developed by the Pacific Gas and Electric Company to solve short-circuit analysis in unbalanced system. Since this method does not work based on forming traditional admittance matrices this method achieves high speed and robust convergence with low needed memory.

1.6 Organization of Project

To obtain the appropriate results, this study has been divided into 5 main chapters. In the first chapter the background information, objectives, scope and significance of study has been discussed. Basically this chapter has been focused on preparing general information about the related topic and clarifies the objectives and scope of the study.

In the second chapter, improvements of two different methods relate to the calculation of arc resistance and short-circuit calculation has been discussed through the time.

Third chapter is consists of the theoretical materials which is needed as basic knowledge to understand the more complicated parts which has been discussed in the next chapter, in terms of fault analysis and specially recent methods of short-circuit analysis. Symmetrical components and basic fault analysis in balanced networks are some of these parts. Some of recent methods like the hybrid compensation method has been discussed in this chapter.

In the next chapter the methodology of this study is discussed which includes two major parts. The first part relates to the arc formula that has been used and second part relates to a fault analysis for unbalanced networks. The fault analysis which has been discussed in this chapter contains the basic concepts of calculating short-circuit analysis in unbalanced networks.

Last chapter relates to the results of utilizing arc resistance formula and using ETAP software and iterative method consequently and analyzing these results. The arc resistance formula has been discussed in both balanced network and unbalanced networks. To test the methodology of this study below networks are used.

i. IEEE 34 Distribution Network
ii. IEEE 30 Bus Power System Test Case

REFERENCES

1. Terzija, V.V., R. Ciric, and H. Nouri, *Improved Fault Analysis Method Based on a New Arc Resistance Formula.* Power Delivery, IEEE Transactions on, 2011. **26**(1): p. 120-126.
2. Terzija, V.V. and H.J. Koglin, *A new approach to arc resistance calculation.* Electrical Engineering, 2001. **83**(4): p. 187-192.
3. Terzija, V.V. and D.M. Dobrijevic. *Short Circuit Studies in Transmission Networks Using Improved Fault Model*. in *Power Tech, 2007 IEEE Lausanne*. 2007.
4. Lin, W.M. and T.C. Ou, *Unbalanced distribution network fault analysis with hybrid compensation.* Generation, Transmission & Distribution, IET, 2011. **5**(1): p. 92-100.
5. Terzija, et al., *Long arc in free air elongation effects modeling and simulation*, 2002, Wiley: Chichester, ROYAUME-UNI. p. 7.
6. Andrade, V.D. and E. Sorrentino. *Typical expected values of the fault resistance in power systems*. in *Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010 IEEE/PES*. 2010.
7. Warrington, A. and C. Van, *Reactance relays negligibly affected by arc impedance.* Electrical World, 1931. **98**(12): p. 502-505.
8. van C. Warrington, A.R., *Protective Relays Their Theory and Practice: Volume Two*1978: Springer.
9. *IEEE Guide for Protective Relay Applications to Transmission Lines.* IEEE Std C37.113-1999, 2000: p. i.
10. Ayrton, H., *The Mechanism of the Electric Arc.* Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character, 1902. **199**(ArticleType: research-article / Full publication date: 1902 / Copyright © 1902 The Royal Society): p. 299-336.
11. Domin, T.J. and J.L. Blackburn, *Protective Relaying: Principles and Applications*2006: Taylor & Francis.
12. Goda, Y., et al., *Arc voltage characteristics of high current fault arcs in long gaps.* Power Delivery, IEEE Transactions on, 2000. **15**(2): p. 791-795.
13. Jeerings, D.I. and J.R. Linders, *Ground resistance-revisited.* Power Delivery, IEEE Transactions on, 1989. **4**(2): p. 949-956.
14. Mason, C.R., *The art and science of protective relaying*1956: Wiley.
15. Strom, A.P., *Long 60-Cycle Arcs in Air.* American Institute of Electrical Engineers, Transactions of the, 1946. **65**(3): p. 113-118.

16. Terzija, V.V., R.M. Ciric, and H. Nouri, *A new iterative method for fault currents calculation which models arc resistance at the fault location.* Electrical Engineering, 2006. **89**(2): p. 157-165.

17. Terzija, V.V. and H.J. Koglin, *New dynamic model, laboratory testing and features of long arc in free air.* Electrical Engineering, 2001. **83**(4): p. 193-201.

18. Terzija, V.V. and H.J. Koglin, *On the modeling of long arc in still air and arc resistance calculation.* Power Delivery, IEEE Transactions on, 2004. **19**(3): p. 1012-1017.

19. Barnard, J. and A. Pahwa, *Determination of the impacts of high impedance faults on protection of power distribution systems using a probabilistic model.* Electric Power Systems Research, 1993. **28**(1): p. 11-18.

20. Ziegler, G. and S. Aktiengesellschaft, *Numerical distance protection: principles and application*2000: Publicis MCD.

21. *IEEE Guide for Power-Line Carrier Applications.* IEEE Std 643-2004 (Revision of IEEE Std 643-1980), 2005: p. 0_1-134.

22. Browne, T.E., *A Study of A-C Arc Behavior Near Current Zero by Means or Mathematical Models.* American Institute of Electrical Engineers, Transactions of the, 1948. **67**(1): p. 141-153.

23. Djurić, M.B., Z.M. Radojević, and V.V. Terzija, *Arcing faults detection on transmission lines using least error squares technique.* European Transactions on Electrical Power, 2007. **8**(6): p. 437.

24. Djuric, M.B. and V.V. Terzija, *A new approach to the arcing faults detection for fast autoreclosure in transmission systems.* Power Delivery, IEEE Transactions on, 1995. **10**(4): p. 1793-1798.

25. Djurić, M.B., V.V. Terzija, and Z.M. Radojević, *Overhead lines fault location and arc voltage estimation numerical algorithm derived in time domain.* Electrical Engineering, 1998. **81**(1): p. 45-53.

26. Engel, T.G., A.L. Donaldson, and M. Kristiansen, *The pulsed discharge arc resistance and its functional behavior.* Plasma Science, IEEE Transactions on, 1989. **17**(2): p. 323-329.

27. Habedank, U., *Application of a new arc model for the evaluation of short-circuit breaking tests.* Power Delivery, IEEE Transactions on, 1993. **8**(4): p. 1921-1925.

28. Hanson, J., et al. *Fault arc resistance of cable bundles for space applications*. in *Electrical Insulation, 1996., Conference Record of the 1996 IEEE International Symposium on*. 1996.

29. Hong-chun, S., P. Shi-xin, and Z. Xing-bing. *Integration of multi-algorithm for single-phase fault detection in distribution system with arc suppression coil grounding using extenics*. in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*. 2008. IEEE.

30. Kim, C.J. and B.D. Russell, *Analysis of distribution disturbances and arcing faults using the crest factor*. Electric Power Systems Research, 1995. **35**(2): p. 141-148.

31. Knobloch, H. and U. Habedank. *Arc resistance at current zero: a tool to describe the breaking capacity of SF₆ circuit-breakers at short-line faults*. in *High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467)*. 1999.

32. Ohnishi, H., et al., *Measurement of arc resistance and dielectric breakdown voltage at intermittent grounding of 6.6 kV distribution CVT cable.* Power Delivery, IEEE Transactions on, 1988. **3**(1): p. 363-367.

33. Radojevic, Z.M., V.V. Terzija, and M.B. Djuric, *Multipurpose overhead lines protection algorithm.* Generation, Transmission and Distribution, IEE Proceedings-, 1999. **146**(5): p. 441-445.

34. Sousa, J., D. Santos, and M.T.C. de Barros. *Fault arc modeling in EMTP*. in *International Conference on Power Systems Transients, Lisboa Portugal*. 1995.

35. Terzija, V. and H.J. Koglin. *On the modeling of long arc in still air and arc resistance calculation*. in *Power Engineering Society General Meeting, 2004. IEEE*. 2004.

36. Terzija, V.V., R.M. Ciric, and H. Nouri. *Fault currents calculation using hybrid compensation method and new arc resistance formula*. in *Universities Power Engineering Conference, 2004. UPEC 2004. 39th International*. 2004. IEEE.

37. Terzija, V.V. and H.J. Koglin. *Long arc in free air: testing, modelling and parameter estimation. II*. in *Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on*. 2000.

38. Terzija, V.V. and H.J. Koglin. *Long arc in free air: testing, modelling and parameter estimation. I*. in *Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on*. 2000.

39. Terzija, V.V. and H.J. Koglin. *Laboratory testing and dynamic modeling of long arc in free air*. in *Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on*. 2000.

40. Terzija, V.V. and H.J. Koglin, *New approach of adaptive automatic load shedding.* European Transactions on Electrical Power, 2001. **11**(5): p. 329-334.

41. Terzija, V.V., Z.M. Radojevic, and M.B. Djuric. *A new approach for arcing faults detection and fault distance calculation in spectral domain*. in *Transmission and Distribution Conference, 1996. Proceedings., 1996 IEEE*. 1996.

42. Tslaf, A.L., *Theory of arc resistance of solid dielectrics.* Physical Science, Measurement and Instrumentation, Management and Education - Reviews, IEE Proceedings A, 1985. **132**(5): p. 291-300.

43. Fisher, L.E., *Resistance of low-voltage ac arcs.* Industry and General Applications, IEEE Transactions on, 1970(6): p. 607-616.

44. Fortescue, C.L., *Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks.* American Institute of Electrical Engineers, Transactions of the, 1918. **XXXVII**(2): p. 1027-1140.

45. Kron, G., *Tensor analysis of networks*1965: Macdonald.

46. Brown, H.E., *Solution of large networks by matrix methods*1975: Wiley.

47. Saadat, H., *Power System Analysis*2002: McGraw-Hill.

48. Singh, L.P., *Advanced Power System Analysis And Dynamics*2008: New Age International (P) Limited.

49. Stevenson, W.D., *Elements of power system analysis*1982: McGraw-Hill.

50. Anderson, P.M. and P. Anderson, *Analysis of faulted power systems*1995: IEEE press New York.

51. Berman, A. and X. Wilsun, *Analysis of faulted power systems by phase coordinates.* Power Delivery, IEEE Transactions on, 1998. **13**(2): p. 587-595.

52. Undrill, J.M. and T.E. Kostyniak, *Advanced power system fault analysis method.* Power Apparatus and Systems, IEEE Transactions on, 1975. **94**(6): p. 2141-2150.

53. Brandwajn, V. and W.F. Tinney, *Generalized Method of Fault Analysis.* Power Apparatus and Systems, IEEE Transactions on, 1985. **PAS-104**(6): p. 1301-1306.

54. Zhang, B. and S. Chen, *Advanced electric power network analysis*, 1996, Tsinghua University Press.

55. Lakervi, E. and E.J. Holmes, *Electricity distribution network design*. Vol. 21. 1995: Peter Peregrinus Ltd.

56. Kersting, W.H. and W.H. Phillips. *Distribution System Short Circuit Analysis*. in *Energy Conversion Engineering Conference, 1990. IECEC-90. Proceedings of the 25th Intersociety*. 1990.

57. Kersting, W.H. and W.H. Phillips. *Distribution feeder line models*. in *Rural Electric Power Conference, 1994. Papers Presented at the 38th Annual Conference*. 1994.

58. Chen, T.H., et al. *Distribution system short circuit analysis-a rigid approach*. in *Power Industry Computer Application Conference, 1991. Conference Proceedings*. 1991.

59. Chen, T.H., et al., *Three-phase cogenerator and transformer models for distribution system analysis.* Power Delivery, IEEE Transactions on, 1991. **6**(4): p. 1671-1681.

60. Xiaofeng, Z., et al., *A distribution short circuit analysis approach using hybrid compensation method.* Power Systems, IEEE Transactions on, 1995. **10**(4): p. 2053-2059.

61. Tan, A., W.H.E. Liu, and D. Shirmohammadi, *Transformer and load modeling in short circuit analysis for distribution systems.* Power Systems, IEEE Transactions on, 1997. **12**(3): p. 1315-1322.

62. Jen-Hao, T., *Systematic short-circuit-analysis method for unbalanced distribution systems.* Generation, Transmission and Distribution, IEE Proceedings-, 2005. **152**(4): p. 549-555.

63. Chen, T.H., et al., *Distribution system short circuit analysis-A rigid approach.* Power Systems, IEEE Transactions on, 1992. **7**(1): p. 444-450.

64. Cheng, C.S. and D. Shirmohammadi, *A three-phase power flow method for real-time distribution system analysis.* Power Systems, IEEE Transactions on, 1995. **10**(2): p. 671-679.

65. Shirmohammadi, D., et al., *A compensation-based power flow method for weakly meshed distribution and transmission networks.* Power Systems, IEEE Transactions on, 1988. **3**(2): p. 753-762.

66. Tinney, W.F., *Compensation Methods for Network Solutions by Optimally Ordered Triangular Factorization.* Power Apparatus and Systems, IEEE Transactions on, 1972. **PAS-91**(1): p. 123-127.

67. Alvarado, F.L., S.K. Mong, and M.K. Enns, *A Fault Program with Macros, Monitors, and Direct Compensation in Mutual Groups.* Power Engineering Review, IEEE, 1985. **PER-5**(5): p. 39-40.

68. Gross, G. and H.W. Hong, *A Two-Step Compensation Method for Solving Short Circuit Problems.* Power Engineering Review, IEEE, 1982. **PER-2**(6): p. 22-23.

69. Abdel-Akher, M., et al., *An Approach to Determine a Pair of Power-Flow Solutions Related to the Voltage Stability of Unbalanced Three-Phase Networks.* Power Systems, IEEE Transactions on, 2008. **23**(3): p. 1249-1257.

70. Abdel-Akher, M. and K.M. Nor, *Fault Analysis of Multiphase Distribution Systems Using Symmetrical Components.* Power Delivery, IEEE Transactions on, 2010. **25**(4): p. 2931-2939.

71. Abdel-Akher, M., K.M. Nor, and A.H.A. Rashid, *Improved Three-Phase Power-Flow Methods Using Sequence Components.* Power Systems, IEEE Transactions on, 2005. **20**(3): p. 1389-1397.

72. Alvarado, F.L., M. Sao Khai, and M.K. Enns, *A Fault Program with Macros, Monitors, and Direct Compensation in Mutual Groups.* Power Apparatus and Systems, IEEE Transactions on, 1985. **PAS-104**(5): p. 1109-1120.

73. An-ning, W., C. Qing, and Z. Zhan-ping. *An improved phase coordinate method for fault analysis in inherently unbalanced power systems.* in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE.* 2008.

74. Aravindhababu, P., S. Ganapathy, and K.R. Nayar, *A novel technique for the analysis of radial distribution systems.* International Journal of Electrical Power & Energy Systems, 2001. **23**(3): p. 167-171.

75. Brandwajn, V. and W.F. Tinney, *Generalized Method of Fault Analysis.* Power Engineering Review, IEEE, 1985. **PER-5**(6): p. 33-34.

76. Bualoti, R., et al. *A generalized method for simultaneous fault analysis*. in *Electrotechnical Conference, 1996. MELECON '96., 8th Mediterranean*. 1996.

77. Castellanos, F. and R. Dillah. *Short circuit analysis in the phase domain for distribution networks*. in *Transmission and Distribution Conference and Exposition: Latin America, 2008 IEEE/PES*. 2008.

78. Chen, T.H., et al., *Distribution system power flow analysis-a rigid approach.* Power Delivery, IEEE Transactions on, 1991. **6**(3): p. 1146-1152.

79. Ciric, R., A. Padilha, and L. Ochoa. *Power flow in four-wire distribution networks - general approach*. in *Power Engineering Society General Meeting, 2004. IEEE*. 2004.

80. Ciric, R.M., A.P. Feltrin, and L.F. Ochoa, *Power flow in four-wire distribution networks-general approach.* Power Systems, IEEE Transactions on, 2003. **18**(4): p. 1283-1290.

81. Ciric, R.M., L.F. Ochoa, and A. Padilha, *Power flow in distribution networks with earth return.* International Journal of Electrical Power & Energy Systems, 2004. **26**(5): p. 373-380.

82. Ciric, R.M., et al., *Fault analysis in four-wire distribution networks.* Generation, Transmission and Distribution, IEE Proceedings-, 2005. **152**(6): p. 977-982.

83. Das, S., et al. *Distribution fault location using short-circuit fault current profile approach*. in *Power and Energy Society General Meeting, 2011 IEEE*. 2011.

84. Filomena, A.D., et al., *Distribution systems fault analysis considering fault resistance estimation.* International Journal of Electrical Power & Energy Systems, 2011. **33**(7): p. 1326-1335.

85. Fuerte-Esquivel, C.R. and E. Acha, *Newton-Raphson algorithm for the reliable solution of large power networks with embedded FACTS devices.* Generation, Transmission and Distribution, IEE Proceedings-, 1996. **143**(5): p. 447-454.

86. Gartia, A., et al. *Power system network modeling for on-line analysis*. in *Power Systems, 2009. ICPS '09. International Conference on*. 2009.

87. GASBAOUI, B. and B. ALLAOUA, *Ant colony optimization applied on combinatorial problem for optimal power flow solution.* Leonardo Journal of Sciences, 2009. **8**(14): p. 01-16.

88. Hamouda, A. and K. Zehar, *Improved algorithm for radial distribution networks load flow solution.* International Journal of Electrical Power & Energy Systems, 2011. **33**(3): p. 508-514.

89. Hasan, K.N., K.S.R. Rao, and Z. Mokhtar. *Analysis of load flow and short circuit studies of an offshore platform using ERACS software*. in *Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International*. 2008.

90. He, W.X. and C.Y. Teo. *Unbalanced short-circuit calculation by phase coordinates*. in *Energy Management and Power Delivery, 1995. Proceedings of EMPD '95., 1995 International Conference on*. 1995.

91. Hsiao, T., *Fault Analysis by Modified Alpha, Beta, and Zero Components-Part I.* Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers, 1962. **81**(3): p. 136-142.

92. Hsiao, T., *Fault Analysis by Modified Alpha, Beta, and Zero Components-Part II.* Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers, 1962. **81**(3): p. 142-146.

93. Idema, R., et al. *Fast Newton load flow*. in *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*. 2010. IEEE.

94. Jen-Hao, T. *Fast short circuit analysis method for unbalanced distribution systems*. in *Power Engineering Society General Meeting, 2003, IEEE*. 2003.

95. Jen-Hao, T., *A direct approach for distribution system load flow solutions.* Power Delivery, IEEE Transactions on, 2003. **18**(3): p. 882-887.

96. Jen-Hao, T., *Unsymmetrical Short-Circuit Fault Analysis for Weakly Meshed Distribution Systems.* Power Systems, IEEE Transactions on, 2010. **25**(1): p. 96-105.

97. Laughton, M.A., *Analysis of unbalanced polyphase networks by the method of phase co-ordinates. Part 1: System representation in phase frame of reference.* Electrical Engineers, Proceedings of the Institution of, 1968. **115**(8): p. 1163-1172.

98. Laughton, M.A., *Analysis of unbalanced polyphase networks by the method of phase co-ordinates. Part 2: Fault analysis.* Electrical Engineers, Proceedings of the Institution of, 1969. **116**(5): p. 857-865.

99. Lu, F.Y. and S. Chen. *Using component technology in power system simulations*. in *Power Engineering Society Winter Meeting, 2002. IEEE*. 2002.

100. Montagna, M. and G.P. Granelli, *A comprehensive approach to fault analysis using phase coordinates.* Electric Power Systems Research, 2002. **61**(2): p. 101-108.

101. Mo-Shing, C. and W.E. Dillon, *Power system modeling.* Proceedings of the IEEE, 1974. **62**(7): p. 901-915.

102. Naiem, A., et al. *A classification technique for protection coordination assessment of distribution systems with distributed generation*. in *Proceedings of the 14th International Middle East Power Systems Conference, Cairo, Egypt.* 2010.

103. Najafi, M., et al., *Fault Analysis in Unbalanced and Unsymmetrical Distribution Systems.* Australian Journal of Basic and Applied Sciences, 2011. **5**(8): p. 743-756.

104. Nor, K.M., H. Mokhlis, and T.A. Gani, *Reusability techniques in load-flow analysis computer program.* Power Systems, IEEE Transactions on, 2004. **19**(4): p. 1754-1762.

105. Penido, D.R.R., et al., *Three-Phase Power Flow Based on Four-Conductor Current Injection Method for Unbalanced Distribution Networks.* Power Systems, IEEE Transactions on, 2008. **23**(2): p. 494-503.

106. Peralta, J.A., F. de Leon, and J. Mahseredjian, *Unbalanced Multiphase Load-Flow Using a Positive-Sequence Load-Flow Program.* Power Systems, IEEE Transactions on, 2008. **23**(2): p. 469-476.

107. Prakash, K. and M. Sydulu. *An effective topological and primitive impedance based distribution load flow method for radial distribution systems*. in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*. 2008.

108. Reichelt, D., E. Ecknauer, and H. Glavitsch. *Estimation of steady-state unbalanced system conditions combining conventional power flow and fault analysis software*. in *Power Industry Computer Application Conference, 1995. Conference Proceedings., 1995 IEEE*. 1995.

109. Rodríguez Paz, M.C., et al., *System unbalance and fault impedance effect on faulted distribution networks.* Computers & Mathematics with Applications, 2010. **60**(4): p. 1105-1114.

110. Roy, L., *Generalised polyphase fault-analysis program: calculation of cross-country fault.* Electrical Engineers, Proceedings of the Institution of, 1979. **126**(10): p. 995.

111. Roytelman, I. *Power flow, optimization and fault calculation methods*. in *Power Engineering Society 1999 Winter Meeting, IEEE*. 1999.

112. Selvan, M.P. and K.S. Swarup. *Unbalanced distribution system short circuit analysis — an Object-Oriented Approach*. in *TENCON 2008 - 2008 IEEE Region 10 Conference*. 2008.

113. Slochanal, S.M.R., S. Latha, and K. Chithiravelu. *A novel approach of power flow analysis incorporating UPFC*. in *Power Engineering Conference, 2005. IPEC 2005. The 7th International*. 2005.

114. Smith, B.C. and J. Arrillaga, *Improved three-phase load flow using phase and sequence components.* Generation, Transmission and Distribution, IEE Proceedings-, 1998. **145**(3): p. 245-250.

115. Stankovic, A.M. and T. Aydin, *Analysis of asymmetrical faults in power systems using dynamic phasors.* Power Systems, IEEE Transactions on, 2000. **15**(3): p. 1062-1068.

116. Stefanski, K. and B.H. Chowdhury. *Analysis of unbalanced system efficiency with a positive sequence power flow program*. in *North American Power Symposium (NAPS), 2011*. 2011.

117. Subrahmanyam, J., C. Radhakrishna, and K. Pandukumar, *A Simple and Direct Approach for Unbalanced Radial Distribution System three phase Load Flow Solution.* Research Journal of Applied Sciences, Engineering and Technology, 2010. **2**(5): p. 452-459.

118. Terzija, V.V., M.B. Djuric, and Z.M. Radojevic, *Fault distance estimation and fault type determination using least error squares method.* European Transactions on Electrical Power, 1998. **8**(1): p. 57-64.

119. Ulinuha, A., M.A.S. Masoum, and S.M. Islam. *Unbalance power flow calculation for a radial distribution system using forward-backward propagation algorithm*. in *Power Engineering Conference, 2007. AUPEC 2007. Australasian Universities*. 2007.

120. Wang, A., Q. Chen, and Z. Zhou. *An improved phase coordinate method for fault analysis in inherently unbalanced power systems*. in *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*. 2008. IEEE.

121. Whei-Min, L., et al., *Three-phase unbalanced distribution power flow solutions with minimum data preparation.* Power Systems, IEEE Transactions on, 1999. **14**(3): p. 1178-1183.

122. Xinye, Z., A. Jubai, and C. Fangming. *A Method of Insulator Fault Detection from Airborne Images*. in *Intelligent Systems (GCIS), 2010 Second WRI Global Congress on*. 2010.

123. Zhu, Y. and K. Tomsovic, *Adaptive power flow method for distribution systems with dispersed generation.* Power Delivery, IEEE Transactions on, 2002. **17**(3): p. 822-827.

124. Glover, J.D., M.S. Sarma, and T.J. Overbye, *Power System Analysis and Design*2011: Nelson Education Limited.

125. Ayrton, H.M., *The electric arc*1902: " The Electrician" printing and publishing company, limited.

126. Maikapar, A., *Extinction of an open electric arc.* Elektrichestvo, 1960. **4**: p. 64-69.

127. *ETAP Help and Tutorial*, 2009, Operation Technology, Inc.: Software Manual.

128. Christie, R. *Power Systems Test Case Archive*. IEEE 30 Bus Power Flow Test Case 1993 [cited 2012 December,30th]; Available from: http://www.ee.washington.edu/research/pstca/pf30/pg_tca30bus.htm.

129. *IEEE 34 Node Test Feeder Manual*, C.a.E.C. IEEE POWER ENGINEERING SOCIETY (Power System Analysis, Editor, The Institute of Electrical and Electronics Engineers, Inc.(IEEE).

130. Kersting, W.H., *Radial distribution test feeders.* Power Systems, IEEE Transactions on, 1991. **6**(3): p. 975-985.

131. Kersting, W.H. *Radial distribution test feeders*. in *Power Engineering Society Winter Meeting, 2001. IEEE*. 2001.

132. McDermott, T.E. *Radial distribution feeder and induction machine test cases - steady state solutions*. in *Power Engineering Society General Meeting, 2006. IEEE*. 2006.

133. Thrash, R., et al., *Southwire Company Overhead Conductor Manual*, 2007, Carrollton, GA: Southwire Co.

134. Gallego, L.A. and A. Padilha-Feltrin. *Voltage regulator modeling for the three-phase power flow in distribution networks*. in *Transmission and Distribution Conference and Exposition: Latin America, 2008 IEEE/PES*. 2008.

135. Owuor, J.O., J.L. Munda, and A.A. Jimoh. *The ieee 34 node radial test feeder as a simulation testbench for Distributed Generation*. in *AFRICON, 2011*. 2011.

136. Chen, M.S. and W.E. Dillon, *Power system modeling.* Proceedings of the IEEE, 1974. **62**(7): p. 901-915.

137. Selvan, M.P. and K.S. Swarup, *Modeling and analysis of unbalanced distribution system using object-oriented methodology.* Electric Power Systems Research, 2006. **76**(11): p. 968-979.

138. Kersting, W.H. and W.H. Phillips. *Modeling and analysis of rural electric distribution feeders*. in *Rural Electric Power Conference, 1990. Papers Presented at the 34th Annual Conference*. 1990.

139. Kersting, W.H. and W.H. Phillips, *Modeling and analysis of rural electric distribution feeders.* Industry Applications, IEEE Transactions on, 1992. **28**(4): p. 767-773.

140. Mihalache, L., et al. *Modeling of a small distribution grid with intermittent energy resources using MATLAB/SIMULINK*. in *Power and Energy Society General Meeting, 2011 IEEE*. 2011.

141. Santoso, S. and Z. Zheng. *Induction machine test case for the 34-bus test feeder: a wind turbine time-domain model*. in *Power Engineering Society General Meeting, 2006. IEEE*. 2006.

142. Xiaofeng, W., N.N. Schulz, and S. Neumann, *CIM extensions to electrical distribution and CIM XML for the IEEE radial test feeders.* Power Systems, IEEE Transactions on, 2003. **18**(3): p. 1021-1028.

143. Mwakabuta, N. and A. Sekar. *Comparative Study of the IEEE 34 Node Test Feeder under Practical Simplifications*. in *Power Symposium, 2007. NAPS '07. 39th North American*. 2007.