UNIVERSITI PUTRA MALAYSIA

IMPROVEMENT ON OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS IN MESH DISTRIBUTION NETWORK SYSTEM USING ARTIFICIAL INTELLIGENCE TECHNIQUE

OSAJI EMMANUEL OLUFEMI

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By

OSAJI EMMANUEL OLUFEMI

Thesis Submitted to the School of Graduate Studies. Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

November 2015

DEDICATION

I would like to dedicate this project to my beloved family, all my supervisors and lecturers in the Department of Electrical and Electronic Engineering and friends. Their guidance and relentless support have been a great inspiration to the realization of this project.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chair: **Mohammad Lutfi Othman, PhD, PEng**
Faculty: **Engineering**

The electrical meshed distribution network (MDN) protection coordination scheme, poses great challenges to protection coordination scheme setup, due to the network topology structure. This always resulted to unexpected miscoordination among selected primary and backup relay pairs due to multi-directional fault current infeed's contributions by all interconnected electrical power sources to the short circuit fault current magnitude level. Moreover, other challenges to be addressed is in the ineffective prediction of the nonlinear time-current characteristic function curve from empirical data as earlier proposed in previous research, for the future determination of the relay operation time response to short circuit fault in other locations. This research work propose the artificial intelligent (AI) solution on the conventional objective function (COF) and the modified objective function (MOF) formulation, with the application of genetic algorithm (GA) optimization solver, to determine each relay best optimal operation parameters selection for the time dial settings (TDS), plug setting (PS) and response time to fault accordingly. Also, the elimination of pending miscoordination amongst relay pair for effective coordination scheme. Furthermore, a novel hybrid GA-ANN technique is proposed for the supervised training, to predict the nonlinear time-current characteristic function fitting of each relay operation time function. A directional overcurrent relay (DOCR) coordination in IEEE 9 bus test system is proposed for this research work with three integrated multi distribution generation electrical power sources (DG) in DigSiLent power factory and Matlab Simulink software. The obtained result from the GA solution of the MOF produced a 91.67% improvement in the obtained optimal parameter values against the 8.33% reduced value from COF. This also translated into the same percentage values in operation time response to fault within each relay protection coverage zones. Furthermore, the pending miscoordination amongst selected relay pairs of 16.67% earlier experienced in COF solution is been eliminated by the GA solution of the MOF with 100% elimination between the selected primary and backup relay pairs. This is substantiated by the lower fitness mean value of 1.3358 from MOF against the 4.7679 from the COF for the same minimization problem. However, the Levenberg–Marquardt nonlinear function fitting algorithm application on solving the novel hybrid GA-ANN technique predicted the nonlinear time –current function fitting of each relay effectively with minimum mean square error (***mse***) between the target output and the actual output for effective generalization during supervised training of the

network. This research work has achieved all proposed objective function by improving and eliminating all pending problem encountered in multi sources MDN.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENINGKATAN ON OPTIMAL PENYELARASAN GEGANTI ARUS ARAH DALAM SISTEM RANGKAIAN DIHANCURKAN MENGGUNAKAN KEPINTARAN BUATAN

Oleh

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Skema koordinasi perlindungan jaringan agihan bercantum elektrik (MDN) memberi satu cabaran yang besar kepada pemasangan skema kordinasi perlindungan, oleh kerana struktur topologi jaringannya. Ini sering membawa kepada kurangnya koordinasi yang tidak dijangka di kalangan pasangan geganti utama dan bantuan disebabkan oleh sumbangan masukan arus rosak berbilang-arah oleh semua sumber kuasa elektrik yang saling berkaitan kepada aras magnitude arus gangguan sirkit atau litar. Tambahan lagi, cabaran-cabaran lain yang perlu ditangani terletak kepada ramalan tidak efektif lengkuk kefungsian ciri bukan-linear dari data empirik seperti yang telah disarankan dalam kajian sebelum ini, untuk menentukan respon masa operasi geganti kepada litar pintas di lokasi yang lain. Kajian ini mencadangkan satu penyelesaian tiruan pintar ke atas formulasi kefungsian objektif konvensyional (COF) dan kefungsian objektif yang diubahsuai (MOF), dengan aplikasi penyelesai optima algoritma genetik (GA), dalam menentukan pilihan parameter optima untuk setiap geganti, untuk tetapan dial masa (TDS), tetapan plag (PS) dan masa respons kepada arus gangguan, serta penyahan kesalahkoordinasian di antara pasangan geganti untuk skema koordinasi yang berkesan. Seterusnya, satu teknik hibrid yang baru, GA-ANN telah dicadangkan untuk latihan dipantau, untuk meramal kesesuaian fungsi ciri arus masa bukan linear untuk setiap kefungsian masa operasi geganti. Satu koordinasi geganti lebih-arus berhala (DOCR) dalam sistem ujian bas IEEE 9 telah dicadangkan dalam kajian ini dengan tiga sumber kuasa elektrik generasi pelbagai agihan (DG) dalam kilang kuasa DigSiLent dan perisian Matlab Simulink. Keputusan yang diperolehi dari penyelesaian GA MOF telah menghasilkan penambahbaikan sebanyak 91.67% dalam nilai parameter optima bertentangan dengan nilai berkurang sebanyak 8.33% dari COF. Ini juga diterjemahkan kepada nilai peratusan yang sama dalam respon masa operasi kepada gangguan dalam setiap zon litupan perlindungan geganti. Tambahan pula, kecelaruan di antara pasangan geganti terpilih sebanyak 16.67% yang dihadapi lebih awal dalam penyelesaian COF telah dibuang oleh penyelesaian GA kepada MOF dengan pembuangan sebanyak 100% di antara pasangan geganti primer dan gantian. Ini berjaya dibuktikan oleh nilai min *fitness* yang lebih rendah iaitu 1.3358 dari MOF berlawanan dengan 4.7679 dari COF untuk masalah minimisasi yang sama. Namun demikian, aplikasi algoritma bersesuaian fungsi bukan-linear Levenberg–Marquardt ke atas teknik GA-ANN hibrid yang baru telah berjaya meramal kesesuaian fungsi masa-arus bukan linear setiap geganti dengan efektif dengan

ralat kuasa dua minimum (***mse***) di antara output sasaran dan output sebenar untuk generalisasi efektif semasa latihan jaringan. Kajian ini telah mencapai semua kefungsian objektif yang disarankan dengan menambahbaiki dan membuang semua masalah yang terbengkalai yang dihadapi dalam MDN pelbagai sumber.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ABC	artificial bees' colony
AI	artificial intelligence
ANFIS	adaptive network and fuzzy inference system
ANN	artificial neural network
BBO	biogeography based optimization
CB	circuit breaker
CCNN	cascade correlation neural network
CD	computational decision
CI	computational intelligence
CS	current setting
CMA-ES	covariance matrix adaptation evolution strategy
COF	conventional objective function
CT	current transformer
CTM	coordination time margin
DE	differential evolution
DOCR	directional overcurrent relay
DSP	digital signal processing
EC	evolutionary computation
EP	evolution programming algorithm
FFA	fire-fly algorithm
FBBC	fuzzy bang- bang controller
GA	genetic algorithm
GA-ANN	genetic algorithm –artificial neural network
GA-NLP	genetic algorithm and nonlinear programing
GAMS	general algebraic modelling software
HBA	honey bees' algorithm

HSA	harmony search algorithm
IDEA	informative differential evolution algorithm
IED	intelligent electronic device
IHSA	improved harmony search algorithm
IT-2-FL	interval type -2-fuzzy logic
LP	linear programming
MDN	meshed distribution network
MLP	multilayer perceptron
MINLP	mixed integer nonlinear programming
MOF	modify objective function
Mse	mean square error
NM	Neldal mean square algorithm
OCR	overcurrent relay
OF	objective function
PID	programmable intelligence device
PS	plug setting
PSM	plug setting multiplier
PSO	particle swarm optimization
RDN	radial distribution network
TDS	time dial setting
TLBO	teaching learning based algorithm
TMS	time multiplier setting

CHAPTER 1

INTRODUCTION

1.1 Background of study

Short circuit fault is one of the major power quality problem in electrical power system network. It imposes the most serious general hazard to power distribution system components and are the prime concerns in protection systems scheme development. Short circuit fault in electrical power system network is accompanied by excessive current flow due to drop in system impedance below the load impedance at the short circuited section (near zero). It can take any of the following form or even combination of two or more forms, as either phase-to-earth fault, phase-to-phase fault or three-phase fault respectively. It is a known fact that the complete elimination of short circuit faults cannot be achieve, but must be quickly isolated as fast as possible with the help of protective sensing elements like the relay, fuses and circuit breaker (CB). Hence, reduce the adverse effects from the flow of extremely high fault current through the short circuited section of the lines as the easiest path of lowest impedance (Dugan et al., 2004). Furthermore, protective relay is an electrical device that initiate the isolation of faulted section(s) of any electrical power system network to an associated circuit breaker, to maintain constant uninterrupted supply to healthy sections of electrical system network. This prevent damages to living things and equipment installations (Singh & Abhyankar, 2012). Fault elimination on power system transmission and distribution networks is important for system stability, safety and power quality control. On detection of fault or malfunction, protective relays trips appropriate circuit breakers to isolate the faulty section of the network (Hussain et al., 2013).

There are two groups of relaying equipment for electrical power system protection against short circuit fault on both transmission and distribution system network. The first is called “primary relay” and the other “backup relay”. The primary or main relay is the first line of protection element on any protection system, the failure of which initiate the next line of protection known as the secondary or backup protection relay (Singh et al., 2011). Effective coordination scheme ensure that, backup relay always operate at least coordination time margin (CTM) in situations where the primary relay fails to initiate or detect same fault earlier (Bedekar & Bhide, 2011). The backup relay protection zones overlaps in a unidirectional orientation to that of its adjacent primary relay for far-end fault protection. This is a secondary line of protection defense in a well-coordinated protection scheme. Hence, improving system selectivity and dependability (Vijeta & Sarma, 2012). Protective relays function by sensing fault states and after an intentional time delay initiate an operation logic and tripping signal to relevant circuit breakers for fault isolation. Coordination of these devices for effective protection scheme is important. In other words, when a short circuit faults occurs, both selected relay pair (primary and backup) normally will start to operate, but primary relay will trip necessary breakers earlier to isolate the short-circuited element from the system, while backup relay reset without completing its operational function (Chen & Chang, 2013) (Singh & Gupta, 2012).

Figure 1.1 illustrate different classification of overcurrent relays amongst which is the directional overcurrent relay (DOCR). The DOCR has two major operational parameter settings that must be optimally selected to achieve effective coordination scheme. The plug setting / current setting (PS or CS) is the minimum pickup current for any relay to initiate trip command to a circuit breaker, this value lies between the maximum overload current and the minimum short circuit fault current. The second important setting is the time dial or time multiplier setting (TDS or TMS), which is the deliberate operation time delay for any relay before operation, mostly a function of fault current magnitude (Painthankar & Bhide, 2003).

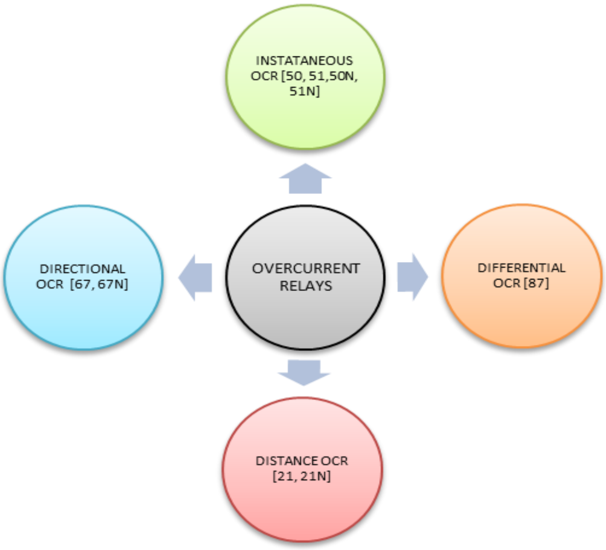

Figure 1.1 Overcurrent relay classification

1.2 Hypothesis of Research

i. Whether Artificial intelligence (AI) optimization technique can help determine a global optimal solution for both COF and MOF with embedded coordination constraints for the determination of the optimal relay operational parameters values (TDS and PS) (Razavi et al., 2008).

ii. Miscoordination elimination between the primary and backup relay pair can be addressed by improving fitness equation formulation. The Output result should address miscoordination elimination among relay pair when compare with other applied optimization techniques results (Bedekar & Bhide 2011b).

iii. The time - current characteristic curve prediction from novel hybrid GA-ANN. The output will predict individual relay operation time at different short circuit current with minimum error for different training algorithm when compared with other nonlinear curve fitting application result.

1.3 Problem Statement

The increase in renewable energy generation and integration in electrical power grid system demands for a smart scheme of protection in electric power transmission and distribution networks (Yang & Liu, 2013). The adverse effect of prolong short circuit fault on the personnel, installation and system stability resulting from multi-current sources contributions to fault current magnitude. Achieving effective coordination in interconnected MDN system with multiple electrical distribution generation sources, can be very difficult to achieve due to its dynamic nature based on multi directional flow of fault currents from all connected sources into the faulted section. The coordination complexity is more as compared to radial network system with just one power source and unidirectional flow of electrical power from the source to several connected terminals load (Abdel-Ghany & Azmy, 2015). However, the system topology fitness formulation is a highly constraint nonlinear optimization problem with mixed integer variables in the OF Equation. From the standard mathematical equation of the relay operation time of a DOCR to short circuit fault, the operation time is directly proportional to the TDS and also inversely proportional to the relay PS. This makes the solution of such equation iterative in nature with high complexity (Damchi et al., 2015). Hence, improvement and modification of the fitness equation will be required to address this problem as proposed in this research work. Moreover, these have been a great challenge to protection engineers, due to multiple energy sources infeed's that contribute to the fault current magnitude level in several directions at any fault location or sections of the network. This makes coordination cumbersome. It may result to wrong trips of healthy sections leading to unnecessarily outages due to miscoordination among protection element.

Furthermore, inappropriate prediction of the nonlinear time-current operation characteristic of the protection DOCR from the obtained optimized empirical data and other statistical nonlinear function fitting computational tools could not predict accurately the actual operation time of relay to short circuit fault within its primary protection zone for another fault location with least minimal error effectively.

1.4 Research Objectives

In order to achieve an effective stable, reliable and enhanced coordinated system that addresses above stated problems, the following objectives are set out to be achieved.

i. Global optimization of DOCR operation parameter setting in MDN to fault within each relay protection coverage zone, by applying GA to solve and compare the results of the proposed COF and MOF. Obtain an improved optimal relay operation parameter settings for TDS and relay response time to fault from the MOF.
ii. Elimination of miscoordination between primary and backup relay pair by improving fitness equation formulation through embedding the operation time difference between relay pair in the MOF. The output result should eliminate coordination constraint violation within the system. Hence, improves system dependability and selectivity.
iii. The time - current characteristic curve prediction from novel hybrid GA-ANN. Output will predict individual relay operation time at different short circuit current with minimum error.

1.5 Scope of Research

In other to realize the set objectives of achieving the global optimal relay operation parameter settings and effective coordination improvement of DOCR in MDN, with the application of proposed artificial intelligence optimization technique solution. The following procedures will be implemented;

i. Modeling of the proposed IEEE 9 bus test MDN system representation with three distribution generation sources (wind or solar station) in DigSiLent power factory modeling and simulation software. Selection of protective relay pairs appropriate for each station bus and branch protection within the entire system to ensure total protection coverage and overlapping of all protection zones. Determination of primary and backup relay pair selections for both bidirectional short circuit overcurrent flow within the proposed modeled network in all direction.
ii. Simulation of the test modeled system for load flow analysis and three-phase short circuit fault analysis on all station buses and lines branch elements in sequence, with conformity to IEC 60909 standard. The simulation data extractions from load flow and short circuit fault analysis test across the test modeled system.
iii. OF problem formulation as linear and nonlinear constraints optimization problem, with several constraints for optimal determination of relay parameter setting for TDS, PS and miscoordination elimination among relay pairs within the mesh network.
iv. Solving the linear formulated COF with linear programming optimization technique (LP) and GA solver for optimal determination of the optimal relay operation parameter settings for the TDS and relay operation time.
v. Formulation of MOF to address both parameter setting and miscoordination elimination with the application of GA solver. This global optimization solver solution should determine a global optimal solution and elimination of miscoordination problem among the primary and backup relay pairs within the proposed network.
vi. Validation of the obtained GA result from both COF and MOF to consider any improvement in the obtained operation parameter setting optimization and miscoordination elimination among the primary and backup relay pairs within the entire network.
vii. Application of the valid experimental data to determine the nonlinear time-current characteristic curve by propose hybrid GA-ANN for individual relay operation time prediction at different fault location.

1.6 Research Contribution

This research work will achieve the following contributions to knowledge in the field of electrical protection and coordination scheme in mesh topology network;

i. Improvement on miscoordination elimination method in integrated multi sources DG network through fitness equation modification and GA solver application for coordination constraints satisfactions for the global optimal determination of relay operational parameters settings.
ii. Discovery of novel hybrid GA-ANN prediction method with the application of experimental data, for the nonlinear time-current characteristic curve prediction for each DOCR. This will generalize the prediction of each relay response time to short circuit fault at different locations within the MDN.

1.7 Thesis Layout

Chapter 1 (Introduction), entails the background of study to this research work, necessary insight on the importance of protective relays, classifications, problem statement, research hypothesis and objectives to be achieve.

Chapter 2 (Literature Review) discusses reviews on the previous proposed techniques as applied in MDN Coordination with strong emphasis on the AI optimizations coordination approaches. Other applied nature inspired optimization algorithm application were also considered in solving this problem. However, recent proposed AI approaches to similar overcurrent relay protection coordination in recent researches in power system were studied and compared with the earlier conventional known methods to determine its merits and weakness. Other optimal coordination methods in MDN were also reviewed in detail till date.

Chapter 3 (Methodology and Procedures) discusses the elaborate steps in achieving the set research objectives that is hypothesized. The modelling of proposed test networks in the DigSilent Power Factory Software, the procedures of achieving this was illustrated in detail in this chapter, with emphasis on international IEC60909 standards. Several simulations of the networks with references to load flow power analysis and three phase short circuit fault were carried out on the modeled networks. Appropriated relevant data extraction and recording for onward application in calculation and programming executions were also discussed in detail. The entire sequence of procedures in achieving the set objectives were fully explained in this chapter.

Chapter 4 (Results and Discussions) presents all obtained results and discussions on the outcome of all findings, validations and testing. Results comparison is also detailed.

Chapter 5 (Conclusion) the derive conclusion on the research work, discussion on the research contributions and recommend with some potential future researches improvement.

Summary

This chapter introduced the basic concepts and guidelines of this research work with illustrations on basic known fact based on the pending challenges faced by electrical MDN with respect to coordination and the impacts on lives, installations and power system stability. A proposed AI method to address these pending problems, through the solution of the modified fitness equation solution with GA application will be discuss in subsequent chapters. The next chapter will illustrate several literature reviewed on recent research works in this area, while the merits and challenges of earlier applied method will also be mention accordingly. The research gap will be discovered to enhance the newly proposed techniques and its merit with future area for improvement also mention.

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