Universidade Estadual de Londrina

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Department of Electrical Engineering

Angel Labrador

Coordination of distance and overcurrent relays using a mathematical optimization technique

A dissertation submitted to the Electrical Engineering Graduate Program at the State University of Londrina in fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering.

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March 1, 2018

To God, my strength and consolation.

To my mother and grandmother, the light that guides my heart.

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In the day when I cried out, You answered me,
And made me bold with strength in my soul..
(Psalm 138:3 Holy Bible (NKJV))

Abstract

Protection of power transmission has an important role in power systems. To improve protection is common to combine different types of relays, which combination of overcurrent and distance relays is a well-known protection scheme. A slow operational speed of overcurrent relay forces application of distance relay as the main protection device. Overcurrent relays are used as backup protection to main distance protection system. To achieve this aim, coordination between primary and backup protection systems should be performed developing an objective function with both parameters. Speed, selectivity, and stability are constraints, which must be satisfied by performing coordination. The coordination of directional overcurrent relays (DOCRs) problem is a nonlinear programming problem (NLP), usually solved with a linear programming technique (LP) only considering the time dial setting (TDS) as a decision variable, without dealing with the non-linear problem of plug setting (PS), or solving the PS component using a heuristic technique. A metaheuristic algorithm method presented to solve the optimization problem is an ant colony optimization (ACO) algorithm. The ACO used is an extension of the ACO algorithm for continuous domain optimization problems implemented to mixed variable optimization problems, condensed in two types of variables both continuous and categorical. In this work, both TDS and PS are decision variables, TDS is considered continuous and PS categorical. Normally, the initial solution is random generated, in addition, those results are compared by using the same random PS values for solving a relaxation of the DOCRs problem with LP to obtain new TDS values. Including distance relays in the formulation will add an additional variable continuous type, but with linear (barely constant) characteristics making no changes in DOCRs formulation for this NLP problem. For this methodology, five transmission systems (3, 6, 8, 9, and 15 Bus accordingly) were evaluated to compare classical DOCR coordination, distance relays introduction and model response to high-quality initial solutions within a hybrid method using LP.

Resumo

A proteção da rede de transmissão tem um papel importante nos sistemas de energia. Para melhorar a proteção é comum combinar diferentes tipos de relés; a combinação de relés de sobrecorrente e distância é um esquema bem conhecido. A lenta velocidade operacional do relé de sobrecorrente força a aplicação do relé de distância como o dispositivo de proteção principal. Os relés de sobrecorrente são usados como proteção de retaguarda tendo o esquema de distância como principal. Para atingir esse objetivo, a coordenação entre os sistemas de proteção primária e de retaguarda deve ser realizada desenvolvendo uma função objetivo com ambos parâmetros. Velocidade, seletividade e estabilidade são restrições, que devem ser satisfeitas através da coordenação. A coordenação do problema de relés direcionais de sobrecorrente (DOCRs) é um problema de programação não linear (NLP), geralmente resolvido com uma técnica de programação linear (LP) apenas considerando a configuração de tempo de atraso (TDS) como uma variável de decisão, sem lidar com o problema não-linear de configuração da corrente de partida (PS), ou com a resolução do componente PS usando uma técnica heurística. Um método meta-heurístico apresentado para resolver o problema de otimização é o algoritmo de otimização de colônias de formigas (ACO). O ACO empregado é uma extensão do algoritmo ACO para problemas de otimização de domínio contínuo implementados para problemas de otimização de variáveis mistas, condensados em dois tipos de variáveis tanto contínuas como categóricas. Neste trabalho, tanto o TDS como o PS são variáveis de decisão, o TDS é considerado contínuo e o PS categórico. Normalmente, a solução inicial é gerada aleatoriamente, além disso, esses resultados são comparados usando os mesmos valores aleatórios PS para resolver um relaxamento do problema DOCR com LP para obter novos valores TDS. A inclusão de relés de distância na formulação adicionará uma variável de tipo contínuo, mas com características lineares (constantes) que não alteram a formulação de DOCR para este problema de PNL. Para esta metodologia, cinco sistemas de transmissão (3, 6, 8, 9 e 15 Barras) foram avaliados para comparar a coordenação DOCR clássica, a introdução dos relés de distância e a resposta do modelo a soluções iniciais de alta qualidade junto a uma metodologia hibrida utilizando LP.

Palavras Chaves: Técnicas de otimização, Proteção do sistema de energia, Coordenação de relés de sobrecorrente, Coordenação de relés de distância, Esquema de proteção misto, Algoritmos Heurísticos.

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List of Abbreviations and Acronyms

ABNT *Associação Brasileira de Normas Técnicas*

ACO ant colony optimization

ACO_R ant colony optimization for continuous domain

BBO Biogeography Based Optimization

BR backup relay

CO combinatorial optimization

COPEL *Companhia Paranaense de Energia*

CSA Cuckoo Search Algorithm

CT current transformer

CTI coordination time interval

CTR current transformer rate

CV constraints violations

CVT capacitor voltage transformer

DG distributed generation

DOCR directional overcurrent relays

DT definite time

DZ-1 Zone 1 for a distance relay

GA genetic algorithm

GACB Genetic Algorithm Chu-Beasley

GE General Electric

HSOC high set overcurrent

I/F-Race Iterated F-Race Algorithm

IAC family of overcurrent relays from General Electric (GE)

IDMT inverse definite minimum time

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IHQS initial high-quality solution

ISO International Organization for Standardization

LP linear programming

MDE Modified Differential Evolution

MDE5 Modified Differential Evolution v5

MINLP mixed-integer nonlinear programming

MVOP mixed-variable optimization problem

NBA No Backup Available

NFE number of function evaluation

NLP nonlinear programming

OCDE Opposition Based Chaotic Differential Evolution

OF objective function

OSL OSL Solver

PR primary relay

PS plug setting

PSO Particle Swarm Optimization

RST Rhetorical Structure Theory

SA solution archive

SBB Standard Branch-and-Bound

SEF Sensitive earth fault

SLS stochastic local search

SOA Seeker Optimization Algorithm

SQP Sequential Quadratic Programming

TDS time dial setting

TSS	Total Search Space
VSS	Valid Search Space
VT	voltage transformer

List of Symbols

Relays and Coordination

A, p, B	Constant parameters for IEEE Relays.
K, E	Constant parameters for IEC Relays.
A to E	Constant parameters for IAC Relays.
I	Input current.
I_{pickup}	Pickup Current.
Δt	Coordination Time Interval, also CTI.
t_{ik}	Operating time of the relay i for a fault in k.
CTR_i	Current Transformer Ratio for relay i.
n	Number of relays to coordinate.
TDS_i^{min}	Minimum value of TDS of relay R_i.
TDS_i^{max}	Maximum value of TDS of relay R_i.
PS_i^{min}	Minimum value of PS of relay R_i.
PS_i^{max}	Maximum value of PS of relay R_i.
t_{ik}^{OC}	Operating time of the primary DOCR i for a fault k.
t_i^{Z2}	Time defined for the second zone of each distance relay.
$t_i^{Z2}min$	Minimum value of t_i^{Z2} of relay R_i.
$t_i^{Z2}max$	Maximum value of t_i^{Z2} of relay R_i.

Model for Mixed-variable Optimization Problems

R	A model for Mixed-variable Optimization Problems
$\mathbf{S}$	Search space $\mathbf{S}$
Ω	Set of constraints among the variables.
o	Ordinal variables.
c	Categorical variables.

d	Discrete variables.
r	Continuous variables.
	ACO for Mixed-variable Optimization Problems
k	Size of solutions in the SA.
S_j	Individuals Solutions from SA
n_s	Number of new solutions (ants).
ω_j	Weight for a solution j in the SA.
q	Parameter of the algorithm (q_r Continuous q_c Categorical)
h_1 h_2	Weighting factors for increasing or decreasing the influence of fitness and unfitness function, respectively.
ϵ	Tolerance for stop criteria.
ξ	Parameter related to pheromone persistence or convergence.
u_l^i	Number of solutions that use PS_i for the categorical variable i in the SA.
η	Number of values from PS vector available ones that are not used by the SA.
σ_{QF}	Stagnation of the QF.
	F-RACE
Θ	Possibly infinite set of candidate configurations.
I	Possibly infinite set of instances.
p_I	Probability measure over the set I.
t	Computation time.
c	Cost measure of a configuration.
p_C	Probability measure over the set C.
T	Total amount of time available for experimenting with the given candidate configurations on the available instances before delivering the selected configuration.
L	Number of iterations.

l	Number of actual iteration.
d	Number of parameters.
B_l	Computational budget in iteration l.
B_{used}	Total computational budget used until iteration $l-1$.
N_{min}	Number of candidate configurations remain.
$N_{survive}$	Number of candidates that withstand the race.
r_z	Rank of of the configuration z.

Contents

1 Introduction

1.1 General considerations

In an electric power system design, system protection is an important consideration. Without system protection, the power system itself, which is intended to be of benefit to the facility in question, would itself become a hazard.

Power systems are designed to be as fault-free as possible through careful design, proper equipment installation, and periodic equipment maintenance. However, even when these practices are followed, it is not practical to design a power system to completely eliminate faults from occurring (STENANE, 2014).

System faults usually, but not always, provide significant changes in the system quantities, which can be used to distinguish between tolerable and intolerable system conditions. These changing quantities include overcurrent, over or under-voltage, power, power factor or phase angle, power or current direction, impedance, frequency, temperature, physical movements, pressure, and contamination of the insulating quantities. The most common fault indicator is a sudden and generally significant increase in the current; consequently, overcurrent protection is widely used (BLACKBURN; DOMIN, 2006).

A detailed model of a protection system is complex and will usually consist of three major parts: instrument transformers, protective relays, and circuit breakers. The instrument transformers lower the power system voltages to safe working levels. The protective relays receive information about the operating conditions of the high-voltage power system via the instrument transformers (MARTINEZ-VELASCO, 2015). The Institute of Electrical and Electronics Engineers (IEEE) defines a protective relay as a relay whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action (IEEE, 2000).

According to (BLACKBURN; DOMIN, 2006), there are five basic facets of protective relay application:

1. Reliability: assurance that the protection will perform correctly.
2. Selectivity: maximum continuity of service with minimum system disconnection.
3. Speed of operation: minimum fault duration and consequent equipment damage and system instability.

4. Simplicity: minimum protective equipment and associated system to achieve the protection objectives.
5. Economics: maximum protection at minimal total cost.

If all five basic objectives could be achieved to their maximum requirement level it would be the ideal scenario but not a real-life situation. Thus, the protection engineer must evaluate these as restrictions for maximizing the protection of the system.

The process of choosing settings or time delay characteristics of protective devices, such that operation of the devices will occur in a specified order to minimize customer service interruption and power system isolation due to a power system disturbance is known as coordination of protection (IEEE, 2000).

Overcurrent and Distance relays are mostly used for transmission and sub-transmission protection systems.

For overcurrent relays, the coordination is performed using linear or non-linear programming techniques but to avoid the complexity of the non-linear programming methods, coordination problem for overcurrent relays is commonly formulated as a linear programming (KALAGE; GHAWGHAWE, 2016). The optimization techniques using methods as Simplex, Two-phase Simplex, and Dual Simplex present a disadvantage because they are based on an initial basic solution and may be trapped in the local minimum values. Intelligent optimization techniques such as genetic algorithm (GA) can adjust the setting of the relays without the mentioned difficulties but requiring a modification of the objective function and constraints (NOGHABI et al., 2009), trending heuristics techniques to solve the problem.

The distance protection is one of the most common protection types since it gives by measuring voltage and current at one point already a very selective information about the fault. However, high time coherence between current and voltage in the order of $1\,\mu s$ is needed for correct results (BRAND; De Mesmaeker, 2013). Distance relays can be used as main or backup protection, to protect the transmission line or power transformer. Nowadays, numerical distance relays have been used widely replacing the electromechanical and static distance relays (IDRIS et al., 2013).

In the cases that the distance relay is considered to be the main relay and the overcurrent one is the backup relay, it is necessary to find the critical fault locations. These are critical fault locations at which the time margin (Δt) between main distance relay and backup overcurrent relay is at a minimum. The coordination is made based on the constraints derived from the values (Δt) for critical fault locations (SINGH et al., 2012). The object function is developed by adding a new term that is the constraint related to the coordination of the distance and overcurrent relays when a fault occurs at the critical location.

1.2 Statement of the problem

The overcurrent protection has an extended implementation in the electrical power system compare to directional overcurrent and distance protection, a simpler operational principle leads to low-cost applications. In situations where a distributed generator is present, a radial scheme is no longer valid because power flow eventually will change, accordingly, modern transmission, sub-transmission, and distribution protection system have many similarities. Since overcurrent protection protects from faults in one direction, it cannot be implemented in these circumstances. In such, a situation directional overcurrent or distance protection would be the ideal protection. Directional overcurrent detects a fault in forward and reverse directions and distance protection uses zones to protect the feeder.

The coordination problem is widely solved using a linear programming implementation as explained in Urdaneta et al. (1988). Many different techniques have been proposed and applied since then. But in this case, the coordination problem requires reformulating the objective function to combine overcurrent and distance settings. For overcurrent relays finding the time dial setting is based on the mathematical statement of the sensitivity, speed, security and selectivity conditions associated with the traditional relay coordination problem. Perez and Urdaneta (2001) proposes a procedure to include backup definite-time relays in the process of computing the time dial setting (TDS) of directional overcurrent relays (DOCR) with inverse time curves. This is useful in transmission and sub-transmission systems which have a mixed scheme with directional overcurrent and distance relays. For the particular case of the coordination of directional overcurrent relays of distance relays, it was proposed to change constraints with the results of improvement of selectivity.

In linear programming techniques, it is not possible to select overcurrent relays characteristic besides relays' time dial setting (TDS) to have the optimal coordination. In some cases of overcurrent/distance relays coordination, it is necessary to find the critical fault locations. A mixed protection scheme with distance relays formulated in Abyaneh et al. (2008) has been modified in such a way that five different critical points as the fault position are taken into account and Chabanloo et al. (2011) adding some new terms fulfill optimal combined coordination of distance and overcurrent relays, using GA-based Heuristic.

Sadeh et al. (2011) proposed to perform optimal coordination between distance and overcurrent relays for every second zone of distance relays; finding time multiplies setting and second zone time for each relay by linear programming, and computing of pickup current by using particle swarm optimization. This hybrid particle swarm optimization was successful in achieving a better coordination than linear programming. According to this reference obtained results of particle swarm optimization and genetic algorithm for a sample network, are equal, but particle swarm optimization performs coordination faster. For combined optimization of relays coordination, Singh et al. (2012) stands differential evolutionary algorithm gives no-miscoordination and coordination time margin is not violated as seen in the result obtained from GA.

1.3 Objectives

The main objective is to present a study of different methodologies for the coordination of distance and/or overcurrent relays in electric power systems, using a mathematical optimization technique and a computational tool to determine the best settings for the relays been selective.

In order to reach the main objective, the above specific objectives are defined:

- Review of specialized methodologies used in the optimal coordination of distance and overcurrent relays, both as individual and/or combined configuration.
- Formulate the problem of relay coordination like a mathematical optimization problem.
- Establish a procedure for the transformation of non-linear mathematical models into linear models applied to the relay study case.
- Develop a metaheuristic algorithm to solve the coordination problem.
- Implement a tool able to improve results, according to the comparison with preceded investigations.
- Analyze a tuning process for the heuristic applied in order to increase the performance of the algorithm and maximize the protection facets.
- Compare and evaluate the results applying the proposed methodology to the literature reviewed.

1.4 Methodology

This dissertation is based on the analysis of results obtained through an applied mathematical modeling procedure to solve a combine relays coordination theory. In this case of study distance and overcurrent relays as individual and as a combine protection system are evaluated in order to obtain potential configuration schemes into coordination problem.

In order to achieve a successful implementation, qualitative research is required to gain an understanding and generate a new approach to combine relay coordination for later quantitative research, based on measuring of the testing systems fault response.

Qualitative research involves investigating the subjects relate to power system protection and the mathematical techniques applied to relays coordination, with an emphasis on the formulation of an objective function and his constraints. In the literature, different methods are applied to solve the coordination problem but this work focuses on an ant colony optimization (ACO) presenting a significant contribution to this study. Computational modeling to run tests on actual power systems, changing the topology to compare evaluation results with literature review as quantitative research.

The bibliographic review was performed constantly throughout the work, maintaining the trends in the research of protection systems, besides its importance of other activities.

In essence, the step of mathematical modeling deals with an extension of what is on the literature review, being dedicated to the analysis, characterization, reproduction, and comparison of existing models and how they may be improved. At this point, it is possible to learn and implement different solutions to problems related to relay coordination, linked to the latest advances, which allow the characterization and comparison of such solutions with new solution techniques. In this way, it offers an in-depth understanding of the solutions of problems present in the literature, highlighting its advantages, deficiencies and specific details of the procedure, opening the way for possible improvements.

It is also worth mentioning that the comparing of results is done through simulations made from routines built for/on Matlab, which constitutes a high-level language, facilitating and accelerating this stage because it offers practicality in the construction of functions and routines. In addition, in the comparative phase, different solutions of problems of the same kind are analyzed and compared in a fair way among each other, being evaluated their performance and complexity.

The main contribution of this work is made through the augmentations to the mathematical model introducing distance relay seeking for coordination improvement considering an extra-level protection with existing devices, whether own protection zone or corresponding backup zones. Another major contribution in the optimization area is the algorithm parameters optimization describing a specific technique to find optimal parameters to get better output from the implemented algorithm. Also relevant would be exhaustive search process to validate metaheuristic results.

Results obtained, overcome some precedents values validating the new algorithm as novel coordination problem solution, besides introducing a new base to combine distance and overcurrent relay coordination, with a feasible model to future works and/or implementation.

1.5 Outline of the dissertation

The dissertation is organized as follows:

Chapter 1: Introduction.

This chapter provides the purpose, statement of the problem, objectives, and research methodology of the project.

Chapter 2: Literature Review.

This chapter gives a State-of-the-Art resume and summarizes protective relaying and the basics schemes required to understand relays as a protective device and the importance of their coordination.

Chapter 3: Mathematical Formulation.

In Chapter 3, the development of a mathematical formulation for distance and overcurrent coordination with limitation for each topology and actual consideration for this problem.

Chapter 4: Implementation.

This chapter presents an overview of methodologies applied to relay coordination, with an implementation of Ant Colony Optimization technique, for multi-variable problems, developing a tool for the analysis of ACO parameters and optimizing them, besides a Hybrid technique based on ACO and Linear Programming.

Chapter 5: Testing Systems.

System types, configuration, and data to apply proposed methodology to generate results to compare.

Chapter 6: Results and Discussions.

In this chapter, the results, and discussions of the applied methodologies. Presenting tables and figures to corroborate results obtained.

Chapter 7: Conclusions.

The conclusions based on research discussions.

Chapter 8: Recommendations for Future Work

Future research trend line to continuing this work.

2 Literature Review

2.1 State of the Art

The incremental quantity of protection technologies impact in faults cleared faster, improving safety with a better power system stability, and preserved equipment life as consequence. Above smart grids design, network topologies are changing-intensively, changes must be deemed for the protection devices in order to heighten their performance. Classical coordination model is still valid but only for single instances of the daily network load profile. Trending brings fast solving techniques able to process dynamic data keeping system all-time coordinated (SHIH; ENRIQUEZ, 2014; SHIH et al., 2017; ENRÍQUEZ; MARTÍNEZ, 2007; PIESCIOROVSKY; SCHULZ, 2017).

Optimal coordination of DOCRs in interconnected power systems originally by Urdaneta et al. (1988) presented two types of tap settings namely plug setting (PS) and TDS to be calculated. Mixed Protection Scheme, composed of distance relays and DOCRs requires considering both relays because separate relay computation would lead to loss of selectivity. Perez and Urdaneta (2001) model considers the best setting for the second zone that assures selectivity differs from used in distance schemes, mixed configurations normally are misestimated due to complex topologies and system-inside considerations to formulate an exact model, this mixed scheme brought back by Chabanloo et al. (2011), Singh et al. (2012) in-light the advantage over low speed of overcurrent relay forcing the application of distance relay for protection transmission system, even when miscoordination exist for sub-transmission systems usually work under those approaches; Ahmadi et al. (2017) studies pickup current effect on reduction of discrimination times improving coordination.

A concept of robust coordination conferred by Costa et al. (2017), which analyzes a classical coordination model but counting different scenarios where the data of the system is continuously changing and the selectivity is no longer correct. Recently, Yazdaninejadi et al. (2017) shows a different kind of coordination for meshed distribution networks, previously developed by Zeineldin et al. (2015), where dual setting relays are provided with two inverse time-current characteristics whose parameters will rely on the fault direction, adding an extra level of protection.

In adaptive protection schemes, it is necessary to compute the DOCRs parameters at each topological change (SHIH et al., 2014; CHEN; LEE, 2014; CORRÊA et al., 2015; SHIH et al., 2015). A practical implementation of adaptive protection is also reported in Piesciorovsky and Schulz (2017). Modern power systems with the addition of distributed generation (DG) impact on protective relaying (GEORGE et al., 2013), especially in radial systems where coordination is performed with no-directional units (HUSSAIN et al., 2013; CHEN et al., 2013), accordingly request the implementation of a meshed network formulation (YANG et al., 2013; SRIVASTAVA et al., 2016)

An introduction to heuristic techniques came to treat the non-linear variable PS, the new evolutionary algorithm applied in Mansour et al. (2007), Zeineldin et al. (2005) shows and advantage for implementation, derivate from simplicity and robustness of GA principle. Also, hybrid methods rise for the benefit of reducing the major problem into small search spaces LP compatible (SINGH et al., 2011). A specialized Genetic Algorithm Chu-Beasley (GACB) that uses an efficient local search, finding solutions to the coordination problem with very low computation times is presented in Kida (2016), this guarantees an applicability in smart grid systems.

The ant colony optimization (ACO) was introduced by Dorigo et al. (1996) a novel nature-inspired metaheuristic for the solution combinatorial optimization (CO) problems. The ACO is inspired by the foraging behavior of real ants. Ants food search begins exploring the area surrounding their nest in a random manner. When an ant finds a food source, proceeds to evaluate quantity and quality taking some back to the nest. During this process, ants deposit a tale of pheromones that create trails for others to follow; increasing the probability of finding food sources.

ACO common implementation is extended to multiple CO problems. But for high-resolution problem CO approach is not convenient, Socha and Dorigo (2008) introduced an ACO expansion to continuous domains named ACO_R this algorithm close to original formulation affords a convenience with the possibility of tackling mixed discrete-continuous variables as develops Solnon (2007) later. The advantage of this algorithm compared to GA is the role of global memory played by the pheromone matrix, which leads to better and faster solution convergence (SHIH et al., 2015).

Initial solutions for ACO is commonly generated using a normal random process within feasible space for each variable (BLUM, 2005). Machine learning algorithms measure performance based on function evaluations, but for big sizes problem with a high number of possible combinations, computational time could be compromised. Evolutionary algorithms look for start evaluation closer to the global optimal and enhancing convergence and solution quality (ZHANG et al., 2011).

The performance of heuristic algorithms is known to be sensitive to the values assigned to its parameters. Ordinarily, studies provide reasonable ranges in which to initialize the parameters based on their long-term behaviors, such prior studies fail to quantify the empirical performance of parameter configurations across a wide variety of benchmark queries. Harrison et al. (2017) is an example of empirical optimization technique in this case for a Particle Swarm Optimization (PSO) algorithm.

Parameters selection can be thought of as machine learning within the problem of finding the best model among a group of possibilities. Hoeffding Races (MARON, 1994) use for quickly discarding bad configurations, concentrating the computational effort at differentiating between the better ones, thereby reducing the number of cross validation queries. Those process rest on regards must statistical (FRIEDMAN, 1937) information to validate parameters and guarantee a final quality solution.

Adenso-Díaz and Laguna (2006) developed CALIBRA, a procedure that uses Taguchi's (BALLANTYNE et al., 2008) fractional factorial experimental designs coupled with a local search procedure to obtain best values parameters even when they are not optimal ones. But when ACO is considered F-RACE (BARTZ-BEIELSTEIN et al., 2010) approached is widely used (BALAPRAKASH et al., 2007) a racing algorithm that starts by considering a number of candidate parameter settings and eliminates inferior ones as soon as enough statistical evidence arises against them. Stochastic local search algorithms develop their tune-up base on this method (BARTZ-BEIELSTEIN et al., 2010).

Table 2.1 aims to provide an exhaustive summary of current literature relevant to Protective relaying and Coordination.

Table 2.1 – Literature Review for Protective Relaying and Coordination.

Characterization	**Theme**	**System Application**	**Citation**
Basics	Protective Relaying	General	(MASON, 1956)
Basics	Relay Protection	Transmission	(ATABEKOV, 1960)
Basics	Protective Relaying	General	(WARRINGTON, 1968)
Coordination	Distance Relays Setting	Transmission	(SA et al., 1984)
Coordination	DOCR	Transmission	(URDANETA et al., 1988)
Coordination	DOCR	Transmission	(URDANETA et al., 1996)
Coordination	DOCR	Distribution	(CHATTOPADHYAY et al., 1996)
Coordination	DOCR	Distribution / Sub-transmission	(ABDELAZIZ et al., 1999)
Combine Coordination	Distance - DOCR	General	(JIMÉNEZ, 1999)
Combine Coordination	Distance - DOCR	Transmission	(PEREZ; URDANETA, 2001)
Coordination	DOCR	Transmission	(ZAPATA; MEJÍA, 2003)
Coordination	DOCR -Review	General	(BIRLA et al., 2005)
Coordination	DOCR	Transmission	(DEEP et al., 2006)
Coordination	DOCR	Distribution	(ESTRADA et al., 2006)
Coordination	DOCR	Transmission	(BIRLA et al., 2006)
Coordination	DOCR	Distribution	(JULIÁN et al., 2007)
Coordination	DOCR - Distribuited Generation	Distribution	(VALLEJO, 2007)
Coordination	DOCR - Software Development	General	(ZENGLI et al., 2007)
Coordination	Distance Relays	Transmission	(TRUNK et al., 2008)
Coordination	Distance Relays	Transmission	(CHAVEZ et al., 2008)
Coordination	DOCR	Radial	(KEIL; JAGER, 2008)
Combine Coordination	Distance - DOCR	Transmission	(ABYANEH et al., 2008)
Coordination	DOCR	Subtransmission / Transmission	(MAZLUMI; ABYANEH, 2009)
Coordination	DOCR	Transmission	(NOGHABI et al., 2009)

Continued on next page

Table 2.1 – continued from previous page

Caracterization	**Theme**	**System Application**	**Citation**
Coordination	DOCR	Transmission	(RATHINAM et al., 2010)
Coordination	DOCR	Transmission	(THANGARAJ et al., 2010)
Coordination	DOCR	Distribution	(BARRETO, 2010)
Coordination	DOCR	Transmission	(SADEH et al., 2011)
Coordination	DOCR	Transmission	(CHABANLOO et al., 2011)
Coordination	DOCR	Distribution	(SINGH et al., 2011)
Coordination	DOCR	Transmission	(BEDEKAR; BHIDE, 2011a)
Coordination	DOCR	Transmission	(GUEVARA,)
Coordination	DOCR	Transmission	(BEDEKAR; BHIDE, 2011b)
Coordination	DOCR	Transmission	(TERESA et al., 2012)
Coordination	DOCR	Transmission	(LIU; YANG, 2012)
Combine Coordination	Distance - DOCR	Transmission	(MORAVEJ et al., 2012)
Basics	Protective Relaying	General	(ELMORE, 2012)
Coordination	DOCR	Transmission	(CORRÊA, 2012)
Combine Coordination	Distance - DOCR	Transmission	(SINGH et al., 2012)
Coordination	DOCR	Transmission	(AMRAEE, 2012)
Coordination	DOCR	Transmission	(SUEIRO et al., 2012)
Coordination	DOCR	Transmission	(YANG; LIU, 2013)
Combine Coordination	Distance - DOCR	Distribution	(CHEDID, 2013)
Coordination	DOCR	Transmission	(NAIR; RESHMA, 2013)
Coordination	DOCR	Transmission	(DASH et al., 2013)
Coordination	DOCR	Distribution	(CHEN et al., 2013)
Basics	Protective System	General	(BRAND; De Mesmaeker, 2013)
Coordination	DOCR	Transmission	(RAMOS et al., 2014)
Coordination	DOCR -Review	General	(HUSSAIN et al., 2013)
Coordination	DOCR -Review	General	(RAZA et al., 2013)
Coordination	DOCR	Industrial	(CESAR, 2013)
Coordination	DOCR	Transmission	(YANG et al., 2013)
Combine Coordination	Diferencial - DOCR	Microgrid	(HARON et al., 2013)
Coordination	DOCR	Transmission	(STENANE, 2014)
Combine Coordination	Distance - DOCR	Transmission	(MARCOLINO, 2014)
Coordination	DOCR	Transmission	(CHEN; LEE, 2014)
Coordination	DOCR	Transmission	(STENANE; FOLLY, 2014)
Coordination	DOCR	Transmission	(HADI et al., 2014)
Coordination	DOCR	Transmission	(SHIH et al., 2014)
Coordination	Review - Smart Grid	General	(SHIH; ENRIQUEZ, 2014)
Coordination	DOCR	General	(LAZO, 2014)
Combine Coordination	Distance - DOCR	Transmission	(FARZINFAR et al., 2014)
Coordination	DOCR	Transmission	(ARREOLA; CONDE, 2014)
Coordination	DOCR	Transmission	(CHELLIAH et al., 2014)
Coordination	DOCR	Transmission	(NEGRÃO; VIEIRA, 2014)
Coordination	DOCR	Wind Power Plants	(REZAEI et al., 2014)
Coordination	DOCR	Transmission	(CORRÊA et al., 2015)
Coordination	DOCR	Transmission	(SALEH et al., 2015)
Coordination	DOCR	Transmission	(SWIEF et al., 2015)
Adaptative Coordination	DOCR	Transmission	(SHIH et al., 2015)
Coordination	DOCR	Transmission	(MANCER et al., 2015)
Coordination	DOCR	Transmission	(MESKIN et al., 2015)
Basics	Protective System	General	(MARTINEZ-VELASCO, 2015)
Coordination	DOCR	Transmission	(ALAM et al., 2015)

Continued on next page

Table 2.1 – continued from previous page

Caracterization	Theme	System Application	Citation
Coordination	DOCR	Transmission	(ALBASRI et al., 2015)
Coordination	DOCR - Distribuited Generation	Distribution	(Bedoya Toro; Cavadid Giraldo, 2015)
Coordination	DOCR	Transmission	(DARJI et al., 2015)
Coordination	DOCR	Transmission	(MORAVEJ et al., 2015)
Coordination	DOCR	Radial	(KIDA; PAREJA, 2015)
Coordination	DOCR	Transmission	(EMMANUEL et al., 2015)
Coordination	DOCR	Transmission	(ZELLAGUI; ABDELAZIZ, 2015)
Coordination	DOCR	Transmission	(ZEINELDIN et al., 2015)
Coordination	DOCR - Distribuited Generation	Distribution	(SRIVASTAVA et al., 2016)
Coordination	DOCR	Subtransmission / Transmission	(NOJAVAN et al., 2016)
Adaptative Coordination	DOCR - Distribuited Generation	Distribution	(ATES et al., 2016)
Coordination	DOCR	General	(KIDA, 2016)
Coordination	DOCR	Radial	(KIDA; PAREJA, 2016b)
Coordination	DOCR	Microgrid	(AHMARINEJAD et al., 2016)
Coordination	DOCR	Transmission	(KIDA; PAREJA, 2016a)
Coordination	DOCR	Transmission	(THAKUR; KUMAR, 2016)
Coordination	DOCR	Transmission	(SWETAPADMA; YADAV, 2016)
Adaptative Coordination	DOCR	Transmission	(KALAGE; GHAWGHAWE, 2016)
Coordination	DOCR	Transmission	(RAJPUT; PANDYA, 2017)
Coordination	DOCR	Transmission	(EL-FERGANY; HASANIEN, 2017)
Adaptative Coordination	DOCR	Transmission	(SHIH et al., 2017)
Adaptative Coordination	DOCR	Transmission	(YAZDANINEJADI et al., 2017)
Coordination	DOCR	Transmission	(RIVAS; PAREJA, 2017)
Adaptative Coordination	DOCR	Transmission	(COSTA et al., 2017)

2.2 Protective Relaying

System protection, also known as protective relaying, is composed of relay devices, mainly installed in substations, designed to detect abnormal system conditions, typically tracking the voltages and currents of the power system but not exclusive to those measures. These devices are set up to trigger the ‘trip’ or ‘close’ signals to circuit breakers if the verge is exceeded.

The IEEE characterize a relay as ‘an electric device that is designed to respond to input conditions in a prescribed manner and, after specified conditions are met, to cause contact operation or similar abrupt change in associated electric control circuits.’ Mentioning: ‘Inputs are usually electric, but may be mechanical, thermal, or other quantities or a combination of quantities. Limit switches and similar simple devices are not relays’ (IEEE Power & Engineering Society, 2012).

2.2.1 Power System Protection Components

Power line

Transmission line parameters are evenly distributed along the line length, and some of them are also functions of frequency. For steady-state studies, such as short-circuit calculations, positive- and zero-sequence parameters calculated at the power frequency from tables and simple handbook formulas may suffice (MARTINEZ-VELASCO, 2015).

Source and Generation

Source models used in protection studies are represented by means of detailed machine models or as ideal sinusoidal sources behind subtransient reactances or the equivalent Thevenin impedances of the system. The choice of a specific model depends on system configuration, the location of the fault and the objectives of the study (MARTINEZ-VELASCO, 2015).

Power Transformer

Transformer modelling over a wide frequency range still presents substantial difficulties: the transformer inductances are nonlinear and frequency dependent, the distributed capacitances between turns, between winding segments and between windings and ground produce resonances that can affect the terminal and internal transformer voltages.

Circuit Breaker

Circuit breakers are usually represented as ideal switches; that is, the switch opens at a current zero and there is no representation of arc dynamics and losses. Custom-made circuit breaker models can be employed for detailed arc modelling. The types of switches that are applicable for protection studies are presented below.

2.2.2 Instrument Transformers

The main tasks of instrument transformers are:

- To transform currents or voltages from usually a high value to a value easy to handle for relays and instruments.
- To insulate the relays, metering, and instruments from the primary high-voltage system.
- To provide possibilities of standardizing the relays and instruments, etc. to a few rated currents and voltages.

IEEE *Std C57.13-2016 Requirements for Instrument Transformers*, International Electrotechnical Commission (IEC) *61869 2007-2016 Instrument transformers* are most recent standards to newly manufactured instrument transformers with analog or digital output for use with electrical measuring instruments or electrical protective devices.

Voltage transformers

There are basically, two types of voltage transformers used for protective equipment.

1. Electromagnetic type (commonly referred to as a voltage transformer (VT))
2. Capacitor type (referred to as a capacitor voltage transformer (CVT))

The electromagnetic type is a step-down transformer whose primary and secondary windings are connected with a number of turns in a winding which is directly proportional to the open-circuit voltage being measured or produced across it. This type of electromagnetic transformers is used in voltage circuits up to 110/132 kV. For still higher voltages, it is common to adopt the second type namely the CVT (HEWITSON et al., 2005).

Accuracy of voltage transformers

The voltage transformers shall be capable of producing secondary voltages, which are proportionate to the primary voltages over the full range of input voltage expected in a system. Voltage transformers for protection are required to maintain reasonably good accuracy over a large range of voltage from 0 to 173% of normal. However, the close accuracy is more relevant for metering purposes, while for protection purposes the margin of accuracy can be comparatively less (HEWITSON et al., 2005). Under transient conditions VTs and CVTs can be subjected to ferroresonance. This phenomenon leads to overvoltages, which can lead to misoperation and (thermal and dielectric) failure (MARTINEZ-VELASCO, 2015). Permissible errors vary depending on the burden and purpose of use and typical values as per IEC are as follows.

Current transformers

All current transformers used in protection are basically similar in construction to standard transformers in that they consist of magnetically coupled primary and secondary windings, wound on a common iron core, the primary winding being connected in series with the network, unlike voltage transformers (HEWITSON et al., 2005). They must, therefore, withstand the networks short-circuit current.

There are two types of current transformers:

1. Wound primary type
2. Bar primary type

The wound primary is used for the smaller currents, but it can only be applied on low fault level installations due to thermal limitations as well as structural requirements due to high magnetic forces. For currents greater than 100 A, the bar primary type is used considering that if the secondary winding is evenly distributed around the complete iron core, its leakage reactance is eliminated. Protection current transformers (CTs) are most frequently of the bar primary, toroidal core with evenly distributed secondary winding type construction.

Performance of instrument transformers under transient conditions have shown the following areas of concern (MARTINEZ-VELASCO, 2015):

- CT saturation reduces the magnitude of the secondary current. The consequence for electromechanical relays is a reduction of the operating force or torque; a reduced torque increases the operation time and reduces the reach of the relay.
- CT saturation affects the zero-crossings of the current wave, and hence will affect schemes that depend on the zero crossings, such as phase comparators.
- The relaxation current in the CT secondary is the current that flows when the primary circuit is de-energized. This current is more pronounced in the case of CTs with an anti-remnant air gap.
- The relaxation current can delay the resetting of low-set overcurrent relays and also cause the false operation of breaker failure relays.

2.2.3 Zones of Protection

Protective relaying should be a part and parcel of overall system planning, design, and operation. Circuit breakers are to be located at appropriate places. The components or equipment and parts of the system to be protected by the circuit breakers must be clearly identified (MURTY, 2017).

Fig. 2.1 illustrates such an identification and demarcation of zones. Overlapping of the zones may be observed. Each zone generally covers one or two of power system elements. Location of current transformers determines the boundaries of the zones. This is purely from the protection point of view only.

A correct zoning should take into account:

- No point in the electrical system should be unprotected.
- All types of short circuits within the zone, including the edge, must be viewed by the appropriate detector elements (Reliability, Sensitivity, and Speed).

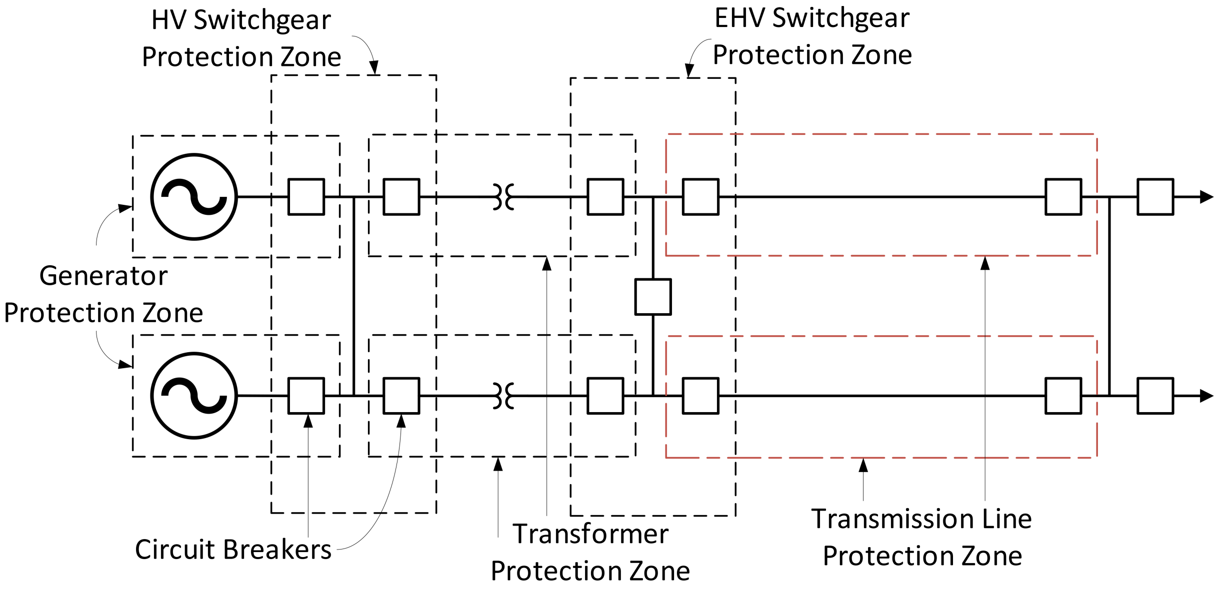

Figure 2.1 – Zones of Protection

- Any type of short circuit outside a zone should be seen by its detector elements but not activate tripping devices. (Selectivity)

The protection zone determines the selection of unitary or no unitary protection schemes, which define an absolute selectivity and are constituted by the backup protections.

2.2.4 Protection system philosophies

There are two main protection philosophies to which all protection systems adhere.

Unit protection

The philosophy of unit protection defines that the protection system should only detect and react to primary system faults within the zone of protection while remaining inoperative for external faults. The protection scheme illustrated in Fig. 2.2 represents a simple unit protection scheme (BOOTH; BELL, 2013; DAVIES, 1998).

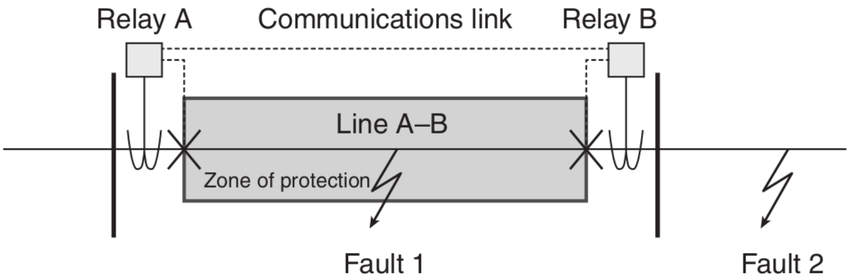

Figure 2.2 – Unit protection system (current differential protection)

Unit schemes typically involve protection relays that monitor the primary system conditions at each *end*, or boundary, of the protected zone. The relays measure some parameter and perform a comparison with the parameter being measured by the other relay within the unit scheme. If some threshold criterion is violated, for example, the measured currents are not equal or the vector summation of the measured currents is not equal to zero, then the protection relay initiate the process which will lead to isolation of the plant within the protected zone (SARKAR, 2015). Because of this requirement for comparison of parameters from each 'end' of the protected zone, almost all unit protection schemes have a requirement for relay-to-relay communications facilities, which may be achieved using a number of methods. For the system above, the zone of protection is clearly defined. To be exact, the zone of detection is between the measurement points, while the zone of protection is between the circuit breakers; normally, the CTs and circuit breakers are at almost identical locations. If, for example, each relay in the system form Fig 2.2 was comparing the magnitude of its measured current with the other relay's measured current, then for Fault 1, the currents will not be equal and the relays will trip. For the case of Fault 2, while both measured currents will be far in excess of normal load current levels, they will still be equal, and the protection relays should remain stable. Unit protection systems offer high levels of discrimination and stability, ensuring that the protection system only operates for faults within the protected zone, while remaining are inoperative for 'external' faults. The main negative aspect associated with unit schemes is that they do not possess backup protection capabilities, and there is a considerable expense associated with the use of communications. Furthermore, reliance on communications for operation gives rise to concern over the reliability of the communications link, which is sometimes addressed through the use of multiple communications systems, further increasing costs. The lack of backup capabilities is usually addressed through the use of non-unit schemes in addition to the unit scheme.

Non-unit protection

The protection scheme arrangement presented in Fig. 2.3 represents a simple non-unit protection scheme. The main difference between unit and non-unit schemes is that individual non-unit schemes do not independently protect one clearly defined zone of the system (BOOTH; BELL, 2013).

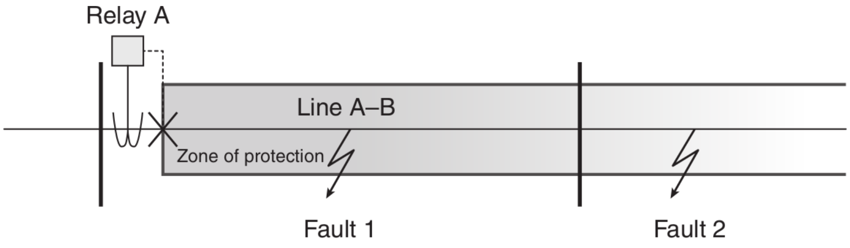

Figure 2.3 – Non-unit protection system (overcurrent protection)

In Fig. 2.3, the zone of protection, certainly covers Fault 1, but in this case, the 'zone' gradually 'fades' on the second line and, for Fault 2, it appears that the protection may provide coverage, but in the case above, this is not certain. The ‘reach’ of non-unit schemes can be varied by altering the settings on the relay, but non-unit schemes invariably exhibit characteristics whereby the reaction of the protection system varies as the location of the fault changes. In the example above, if the protection relay was an overcurrent relay, then it will operate quickly for Fault 1, but with an increasing time delay as the fault location moved further along the system to the right, operating with a relatively long time delay for Fault 2, and ceasing to operate as the fault moved further along Line 2. Impedance, or distance protection, is also a non-unit scheme, but rather than a continuously decreasing operation time, it exhibits a stepped characteristic, operating with fixed delays as the fault position moves from one zone to another in terms of its distance from the relay’s measurement point.

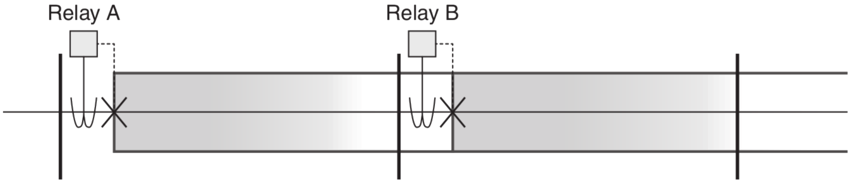

Figure 2.4 – Overlapping zone of protection in a non-unit arrangement (overcurrent protection)

Adjacent non-unit protection schemes on an interconnected power system have an element of overlap with respect to their respective zones of protection as shown in Fig. 2.4. This overlap is useful for providing backup protection in the event of failure of one element of the overall protection system. However, the criterion of selectivity, or discrimination, must still be satisfied and the non-unit scheme closest to the fault should always trip before any other non-unit schemes, which must remain stable until the closest schemes have operated, only operating if the primary protection fails to operate. Non-unit schemes, when compared to unit schemes, do not offer such high levels of discrimination and stability, but, as already mentioned, provide valuable backup protection capabilities.

2.2.5 Primary and backup protection

Every zone identified for protection will have a suitable protection specified. If a fault occurs in that zone, it is the duty of the relays in that zone to identify and isolate the faulty element in that zone. The relay in that zone will be designated as the primary relay. If for what so ever reason this primary relay fails to operate, there should be a second line of defense called backup protection. The relay in the backup protection is set to operate after a predetermined delay time given to primary relay so that continued existence of the fault in the system may not cause serious trouble (BAYLISS; HARDY, 2007; MURTY, 2017).

It is understood from the above that when primary protection fails, the backup or secondary protection operates and saves the system. But, then a large part of the system may get isolated in such an event. This cannot be avoided.

2.2.6 Protection techniques

Using measurement inputs from CTs and VTs, protection relays detect the presence of a fault on the system using a number of techniques. Unit and non-unit are used, in parallel, at transmission levels to provide high levels of discrimination and stability from the unit schemes, with the backup being provided by non-unit schemes, although it is important to emphasize that non-unit schemes can also operate extremely quickly, depending on the settings employed. At distribution and consumer voltage levels, non-unit schemes are normally employed (BOOTH; BELL, 2013).

Current Relays

The following types of current relays are normally considered into actual transmission power systems:

- Plain overcurrent and/or earth fault relay with an inverse definite minimum time (IDMT) interval or definite time (DT) delay characteristics.
- Overcurrent and/or earth fault relay as above but including directional elements. Note that a directional overcurrent relay requires a voltage connection and is not therefore operated by current alone.
- Instantaneous overcurrent and/or earth fault relays. For example, a high set overcurrent (HSOC) relay.
- Sensitive earth fault (SEF) relays.

As the name suggests, this method is based on measurement of current magnitudes, and a fault may be deemed to exist when the measured current exceeds a predetermined threshold level.

Historically this type of relay characteristic has been produced using electromagnetic relays, and many such units still exist in power systems. A metal disc is pivoted so as to be free to rotate between the poles of two electromagnets each energized by the current being monitored. The torque produced by the interaction of fluxes and eddy currents induced in the disc is a function of the current. The disc speed is proportional to the torque. As operating time is inversely proportional to speed, operating time is inversely proportional to a function of current (see Figure 2.5). The disc is free to rotate against the restraining or resetting torque of a control spring. Contacts are attached to the disc spindle and under preset current levels operate to trip, via the appropriate circuitry, the required circuit breaker(BAYLISS; HARDY, 2007).

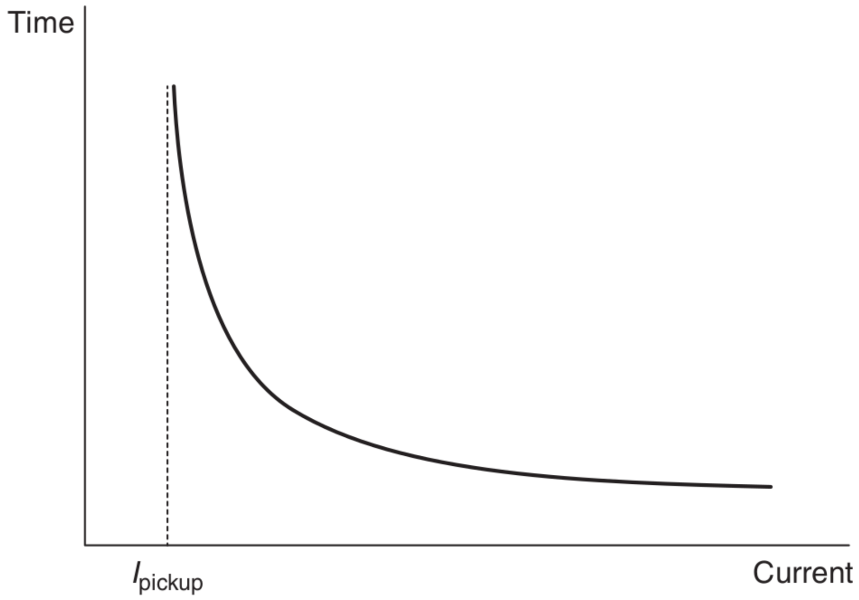

Figure 2.5 – Simplified time-current characteristic of standard inverse overcurrent protection

Current relay application

- Radial network: Consider from individual industrial application to distribution power system, reliable depending exclusively on a CT connection.
- Meshed network: The use of inverse time overcurrent relays on a meshed system requires the use of directional relays at all points where fault current could flow in both directions. A directional relay is merely a combination of the inverse time overcurrent relay and a directional sensing unit.

IDMT backup protection

In more important networks and at higher voltage levels current relays are used as a ‘back-up’ to more sophisticated and faster acting ‘main’ protection systems. The backup protection should be graded to achieve selective tripping if the main protection fails to operate. However, it must be noted that this is not always possible on highly interconnected networks involving widespread generation sources(BAYLISS; HARDY, 2007). Figure 2.6 shows a simple relay scheme for a transmission line where relay A (Backup) and relay B (Primary) should be coordinated based on their operation curve (Figure 2.7), where between both curves must respect the coordination time interval .

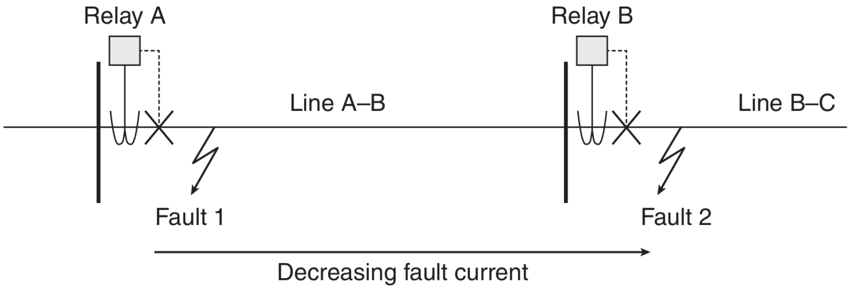

Figure 2.6 – Overcurrent protection for two serially connected feeders

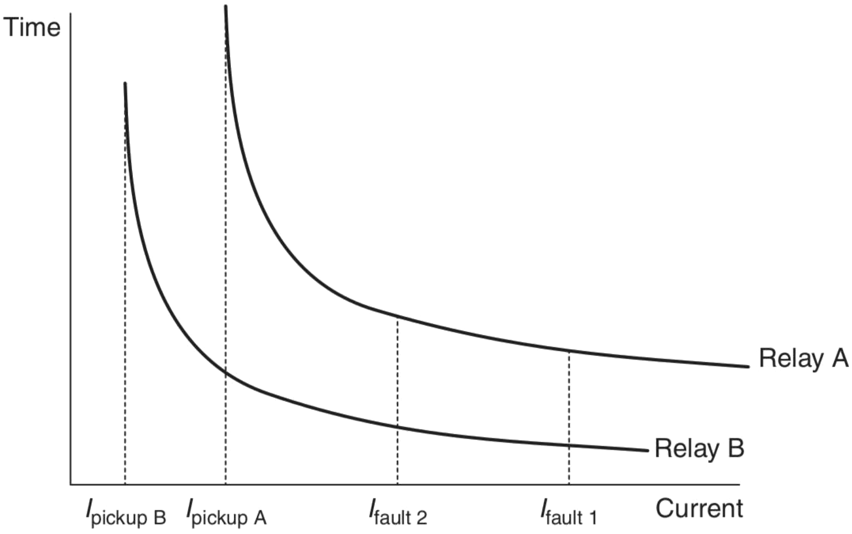

Figure 2.7 – Time-current characteristics with settings and fault currents for two coordinated overcurrent relays

Instantaneous HSOC relays

The tripping times at high fault levels associated with the IDMT characteristic may be shortened by the addition of instantaneous HSOC elements. These may be an integral part, for optional use depending upon front panel settings, of a modern solid state relay (BAYLISS; HARDY, 2007).

Distance relays

Designed to respond to current, voltage, and the phase angle between the current and voltage. These quantities can be used to compute the impedance seen by the relay. which is proportional to the distance to the fault (ANDERSON, 1999).

Early applications of distance protection utilized relay operating times that were a function of the impedance for the fault. The nearer the fault, the shorter the operating time. This has the same disadvantages as overcurrent protection, the grading settings may lead to tripping times that are too long to prevent damage and service interruption, and that satisfactory grading for complex networks is quite difficult to attain (EL-HAWARY, 1995).

Present practice is to set the relay to operate simultaneously for faults that occur in the first 80 percent of the feeder length (known as the first zone). Faults beyond this point and up to a point midway along the next feeder are cleared by arranging for the zone setting of the relay to be extended from the first zone value to the second zone value after a time delay of about 0.5 to 1 second. The second zone for the first relay should never be less than 20 percent of the first feeder length. The zone setting extension is done by increasing the impedance in series with the relay voltage coil current. A third zone is provided (using a starting relay) extending from the middle of the second feeder into the third feeder up to 25 percent of the length with a further delay of 1 or 2 seconds. This provides backup protection as well (EL-HAWARY, 1995; ANDERSON, 2009).

Fig. 2.8 presents a simple distance protection scheme in terms of its zones of protection and the time delays associated with operation of the relay for faults detected in each zone. Time definition for each zone usually depends on individual coordination of distance or manufacturer recommendations (EL-HAWARY, 1995; THOMPSON; HEIDFELD, 2015).

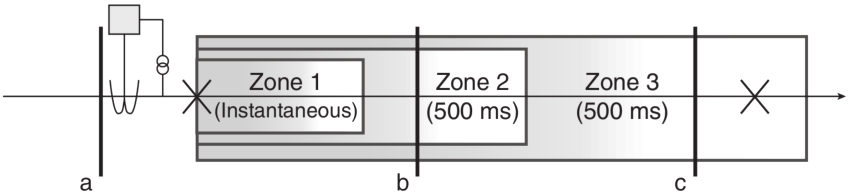

Figure 2.8 – Zones of protection of distance protection with indicative time delays of operation for faults detected in each zone.

Fig. 2.9 below illustrates the zone boundaries for each of the three zones in the complex impedance plane. The reason that the zone boundaries are circular is historical. When electromechanical relays were used, they effectively compared only the magnitudes (and not the relative phases) of the measured currents and voltages, and thus could only determine the magnitude of the impedance, which equates to a circle when plotted in the impedance plane. This circular characteristic is also a useful feature, as resistive faults can also be detected to a certain degree. For example, if a fault in the middle of Line 1 had a resistive element, then the locus of the measured impedance may lie in the vicinity of the cross indicated in the figure, and will still be detected (BOOTH; BELL, 2013).

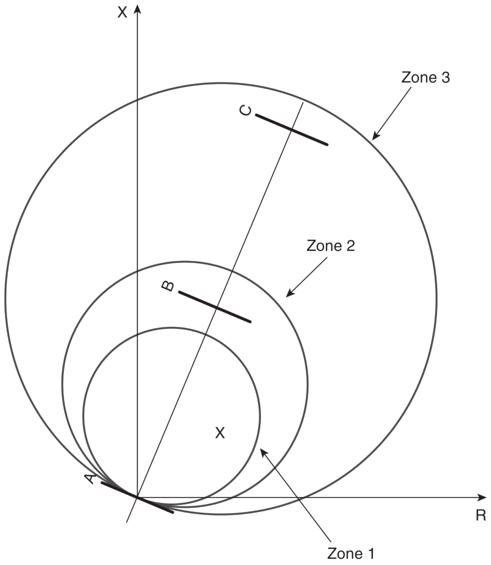

Figure 2.9 – Illustration of distance protection zone boundaries in the complex impedance plane.

2.2.7 Modernization of the Protection System

The microprocessor or digital relays offer many advantages and benefits over electromechanical relays such as reduced installation and maintenance costs, application flexibility besides increasingly developed control and monitoring functions. But the use of electromechanical relays has not been abandoned because they still meet the protection requirements of electrical power systems, finance is still an important factor against increasing sophistication and number of functions and facilities that digital relays have offered to Protection Engineers and event analysis energy companies and industry (MADRIGAL; ULUSKI, 2015; AGUERO et al., 2017).

One of the main advantages related to the modernization of the relays is the inherent flexibility of the digital technology and the possibility of producing adaptive characteristics and multiple adjustments to the system. The author Rufato Junior (2006) showed the feasibility and technical and economic benefits of using digital relays, considering high interruption rates caused by a fail in selectivity of the protections in the distribution system. In Brazil, Ribeiro and Goes (2013) shows a modernization of protection systems, a control, and supervision integration project presented with *Companhia Paranaense de Energia* (COPEL).

Making better use of existing and new technologies can reduce costs and facilitate the siting of transmission circuits. An accurate control of the system delivers an aptitude to increase capacity and availability (U.S. DOE, 2015).

3 Mathematical Formulation

In this chapter, the problem of coordination is formulated as a mathematical optimization problem, containing an objective function, which is responsible for minimizing the times of relay performance and a set of constraints. Both Distance and Overcurrent relays are considered into formulation, as individuals or together. Studying also the space of solution for this problem.

3.1 Mathematical Modeling DOCR

An IDMT, a compromise worldwide popular curve, introduced about 1920 have been a satisfied solution. Theoretically, their time ordinates should be proportional to the time dial setting (contact travel) so that, if the times for a given current were divided by the time dial setting, all the curves should be coinciding. Unfortunately, the inertia of the disc makes was impracticable at low current values because it takes a short time for the disc to accelerate from standstill to its steady speed (WARRINGTON, 1968).

A solution for limiting this obstacle was publishing a family of curves, the inverse time overcurrent most common curves are the IEEE, IEC, GE Type family of overcurrent relays from GE (IAC), and I2t standard curve shapes within their types shows in Tab. 3.1.

Table 3.1 – Overcurrent Relay Types

IEEE	**IEC**	**GE TYPE IAC**	**OTHER**
IEEE Extremely Inv.	IEC Curve A	IAC Extremely Inv.	I2t
IEEE Very Inverse	IEC Curve B	IAC Very Inverse	FlexCurves
IEEE Moderately Inv.	IEC Curve C	IAC Inverse	Recloser Curves
	IEC Short Inverse	IAC Short Inverse	Definite Time

Before considering the setting of these relays, the following definitions will be helpful.

Time Dial Setting or Time Multiplier Setting. A means of adjusting the mobile backstop which controls the driving of the disc and thereby varies the time in which the relay will close its contacts for given values of fault current.

Plug Setting, Pickup Current, or Tap Block. A device providing a range of current settings at which the relay will start to operate.

IDMT characteristics are selectable from a choice of curves conforming to the following formula (GE Industrial Systems, 2009).

3.1.1 IEEE Curves

The IEEE time overcurrent curve shapes conform to industry standards and the IEEE C37.112-1996 curve classifications for extremely, very, and moderately inverse. The IEEE curves are derived from the formula:

$$t = TDS\left(\frac{A}{(\frac{I}{I_{pickup}})^{p} - 1} + B\right) \tag{3.1}$$

where t is operating time (in seconds), TDS Time Dial Setting, I input current, I_{pickup} Pickup Current setting and A, p, B are constant parameters.

Table 3.2 – IEEE Inverse Time Curve Constants

IEEE CURVE SHAPE	**A**	**B**	**p**
IEEE Extremely Inverse	28.2	0.1217	2
IEEE Very Inverse	19.61	0.491	2
IEEE Moderately Inverse	0.0515	0.114	0.02

3.1.2 IEC Curves

For European applications, the relay offers three standard curves defined in IEC 255-4 and British standard BS142. These are defined as IEC Curve A, IEC Curve B, and IEC Curve C. The formula for these curves is:

$$t = TDS\left(\frac{K}{(\frac{I}{I_{pickup}})^{E} - 1}\right) \tag{3.2}$$

where t is operating time (in seconds), TDS Time Dial Setting, I input current, I_{pickup} Pickup Current setting and K, E are constant parameters.

Table 3.3 – IEC (BS) Inverse Time Curve Constants

IEC (BS) CURVE SHAPE	**K**	**E**
IEC Curve A (BS142)	0.14	0.02
IEC Curve B (BS142)	13.5	1
IEC Curve C (BS142)	80	2
IEC Short Inverse	0.05	0.04

3.1.3 IAC Curves

The curves for the General Electric type IAC relay family are derived from the formula:

$$t = TDS\left(A + \frac{B}{(\frac{I}{I_{pickup}}) - C} + \frac{D}{(\frac{I}{I_{pickup}})^2 - C} + \frac{E}{(\frac{I}{I_{pickup}})^3 - C}\right) \tag{3.3}$$

where t is operating time (in seconds), TDS Time Dial Setting, I input current, I_{pickup} Pickup Current setting and A to E are constant parameters.

Table 3.4 – GE TYPE IAC Inverse Time Curve Constants

IAC CURVE SHAPE	**A**	**B**	**C**	**D**	**E**
IAC Extreme Inverse	0.004	0.6379	0.62	1.7872	0.2461
IAC Very Inverse	0.09	0.7955	0.1	-1.2885	7.9586
IAC Inverse	0.2078	0.863	0.8	-0.4180	0.1947
IAC Short Inverse	0.0428	0.0609	0.62	-0.0010	0.0221

3.1.4 I^2t Curves

The curves for the I^2t are derived from the formula:

$$t = TDS\left(\frac{100}{(\frac{I}{I_{pickup}})^2}\right) \tag{3.4}$$

where t is operating time (in seconds), TDS Time Dial Setting, I input current, I_{pickup} Pickup Current setting.

3.1.5 Objective Function

In the Brazilian electrical sector, the 20th century witnessed a mixture of influences from North America and Europe. A key breakthrough in Brazilian electrical history was the government's decision to embrace the adoption of International Organization for Standardization (ISO)/IEC standards and guidelines for the national technical universe. This decision prompted *Associação Brasileira de Normas Técnicas* (ABNT) to select IEC standards as the main reference for Brazilian Technical Standards. In the last two decades, all related power systems standards moved closed to the IEC culture. Besides, a number of previous works using IEC standard make a better decision only to evaluate the behavior of coordination considering only (COSTA et al., 2014).

Eq. 3.5 is an extension of the Eq. 3.2 evaluating operating time of the DOCRs even when they are use as main or backup protection.

$$t_{ik} = TDS_i \left(\frac{K}{(\frac{I_{ik}}{I_{pickup}})^E - 1} \right) \tag{3.5}$$

where t_{ik} is the operating time of the relay i for a fault in k, TDS_i Time Dial Setting for the relay i, I_{ik} input current from a fault k seen by relay i, I_{pickup} Pickup Current setting and K, E are constant parameters.

The concept of relay pickup tap setting could be formulated by

$$PS_i = \frac{I_{pickup}}{CTR_i} \tag{3.6}$$

where I_{pickup} is the primary pickup current and CTR_i stands for the CT ratio. Pickup current should be above maximum load current ensuring that relay does not trip on normal load conditions, normally with values within a continuous range but when related to PS depends on relay's available settings (continuous or discrete).

DOCR coordination problem can be stated as a parametric optimization problem, where the objective function (OF) to be minimized is the sum of the operating times of the relays connected to the system, subject to the following constraints (URDANETA et al., 1988).

This problem can be formulated mathematically as

$$min \quad \sum_{i=1}^{n} \sum_{k=1}^{n} t_{ik} \tag{3.7}$$

where t_{ik} is the operating time of the primary relay i for a fault k

3.1.6 Coordination Constraints

Coordination criteria (Selectivity Constraint) A fault is sensed by both primary as well as secondary relay together. To avert violation in operation, the backup relay (BR) should take over the tripping action only after primary relay (PR) flops to operate (MANSOUR et al., 2007). If R_i is the primary relay for defect at k, and R_j is backup relay for the same fault, next the coordination constraint can be seated as:

$$t_{j,k} - t_{i,k} = \triangle t \tag{3.8}$$

Where $t_{i,k}$ is the operating time of the primary relay R_i , for fault at k; $t_{j,k}$ is the operating time for the backup relay R_j , for the same fault at k, $\triangle t$ is the coordination time interval (CTI)

Bounds on TDS of each relay

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \tag{3.9}$$

TDS_i^{min} and TDS_i^{max} are minimum and maximum value of TDS of relay R_i, and TDS_i in continuous domain.

Bounds on pickup current I_{pickup} setting of each relay

$$I_{pickup}^{min} \leq I_{pickup} \leq I_{pickup}^{max} \tag{3.10}$$

I_{pickup}^{min} and I_{pickup}^{max} are minimum and the maximum value of pickup current setting of each relay, and I_{pickup} in continuous domain but when convert to PS may be discrete or continuous.

The range for all parameters is defined by the network topologies, manufacturer recommendations, and standards limits and are individually described for each problem propose in this work.

3.2 Mathematical Modeling DOCR & Distance

Transmission and sub-transmission systems normally have a mixed scheme with DOCR and distance relays. Considering a pair of this relays for each circuit breaker, distance zones definition have an important matter in coordination. Distance relay zone-1 has an instantaneous trip, been faster than DOCR units considered in this formulation; fact defining DOCR as the backup for Zone 1 for a distance relay (DZ-1) relays in certain fault locations. This approach is normally not considered due to fault location dependence to configure zones on distance relays. For example, last resolution would be valid for near-end and half-end fault locations but dismissed for far-end faults, supposing zone-1 to an 80% of the line.

Examining zone-2 of distance relay requires fault location evaluation, as seen in Fig. 3.1, with three faults location by line (near-end, midpoint, and far-end) and holding DOCRs primary relays to all cases, the backup configuration has a different pondered definition.

Fig. 3.1 diagram shows how it should be guaranteed the selectivity for the relays of overcurrent for all the faults, but how it changes for the relays of distance that has as a rear zone 2. At the beginning of the line, zone 2 of the distance relay located where

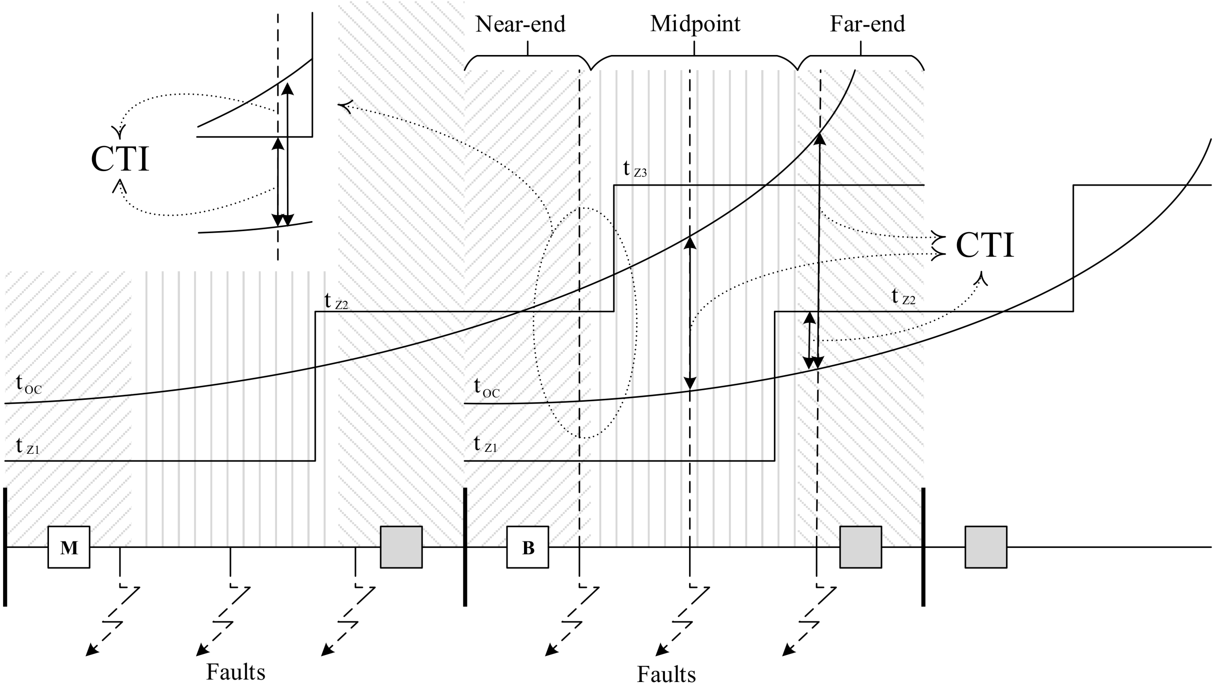

Figure 3.1 – Critical fault locations for the coordination between overcurrent and distance relays

you find the backup overcurrent relay. In the middle of the line, has no zone 2 of acting distance relay (Normally configured between 80

3.2.1 Objective Function

Considering the primary actuation times of the overcurrent relays and the tripping times for zone 2 of the distance relays, the objective function for coordination combined with relays of distance is written as Eq 3.11.

$$min \quad \sum_{i=1}^{n}\left(\sum_{k=1}^{n} t_{ik}^{OC} + t_{i}^{Z2}\right) \tag{3.11}$$

where t_{ik}^{OC} is the operating time of the primary DOCR i for a fault k and t_i^{Z2} is the time defined for the second zone of each distance relay.

3.2.2 Coordination Constraints

Eq. 3.8, 3.9, and 3.10 are still valid for the mixed mathematical model. Constraints considered in the scheme are increased by new conditions depending on fault location.

Near-end faults

Coming from the DOCR model where R_i^{OC} is the primary relay for a fault at k and R_j^{OC} is the backup relay for the same fault, the second zone of the R_j^D is priority backup relay. Meaning, three levels of protection, first, R_i^{OC} following R_j^D and R_j^{OC}.

$$t_j^{Z2} - t_{i,k}^{OC} = \triangle t \tag{3.12}$$

$$t_{j,k}^{OC} - t_{i,k}^{OC} = \triangle t \tag{3.13}$$

Midpoint faults

There is a lack where the second zone for distance relays is not under the protection scheme, according to 2.2.6 between 20% and 80% of the line only actual zone-1 and backup from zone-3 of adjacent backup. Zone-3 is not considered in this work, that's why exclusively DOCR generates constraints in this case.

$$t_{j,k}^{OC} - t_{i,k}^{OC} = \triangle t \tag{3.14}$$

Far-end faults

On the contrary for far-end fault location, the second zone of the R_i^D is priority backup relay of the R_i^{OC} leaving R_j^{OC} behind. Intending, three levels of protection as near-end faults constraints.

$$t_i^{Z2} - t_{i,k}^{OC} = \triangle t \tag{3.15}$$

$$t_{j,k}^{OC} - t_{i,k}^{OC} = \triangle t \tag{3.16}$$

Bounds on TDS of each relay

$$t_i^{Z2}min \leq t_i^{Z2} \leq t_i^{Z2}max \tag{3.17}$$

$t_i^{Z2}min$ and $t_i^{Z2}max$ are minimum and maximum value of t_i^{Z2} of relay R_i.

Zone-2 is set with an 18 ($t_i^{Z2}min$) to 36 ($t_i^{Z2}max$) cycles delay to coordinate with remote relays (THOMPSON; HEIDFELD, 2015). The remote relays use that time to clear the fault and give breaker failure functions time to operate.

Table 3.5 – Distance relays second zone configuration time interval

Frequency	**Zone-2 set time (s)**	
	min	*max*
Cycles	18	36
50 Hz	0.36	0.72
60 Hz	0.3	0.6

3.3 Feasible Region and Problem Characterization

The coordination problem is formulated as mixed-integer nonlinear programming (MINLP) when TDS or PS are analyzed as discrete variables. Even considering both as continuous the relaxation maintains the nonlinear component into the problem. In meshed networks, feasible region tends to a highly restricted hyperspace which does not support a convex set. Nonconvex MINLPs are especially challenging because they contain nonconvex functions in the objective or the constraints, as seen in Fig. 3.2, the feasible region for a relay pair considering TDS fixed has nonconvex characteristics (Between point A and B there are points not contained in the feasible set); within a relaxation as Fig. 3.3 the solution space has convex and linear but only consider one problem variable obtaining a local optimum but certainly not a response closer to the global solution. In Fig. 3.4 a 3D surface plotting individual relay time considering TDS and PS variables.

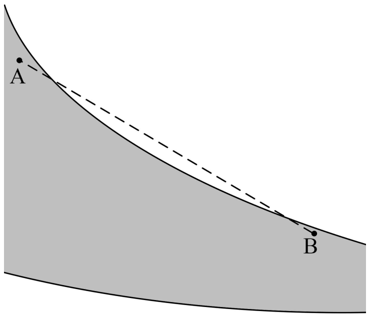

Figure 3.2 – Feasible region for Primary-Backup Relay Considering TDS fixed.

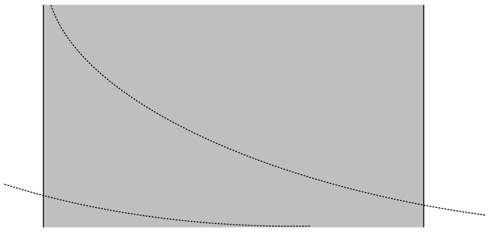

Figure 3.3 – Feasible region for Primary-Backup Relay Considering PS fixed.

Solving nonconvex MINLPs may be replacing the nonconvex functions with convex piecewise linear approximations and solve the corresponding approximation by using mixed-integer linear programming solvers. Also, components of methods for directly solving nonconvex MINLPs, generic tactics for reaching convex relaxations nonconvex functions or spatial branching can be used with these relaxations to get a convergent algorithm (BELOTTI et al., 2012).

Some real-world applications cannot be solved to global optimality by using the prior methods discussed, because the problems are too large, generate a huge search tree, or like coordination must be solved in real time. In these situations, it is more desirable to obtain a good solution quickly than to wait for an optimal solution. Heuristic search

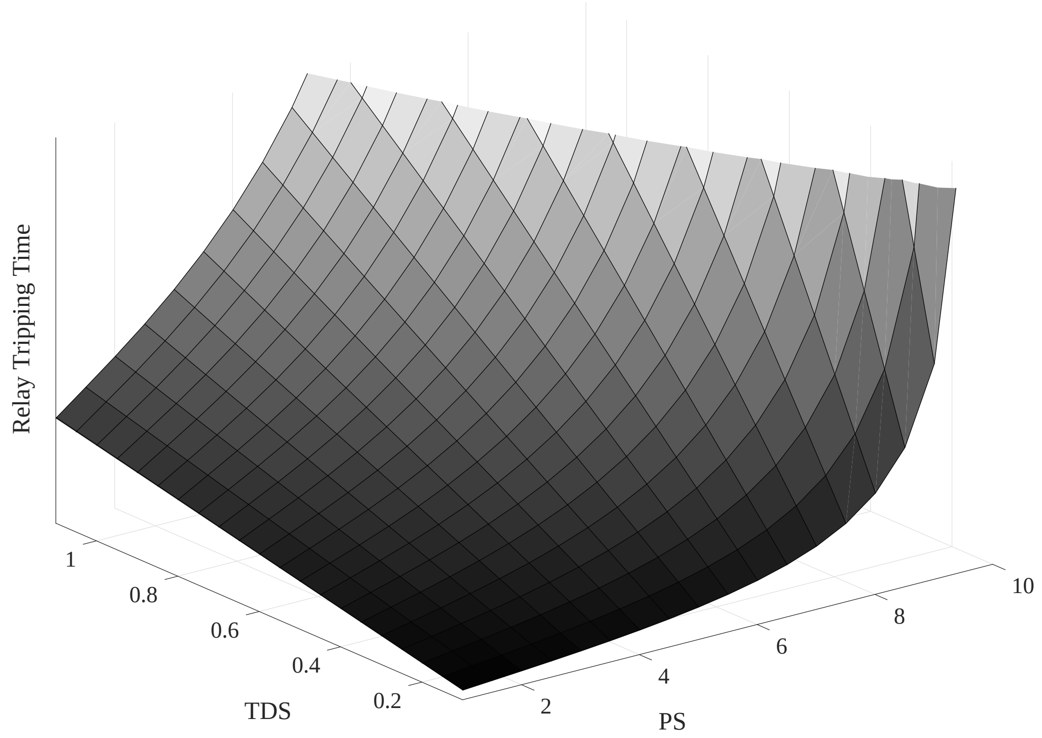

Figure 3.4 – Overcurrent Relay 3D time plot considering TDS and PS Variation.

techniques that provide a feasible point without any optimality guarantees. But also quickening deterministic techniques by promptly distinguishing an incumbent with a low value of the objective function (BELOTTI et al., 2012; BURER; LETCHFORD, 2012)

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4 Implementation

4.1 Ant Colony Optimization

The colonies of ants, and in general, insect societies, are distributed systems that despite the simplicity of their individuals have a highly structured social organization. The main idea is that these principles be exploited to coordinate populations of artificial agents that collaborate to solve computational problems. Ants coordinate their activities via stigmergy, a form of indirect communication mediated by changes in the environment (DORIGO; STÜTZLE, 2004). The idea of ant algorithms is then to use a form of artificial stigma to coordinate societies of artificial agents.

Some considerations came from ants in the real world to inspire this technique. First, many ant species are almost blind, the communication between the ants is carried out through a chemical called pheromone, and in some species, the pheromone is used to create paths (ant's trails), see Fig. 4.1.

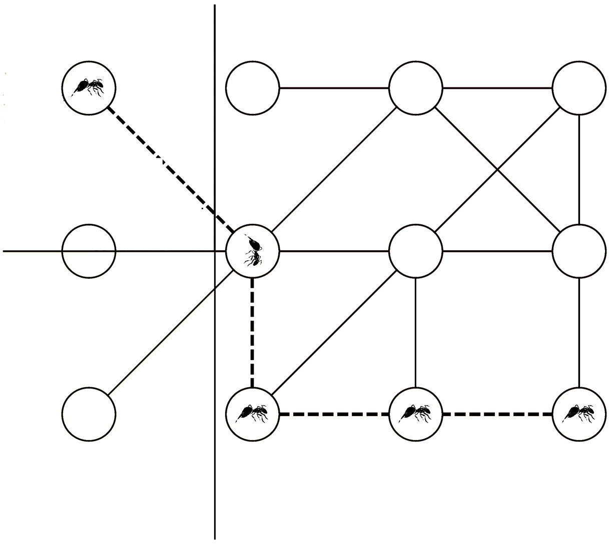

Figure 4.1 – Ants build solutions, that is, paths from a source to a destination node.

ACO algorithms for CO problems make use of a supposed pheromone model in order to probabilistically construct solutions. A pheromone model consists of a set of numerical values, called pheromones, that is a function of the search experience of the algorithm (DORIGO; BLUM, 2005). The pheromone model is used to bias the solution construction toward regions of the search space enclosing high-quality solutions. An advantage for model coordination problem using mixed ACO approach is a high probability of finding better solutions for actual systems.

Fig. 4.2 is an experiment performed by Deneubourg to study the behavior of ants, describe in Dorigo and Blum (2005) explaining the process for an ant to look for food from the nest. Mathematically, the proposed model assumes the following conditions:

- Time and space are discrete.
- During each interval of time, the individuals of the colony have the same speed in the system.
- Each individual deposits a small amount of pheromone in their path.
- One path is twice longer than the other.
- The argument for the ant to choose the path is determined by the higher level of pheromone accumulated.

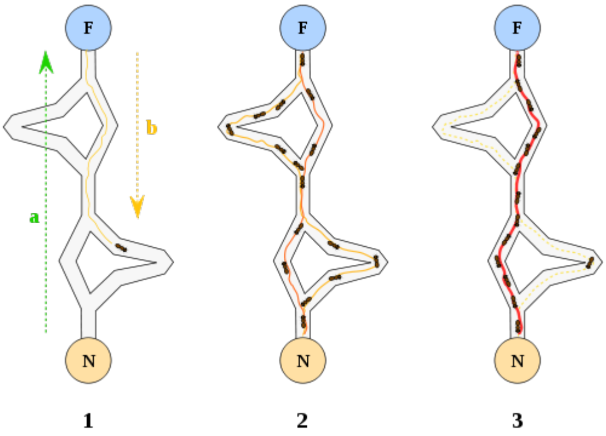

Figure 4.2 – Ants paths from the nest to the food.

4.2 Model for Mixed-variable Optimization Problems

A model for a mixed-variable optimization problem (MVOP) may be formally represented defining a model $R = (\mathbf{S}, \Omega, f)$ of a MVOP outlined as follows.

1. Search space $\mathbf{S}$ defined over a finite set of both discrete and continuous decision variables and a set Ω of constraints among the variables.
2. An objective function $f : \mathbf{S} \leftarrow R_0^+$ to be minimized. The search space $\mathbf{S}$ is defined by a set of $n = d + r$ variables $x_i, i = 1, ..., n$, of which d are discrete and r are continuous. The discrete variables include o ordinal variables and c categorical ones, $d = o + c$. A solution $S \in \mathbf{S}$ is a complete value assignment, that is, each decision variable is assigned a value. A feasible solution is a solution that satisfies all

constraints in the set Ω. A global optimum $S^* \in \mathbf{S}$ is a feasible solution that satisfies $f(S^*) \leq f(S) \quad \forall S \in \mathbf{S}$. The set of all globally optimal solutions is denoted by $\mathbf{S}^*$, $S^* \subseteq \mathbf{S}$. Solving an MVOP requires finding at least one $S^* \in \mathbf{S}^*$.

This method to tackle MVOPs combines a continuous relaxation and a categorical optimization approach. This strategy uses a categorical optimization approach to directly handle discrete variables without a continuous relaxation and continuous variables are handled by a continuous optimization method, without the need to handle dependency between variables belonging to different distributions avoiding to find sub-optimal solutions (SOLNON, 2007).

4.3 ACO for Mixed-variable Optimization Problems

Initially, is described the structure of the multivariable algorithm (Fig. 4.3). Then, how the probabilistic solution construction for continuous variables, and categorical variables, is developed respectively. During the construction process, ordinal choose is dismissed due to similar construction compare to continuous variables, using categorical procedure guarantee independent convergence during function evaluation.

4.3.1 Codification

Derivate from the mathematical model, chosen variables are TDS and PS parametrized as Continuous and Categorical, respectively. Codification bases in the next structure:

Based on an array of Fig. 4.3, solution archive (SA) form k solutions of n variables each. In association with each solution S_j is a quality function $f(S_j)$, which from best to worst, sorts the array and defines a weight ω_j calculated using a Gaussian function with mean related to rank and standard deviation depending on the size k of the SA and a q as a parameter of the algorithm.

$$Quality\,Function\ = h_1 \sum_{i=1}^{n} \sum_{k=1}^{n} t_{ik} + h_2 \sum_{i=1}^{n_{Const}} CV \tag{4.1}$$

Where h_1 and h_2 are weighting factors for increasing or decreasing the influence of fitness and unfitness function, respectively. Constraints violations (CV) is a time variable for each violation.

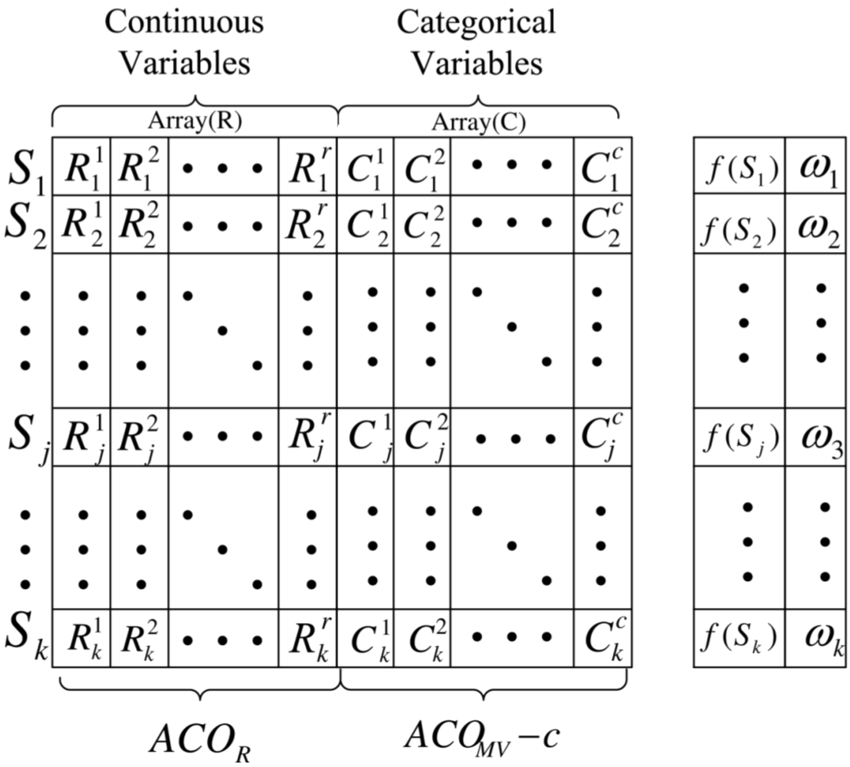

Figure 4.3 – Structure of the solution archive used by ACO_{MV} (SOLNON, 2007) In this case, reduced to two variable types.

4.4 Construction of a solution (an ant)

The process of building an alternative solution is basically a construction in which elements are added gradually. The difference with classical heuristic methods lies in the fact that the added element is the product of learning, leaving behind the impact that the objective function may have. Also, in order to generate a larger exploration of the solution space, the formation of feasible solutions is allowed.

In constructing an alternative solution by an ant algorithm it is essential to know the pheromone model, and whether the heuristic to guide the search for promising career paths based on information as possible. In addition, it is necessary to introduce an essential criterion for the construction of an alternative solution, which is *neighborhood* represented by a Gaussian Kernel as shows Fig. 4.4.

This type of construct algorithm is typically faster among approximate methods, the quality of the solutions they generate is often worst than the quality of the solutions found by local search algorithms.

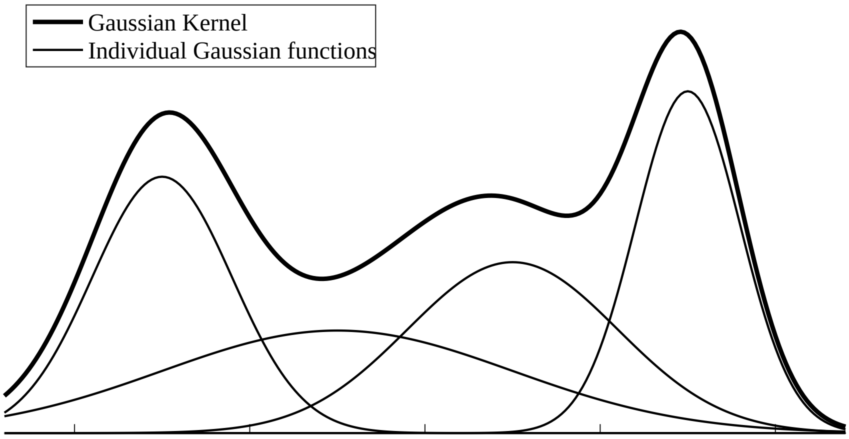

Figure 4.4 – Gaussian Kernel of the SA

4.4.1 ACO_{MV} Parameters

Construction for Continuous Variables

Continuous variables use the ant colony optimization for continuous domain (ACO_R) algorithm (SOCHA; DORIGO, 2008) where an ant build probabilistically one solution based on the SA. Probability of designating a solution j is defined by his weight ω_j in the SA (Figure 4.3) and ω_l weight of all k solutions.

$$p_j = \frac{\omega_j}{\sum_{l=1}^{k} \omega_l} \tag{4.2}$$

After selection of jth solution, in order to attach a value to variable i, the ant samples the neighborhood over the value R_j^i of the chosen jth solution compare to all R_l^i variables in the SA. The sampling is done using a normal probability density function with mean $\mu = R_j^i$ and standard deviation σ define by 4.3.

$$\sigma = \xi \sum_{l=1}^{k} \frac{|R_l^i - R_j^i|}{k-1} \tag{4.3}$$

Parameter ξ has an important effect similar to pheromone persistence in the ACO first algorithm, with a particular impact on the convergence speed of the algorithm.

Construction for Categorical Variables

In this case, the PS variable could be treated as ordinal and use a relaxation ACO_R to solve it, but treating the PS variable as categorical is a guarantee for diversity, choosing from vector data.

Now, an ant choose between PS available values, probabilistically based on the next equation:

$$p_l^i = \frac{\omega_l}{\sum_{j=1}^{PS_i} \omega_j} \tag{4.4}$$

where ω_l is the weight associated to each PS value, and calculated by:

$$\omega_l = \begin{cases} \frac{\omega_{jl}}{u_l^i} + \frac{q}{\eta} & if(\eta > 0, u_l^i > 0) \\ \frac{\omega_{jl}}{u_l^i} & if(\eta = 0, u_l^i > 0) \\ \frac{q}{\eta} & if(\eta > 0, u_l^i = 0) \end{cases} \tag{4.5}$$

Where ω_{jl} is calculated according to 4.5. u_l^i is the number of solutions that use PS_i for the categorical variable i in the SA. η is the number of values from PS vector available ones that are not used by the SA. q has the same characteristics from the continuous part.

4.5 Restart Mechanism

The ACO algorithm is usually used with a restart strategy for struggling stagnation and avoiding local optimum. Always keeping the best-so-far solution in the SA. When a number of successive iterations have a relative solution enhancement lower than certain ϵ a restart is started (SOLNON, 2007). Normally, this strategy stands on generating a new SA only keeping the best-so-far, this work introduces a new restart technique using the parameter q increasing elitism of the algorithm.

4.6 Algorithm and Flowchart

A detailed Flowchart (see Fig. 4.5) for the algorithm implementation containing the iterative process to find a solution.

The computational steps of ACO are given below based on (SOLNON, 2007):

4.7 Analysis of ACO parameters

Hard optimization problems often required algorithms which typically have several parameters that need to be set or tuned such that some features of performance is optimized. Based on a statistical strategy for selecting the best configuration out of a set of candidate configurations under stochastic evaluations, F-Race is a racing algorithm for the task of automatic algorithm configuration. This work uses an extension of the initial F-Race

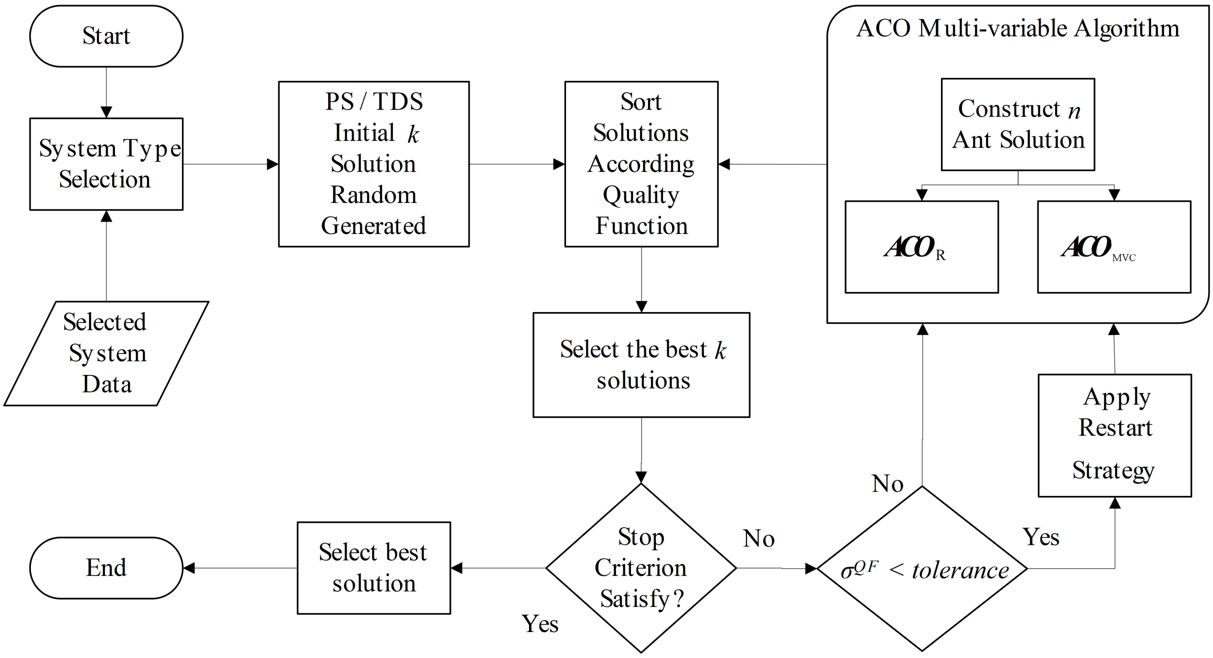

Figure 4.5 – Flowchart for ACO_{MV}

Algorithm 1 Outline of ACO_{MV}

```
Initialize decision variables
Initialize and evaluate $k$ solutions
{Sort solutions and store them in the archive SA}
$SA \leftarrow Sort(S_1 S_k)$
while termination criterion is not satisfied do
    {ConstructAntSolution}
    for 1 to m do
        Probabilistic Solution Construction for $ACO_R$
        Probabilistic Solution Construction for $ACO_{MVC}$
        Store and evaluate newly generated solutions
    end for
    Sort solutions and select the best $k$ solutions
    $SA \leftarrow Best(Sort(S_1 S_k))$
    if $\sigma_{QF} < \epsilon$ then
        Apply Restart Strategy
    end if
end while
```

algorithm, which leads to a family of algorithms called iterated F-Race implemented to tuned up ACO algorithm.

4.7.1 F-RACE approach

Algorithms for tackling computationally complex problems have a number of parameters that influence their search behavior. Many state-of-the-art algorithms cover exact algorithms such as branch-and-bound algorithms, algorithm packages for integer programming, and relative algorithms such as stochastic local search (SLS) algorithms. The parameters can approximately be grouped into numerical and categorical parameters.

Examples of numerical parameters are the tabu tenure in tabu search algorithms or the pheromone evaporation rate in ACO algorithms. Moreover, many algorithms can be seen as being composed of a set of specific components that are frequently interchangeable. Examples are diverse branching maneuverings in branch-and-bound algorithms, different types of crossover operators in evolutionary algorithms, and different types of local search algorithms in iterated local search. These intervariable elements are frequently well expressed as categorical parameters of the underlying search method. Analysis has definitely shown that the performance of parameterized algorithms depends strongly on the particular values of the parameters, and the choice of a suitable setting of these parameters is itself a challenging optimization problem (ADENSO-DÍAZ; LAGUNA, 2006; BIRATTARI, 2005; BIRATTARI et al., 2002).

Typically not only the setting of numerical parameters but also that of categorical parameters needs to be settled, many state-of-the-art refers to an algorithm configuration problem. An essential aspect of this problem is that it is typically a stochastic problem. Actually, there are two main sources of Ergodicity. The first is that often the algorithm itself is stochastic because it uses some randomized arrangements during the search. In fact, this stochasticity is typical for SLS algorithms (HOOS; STÜTZLE, 2005).

However, even if an algorithm is deterministic, its performance and search behavior depend on the circumstantial instance to which it is applied. In fact, the particular instance being tackled can be seen as having been described according to some underlying, possibly unknown probability distribution, adding in this way a second stochastic factor.

Hoeffding races (MARON; MOORE, 1993; MARON, 1994), an accelerating model selection search for classification and function approximation, is an important racing algorithm in machine learning which inspires methods like F-Race method convenient for dealing with the stochastic characteristics of the ACO algorithm. The basic idea of racing methods, in general, and this method in particular, is to evaluate a distributed set of candidate configurations iteratively on a succession of instances. As soon as enough statistical evidence is deduced against some candidate configurations, these are filtered and the race continues only with the surviving ones. In our case, this method uses after each evaluation round of the candidate arrangements the nonparametric Friedman test (FRIEDMAN, 1937) as a family-wise test: it checks whether there is confirmation that at least one of the configurations is significantly different from others. If the null hypothesis of no differences is rejected, Friedman post-tests are applied to eliminate those candidate configurations that are significantly worse than the best one.

4.7.2 Algorithm Configuration Problem

F-Race is a pre-process to obtain an offline configuration of parameterized algorithms. In the training phase of offline tuning, an algorithm configuration is to be settled in a limited quantity of time that optimizes some pattern of algorithm performance. The final algorithm configuration is then expanded in a production phase where the algorithm is used to solve earlier undiscovered instances. A significant aspect of this algorithm configuration problem is that it is a problem of generalization, as occurs in other disciplines such as machine learning. Based on a given set of training instances, the goal is to find high-performing algorithm configurations that perform well on (a probably infinite set of) unseen instances that are not available when deciding on the algorithm's parameters. Hence, one conjecture that is tacitly done is that the set of training instances is representative of the instances the algorithm faces once it is employed in the production phase. The awareness of best performance or generalization is made explicit in the formal sense of the algorithm configuration problem.

The problem of configuring a parameterized algorithm can be properly defined as a 7-tuple $\langle \Theta, I, p_I, p_C, t, \mathcal{C}, T \rangle$ where:

- Θ is the possibly infinite set of candidate configurations.
- I is the possibly infinite set of instances.
- p_I is a probability measure over the set I.
- $t : I \rightarrow \Re$ is a function associating to every instance the computation time that is allocated to it.
- $c(\theta, i, t, t(i))$ is a random variable representing the cost measure of a configuration $\theta \in \Theta$ on instance $i \in I$ when run for computation time $t(i)$.
- $C \subset \Re$ is the range of c, that is, the possible values for the cost measure of the configuration $\theta \in \Theta$ on an instance $i \in I$.
- p_C is a probability measure over the set C: With the notation $p_C(c|\theta, i)$ we indicate the probability that c is the cost of running configuration θ on instance i.
- $\mathcal{C}(\theta) = \mathcal{C}(\theta|\Theta, I, p_I, p_C, t)$ is the criterion that needs to be optimized with respect to θ. In the most general case it measures in some sense the desirability of θ .
- T is the total amount of time available for experimenting with the given candidate configurations on the available instances before delivering the selected configuration.

On the basis of these concepts, solving the problem of configuring a parameterized algorithm is to find the configuration $\overline{\theta}$ such that

$$\overline{\theta} = \arg\min_{\overline{\theta}\in\Theta} \mathcal{C}(\theta) \tag{4.6}$$

consider for $\mathcal{C}$ the expected value of the cost measure c

$$\mathcal{C}(\theta) = E_{I,C}(c) = \iint c\, dp_C(c|\theta, i) dp_I(i) \tag{4.7}$$

where the expectation is considered with respect to both p_I and p_C, and the integration is taken as defined by Bartz-Beielstein et al. (2010).

4.7.3 Iterated F-Race Algorithm

This implementation is based on the previous published by Balaprakash et al. (2007) and Bartz-Beielstein et al. (2010). However, it changes in some parameter choices and extends the earlier version by defining a way to handle categorical parameters.

The number of iterations. Denoted by L the number of iterations of Iterated F-Race Algorithm (I/F-Race), and increase L with d, the number of parameters, using a set of $L = 2 + round(log_2 d)$.

Computational budget at each iteration. The computational budget is distributed as equally as possible across the iterations. B_l, the computational budget in iteration l, where $l = 1, ..., L$, is set to $B_l = B_{used}/(L - l + 1)$; B_{used} denotes the total computational budget used until iteration $l - 1$.

The number of candidate configurations. Introducing a parameter μ_l, and set the number of candidate configurations sampled at iteration l to be $N_l = \lfloor B_l/\mu_l \rfloor$. Letting μ_l increase with the number of iterations, using a set of $\mu_l = 5 + l$. Under this conditions μ_l allows more evaluation steps to identify the winners when the configurations are deemed to become more similar.

The terminus of F-Race at each iteration. In appreciation to the usual termination criteria of F-Race, we stop it if at most $N_{min} = 2 + round(log_2 d)$ candidate configurations remain.

Creation of candidate configurations. In the first iteration, all candidate configurations are randomly sampled uniformly. Once F-Race terminates, the best N_s candidate configurations are selected for the update of the probability model.

We use $N_s = min(N_{survive}, N_{min})$, where $N_{survive}$ expresses the number of candidates that withstand the race. These N_s elite configurations are then weighted according to their ranks, where the weight of an elite configuration with rank $r_z(z = 1, ..., N_s)$ is given by

$$w_z = \frac{N_s - r_z + 1}{N_s(N_s + 1)/2} \tag{4.8}$$

Particularly, the weight of an elite configuration is inversely proportional to its rank. Because the instances for configuration are sampled randomly from the training set, the N_s elite configurations of the lth iteration will be re-evaluated in the $(l + 1)$st iteration, synchronically with the $N_{l+1} - N_s$ candidate configurations to be sampled a new. (Alternatively, it is possible to evaluate the arrangements on determined instances, so that the results of the elite configurations from the last iteration could be reused, not entirely applicable to this version of ACO algorithm due to instance related to computational capabilities.). The $N_l + 1 - N_s$ new candidate configurations are iteratively sampled around one of the elite configurations. Toward, for sampling each new candidate configuration, first, one elite solution $E_z(z \in 1, ..., N_s)$ is chosen with a probability proportional to its weight w_z and next a value is sampled for each parameter. The sampling distribution of each parameter depends on whether it is a numerical one (the set of such parameters being denoted by X_num) or a categorical one (the set of such parameters being denoted by X_{cat}). We have that the parameter space $X = X^{num} \cup X^{cat}$.

First suppose that X_i is a numerical parameter, i.e. $X_i \in X^{num}$, with boundary $X_i \in [\underline{X_i}, \overline{X_i}]$. Denote by $v_i = \overline{X_i} - \underline{X_i}$ the range of the parameter X_i. The sampling distribution of X_i follows a normal distribution $\mathcal{N}(x_i^z, \sigma_i^l)$, with x^z being the mean and σ_i^l being the standard deviation of X_i in the lth iteration. The standard deviation is reduced in a geometric fashion from iteration to iteration using a setting of

$$p_{l+1}(f_j) = p_l(f_j)\left(1 - \frac{l}{L}\right) + I_j = f_i^z \frac{1}{L} \qquad for \quad l = 1, ..., L-1 \qquad and \quad j = 1, ..., n_i \tag{4.9}$$

In other words, the standard deviation of the normal distribution is reduced by a factor of $\left(\frac{1}{N_l+1}\right)^{\frac{l}{d}}$ as the iteration counter increments. Hence, the more parameters, the smaller the update factor becomes, resulting in a stronger bias of the elite configuration on the sampling. Moreover, the larger the number of candidate arrangements to be sampled, the stronger the bias of the sampling distribution. Now, suppose that $X_i \in X^{cat}$ with n_i levels $Fi = f1, ..., f_{n_i}$. Then we use a discrete probability distribution $p_l(F_i)$ with iteration $l = 1, ..., L$, and initialize p_1 to be uniformly distributed over F_i. Suppose further that after the lth iteration $(l \geq 1)$, the ith parameter of the selected elite configuration E^z

takes level f_i^z. Then, the discrete distribution of parameter X_i is updated as

$$\sigma_i^{l+1} = v_i \left(\frac{1}{N_l + 1} \right)^{\frac{l}{d}} \qquad for \quad l = 1, ..., L-1 \tag{4.10}$$

where I is an indicator function; the bias of the elite configuration on the sampling distribution is getting stronger as the iteration counter increments. The conditional parameters are sampled only when they are activated by their associated upper-level categorical parameter, and their sampling model is updated only when they appear in elite configurations.

The ACO parameters, the range considered before discretization, and the number of levels considered after discretization for the case study are shown in Table 4.1. The number of candidate parameter settings rise to 3200000 possible combinations. Figure 4.6 represents F-RACE implementation where on each step will discard all configurations but those candidates with the best response to the ACO algorithm.

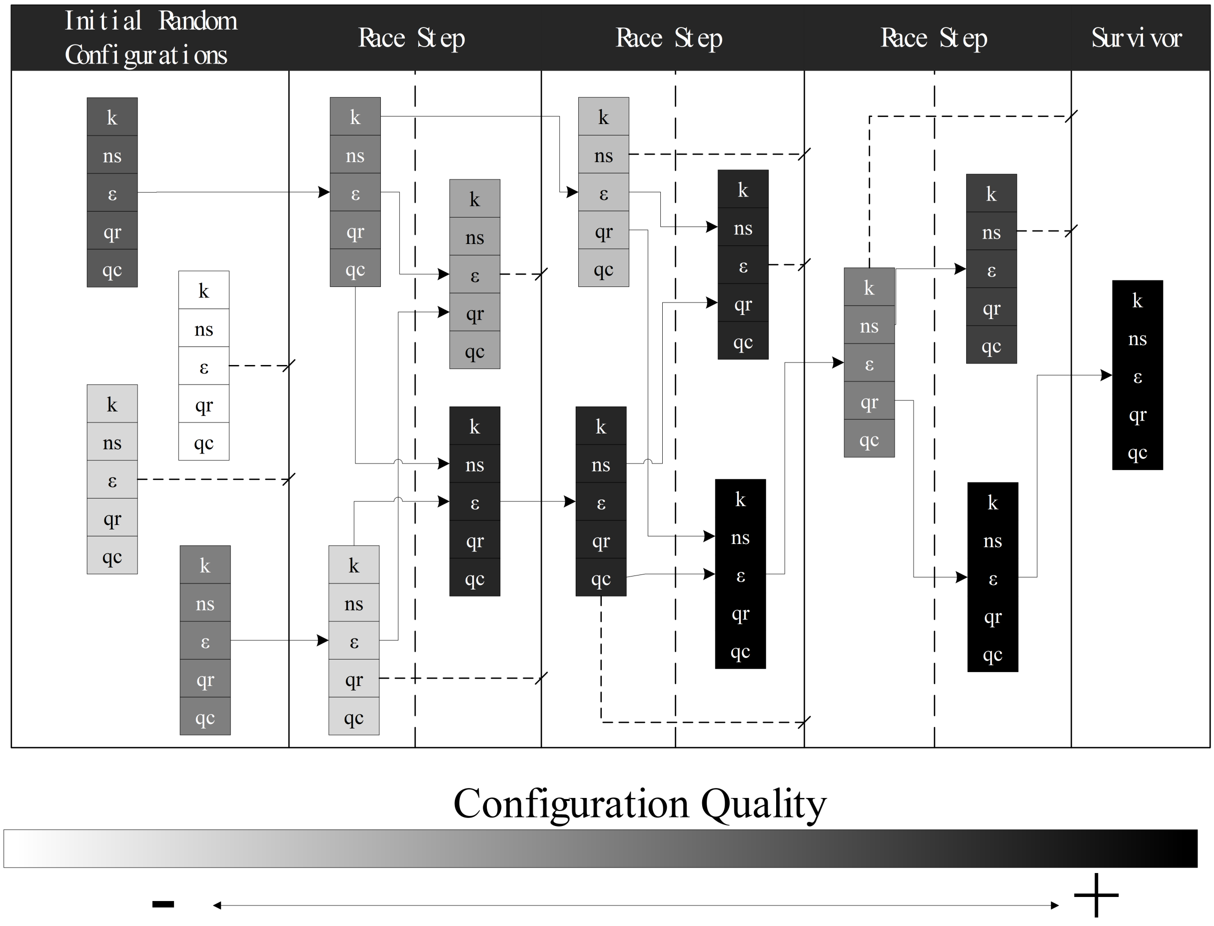

Figure 4.6 – F-RACE representation step by step until reach survivor.

Where K_i Size of solutions in the SA; ξ similar to pheromone persistence in the ACO first algorithm, with a particular impact on the convergence speed of the algorithm;

Table 4.1 – The range of ACO parameters considered.

Parameters	**Range**	**No. of levels**
K_i	[10 - 800]	20
ξ	[0.1 - 1.2]	
n_s	[1 - 80]	
q_R	[0.0001 - 0.1]	
q_C		

n_s Number of new solutions (ants); q Parameter to increase elitism of the algorithm (q_r Continuous q_c Categorical).

4.8 High-Quality Initial Solution

Ordinarily, SA initiates by a random sampling of the feasible space gives by constraints 3.9 and 3.10. Formally, ACO uses a normal random generation for the initial solution, limiting such procedure to constraints feasible values improve the quality of the SA (GOTTLIEB et al., 2003; BLUM, 2005).

Normally, improving initial solution leads to better solutions quality (ZHANG et al., 2011). For the coordination of DOCRs as nonlinear programming (NLP) problem, relaxation introduced by (URDANETA et al., 1988) gives an opportunity to create a new high-quality SA based on it. Creating k PS vectors part of the ACO, remembering k is the size of initial population for de ACO algorithm and consequently, the size of ACO. k will be, also, the number of linear programming (LP) problems to solve, and the TDS obtain will replace TDS random generated as shown in Fig. 4.7.

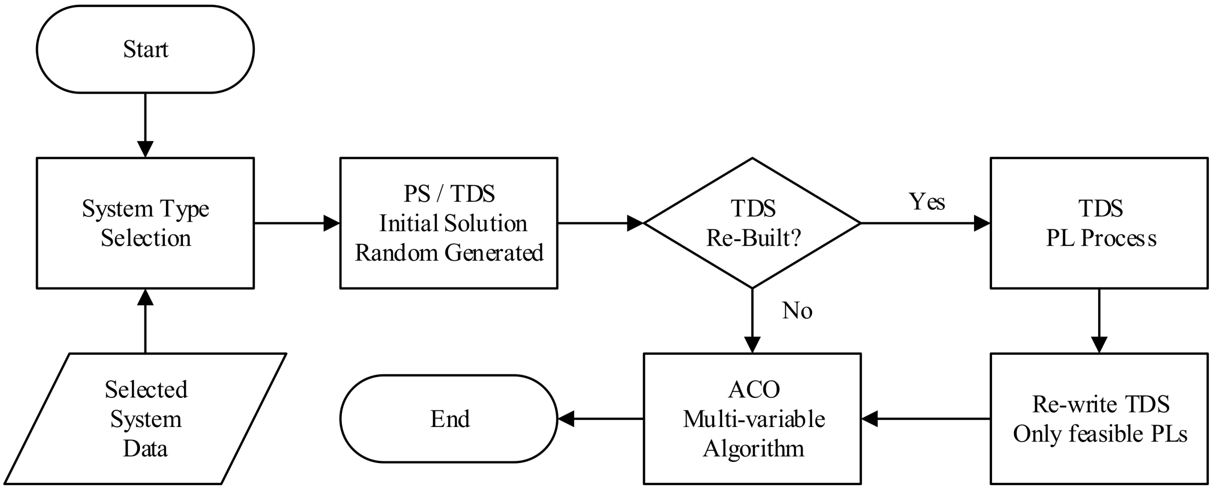

Figure 4.7 – Flowchart including high-quality initial solution built

Notice, the possibility of finding unfeasible LP problems derivate that TDS initial random values must stay in memory until LP Process is completed because a PS vector could create a non-feasible LP problem. It is expected a minimum of unfeasible LP problems from the last step, required for diversity in the ACO building solution process.

In general, the flowchart on Fig. 4.7, stand on the next premises, starts with the selection of the system (3 and 8 Bus for this work), loading data for such system. Random generation for relay PS/TDS to build the ACO. A decision box plants if is required to build an improved initial solution, if Yes is chosen, trigger a LP problem solver for each PS initial solution vector, if solution found is feasible it re-writes TDS values random generated. At this point, also if the choice NO is selected, the ACO is passed to the ACO Multi-variable algorithm to solve the entire Coordination Problem.

4.9 Hybrid Technique ACO-LP

Many hybrid methods are an important mechanism in integer programming, as they combine the best features of different methods in a complementary manner. With an effort to reduce computation times and relax this non-linear problem next framework (see Fig. 4.8) is presented with the idea to solve the categorical variable using a classical approach of *ACO* Algorithm, as showed in Section 4.4.1, and solving continuous variable through a relaxation of the problem using linear programming.

The flowchart on Fig. 4.8 follows with the selection of the system, loading such data. Random generation for relay PS/TDS (and t_{Z2} according case of study) to build the LP problem to solve the relaxed problem, and re-writing TDS and t_{Z2} to only feasible configurations. Initiating *ACO* predefined process based on ranking and quality function to build new PSs is needed. At this point, stop criteria is evaluated to is passed or to the ACO algorithm or to the end with the optimal solution.

4.10 Solution Space Estimate - Linear Relaxation

As Noghabi et al. (2009) is valid to count the number of possible combinations of PS (Only for discrete characteristics) for estimation. Once all available PS combinations are estimated, the optimal solution to the problem may be found. Because, for each combination of PS, the optimal TDS can be calculated using LP. Thus, the estimation of the solution space (LP_{max}) based on LP can be calculated by

$$LP_{max} = \prod_{i}^{n} NPS_i \tag{4.11}$$

where NPS_i is the number of PS adjustments available for n relays.

For a small number of relays is possible to do an exhaustive analysis to compare heuristics performance. Getting to the global optimal solution of the problem.

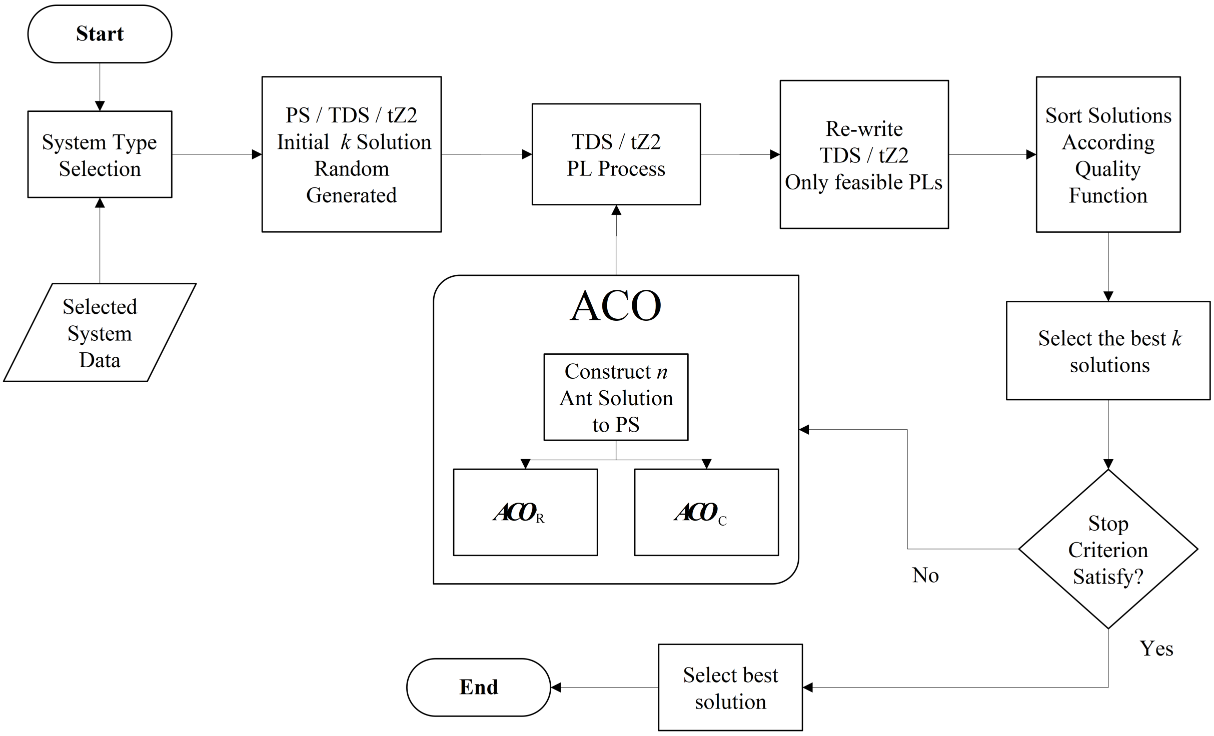

Figure 4.8 – Flowchart for Hybrid Scheme ACO-LP

5 Testing Systems

The proposed methods are applied to five transmission systems (3, 6, 8, 9, and 15 Bus accordingly) IEEE bus systems. Numerical results designate the advantages and validation of this work.

5.1 System I: Three Bus Network

In the System I, the proposed algorithm is applied to the three-bus system presented in Fig. 5.1. It has three buses, three lines, three generators and six DOCRs. Detailed data of this system are presented by author Amraee (2012). The coordination is done for three-phase faults in the midpoint of each line. Moreover, there are six selectivity constraints for the steady and transient configuration of the system, totalizing 12 constraints. Steady and transient configuration where normally considered for analog relays within former power systems. The PS is considered as discrete, and it varies from 1.5 to 5.0 A, in uniform steps of 0.5 A. Thus, this system has discrete PS and continuous TDS. The maximum and minimum TDS are 1.1 and 0.1, respectively. The adopted value of CTI is 0.2 s.

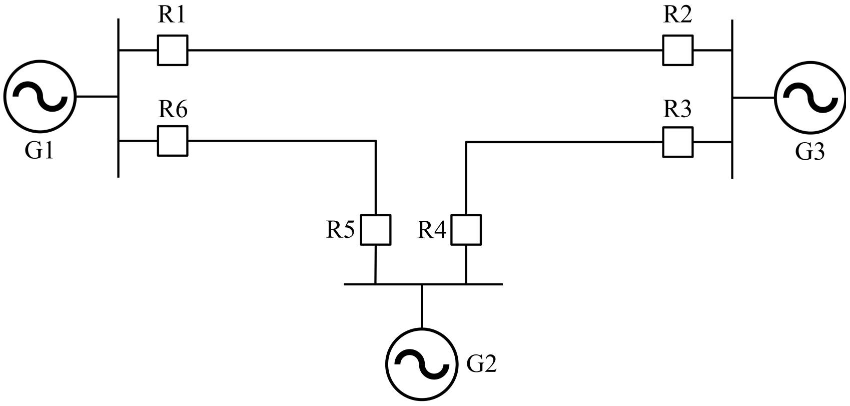

Figure 5.1 – Single-line diagram of the three-bus system.

Table 5.1 – Short-circuit current values for normal and transient configuration for a three-phase fault at the midpoint of the line, including CTR value / Three Bus Network

R_{main}	**CT Ratio**	**Normal (A)**		**Transient (A)**		R_{backup}
		main	*backup*	*main*	*backup*	
R_1	300/5	1978.90	617.22	2075.00	760.17	R_5
R_2	200/5	1525.70	145.34	1621.70	380.70	R_4
R_3	200/5	1683.90	384.00	1779.60	558.13	R_1
R_4	300/5	1815.40	545.00	1911.50	700.64	R_6
R_5	200/5	1499.66	175.00	1588.50	400.70	R_3
R_6	400/5	1766.30	466.17	1855.40	622.65	R_2

For the coordination problem of IEEE 3-bus model, there is another approach, maintaining 12 selectivity constraints related to both close-end and far-end faults, but 2 of these are relaxed, Fig. 5.2 (THANGARAJ et al., 2010), considering No Backup Available (NBA).

Table 5.2 – Short-circuit current values for a fault at the near-end and far-end of the line / Three Bus Network

R_{main}	**Near-end**		**Far-end**		R_{backup}
	$\frac{I_{main}}{CTR}$ (A)	$\frac{I_{backup}}{CTR}$ (A)	$\frac{I_{main}}{CTR}$ (A)	$\frac{I_{backup}}{CTR}$ (A)	
R_1	13.063	-	48.850	-	R_5
R_2	4.592	11.825	6.835	17.600	R_4
R_3	17.938	9.320	24.000	17.938	R_1
R_4	22.413	8.040	32.375	11.614	R_6
R_5	3.951	11.013	5.413	15.088	R_3
R_6	16.897	-	61.090	-	R_2

5.2 System II: Six Bus Network

In this case, the coordination is held for the six-bus system shown in Fig. 5.2. This system has six buses, seven lines, three generators and fourteen DOCRs. Both close-in and far-end three-phase faults are examined in its main topology. The detailed data of the system are available in Thangaraj et al. (2010).

For a fair comparison, the same OF presented in Thangaraj et al. (2010) is considered. There are 48 selectivity constraints related to both close-in and far-end faults, but 10 of these are relaxed (BIRLA et al., 2006). The TDS varies continuously from 0.05 to 1.10. PS varies from 1.25 to 1.50 A continuously. A CTI of 0.2 s is considered. Thus, this system has continuous PS and TDS. In this problem, T_{min} and T_{max} are considered as 0.05 and 1.00 s, respectively.

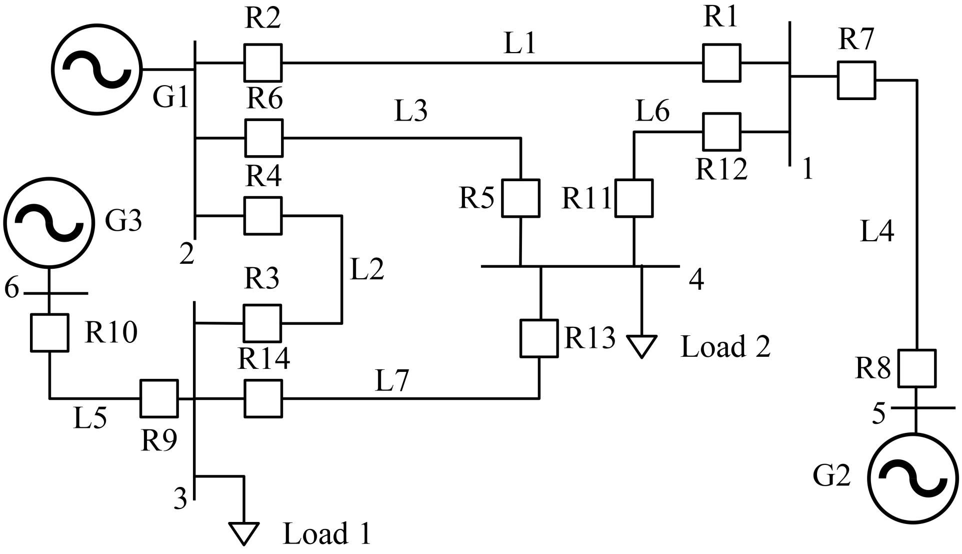

Figure 5.2 – Single-line diagram of the six-bus system.

Table 5.3 – Short-circuit current values for a fault at the near-end and far-end of the line

R_{main}	R_{backup}	**Near-end**		**Far-end**	
		$\frac{I_{main}}{CTR}\,(A)$	$\frac{I_{backup}}{CTR}\,(A)$	$\frac{I_{main}}{CTR}\,(A)$	$\frac{I_{backup}}{CTR}\,(A)$
R_1	R_8	9.791	1.679	20.794	2.343
	R_{11}		-		1.667
R_2	R_3	10.590	1.278	23.015	3.425
	R_5		-		-
R_3	R_{10}	6.112	2.457	9.438	0.089
	R_{13}		-		2.551
R_4	R_1	8.529	3.431	13.704	5.897
	R_5		-		-
R_5	R_{12}	2.738	1.882	5.964	3.292
	R_{14}		-		2.916
R_6	R_1	3.878	-	8.734	-
	R_3		3.014		4.345
R_7	R_2	2.201	7.241	2.393	7.874
	R_{11}		2.550		2.773
R_8		No Backup Available			
R_9	R_4	4.465	6.245	5.055	7.071
	R_{13}		2.752		3.116
R_{10}		No Backup Available			
R_{11}	R_6	3.343	1.555	5.047	2.541
	R_{14}		2.508		3.550
R_{12}	R_2	4.917	1.831	7.911	5.970
	R_8		1.906		2.619
R_{13}	R_6	4.107	-	7.374	2.253
	R_{12}		2.375		3.528
R_{14}	R_4	4.935	1.801	9.107	5.310
	R_{10}		1.944		2.665

5.3 System III: Eight Bus Network

The next system is shown in Fig. 5.3. This network has eight buses, seven lines, two generators and fourteen DOCRs. EG is an external grid modeled with a short-circuit capacity of 400 MVA. Detailed data of this system are presented in Amraee (2012). There are 20 selectivity constraints related to near-end three-phase faults. The available PS are 0.5, 0.6, 0.8, 1.0, 1.5, 2.0 and 2.5 A. The TDS is considered as continuous and it varies from 0.1 to 1.1. A CTI of 0.3 s is considered according to previous authors.

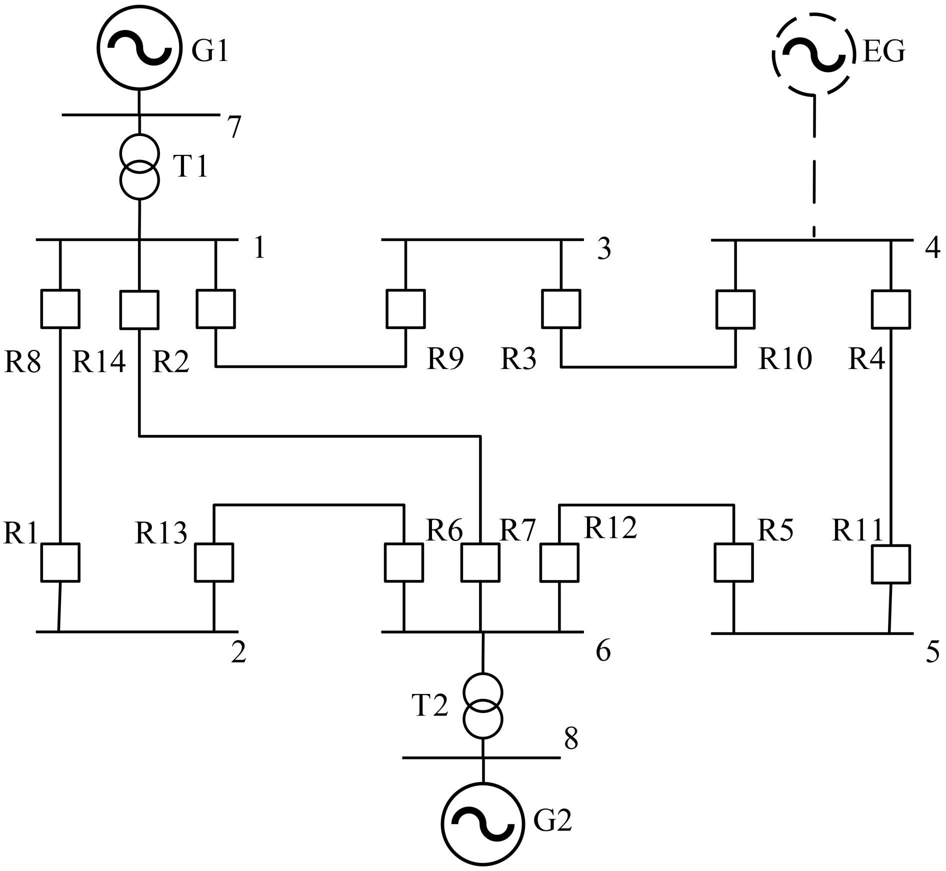

Figure 5.3 – Single-line diagram of the eight-bus system.

Table 5.4 – Short-circuit current values for normal and transient configuration for a fault at the midpoint of the line, including CTR value

R_{main}	**CT Ratio**	I_{main} **(A)**	I_{backup} **(A)**	R_{backup}
R_1	1200/5	3232	996	R_6
R_2	1200/5	5924	3556	R_1 R_7
R_3	800/5	3556	2244	R_2
R_4	1200/5	3783	2401	R_3
R_5	1200/5	2401	1197	R_4
R_6	1200/5	6109	3232	R_{14} R_5
R_7	800/5	5223	1890	R_{13} R_5
R_8	1200/5	6093	2991	R_9 R_7
R_9	800/5	2484	1165	R_{10}
R_{10}	1200/5	3883	2484	R_{11}
R_{11}	1200/5	3707	2344	R_{12}
R_{12}	1200/5	5899	3707	R_{14} R_{13}
R_{13}	1200/5	2991	987	R_8
R_{14}	800/5	5199	1874	R_1 R_9

5.4 System IV: Nine Bus Network

The system IV presented, shown in Fig. 5.4. This network has nine buses, twelve lines, one generator and twenty-four DOCRs. Detailed data of the system are available in Bedekar and Bhide (2011b). All current transformer rate (CTR) are considered as 500/1. In this case, the minimum and maximum value of PS are computed with practical considerations, as shown in (5.1) Bedekar and Bhide (2011b). The minimum and maximum values of TDS are 0.025 and 1.2, respectively. Both TDS and PS are considered as continuous variables. There are 44 selectivity constraints in this problem. A CTI of 0.2 s is adopted according to previous authors. The minimum operational time is 0.2 s. 1.25 is the load factor apply in previous works.

$$\frac{1.25 \cdot I^i_{load}}{CTR_i} \leq PS_i \leq \frac{2 \cdot Icc^i_{min}}{3 \cdot CTR_i} \tag{5.1}$$

where I^i_{load} is the maximum load current through R_i, Icc^i_{min} is the minimum fault current sensed by R_i.

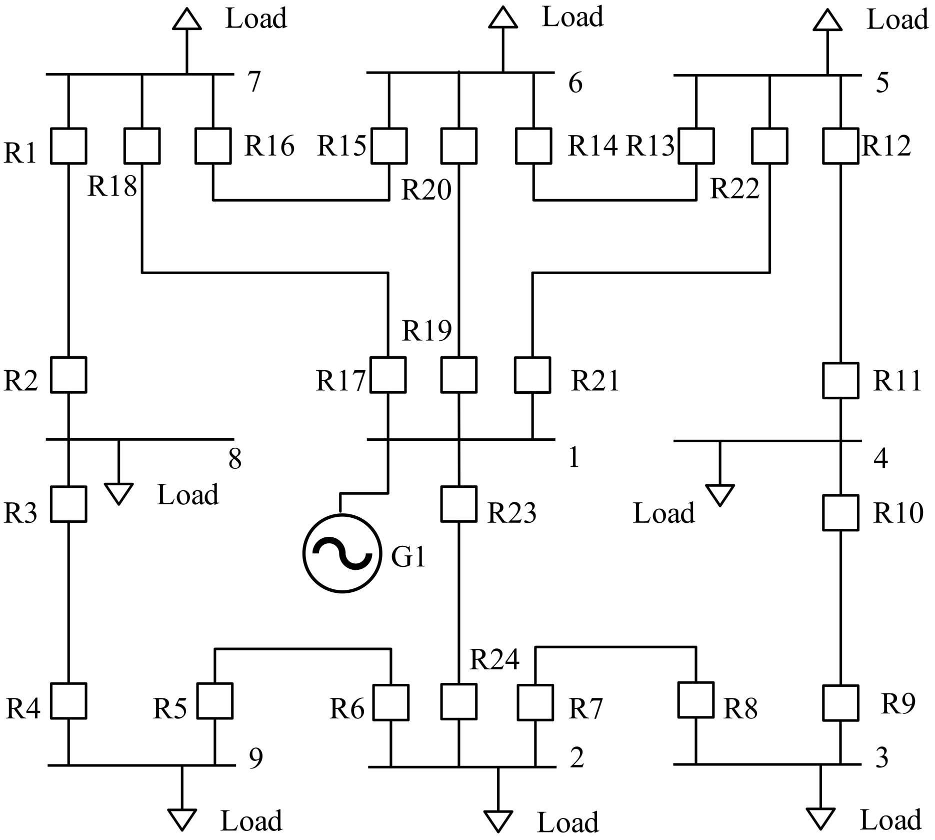

Figure 5.4 – Single-line diagram of the nine-bus system.

Table 5.5 – Short-circuit current values for normal and transient configuration for a fault at the midpoint of the line

R_{main}	I_{main} **(A)**	$I_{l}oad$ (A)	I_{backup} (A)	R_{backup}
R_1	4863.60	121.74	1293.90	R_{17}
			1168.30	R_{15}
R_2	1634.40	212.74	1044.20	R_4
R_3	2811.40	21.74	1361.60	R_1
R_4	2610.50	21.74	1226.00	R_6
R_5	1778.00	78.26	1124.40	R_3
R_6	4378.50	78.26	1345.50	R_{23}
			711.20	R_8
R_7	4378.50	78.26	1345.50	R_{23}
			711.20	R_5
R_8	1778.00	78.26	1124.40	R_{10}
R_9	2610.50	21.74	1226.00	R_7
R_{10}	2811.40	21.74	787.20	R_{12}
R_{11}	1634.40	121.74	1044.20	R_9
R_{12}	2811.40	121.74	1293.90	R_{21}
			1168.30	R_{14}
R_{13}	3684.50	30.44	1293.90	R_{21}
			653.60	R_{11}
R_{14}	4172.50	30.44	1264.10	R_{19}
			1031.70	R_{16}
R_{15}	4172.50	30.44	1264.10	R_{19}
			1031.70	R_{13}
R_{16}	3684.50	30.44	1293.90	R_{17}
			653.60	R_2
R_{17}	7611.20	441.30	1432.30	R_{24}
R_{18}	2271.70	441.30	1168.30	R_{15}
			653.60	R_2
R_{19}	7435.80	410.87	1432.30	R_{24}
R_{20}	2624.20	410.87	1031.70	R_{13}
			1031.70	R_{16}
R_{21}	7611.20	441.30	1432.30	R_{24}
R_{22}	2271.70	441.30	653.60	R_{11}
			1168.30	R_{14}
R_{23}	7914.70	506.52	1953.70	R_{22}
R_{24}	1665.50	506.52	711.20	R_8
			711.20	R_5

5.5 System V: Fifteen Bus Network

The last case relates to the system presented in Fig. 5.5. This network has 15 buses, 21 lines, 6 generators and 42 DOCRs. EG is an external grid molded with a short-circuit capacity of 200 MVA. Complete data of this system are presented in Amraee (2012). This problem has 82 selectivity constraints associated to near-end three-phase faults.

The minimum and maximum values of PS are 0.5 and 2.5 A, in uniform steps of 0.5 A, respectively. The TDS are continuous variables that vary from 0.1 to 1.1. It is considered a CTI of 0.2 s.

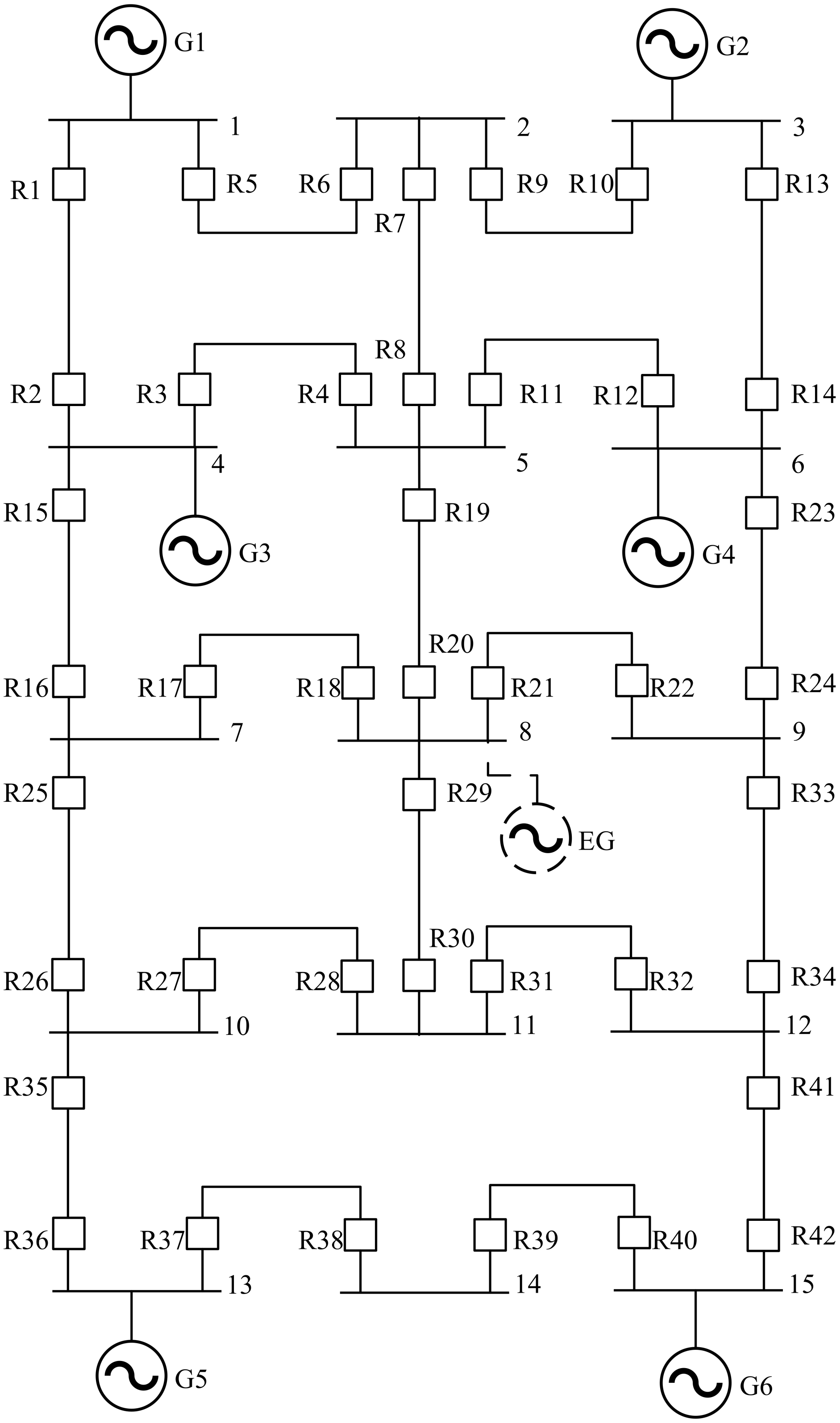

Figure 5.5 – Single-line diagram of the fifteen-bus system.

Table 5.6 – Short-circuit current values for normal and transient configuration for a fault at the midpoint of the line

R_{main}	**CT Ratio**	I_{main} **(A)**	I_{backup} **(A)**	R_{backup}
R_1	800/5	3621	853	R_6
R_2	1200/5	4597	922	R_4 R_{16}
R_3	800/5	3984	1424	R_1 R_{16}
R_4	1200/5	4382	1477	R_7 R_{12} R_{20}
R_5	800/5	3319	1397	R_2
R_6	600/5	2647	1233	R_{10} R_8
R_7	600/5	2497	1111	R_5 R_{10}
R_8	1200/5	4695	1548	R_3 R_{12} R_{20}
R_9	600/5	2943	1009	R_5 R_8
R_{10}	800/5	3568	1100	R_{14}
R_{11}	1200/5	4342	1475	R_7 R_3 R_{20}
R_{12}	1200/5	4195	1463	R_{13} R_{24}
R_{13}	800/5	3402	1503	R_9
R_{14}	1200/5	4606	1175	R_{11} R_{24}
R_{15}	1200/5	4712	969	R_1 R_4
R_{16}	600/5	2225	743	R_{18} R_{26}
R_{17}	400/5	1875	599	R_{15} R_{26}
R_{18}	1600/5	8426	1320	R_{19} R_{22} R_{30}
R_{19}	800/5	3998	1372	R_7 R_3 R_{12}
R_{20}	1600/5	7662	1808	R_{17} R_{22}

R_{main}	**CT Ratio**	I_{main} **(A)**	I_{backup} **(A)**	R_{backup}
R_{20}	1600/5	7662	1808	R_{30}
R_{21}	1600/5	8384	1326	R_{19} R_{17} R_{30}
R_{22}	400/5	1950	642	R_{23} R_{34}
R_{23}	1200/5	4910	979	R_{13} R_{11}
R_{24}	600/5	2296	753	R_{21} R_{34}
R_{25}	600/5	2289	903	R_{15} R_{18}
R_{26}	600/5	2300	905	R_{28} R_{36}
R_{27}	600/5	2011	1039	R_{25} R_{36}
R_{28}	600/5	2525	1192	R_{29} R_{32}
R_{29}	1600/5	8346	1828	R_{19} R_{17} R_{22}
R_{30}	400/5	1736	681	R_{27} R_{32}
R_{31}	600/5	2867	809	R_{29} R_{27}
R_{32}	600/5	2069	697	R_{33} R_{42}
R_{33}	600/5	2305	1162	R_{23} R_{21}
R_{34}	400/5	1715	970	R_{31} R_{42}
R_{35}	600/5	2095	910	R_{25} R_{28}
R_{36}	800/5	3283	1109	R_{38}
R_{37}	800/5	3301	1434	R_{35}
R_{38}	400/5	1403	882	R_{40}
R_{39}	400/5	1434	896	R_{37}
R_{40}	800/5	3140	1403	R_{41}
R_{41}	400/5	1971	745	R_{33} R_{31}
R_{42}	800/5	3295	907	R_{39}

6 Results and Discussions

This chapter refers to the results and discussions resulting from simulating the methodology proposed for the relay coordination in meshed transmission systems.

The method was validated using five transmission systems in the specialized literature, the 3, 6, 8, 9 and 15 standard systems, the results are compared with those reported in the literature under same conditions, when there is no available data for the model propose, validation goes by feasible evaluation for the specific problem.

Simulations were performed on an Intel ®-based processor Core™i5-2430M 2.4GHz with 8GB of RAM DDR3 running operating system Windows 10 64 bits and for parallel computing testing an Intel ®-based processor Xeon™E5-2430v2 2.2 Ghz with 24GB of RAM DDR3 running operating system Windows 7 64 bits. Implemented in Matlab 2016a.

The objective function verifies the minimization of the time for the primary relays (DOCR and/or Distance), also evaluating how feasible is the solution and computing it as unfitness, getting a quality function to guide the algorithm.

6.1 System I: Three Bus Network

For System I, there are two possible configurations, first, Mid-Point Faults which is only able to perform DOCRs Coordination, and Near-end and Far-end Faults to apply a simple DOCRs Coordination and also a combined scheme with Distance Relays. For Mid-Point Fault besides comparing with other meta-heuristic techniques in the literature is also an additional validation using an exhaustive search to get a deterministic solution using LP.

6.1.1 DOCRs Only

Mid-Point Fault for 3-bus System

The algorithm runs a hundred times with five different configurations evaluating OF value (See Tab. 6.1) and Execution time (See Tab. 6.2). Those configurations are Optimized ACO_{MV} for 5000 and 1000 Iterations, an additional 1000 iterations using an initial high-quality solution (IHQS), ACO_{MV} with not optimized parameters, and a Hybrid configuration based on $ACO-LP$.

The best solution found occurs under $ACO-LP$ (Hybrid) scenario and is shown on Tab. 6.4. Tripping times for coordinated configuration may be checked on Table 6.3 for best implemented technique.

Table 6.1 – Hundred Evaluation of DOCR Objective Function Value for 3-Bus System

ACO version	**Objective Function Value (s)**			
	mean	***max***	***min***	***std***
5000	1.6036	1.6549	1.5987	0.0075
1000	1.6452	1.7967	1.5990	0.0337
NOT OPT	3.3070	5.7947	1.8828	0.7631
1000 + IHQS	1.6047	1.6568	1.5990	0.0091
HYBRID	1.6015	1.6134	1.5987	0.0049

Table 6.2 – Hundred Evaluation of DOCR Algorithm Execution Time for 3-Bus System

ACO version	**Algorithm Execution Time (s)**			
	mean	***max***	***min***	***std***
5000	152.69	219.17	135.00	18.41
1000	12.97	43.33	11.58	3.90
NOT OPT	8.83	18.70	7.95	1.23
1000 + IHQS	9.20	35.76	7.61	3.37
HYBRID	4.62	6.75	4.08	0.51

Mid-Point Fault for 3-bus System

Table 6.3 – Tripping times for coordinated configuration - Mid-Point Fault for 3-bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
Normal Configuration				
R_1	R_5	0.2820	1.2439	0.9618
R_2	R_4	0.2496	0.5356	0.2860
R_3	R_1	0.2836	1.2621	0.9784
R_4	R_6	0.2516	0.5948	0.3433
R_5	R_3	0.2581	0.5204	0.2623
R_6	R_2	0.2738	0.5696	0.2958
Transient Configuration				
R_1	R_5	0.2768	0.4973	0.2205
R_2	R_4	0.2444	0.4472	0.2028
R_3	R_1	0.2784	0.4784	0.2000
R_4	R_6	0.2462	0.4484	0.2022
R_5	R_3	0.2526	0.4526	0.2000
R_6	R_2	0.2681	0.4681	0.2000

Exhaustive Search for 3-bus System

Maximum number of LP problems (LP_{max}) for the three-bus system is 262144 LP to solve with only eight PSs available and six relays to configure. If reduced only to feasible PS, according to short-current limits it decrease to 122880. Those numbers are possible to compute because it is a small system. Results for best feasible solutions are shown in Table 6.5, respectively. Best configuration found is equal to proposed algorithm.

Table 6.4 – Best solution found for 3-Bus System Mid-Point Fault of DOCR

Relay	**TDS**	**PS (A)**
1	0.1067	2.5
2	0.1083	2.0
3	0.1000	3.0
4	0.1000	2.5
5	0.1000	2.5
6	0.1119	1.5

The worst possible solutions (Tab. 6.6), delineating feasible search space for this problem.

Table 6.5 – Top 10 feasible and optimal solutions from exhaustive LP solver for three-bus system.

No. Sol.	**TDS**						**PS (A)**						**OF (s)**
	R_1	R_2	R_3	R_4	R_5	R_6	R_1	R_2	R_3	R_4	R_5	R_6	
1	0.1067	0.1083	0.1000	0.1000	0.1000	0.1119	2.5	2.0	3.0	2.5	2.5	1.5	1.5987
2	0.1067	0.1000	0.1000	0.1000	0.1000	0.1119	2.5	2.5	3.0	2.5	2.5	1.5	1.5990
3	0.1067	0.1084	0.1000	0.1000	0.1000	0.1000	2.5	2.0	3.0	2.5	2.5	2.0	1.5998
4	0.1067	0.1000	0.1000	0.1000	0.1000	0.1000	2.5	2.5	3.0	2.5	2.5	2.0	1.6000
5	0.1000	0.1083	0.1000	0.1000	0.1000	0.1119	3.0	2.0	3.0	2.5	2.5	1.5	1.6017
6	0.1000	0.1000	0.1000	0.1000	0.1000	0.1119	3.0	2.5	3.0	2.5	2.5	1.5	1.6020
7	0.1000	0.1084	0.1000	0.1000	0.1000	0.1000	3.0	2.0	3.0	2.5	2.5	2.0	1.6028
8	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	3.0	2.5	3.0	2.5	2.5	2.0	1.6030
9	0.1216	0.1083	0.1000	0.1000	0.1000	0.1119	2.0	2.0	3.0	2.5	2.5	1.5	1.6119
10	0.1067	0.1084	0.1000	0.1141	0.1000	0.1000	2.5	2.0	3.0	2.0	2.5	2.0	1.6120

Table 6.6 – Worst 5 feasible solutions from exhaustive LP solver for three-bus system.

No. Sol	**TDS**						**PS (A)**						**OF (s)**
	R_1	R_2	R_3	R_4	R_5	R_6	R_1	R_2	R_3	R_4	R_5	R_6	
122876	0.1680	0.1746	0.1700	0.1000	0.1557	0.1000	1.5	1.5	1.5	4.5	1.5	5.0	2.2320
122877	0.1000	0.1746	0.1685	0.1672	0.1534	0.1000	5.0	1.5	1.5	1.5	1.5	5.0	2.2371
122878	0.1000	0.1746	0.1685	0.1000	0.1534	0.1000	5.0	1.5	1.5	5.0	1.5	5.0	2.2411
122879	0.1680	0.1746	0.1700	0.1672	0.1557	0.1000	1.5	1.5	1.5	1.5	1.5	5.0	2.2496
122880	0.1680	0.1746	0.1700	0.1000	0.1557	0.1000	1.5	1.5	1.5	5.0	1.5	5.0	2.2535

Near-end and Far-end Fault for 3-bus System

The algorithm runs a hundred times evaluating OF value (See Tab. 6.7) and Execution time (See Tab. 6.8). Those configurations are an optimized ACO_{MV} using an IHQS, and a Hybrid configuration based on $ACO - LP$.

Table 6.7 – Hundred Evaluation of DOCR (Near-end and Far-end Fault) Objective Function Value for 3-Bus System

ACO version	**Objective Function Value (s)**			
	mean	***max***	***min***	***std***
1000	4.9798	5.0414	4.9570	0.0150
HYBRID	4.9571	4.9657	4.9502	0.0032

Table 6.8 – Hundred Evaluation of DOCR (Near-end and Far-end Fault) Algorithm Execution Time for 3-Bus System

ACO version	**Algorithm Execution Time (s)**			
	mean	***max***	***min***	***std***
1000	121.10	175.36	115.57	6.02
HYBRID	15.45	19.74	13.77	1.57

The best solution found is shown on Tab. 6.11 for both parameters, TDS and PS. Tripping times for coordinated configuration may be checked on Table 6.9 for best prior implemented technique and Table 6.10 for the hybrid algorithm.

Table 6.9 – Tripping times for coordinated configuration - Near-end and Far-end Fault for 3-bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
		Near-end		
R_1	R_5	0.1457	0.3457	0.2000
R_2	R_4	0.5911	0.7928	0.2016
R_3	R_1	0.7170	NBA	NBA
R_4	R_6	0.4916	NBA	NBA
R_5	R_3	0.6607	0.9708	0.3101
R_6	R_2	0.1310	0.3387	0.2077
		Far-end		
R_1	R_5	0.0920	0.3010	0.2090
R_2	R_4	0.4507	0.6507	0.2000
R_3	R_1	0.6418	NBA	NBA
R_4	R_6	0.4319	NBA	NBA
R_5	R_3	0.5170	0.7170	0.2000
R_6	R_2	0.0865	0.2865	0.2000

Table 6.10 – Tripping times for coordinated (Hybrid) configuration - Near-end and Far-end Fault for 3-bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
		Near-end		
R_1	R_5	0.1457	0.3457	0.2000
R_2	R_4	0.5909	0.7956	0.2048
R_3	R_1	0.7170	NBA	NBA
R_4	R_6	0.4894	NBA	NBA
R_5	R_3	0.6606	0.9795	0.3189
R_6	R_2	0.1309	0.3387	0.2077
		Far-end		
R_1	R_5	0.0920	0.3011	0.2090
R_2	R_4	0.4506	0.6505	0.2000
R_3	R_1	0.6390	NBA	NBA
R_4	R_6	0.4306	NBA	NBA
R_5	R_3	0.5170	0.7170	0.2000
R_6	R_2	0.0865	0.2865	0.2000

Table 6.11 – Best solution found for 3-Bus System (Near-end and Far-end Fault) of DOCR

Relay	**TDS**	**PS (A)**
1	0.0500	1.251
2	0.1110	1.2528
3	0.2613	1.4896
4	0.1945	1.4935
5	0.1098	1.2506
6	0.0500	1.2501

6.1.2 Distance and DOCRs (Near-end and Far-end Fault)

The algorithm runs a hundred times evaluating OF value (See Tab. 6.12) and Execution time (See Tab. 6.13). Those configurations are an optimized ACO_{MV} using an IHQS, and a Hybrid configuration based on $ACO - LP$.

Table 6.12 – Hundred Evaluation of Distance-DOCR Objective Function Value for 3-Bus System

ACO version	**Objective Function Value (s)**			
	mean	***max***	***min***	***std***
1000	13.0659	13.1952	12.9951	0.0772
HYBRID	11.5003	11.6378	11.3129	0.0699

The best solution found is shown on Tab. 6.16 for three parameters, TDS,PS, and t_{Z2}. Tripping times for coordinated configuration may be checked on Table 6.14 for best prior implemented technique and Table 6.15 for the hybrid algorithm.

Table 6.13 – Hundred Evaluation of Distance-DOCR Algorithm Execution Time for 3-Bus System

ACO version	**Algorithm Execution Time (s)**			
	mean	***max***	***min***	***std***
1000	145.58	219.35	112.36	40.00
HYBRID	14.78	20.38	13.02	1.55

Table 6.14 – Tripping times for coordinated configuration - Distance / DOCR for 3-bus System

R^{OC}_{main}	R^{OC}_{backup}	t_{main}	t_{backup}	Δt	R^{OC}_{main}	R^{Z2}_{backup}	t_{main}	t_{backup}	Δt
Near-end									
R_1	R_5	0.1461	0.4510	0.3049	R_1	R_5	0.1461	0.9776	0.8315
R_2	R_4	0.7987	1.0989	0.3002	R_2	R_4	0.7987	1.0990	0.3002
R_3	R_1	0.9778	NBA	NBA	R_3	R_1	0.9778	1.2781	0.3003
R_4	R_6	0.6926	NBA	NBA	R_4	R_6	0.6926	0.9926	0.3000
R_5	R_3	0.8691	1.3235	0.4544	R_5	R_3	0.8691	1.1753	0.3063
R_6	R_2	0.1310	0.4570	0.3260	R_6	R_2	0.1310	0.9085	0.7775
Far-end									
R_1	R_5	0.0922	0.3923	0.3001	R_1	R_1	0.0922	1.2781	1.1858
R_2	R_4	0.6085	0.9089	0.3004	R_2	R_2	0.6085	0.9085	0.3000
R_3	R_1	0.8751	NBA	NBA	R_3	R_3	0.8751	1.1753	0.3002
R_4	R_6	0.6105	NBA	NBA	R_4	R_4	0.6105	1.0990	0.4885
R_5	R_3	0.6776	0.9778	0.3002	R_5	R_5	0.6776	0.9776	0.3001
R_6	R_2	0.0866	0.3866	0.3000	R_6	R_6	0.0866	0.9926	0.9061

Table 6.15 – Tripping times for coordinated (Hybrid) configuration - Distance / DOCR for 3-bus System

R^{OC}_{main}	R^{OC}_{backup}	t_{main}	t_{backup}	Δt	R^{OC}_{main}	R^{Z2}_{backup}	t_{main}	t_{backup}	Δt
Near-end									
R_1	R_5	0.1020	0.5031	0.4011	R_1	R_5	0.1020	1.0737	0.9716
R_2	R_4	0.5470	0.9031	0.3561	R_2	R_4	0.5470	1.0839	0.5368
R_3	R_1	0.0894	NBA	NBA	R_3	R_1	0.0894	1.1399	1.0506
R_4	R_6	0.6625	NBA	NBA	R_4	R_6	0.6625	1.0669	0.4044
R_5	R_3	0.3593	0.7478	0.3886	R_5	R_3	0.3593	1.1265	0.7673
R_6	R_2	0.3328	0.6426	0.3098	R_6	R_2	0.3328	1.0821	0.7493
Far-end									
R_1	R_5	0.8337	1.4430	0.6093	R_1	R_1	0.8337	1.1399	0.3063
R_2	R_4	0.7175	1.0344	0.3169	R_2	R_2	0.7175	1.0821	0.3646
R_3	R_1	0.1374	NBA	NBA	R_3	R_3	0.1374	1.1265	0.9892
R_4	R_6	0.1637	NBA	NBA	R_4	R_4	0.1637	1.0839	0.9201
R_5	R_3	0.4026	0.7111	0.3086	R_5	R_5	0.4026	1.0737	0.6711
R_6	R_2	0.3791	0.7004	0.3213	R_6	R_6	0.3791	1.0669	0.6878

Table 6.16 – Best solution found for 3-Bus System (Near-end and Far-end Fault) of Distance-DOCR

Relay	**TDS**	**PS (A)**	t_{Z2} **(s)**
1	0.0541	1.3605	1.1399
2	0.1348	1.2536	1.0820
3	0.1463	1.4978	1.1265
4	0.1515	1.4722	1.0838
5	0.1406	1.2517	1.0736
6	0.0500	1.4085	1.0669

6.1.3 ACO Parameters Optimization with F-RACE

Table 6.17 contains survivors from the racing optimization algorithm for System I, based on a quality function to get better configuration on each iteration. Time needed to this algorithm seizes that answer was over 3 hours for a single 4-core desktop and 36 minutes for a 24-core cluster.

Table 6.17 – Survivors of the F-RACE Algorithm for 3-Bus System

k	ξ	n_S	q_R	q_C	
210	0.815	55	0.0201	0.0201	1.6012
50	1.035	58	0.0151	0.0650	1.6030
130	0.980	52	0.0201	0.0401	1.6044
130	1.145	73	0.0201	0.0301	1.6049
130	1.035	43	0.0151	0.0600	1.6058
50	1.200	43	0.0251	0.0900	1.6069
170	0.815	55	0.0301	0.0451	1.6073
210	0.815	58	0.0301	0.0451	1.6081
210	0.760	58	0.0301	0.0201	1.6093
130	1.090	49	0.0151	0.0850	1.6093
250	0.815	46	0.0251	0.0251	1.6094
170	0.870	52	0.0201	0.0501	1.6101
130	0.815	73	0.0301	0.0600	1.6116
170	0.870	52	0.0251	0.0650	1.6121
170	1.090	67	0.0251	0.0401	1.6122
170	1.090	67	0.0301	0.0600	1.6123
130	1.035	43	0.0201	0.1000	1.6127
130	0.980	49	0.0251	0.0900	1.6127
250	0.980	43	0.0201	0.0700	1.6137
210	0.925	37	0.0351	0.0650	1.6182
170	0.650	34	0.0301	0.0251	1.6204
90	1.035	49	0.0151	0.0750	1.6209
250	0.760	58	0.0301	0.0650	1.6214
170	0.705	73	0.0251	0.0700	1.6243
50	0.980	40	0.0201	0.1000	1.6271

Within that result is measure statistical data (see Tab. 6.18) to select the parameters according to the race survivors, this data is also important to define which parameter has more influence on the algorithm performance.

Table 6.18 – Comparing for Survivors of the F-RACE Algorithm for 3-Bus System

	k	ξ	n_S	q_R	q_C
mean	157	0.932	53	0.024	0.058
max	250	1.200	73	0.035	0.100
min	50	0.650	34	0.015	0.020
std	57	0.143	11	0.006	0.024
Influence	13.18%	31.38%	23.37%	20.16%	11.90%

6.1.4 Validation

Fig. 6.1 represent three OF, according to ACO optimized, ACO optimized with the introduction of an initial High-Quality Solution and an ACO without parameters optimization. Except for ACO NOT OPT, both get optimal answers based on Table 6.1, in this occasion ACO + IHQS, obtain the best optimal solution as may be confirmed by Table 6.5, but is also evident how fast is the convergence of this method which for an small size system is optimal may not be guaranteed for larger systems. It is important to notice how restart mechanism acts over OF (around iteration No 500) fighting stagnation and improving value closer to the optimal.

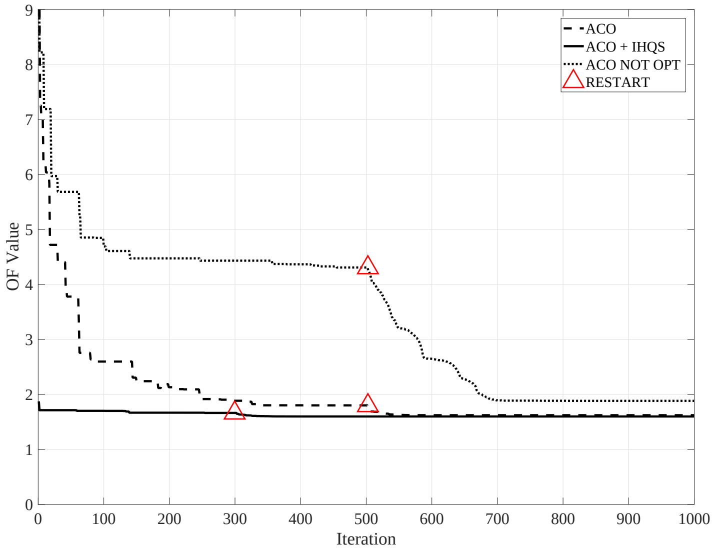

Figure 6.1 – OF Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 3-Bus System.

OF value from ACO-LP for a 3-Bus System shows in Fig. 6.2 fast convergence in few iterations into optimal value.

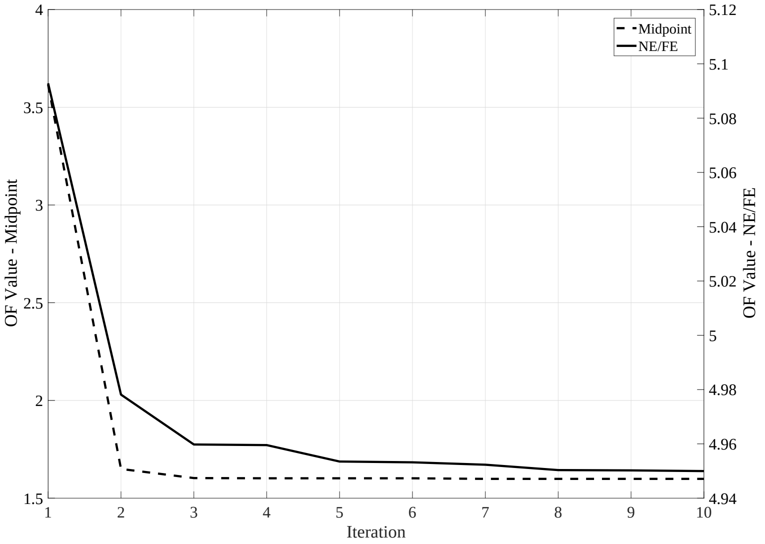

Figure 6.2 – OF value Coordination with ACO-LP for a 3-Bus System

The output from Distance-DOCR Coordination with ACO-LP for a 3-Bus System (Fig. 6.3), shows an inverse convergence in the OF value until configuration enters into the feasible region.

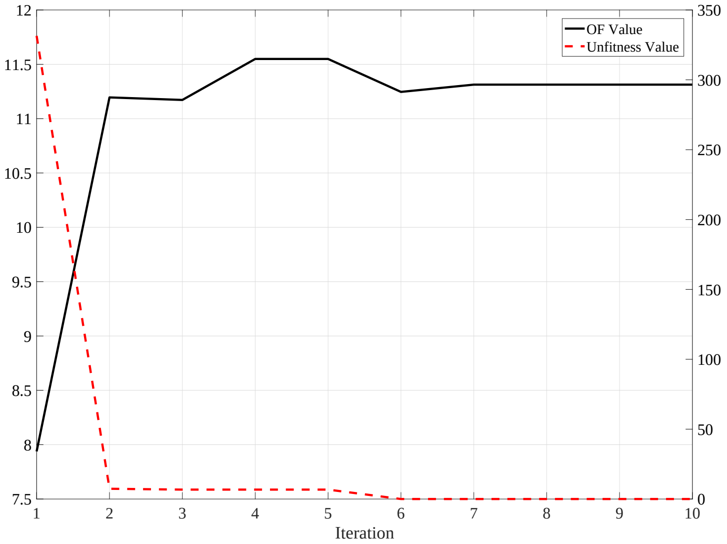

Figure 6.3 – Distance-DOCR Coordination with ACO-LP for a 3-Bus System

This work, for System I, obtained optimal for this problem ($OF = 1.5987$) in 4.6154 s for $ACO - LP$ and 12.5591 s for $ACO - MV$, better than PSO (MANSOUR et al., 2007), Biogeography Based Optimization (BBO) (ALBASRI et al., 2015), and Seeker Optimization Algorithm (SOA) (AMRAEE, 2012), and same as BBO-LP (ALBASRI et al., 2015) and GACB-LP (KIDA, 2016) but slower than both (Table 6.19).

Table 6.19 – Results Comparison for 3-Bus System Mid-Point Fault DOCR

Tech	**Autor**	**Exe Time (s)**	**OF - Time (s)**
PSO	(MANSOUR et al., 2007)	0.5129	1.9258
BBO	(ALBASRI et al., 2015)	16.2300	1.6837
SOA	(AMRAEE, 2012)	10.4500	1.5990
BBO-LP	(ALBASRI et al., 2015)	2.9900	1.5987
GACB-LP	(KIDA, 2016)	0.2047	1.5987
ACO-MV	**This Work**	**12.5591**	**1.5987**
ACO-LP	**This Work**	**4.6154**	**1.5987**

For Near-end and Far-end Fault solution found is close to those from Rhetorical Structure Theory (RST) (DEEP et al., 2006) and Modified Differential Evolution v5 (MDE5) (THANGARAJ et al., 2010) but with a number of function evaluation (NFE) consistently better than best answer available for both techniques applied.

Table 6.20 – Results Comparison for 3-Bus System (Near-end and Far-end Fault) DOCR

Tech	**Autor**	**NFE**	**OF - Time (s)**
ACO-MV	**This Work**	**1000**	**4.9570**
ACO-LP	**This Work**	**10**	**4.9502**
RST	(DEEP et al., 2006)	N/A	4.8354
MDE5	(THANGARAJ et al., 2010)	69270	4.7806

Distance-DOCR coordination based on Near-end and Far-end Fault was not possible to validate with literature, in order to build this model must be assumed fault locations to distinguish Primary-Backup for this mixed scheme. Data from Table 6.12 shows violation of the upper limit according to Table 3.5 where maximum is mark by 0.6 s, but as shows in Perez and Urdaneta (2001) those limits are normally design by dealers under unique distance coordination.

6.2 System II: Six Bus Network

For System II, there is only one possible configuration Near-end and Far-end Faults to apply a simple DOCRs Coordination and also a combined scheme with Distance Relays.

For this system comparing with other meta-heuristic techniques in the literature is also offered.

6.2.1 DOCRs Only

The algorithm runs a hundred times with four different configurations evaluating OF value (See Tab. 6.21) and Execution time (See Tab. 6.22). Those configurations are Optimized ACO_{MV} for 2000 Iterations, an additional 2000 iterations using an IHQS, also is presented an ACO_{MV} with not optimized parameters, and a Hybrid configuration based on $ACO-LP$.

Table 6.21 – Hundred Evaluation of DOCR (Near-end and Far-end Fault) Value for 6-Bus System

ACO version	**OF**			
	mean	***max***	***min***	***std***
2000	10.4429	12.7379	10.1584	0.3247
NOT OPT	14.9275	15.2051	14.2624	0.3392
2000 + IHQS	11.2525	12.5791	10.5670	0.4285
HYBRID	11.3209	13.9236	10.0742	1.4761

Table 6.22 – Hundred Evaluation of DOCR Algorithm Execution Time for 6-Bus System

ACO version	**Execution Time (s)**			
	mean	***max***	***min***	***std***
2000	100.07	159.53	90.25	13.63
NOT OPT	33.23	38.62	28.95	3.72
2000 + IHQS	113.50	170.81	91.99	16.63
HYBRID	8.85	13.33	4.48	3.03

The best solution found occurs under $ACO-LP$ scenario and is shown on Tab. 6.23.

The best solution found is shown on Tab. 6.23 for both parameters, TDS and PS. Tripping times for coordinated configuration may be checked on Appendix A.1 for best prior implemented technique and Appendix A.2 for the hybrid algorithm.

Table 6.23 – Best solution found for 6-Bus System (Near-end and Far-end Fault) of DOCR

Relay - TDS				**Relay - PS (A)**			
1	0.1099	*8*	0.0500	*1*	1.4981	*8*	1.2500
2	0.1863	*9*	0.0500	*2*	1.4999	*9*	1.2501
3	0.0500	*10*	0.0504	*3*	1.5000	*10*	1.5000
4	0.1181	*11*	0.0649	*4*	1.3974	*11*	1.4999
5	0.0500	*12*	0.0541	*5*	1.2501	*12*	1.4110
6	0.0500	*13*	0.0500	*6*	1.3807	*13*	1.4330
7	0.0500	*14*	0.0708	*7*	1.2500	*14*	1.4986

6.2.2 Distance and DOCRs

The algorithm runs a hundred times evaluating OF value (See Tab. 6.24) and Execution time (See Tab. 6.25). Those configurations are an optimized ACO_{MV} using an IHQS, and a Hybrid configuration based on $ACO-LP$.

Table 6.24 – Hundred Evaluation of Distance-DOCR Coordination of Value for 6-Bus System

ACO version	**OF**			
	mean	***max***	***min***	***std***
2000	18.2597	18.3696	17.8770	0.1916
HYBRID	11.3209	13.9236	10.0742	1.4761

Table 6.25 – Hundred Evaluation of Distance-DOCR Coordination Algorithm Execution Time for 6-Bus System

ACO version	**Execution Time (s)**			
	mean	***max***	***min***	***std***
2000	69.94	70.76	68.75	0.69
HYBRID	10.03	12.38	7.70	1.60

The best solution found is shown on Tab. 6.26 for three parameters, TDS, PS, and t_{Z2}. Tripping times for coordinated configuration may be checked on Appendix A.3 and A.4 for best prior implemented technique and Appendix A.5 and A.6 for the hybrid algorithm.

Table 6.26 – Best solution found for 6-Bus System (Near-end and Far-end Fault) of Distance-DOCR

Relay - TDS				**Relay - PS (A)**				**Relay - t_{Z2} (s)**			
1	0.0994	*8*	0.0500	*1*	1.4999	*8*	1.2500	*1*	0.5857	*8*	0.4915
2	0.0819	*9*	0.0500	*2*	1.4999	*9*	1.2500	*2*	0.8153	*9*	0.6428
3	0.0500	*10*	0.0500	*3*	1.5000	*10*	1.4920	*3*	0.7354	*10*	0.7384
4	0.0975	*11*	0.0621	*4*	1.4999	*11*	1.4999	*4*	0.7385	*11*	0.5016
5	0.0500	*12*	0.0505	*5*	1.2500	*12*	1.4989	*5*	0.4470	*12*	0.5057
6	0.0500	*13*	0.0500	*6*	1.2500	*13*	1.4329	*6*	0.5641	*13*	0.8153
7	0.0500	*14*	0.0688	*7*	1.2500	*14*	1.4999	*7*	0.6357	*14*	0.5905

6.2.3 ACO Parameters Optimization with F-RACE

Table 6.27 contains survivors from the racing optimization algorithm for System II, based on a quality function to get better configuration on each iteration. Time needed to this algorithm seizes that answer was over 10 hours for a single 4-core desktop and 138 minutes for a 24-core cluster.

Table 6.27 – Survivors of the F-RACE Algorithm for 6-Bus System

k	ξ	n_S	q_R	q_C	QF
690	0.43	19	0.0251	0.0401	10.5640
610	0.54	31	0.0550	0.0051	10.5842
610	0.54	31	0.0550	0.0051	10.6089
610	0.54	31	0.0550	0.0051	10.6440

Within that result is measure statistical data (see Tab. 6.28) to select the parameters according to the race survivors, this data is also important to define which parameter has more influence on the algorithm performance.

Table 6.28 – Comparing for Survivors of the F-RACE Algorithm for 6-Bus System

	k	ξ	n_S	q_R	q_C
mean	630	0.51	28	0.0476	0.0138
max	690	0.54	31	0.0550	0.0401
min	610	0.43	19	0.0251	0.0051
std	34.64	0.05	5.1962	0.0130	0.0151
Influence	46.74%	27.65%	13.85%	9.42%	2.35%

6.2.4 Validation

As well, Fig. 6.4 represent three OF, according to ACO optimized, ACO optimized with the introduction of an initial High-Quality Solution and an ACO without parameters optimization. Except for ACO NOT OPT, both get optimal answers based on Table 6.1, on the contrary from last, this system has an alike convergence rate, even when it is noticed a better start for the ACO + IHQS (around 25-30) curves has no significant difference for both optimized algorithm but with clear win to the single ACO version. Once again, it is important to notice how restart mechanism acts over OF (around iteration No 1000) fighting stagnation.

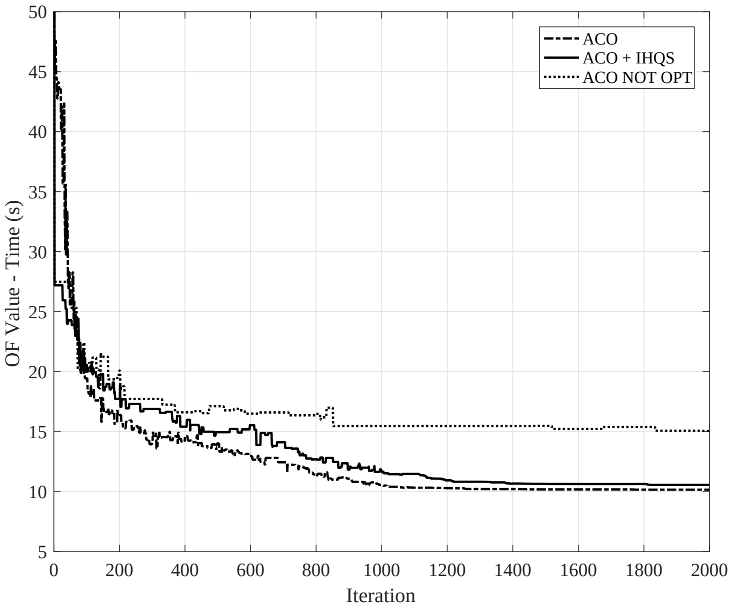

Figure 6.4 – OF Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 6-Bus System.

OF value from ACO-LP for a 6-Bus System shows in Fig. 6.5 and Fig. 6.6 fast convergence in few iterations into optimal value for both DOCRs Only and Distance-DOCR Coordination.

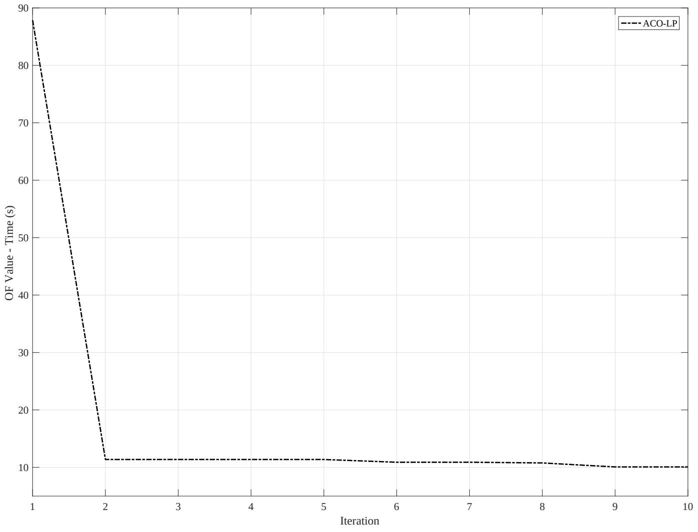

Figure 6.5 – OF value DOCR Coordination with ACO-LP for a 6-Bus System

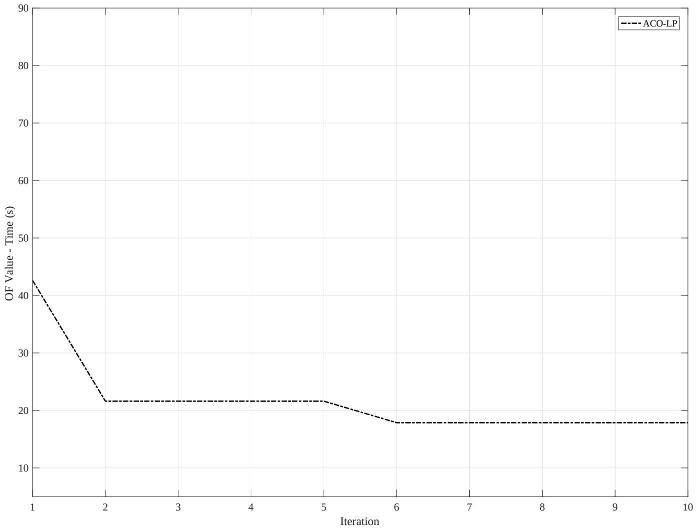

Figure 6.6 – OF value Distance-DOCR Coordination with ACO-LP for a 6-Bus System

ACO-LP algorithm applied to System II obtained the best solution for this problem ($OF = 10.0742$) in 11.87 s compare to GA (SWIEF et al., 2015), Modified Differential Evolution (MDE) (CHELLIAH et al., 2014), MDE5 (THANGARAJ et al., 2010), and Opposition Based Chaotic Differential Evolution (OCDE) (CHELLIAH et al., 2014) GACB-LP (KIDA, 2016). A complete chart is shown in Table 6.29.

Table 6.29 – Results Comparison for 6-Bus System Mid-Point Fault DOCR

Tech	**Autor**	**Exe Time (s)**	**OF - Time (s)**
GA	(SWIEF et al., 2015)	-	10.7345
MDE	(CHELLIAH et al., 2014)	129.80	10.6272
MDE5	(THANGARAJ et al., 2010)	-	10.3514
OCDE	(CHELLIAH et al., 2014)	10.14	10.3286
ACO-MV	**This Work**	**100.07**	**10.1584**
GACB-LP	(KIDA, 2016)	89.09	10.1512
ACO-LP	**This Work**	**11.87**	**10.0742**

Distance-DOCR coordination based on Near-end and Far-end Fault was not possible to validate with literature, in order to build this model must be assumed fault locations to distinguish Primary-Backup for this mixed scheme. Data from Table 6.26 shows limit according to Table 3.5.

6.3 System III: Eight Bus Network

For System III, there is only one possible configuration Near-end Faults to apply a simple DOCRs Coordination and also a combined scheme with Distance Relays. For this system comparing with other meta-heuristic techniques in the literature is also offered.

6.3.1 DOCRs Only

The algorithm runs a hundred times with four different configurations evaluating OF value (See Tab. 6.30) and Execution time (See Tab. 6.31). Those configurations are Optimized ACO_{MV} for 10000 Iterations, an additional 10000 iterations using an IHQS, an ACO_{MV} with not optimized parameters, and a Hybrid configuration based on $ACO - LP$.

Table 6.30 – Hundred Evaluation of DOCR Objective Function Value for 8-Bus System

ACO version	**OF**			
	mean	***max***	***min***	***std***
10000	10.1028	11.0182	9.2719	0.3657
NOT OPT	16.7339	23.6919	11.8787	2.7388
10000 + IHQS	8.9794	9.0526	8.8609	0.0281
HYBRID	8.4910	8.6423	8.4271	0.0588

Table 6.31 – Hundred Evaluation of DOCR Algorithm Execution Time for 8-Bus System

ACO version	**Execution Time (s)**			
	mean	***max***	***min***	***std***
10000	68.34	82.82	66.43	2.53
NOT OPT	34.65	42.50	25.01	3.23
10000 + IHQS	0.40	1.28	0.23	0.17
HYBRID	7.77	11.02	6.62	0.94

The best solution found occurs under $ACO - LP$ scenario and is shown on Tab. 6.32. Tripping times for coordinated configuration may be checked on Appendix A.7 for best prior implemented technique and Appendix A.8 for the hybrid algorithm.

Table 6.32 – Best solution found for 8-Bus System (Near-end Fault) of DOCR

Relay - TDS				***Relay - PS (A)***			
1	0.1131	*8*	0.1696	*1*	2	*8*	2.5
2	0.2602	*9*	0.1472	*2*	2.5	*9*	2.5
3	0.2251	*10*	0.1758	*3*	2.5	*10*	2.5
4	0.1602	*11*	0.1868	*4*	2.5	*11*	2.5
5	0.1	*12*	0.2663	*5*	2.5	*12*	2.5
6	0.1731	*13*	0.1138	*6*	2.5	*13*	2
7	0.2427	*14*	0.2458	*7*	2.5	*14*	2.5

Exhaustive Reduced Space Search for 8-bus System

Total Search Space (TSS) for eight-bus system is 6.78E+11 LP to solve with only seven PSs available and fourteen relays to configure. If reduced only to feasible PS between 1.5 and 2.5 Valid Search Space (VSS) decrease to 4782969. Those numbers are possible to compute for this kind of system, results for 10 best solutions are shown in Table 6.33, respectively. The best configuration found is equal to proposed algorithm.

Table 6.33 – Top 10 feasible & optimal solutions from exhaustive from limited LP solver for eight-bus system.

N Sol		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
TDS	R_1	0.1132	0.1132	0.1132	0.1132	0.1132	0.1132	0.1132	0.1132	0.1132	0.1132
	R_2	0.2602	0.2602	0.2602	0.2602	0.2602	0.2602	0.2602	0.2602	0.2602	0.2602
	R_3	0.2251	0.2251	0.2251	0.2251	0.2251	0.2251	0.2251	0.2251	0.2251	0.2251
	R_4	0.1603	0.1603	0.1603	0.1603	0.1603	0.1603	0.1603	0.1603	0.1603	0.1603
	R_5	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
	R_6	0.1731	0.1731	0.1965	0.1965	0.1731	0.1731	0.1731	0.2268	0.1731	0.1965
	R_7	0.2428	0.2428	0.2428	0.2428	0.2428	0.2428	0.2783	0.2428	0.2783	0.2428
	R_8	0.1697	0.1700	0.1697	0.1700	0.1937	0.1940	0.1697	0.1697	0.1700	0.1937
	R_9	0.1473	0.1473	0.1473	0.1473	0.1473	0.1473	0.1473	0.1473	0.1473	0.1473
	R_{10}	0.1759	0.1759	0.1759	0.1759	0.1759	0.1759	0.1759	0.1759	0.1759	0.1759
	R_{11}	0.1869	0.1869	0.1869	0.1869	0.1869	0.1869	0.1869	0.1869	0.1869	0.1869
	R_{12}	0.2664	0.2664	0.2664	0.2664	0.2664	0.2664	0.2664	0.2664	0.2664	0.2664
	R_{13}	0.1138	0.1000	0.1138	0.1000	0.1138	0.1000	0.1138	0.1138	0.1000	0.1138
	R_{14}	0.2459	0.2459	0.2459	0.2459	0.2459	0.2459	0.2459	0.2459	0.2459	0.2459
PS (A)	$R1$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	R_2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_6	2.5	2.5	2.0	2.0	2.5	2.5	2.5	1.5	2.5	2.0
	R_7	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.5	2.0	2.5
	R_8	2.5	2.5	2.5	2.5	2.0	2.0	2.5	2.5	2.5	2.0
	R_9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_{10}	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_{11}	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_{12}	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	R_{13}	2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.0	2.5	2.0
	R_{14}	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
OF (s)		8.4271	8.4292	8.4440	8.4461	8.4466	8.4487	8.4608	8.4619	8.4629	8.4635

6.3.2 Distance and DOCRs

The algorithm runs a hundred times evaluating OF value (See Tab. 6.34) and Execution time (See Tab. 6.35). Those configurations are an optimized ACO_{MV} using an IHQS, and a Hybrid configuration based on $ACO - LP$.

Table 6.34 – Hundred Evaluation of Distance-DOCR Objective Function Value for 8-Bus System

ACO version	**Objective Function Value (s)**			
	mean	***max***	***min***	***std***
1000	24.0156	24.7815	23.5084	0.4606
HYBRID	24.5721	25.3711	23.3001	0.5210

The best solution found is shown on Tab. 6.36 for both parameters, TDS and PS. Tripping times for coordinated configuration may be checked on Appendix A.9 for best prior implemented technique and Appendix A.10 for the hybrid algorithm.

Table 6.35 – Hundred Evaluation of Distance-DOCR Algorithm Execution Time for 8-Bus System

ACO version	**Algorithm Execution Time (s)**			
	mean	***max***	***min***	***std***
1000	270.79	376.94	230.24	56.46
HYBRID	6.55	8.25	6.12	0.39

Table 6.36 – Best solution found for 8-Bus System (Near-end) of Distance-DOCR

Relay - TDS				**Relay - PS (A)**				**Relay - t_{Z2} (s)**			
1	0.1625	*8*	0.2251	*1*	1.5	*8*	1.5	*1*	1.0693	*8*	0.7287
2	0.2699	*9*	0.165	*2*	2.5	*9*	2.5	*2*	1.1065	*9*	1.1632
3	0.2371	*10*	0.2199	*3*	2.5	*10*	2	*3*	0.807	*10*	1.0432
4	0.1731	*11*	0.235	*4*	2.5	*11*	2	*4*	1.1065	*11*	1.0211
5	0.1312	*12*	0.2883	*5*	2	*12*	2.5	*5*	0.9212	*12*	0.946
6	0.1974	*13*	0.1	*6*	2.5	*13*	2.5	*6*	1.1632	*13*	1.0885
7	0.2857	*14*	0.3486	*7*	2	*14*	1.5	*7*	0.9965	*14*	0.8617

6.3.3 ACO Parameters Optimization with F-RACE

Table 6.37 contains survivors from the racing optimization algorithm for System III, based on a quality function to get better configuration on each iteration. Time needed to this algorithm seizes that answer was over 12 hours for a single 4-core desktop and 112 minutes for a 24-core cluster.

Table 6.37 – Survivors of the F-RACE Algorithm for 8-Bus System

k	ξ	n_S	q_R	q_C	QF
290	0.485	13	0.000	0.100	14.296
50	0.815	28	0.025	0.005	17.187
290	0.375	10	0.000	0.075	17.580
290	0.485	13	0.000	0.100	17.706
90	0.430	31	0.005	0.005	17.823
170	0.210	1	0.000	0.040	19.258
273	1.200	53	0.000	0.000	19.351
290	0.430	10	0.005	0.050	19.416
290	0.485	40	0.005	0.075	19.797
170	0.925	58	0.045	0.070	19.806
50	0.320	52	0.020	0.035	21.219
536	0.833	53	0.000	0.033	21.346
610	0.760	43	0.040	0.060	22.491
650	0.595	19	0.005	0.035	23.004
730	0.760	43	0.040	0.060	23.686
690	0.760	43	0.040	0.060	26.452
650	0.760	43	0.040	0.060	26.601
690	0.760	43	0.040	0.060	26.905
650	0.760	43	0.040	0.060	26.941
770	0.760	43	0.040	0.060	27.702
570	0.100	28	0.010	0.095	29.003
130	1.090	28	0.010	0.040	29.585
650	0.760	43	0.040	0.060	29.952
650	0.760	43	0.040	0.060	30.555
730	0.760	43	0.040	0.060	32.638

Within that result is measure statistical data (see Tab. 6.38) to select the parameters according to the race survivors, this data is also important to define which parameter has more influence on the algorithm performance.

Table 6.38 – Comparing for Survivors of the F-RACE Algorithm for 8-Bus System

	k	ξ	n_S	q_R	q_C
mean	319	0.61	32	0.0128	0.0496
max	770	1.20	58	0.0451	0.1000
min	50	0.10	1	0.0001	0.0001
std	243.85	0.25	15	0.0180	0.0258
Influence	15.65%	28.61%	24.23%	8.49%	23.02%

6.3.4 Validation

Systems III has some difference among all tested, Fig. 6.7 represent three OF, according to ACO optimized, ACO optimized with the introduction of an initial High-Quality Solution and an ACO without parameters optimization. Except for ACO NOT

OPT which does not even shows a convergence characteristic, in this occasion ACO, obtain good quality solution as shown in Table 6.47, this system only shows an expected convergence rate for the ACO single version, it is noticed a better start for the ACO + IHQS but reduced after few iterations keeping trapped into a minimum better although other algorithm. For this System is also added Fig. 6.8 correspondent to Unfitness, showing how important is parameter optimization for this case.

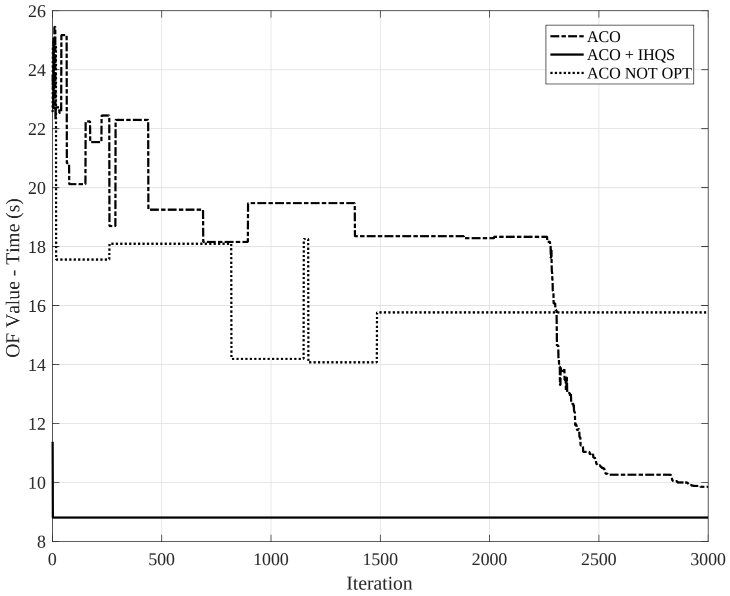

Figure 6.7 – OF Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 8-Bus System.

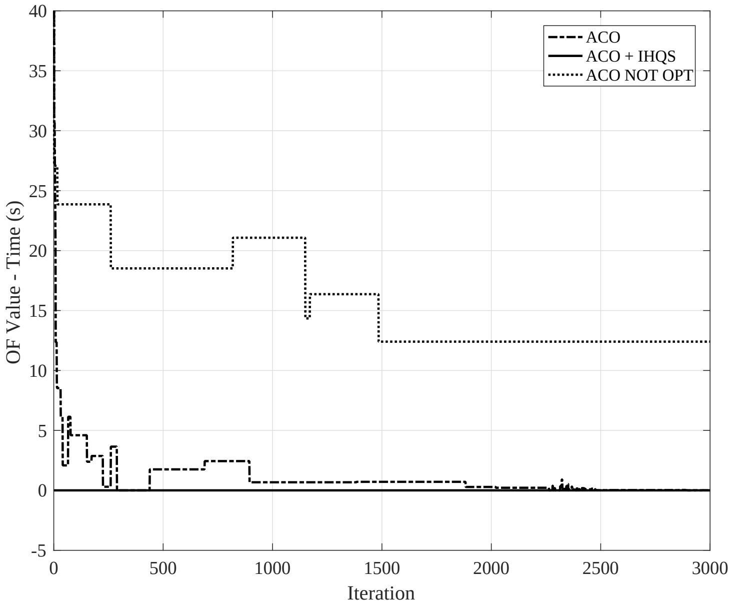

Figure 6.8 – Unfitness Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 8-Bus System.

OF value from ACO-LP for a 8-Bus System shows in Fig. 6.9 fast convergence in few iterations into optimal value for both DOCRs Only and Distance-DOCR Coordination.

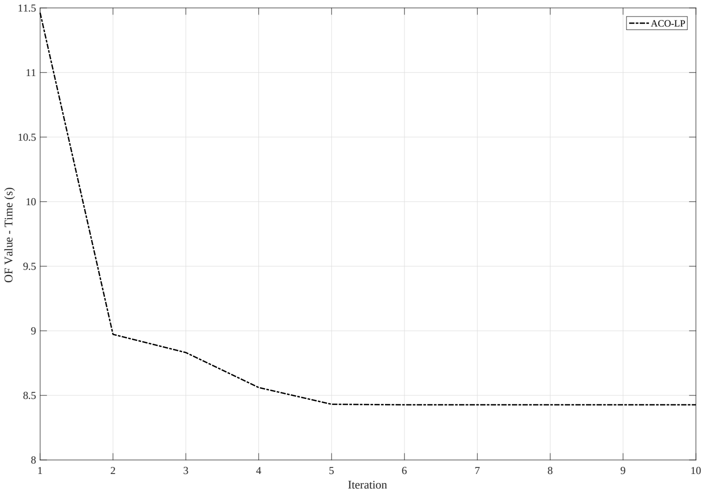

Figure 6.9 – OF Value for DOCR Coordination with ACO-LP for a 8-Bus System.

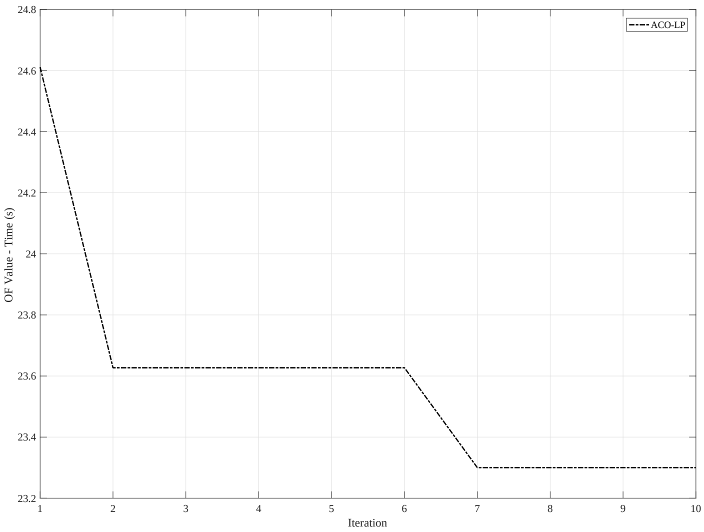

Figure 6.10 – OF Value for Distance-DOCR Coordination with ACO-LP for a 8-Bus System.

ACO-MV algorithm applied to System III obtained a better solution for this problem ($OF = 8.8609$) in 0.23 s than GA, GA-NLP (NOGHABI et al., 2009), BBO (ALBASRI et al., 2015),, OSL Solver (OSL) (ZEINELDIN et al., 2005) and worst than GACB-LP (KIDA, 2016) or SOA (AMRAEE, 2012). ACO-LP algorithm applied to System III obtained the best solution for this problem ($OF = 8.4271$) in 7.07 s. A complete chart is shown in Table 6.39.

Table 6.39 – Results Comparison for 8-Bus System Fault DOCR

Tech	**Autor**	**Exe Time (s)**	**OF - Time (s)**
OSL	(ZEINELDIN et al., 2005)	-	17.33
GA	(NOGHABI et al., 2009)	36000.00	11.001
GA-PL	(NOGHABI et al., 2009)	300.00	10.949
BBO	(ALBASRI et al., 2015)	2065.02	10.5495
ACO-MV	**This Work**	**0.23**	**8.8609**
BBO-LP	(ALBASRI et al., 2015)	6.79	8.7556
SOA	(AMRAEE, 2012)	50.45	8.4271
GACB-LP	(KIDA, 2016)	0.20	8.4271
ACO-LP	**This Work**	**7.07**	**8.4271**

6.4 System IV: Nine Bus Network

For System IV, the configuration is given for a Mid-Point Faults to apply a simple DOCRs Coordination. For this system validation with other meta-heuristic techniques in the literature are considered.

6.4.1 DOCRs Only

The algorithm runs a hundred times with four different configurations evaluating OF value (See Tab. 6.40) and Execution time (See Tab. 6.41). Those configurations are Optimized ACO_{MV} for 10000 Iterations, an additional 10000 iterations using an IHQS, also presented an ACO_{MV} with not optimized parameters, and a Hybrid configuration based on $ACO - LP$.

Table 6.40 – Hundred Evaluation of DOCR Objective Function Value for 9-Bus System

ACO version	**OF**			
	mean	***max***	***min***	***std***
10000	5.3882	6.3056	4.9125	0.2935
NOT OPT	19.4870	34.6103	13.3393	5.0521
10000 + IHQS	5.0536	5.4200	4.8017	0.1399
HYBRID	6.3506	6.9108	5.8713	0.2102

Table 6.41 – Hundred Evaluation of DOCR Algorithm Execution Time for 9-Bus System

ACO version	**Execution Time (s)**			
	mean	***max***	***min***	***std***
10000	127.78	1280.16	90.42	116.94
NOT OPT	133.40	277.13	43.41	50.43
10000 + IHQS	41.99	67.56	39.97	2.72
HYBRID	21.32	34.17	18.83	2.08

The best solution found occurs under 10000 iteration using an IHQS scenario and is shown on Tab. 6.42 and Tab. 6.43. Tripping times for coordinated configuration may be checked on Appendix A.11 for best prior implemented technique and Appendix A.12 for the hybrid algorithm.

Table 6.42 – Best TDS solution found for 9-Bus System (Near-end and Far-end Fault) of DOCR

Relay - TDS					
1	0.0676	*9*	0.0445	*17*	0.0680
2	0.0402	*10*	0.0523	*18*	0.0403
3	0.0326	*11*	0.0407	*19*	0.0736
4	0.0341	*12*	0.0384	*20*	0.0464
5	0.0312	*13*	0.0586	*21*	0.0689
6	0.0621	*14*	0.0604	*22*	0.0398
7	0.0529	*15*	0.0733	*23*	0.0737
8	0.0340	*16*	0.0398	*24*	0.0279

Table 6.43 – Best PS solution found for 9-Bus System (Near-end and Far-end Fault) of DOCR

Relay - PS (A)					
1	0.9646	*9*	1.1280	*17*	1.4892
2	0.8170	*10*	0.9326	*18*	1.1311
3	1.8190	*11*	0.8037	*19*	1.2077
4	1.6054	*12*	1.4919	*20*	1.0625
5	1.2099	*13*	0.9893	*21*	1.4468
6	1.0420	*14*	1.0536	*22*	1.1544
7	1.4229	*15*	0.6847	*23*	1.2791
8	1.0990	*16*	1.8674	*24*	1.2665

6.4.2 ACO Parameters Optimization with F-RACE

Table 6.44 contains survivors from the racing optimization algorithm for System IV, based on a quality function to get a better configuration on each iteration. Time needed to this algorithm seizes that answer was over 72 hours for a single 4-core desktop and 11 hours for a 24-core cluster.

Table 6.44 – Survivors of the F-RACE Algorithm for 9-Bus System

k	ξ	n_S	q_R	q_C	QF
650	0.705	40	0.0950	0.0051	8.2579
610	0.760	40	0.0900	0.0051	8.2643
610	0.760	40	0.0900	0.0051	8.2645
570	0.760	40	0.0950	0.0051	8.2646
610	0.760	37	0.0850	0.0001	8.2656
610	0.760	40	0.0850	0.0001	8.2659
610	0.760	40	0.0850	0.0001	8.2696
610	0.760	37	0.0950	0.0051	8.2874
650	0.760	40	0.1000	0.0001	8.2964
570	0.760	40	0.0900	0.0151	8.3029
650	0.760	37	0.0950	0.0101	8.3169
610	0.760	37	0.0950	0.0051	8.3850
610	0.815	43	0.0850	0.0101	8.5485
650	0.815	40	0.1000	0.0001	8.7108
610	0.815	40	0.0950	0.0101	8.7178
610	0.815	40	0.0900	0.0051	8.7479
570	0.815	34	0.0950	0.0051	8.8072
570	0.815	37	0.0900	0.0051	9.0201
690	0.815	43	0.1000	0.0101	9.4548
690	0.815	40	0.0950	0.0051	9.6279

Within that result is measure statistical data (see Tab. 6.45) to select the parameters according to the race survivors, this data is also important to define which parameter has more influence on the algorithm performance.

Table 6.45 – Comparing for Survivors of the F-RACE Algorithm for 9-Bus System

	k	ξ	n_S	q_R	q_C
mean	618	0.779	39	0.0925	0.0053
max	690	0.815	43	0.1000	0.0151
min	570	0.705	34	0.0850	0.0001
std	34.87	0.031	2	0.0049	0.0040
Influence	21.73%	30.36%	22.98%	23.30%	1.63%

6.4.3 Validation

As well, Fig. 6.11 represent three OF, according to ACO optimized, ACO optimized with the introduction of an initial High-Quality Solution and an ACO without parameters optimization. Except for ACO NOT OPT, in this occasion ACO, obtain good quality solution as shown in Table 6.40, compare to System I, this system has an alike initial convergence rate, it is noticed a better start for the ACO + IHQS but after 3000 iterations there is no significant difference for both optimized algorithm but with clear win to the ACO with IHQS. Once again, It is important to notice how restart mechanism acts over OF (around iteration No 1000 for ACO+IHQS and 2500 for single ACO) fighting stagnation.

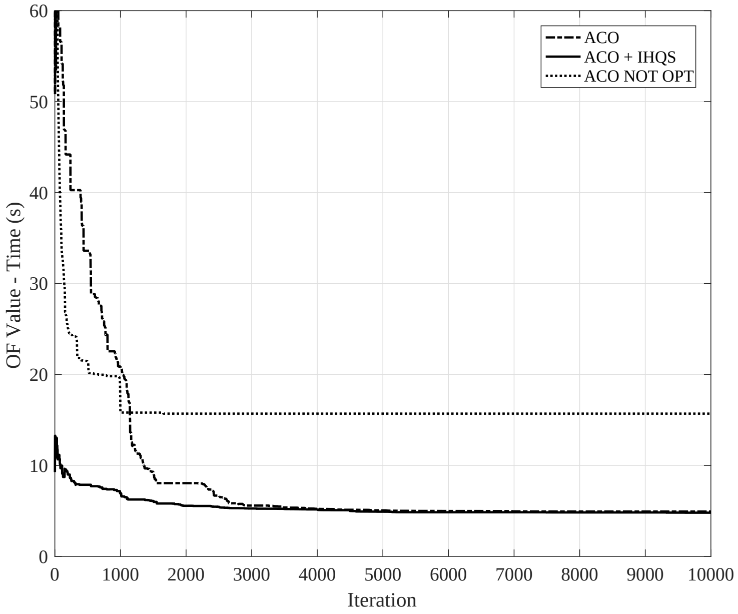

Figure 6.11 – OF Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 9-Bus System.

The output from Distance-DOCR Coordination with ACO-LP for a 9-Bus System (Fig. ??), shows an difference convergence rate in the OF value until configuration enters into the feasible region.

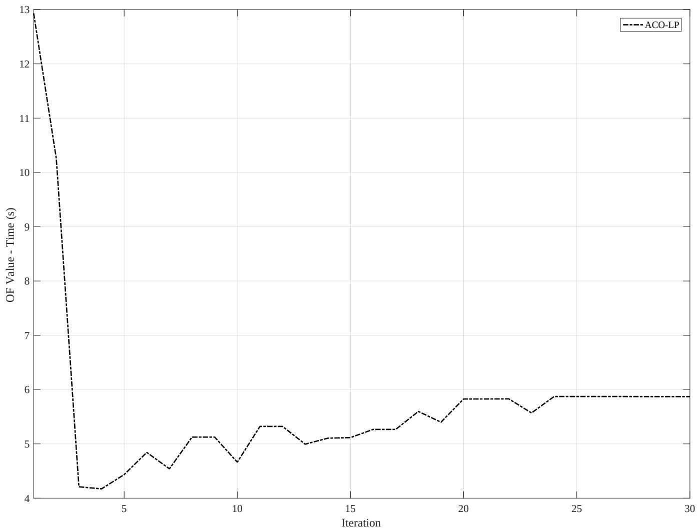

Figure 6.12 – OF Value of DOCR Coordination with ACO-LP for a 9-Bus System.

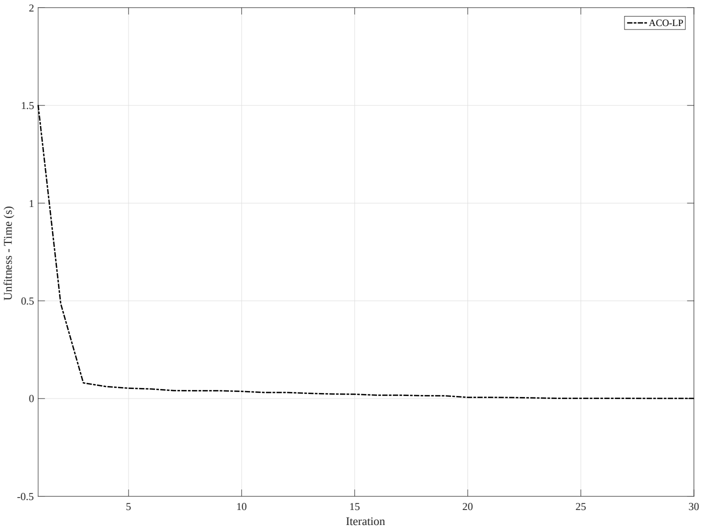

Figure 6.13 – Unfitness Value of DOCR Coordination with ACO-LP for a 9-Bus System.

ACO-MV and ACO-LP algorithm applied to System IV obtained better solutions for this problem (OF = 4.8017 and OF = 5.8713) in 40.19 s and 18.83 s, respectively, compare toGA, GA-NLP, Sequential Quadratic Programming (SQP) (BEDEKAR; BHIDE, 2011a), and BBO (ALBASRI et al., 2015) and close but worst than GACB-LP (KIDA, 2016) and BBO-LP (ALBASRI et al., 2015). A complete chart is shown in Table 6.46. OF will be limited to 4.8 s due to T_min constraint for relay minimum time 0.2 s.

Table 6.46 – Results Comparison for 9-Bus System Fault DOCR

Tech	Autor	Exe Time (s)	OF - Time (s)
GA	(BEDEKAR; BHIDE, 2011a)	-	32.6058
BBO	(ALBASRI et al., 2015)	-	28.8348
SQP	(BEDEKAR; BHIDE, 2011a)	-	19.4041
GA-NLP	(BEDEKAR; BHIDE, 2011a)	-	6.1786
ACO-LP	**This Work**	**18.83**	**5.8713**
ACO-MV	**This Work**	**40.19**	**4.8017**
BBO-LP	(ALBASRI et al., 2015)	-	4.8000
GACB-LP	(KIDA, 2016)	4.11	4.8000

6.5 System V: Fifteen Bus Network

For System V, the configuration is given for a Mid-Point Faults to apply a simple DOCRs Coordination. For this system validation with other meta-heuristic techniques in the literature are considered.

6.5.1 DOCRs Only

The algorithm runs a hundred times with four different configurations evaluating OF value (See Tab. 6.47) and Execution time (See Tab. 6.48. Those configurations are Optimized ACO_{MV} for 10000 Iterations, an additional 10000 iterations using an IHQS, within an ACO_{MV} with not optimized parameters, and a Hybrid configuration based on $ACO - LP$.

Table 6.47 – Hundred Evaluation of DOCR Objective Function Value for 15-Bus System

ACO version	OF			
	mean	*max*	*min*	*std*
10000	15.5769	16.8223	14.5381	0.4862
NOT OPT	64.3561	66.4206	59.9903	2.3812
10000 + IHQS	13.9052	13.9052	13.9052	0.0000
HYBRID	12.9878	13.2660	12.7001	0.1232

Table 6.48 – Hundred Evaluation of DOCR Algorithm Execution Time for 15-Bus System

ACO version	Execution Time (s)			
	mean	*max*	*min*	*std*
10000	472.14	506.49	464.46	13.83
NOT OPT	597.51	757.83	491.31	94.22
10000 + IHQS	0.58	1.75	0.63	0.00
HYBRID	13.20	28.62	11.22	2.57

The best solution found occurs under $ACO - LP$ scenario and is shown on Tab. 6.49 and Tab. 6.50. Tripping times for coordinated configuration may be checked on Appendix A.13 for best prior implemented technique and Appendix A.14 for the hybrid algorithm.

Table 6.49 – Best TDS solution found for 15-Bus System (Near-end and Far-end Fault) of DOCR

Relay - TDS							
1	0.1000	*12*	0.1315	*23*	0.1103	*34*	0.1111
2	0.1042	*13*	0.1000	*24*	0.1063	*35*	0.1000
3	0.1000	*14*	0.1128	*25*	0.1061	*36*	0.1000
4	0.1165	*15*	0.1055	*26*	0.1186	*37*	0.1222
5	0.1034	*16*	0.1022	*27*	0.1069	*38*	0.1062
6	0.1000	*17*	0.1000	*28*	0.1105	*39*	0.1039
7	0.1082	*18*	0.1000	*29*	0.1076	*40*	0.1043
8	0.10000	*19*	0.1000	*30*	0.1000	*41*	0.1041
9	0.1082	*20*	0.1000	*31*	0.1000	*42*	0.1067
10	0.1021	*21*	0.1116	*32*	0.1000		
11	0.1000	*22*	0.1157	*33*	0.1016		

Table 6.50 – Best PS solution found for 15-Bus System (Near-end and Far-end Fault) of DOCR

Relay - PS (A)							
1	1.5	*12*	1.0	*23*	1.0	*34*	2.5
2	1.0	*13*	2.5	*24*	1.5	*35*	2.5
3	2.5	*14*	1.0	*25*	2.0	*36*	2.0
4	1.0	*15*	1.0	*26*	1.5	*37*	2.0
5	2.5	*16*	1.5	*27*	2.0	*38*	2.5
6	2.5	*17*	2.5	*28*	2.5	*39*	2.5
7	1.0	*18*	1.5	*29*	1.5	*40*	2.5
8	2.0	*19*	2.0	*30*	2.0	*41*	2.5
9	2.0	*20*	2.0	*31*	2.5	*42*	1.5
10	2.0	*21*	1.0	*32*	2.0		
11	2.0	*22*	1.5	*33*	2.5		

6.5.2 ACO Parameters Optimization with F-RACE

Table 6.51 contains survivors from the racing optimization algorithm for System V, based on a quality function to get better configuration on each iteration. Time needed to this algorithm seizes that answer was over 120 hours for a single 4-core desktop and 21 hours for a 24-core cluster.

Table 6.51 – Survivors of the F-RACE Algorithm for 15-Bus System

k	ξ	n_S	q_R	q_C	QF
250	0.650	19	0.0001	0.0750	23.3422
410	0.595	19	0.0001	0.0800	27.9935
330	0.650	19	0.0001	0.0850	30.3546
170	0.375	31	0.0501	0.0001	57.0303
170	0.375	28	0.0550	0.0301	67.8027
170	0.375	28	0.0550	0.0301	67.8027
450	0.210	37	0.0351	0.0001	67.8235
450	0.210	37	0.0351	0.0001	67.8235
210	0.925	49	0.0351	0.0051	82.9106
210	0.925	49	0.0351	0.0051	82.9106

Within that result is measure statistical data (see Tab. 6.52) to select the parameters according to the race survivors, this data is also important to define which parameter has more influence on the algorithm performance.

Table 6.52 – Comparing for Survivors of the F-RACE Algorithm for 15-Bus System

	k	ξ	n_S	q_R	q_C
mean	282	0.529	31.6	0.0301	0.0311
max	450	0.925	49	0.0550	0.0850
min	170	0.210	19	0.0001	0.0001
std	111.43	0.249	10.8	0.0211	0.0339
Influence	25.51%	21.38%	29.49%	14.38%	9.25%

6.5.3 Validation

To keep in line with last Systems, Fig. 6.14 represent three OF, according to ACO optimized, ACO optimized with the introduction of an initial High-Quality Solution and an ACO without parameters optimization. Except for ACO NOT OPT which does not even shows a convergence characteristic, in this occasion ACO, obtain good quality solution as shown in Table 6.47, this system only shows an expected convergence rate for the ACO single version, it is noticed a better start for the ACO + IHQS but reduced after few iterations keeping trapped into a minimum better although other algorithm.

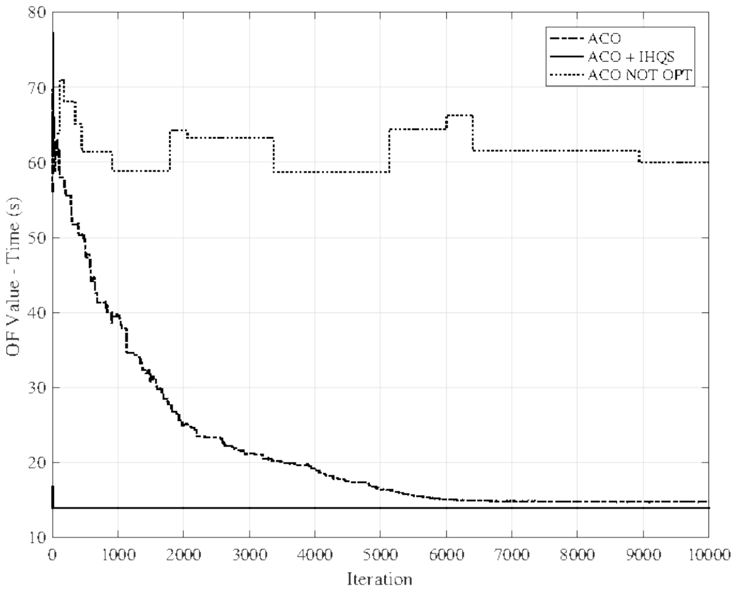

Figure 6.14 – OF Value for Single ACO, ACO NOT OPT, and ACO + IHQS for a 15-Bus System.

OF value from ACO-LP for a 15-Bus System shows in Fig. 6.15 fast convergence in few iterations into optimal value.

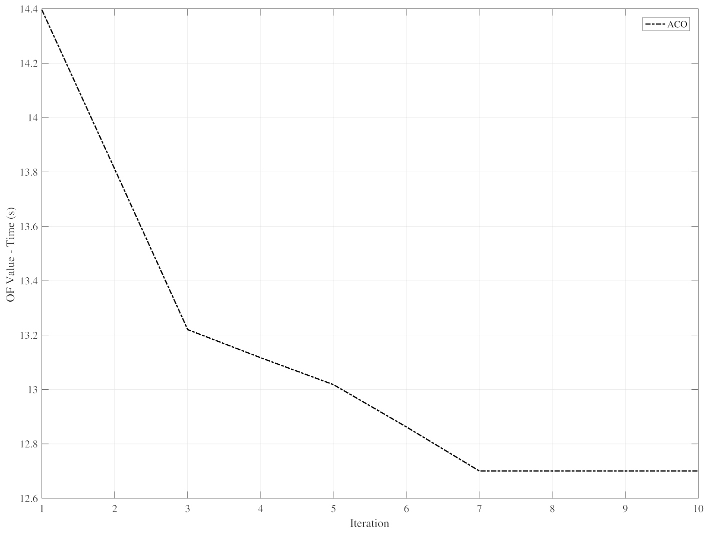

Figure 6.15 – OF Value for DOCR Coordination with ACO-LP for a 15-Bus System.

ACO-MV and ACO-LP algorithms applied to System II obtained better solutions for this problem ($OF = 14.5381$ and $OF = 12.7001$)) than GA, GA-NLP Cuckoo Search Algorithm (CSA) (DARJI et al., 2015), Standard Branch-and-Bound (SBB) SBB-NLP (AMRAEE, 2012), and worst than GACB-LP (KIDA, 2016) or SOA (AMRAEE, 2012) . A Complete chart is shown in Table 6.53.

Table 6.53 – Results Comparison for 15-Bus System Mid-Point Fault DOCR

Tech	Autor	Exe Time (s)	OF - Time (s)
GA	(DARJI et al., 2015)	-	35.8812
GA-NLP	(DARJI et al., 2015)	-	19.5843
CSA	(DARJI et al., 2015)	-	19.5521
SBB	(AMRAEE, 2012)	-	15.3350
SBB-NLP	(AMRAEE, 2012)	60.70	15.0020
ACO-MV	**This Work**	**0.63**	**14.5381**
ACO-LP	**This Work**	**11.22**	**12.7001**
SOA	(AMRAEE, 2012)	406.30	12.2270
GACB-LP	(KIDA, 2016)	5.11	12.2149

6.6 Discussions and Final Considerations

The IHQS open a debate due to how fast locates good sub-optimal solutions, even after some ACO iterations there is no guarantee of finding better solutions but an initial feasible space. In general would be possible using directly a technique based on LP to get a system coordinated in a fraction of the time required by a heuristic technique. Hybrid approach validate last statement improving almost every single value for all systems applications.

F-RACE algorithm has additional information to be considered for application where computing time for optimization is no longer available and a tunning must be performed as fast as possible. Table 6.54 shows a percentage relation between the standard deviation and the mean value per parameter for each system tested. Table 6.54 marks the parameters influence under our solution, saying that there are two parameters with a notorious qualification, ξ the convergence parameter of the algorithm is most important value to be configured, only follow by n_S the number of ants working to build new solutions. Those parameters are important not only to find a high-quality solution but improve the performance of the algorithm. On the contrary, q_C is the parameter which no requires a specific configuration.

Table 6.54 – Parameter influence for all tested system

System	k	ξ	n_S	q_R	q_C
3-BUS	13.18%	31.38%	23.37%	20.16%	11.90%
6-BUS	46.74%	27.65%	13.85%	9.42%	2.35%
8-BUS	15.65%	28.61%	24.23%	8.49%	23.02%
9-BUS	21.73%	30.36%	22.98%	23.30%	1.63%
15-BUS	25.51%	21.38%	29.49%	14.38%	9.25%

Corroborate the advantage of parallel programming providing concurrency, performing simultaneously multiple actions at the same time, reducing execution time.

Besides, there are difference contingency scenarios where relay settings should (or could) not be reset (e.g. utility requirements or communication failure) and coordination is made disabling constraints where those relays are present finding a new suboptimal answer but feasible.

7 Conclusion

In this work was proposed a methodology to solve the problem of the coordination of directional (inverse time) overcurrent relays as a combined scheme with distance relays (Second Zone Configuration). This problem consists in finding the adjustments of the relays in order to minimize their working times, without endangering the selectivity, reliability, and sensitivity of the protection scheme. The most important contributions of this work are the consideration of distance relays into the coordination mathematical model where normally only overcurrent relays are considered, and the parameter optimization for the *ACO* algorithm implemented. Among the proposed methodologies, the introduction of an additional restart mechanism to fight algorithm stagnation is to be highlighted due to its effectiveness and efficiency to lead the methodologies implemented in this work to better responses.

The proposed method delimits the optimum timing for the second zone of distance relays in a mixed scheme with directional overcurrent relays. When the line protection schemes are composed of distance relays and directional overcurrent relays, the settings of the relays must be computed considering both relays because separate relay computation would lead to loss of selectivity. The time setting of distance relays' second zone on the combine coordination tends to be greater than standards for only overcurrent coordination remarking the importance of the introduction of this component to the coordination of the transmission system.

The experimental results illustrate that the good performance of the ACO Multi-Variable is due to the pre-process of parametrizing of the algorithm based on F-RACE for each case of study since it allows to leaves empirical tunning process to find specific configurations combining a good convergence rate getting fast solutions of high-quality avoiding local optimal solutions. But also F-RACE lets identify how importance a parameter is, no matter in which system is tested, there is a trending which defines a rank for parameters inside the ACO algorithm. ACOMV not only can tackle various classes of decision variables for different system topologies robustly but, in addition, that it is efficient in finding high-quality solutions.

Finally, the inclusion of a hybrid technique is required to compare ACOMV through a relaxation to improve the number of function evaluations and computational times, which not only showed success finding a better response time but without requiring a pre-parametrizing for ACO classical algorithm.

8 Recommendations for Future Work

- Application of local non-convex optimization based on piecewise linear approximation.
- Software integration for power flow calculations, short circuits and the parameterization of relays with optimization techniques.
- Analysis of various fault scenarios and different operating configurations, Plug and Play considerations.
- Force solving with non-linear techniques for non-convex problem validating with heuristics results.

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Appendix

APPENDIX A – Coordination times Results

A.1 System II: Six Bus Network

A.1.1 DOCRs Only

Table A.1 – Tripping times for coordinated configuration - 6 Bus System

R_{main}	R_{backup}	Near-end			Far-end		
		t_{main}	t_{backup}	Δt	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.4148	NBA	NBA	0.2997	4.2909	3.991
R_1	R_8	0.4148	1.1873	0.773	0.2997	0.5557	0.256
R_2	R_3	0.6542	2.1845	1.530	0.4646	0.7204	0.256
R_3	R_{13}	0.2457	0.7283	0.483	0.1868	0.3930	0.206
R_3	R_{10}	0.2996	NBA	NBA	0.1868	0.6041	0.417
R_4	R_1	0.4533	0.8734	0.420	0.3549	0.5570	0.202
R_5	R_{12}	0.4444	1.3382	0.894	0.2211	0.4446	0.224
R_5	R_{14}	0.4444	NBA	NBA	0.2211	0.7168	0.496
R_6	R_3	0.1863	0.4980	0.312	0.1863	0.3956	0.209
R_7	R_2	0.6153	0.8523	0.237	0.5354	0.7354	0.200
R_7	R_{11}	0.6153	0.8163	0.201	0.5354	0.7734	0.238
R_9	R_4	0.2717	0.5333	0.262	0.2472	0.4474	0.200
R_9	R_{13}	0.2717	0.5535	0.282	0.2472	0.5088	0.262
R_{11}	R_6	0.5630	0.8913	0.328	0.3704	0.5704	0.200
R_{11}	R_{14}	0.5630	2.9567	2.394	0.3704	0.5709	0.200
R_{12}	R_2	0.2996	0.8292	0.530	0.2156	0.4713	0.256
R_{12}	R_8	0.2996	6.5204	6.221	0.2156	0.9311	0.716
R_{13}	R_{12}	0.3292	NBA	NBA	0.2103	0.4104	0.200
R_{13}	R_6	0.3292	0.7298	0.401	0.2103	0.7119	0.502
R_{14}	R_4	0.4246	1.3900	0.965	0.2868	0.6246	0.338
R_{14}	R_{10}	0.4246	4.1820	3.757	0.2868	0.6250	0.338

Table A.2 – Tripping times for coordinated (Hybrid) configuration - 6 Bus System

R_{main}	R_{backup}	Near-end			Far-end		
		t_{main}	t_{backup}	Δt	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.4024	NBA	NBA	0.2850	4.2984	4.013
R_1	R_8	0.4024	1.1818	0.779	0.2850	0.5536	0.269
R_2	R_3	0.6542	2.1845	1.530	0.4646	0.7204	0.256
R_3	R_{13}	0.2457	0.7129	0.467	0.1868	0.6036	0.417
R_3	R_{10}	0.2457	NBA	NBA	0.1868	0.4285	0.242
R_4	R_1	0.4491	0.9213	0.472	0.3541	0.5541	0.200
R_5	R_{12}	0.4429	1.3125	0.870	0.2205	0.4440	0.224
R_5	R_{14}	0.4429	NBA	NBA	0.2205	0.7405	0.520
R_6	R_3	0.3355	0.6980	0.363	0.1863	0.4256	0.239
R_7	R_2	0.6153	0.8173	0.202	0.5354	0.7734	0.238
R_7	R_{11}	0.6153	0.8523	0.237	0.5354	0.7354	0.200
R_9	R_4	0.2715	0.5443	0.273	0.2470	0.5019	0.255
R_9	R_{13}	0.2715	0.5328	0.261	0.2470	0.4470	0.200
R_{11}	R_6	0.5629	2.9432	2.380	0.3703	0.5703	0.200
R_{11}	R_{14}	0.5629	0.9586	0.396	0.3703	0.5703	0.200
R_{12}	R_2	0.3001	6.5205	6.220	0.2163	0.9311	0.715
R_{12}	R_8	0.3001	0.8258	0.526	0.2163	0.4696	0.253
R_{13}	R_{12}	0.3290	NBA	NBA	0.2102	0.4102	0.200
R_{13}	R_6	0.3290	0.7246	0.396	0.2102	0.7111	0.501
R_{14}	R_4	0.2700	3.2544	2.984	0.4114	0.6114	0.200
R_{14}	R_{10}	0.2700	1.3609	1.091	0.4114	0.6114	0.200

A.1.2 Distance and DOCRs

Table A.3 – Tripping times for coordinated configuration - Distance / DOCR for 6-bus System - Part I

R_{main}	R_{backup}	Near-end			Far-end		
		t_{main}	t_{backup}	Δt	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.3640	NBA	NBA	0.2577	4.1098	3.852
R_1	R_8	0.3640	1.1876	0.824	0.2577	0.5549	0.297
R_2	R_3	0.2879	NBA	NBA	0.2045	0.4203	0.216
R_3	R_{13}	0.2456	0.6992	0.454	0.1868	0.6035	0.417
R_3	R_{10}	0.2456	NBA	NBA	0.1868	NBA	NBA
R_4	R_1	0.3859	0.8344	0.448	0.3017	0.5114	0.210
R_5	R_{12}	0.4429	1.5384	1.095	0.2205	0.4466	0.226
R_5	R_{14}	0.4429	NBA	NBA	0.2205	0.7197	0.499
R_6	R_3	0.3057	0.5280	0.222	0.1765	0.3816	0.205
R_7	R_2	0.6153	NBA	NBA	0.5354	NBA	NBA
R_7	R_{11}	0.6153	0.8153	0.200	0.5354	0.7535	0.218
R_9	R_4	0.2715	0.4717	0.200	0.2470	0.5334	0.286
R_9	R_{13}	0.2715	0.5327	0.261	0.2470	0.4480	0.201
R_{11}	R_6	0.5385	1.6008	1.062	0.3543	0.5899	0.236
R_{11}	R_{14}	0.5385	0.932	0.394	0.3543	0.5547	0.200
R_{12}	R_2	0.2949	2.8701	2.575	0.2097	0.4098	0.200
R_{12}	R_8	0.2949	0.8287	0.534	0.2097	0.4705	0.261
R_{13}	R_{12}	0.3289	NBA	NBA	0.2102	0.4103	0.200
R_{13}	R_6	0.3289	0.7638	0.435	0.2102	0.59056	0.380
R_{14}	R_4	0.2622	3.7278	3.466	0.3996	0.599924	0.200
R_{14}	R_{10}	0.2622	1.3234	1.061	0.3996	0.6004	0.201

Table A.4 – Tripping times for coordinated configuration - Distance / DOCR for 6-bus System - Part II

Near-end					Far-end			
R_{main}	R_{backup}	t_{main}	t_{backup}	Δt	Relay	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.3640	0.8158	0.452	R_1	0.2577	0.5864	0.329
R_1	R_8	0.3640	0.5650	0.201	R_2	0.2045	0.8155	0.611
R_2	R_3	0.2879	0.5056	0.218	R_3	0.1868	0.5056	0.319
R_3	R_{13}	0.2456	0.4715	0.226	R_4	0.3017	0.5024	0.201
R_3	R_{10}	0.2456	0.5808	0.335	R_5	0.2205	0.5859	0.365
R_4	R_1	0.3859	0.5864	0.200	R_6	0.1765	0.7387	0.562
R_5	R_{12}	0.4429	0.6431	0.200	R_7	0.5354	0.735475	0.200
R_5	R_{14}	0.4429	0.7387	0.296	R_8	0.3237	0.5650	0.241
R_6	R_3	0.3057	0.5056	0.200	R_9	0.2470	0.4470	0.200
R_7	R_2	0.6153	0.8155	0.200	R_{10}	0.3807	0.5808	0.200
R_7	R_{11}	0.6153	0.8158	0.200	R_{11}	0.3543	0.8158	0.462
R_9	R_4	0.2715	0.5024	0.231	R_{12}	0.2097	0.6431	0.433
R_9	R_{13}	0.2715	0.4715	0.200	R_{13}	0.2102	0.4715	0.261
R_{11}	R_6	0.5385	0.7387	0.200	R_{14}	0.3996	0.7387	0.339
R_{11}	R_{14}	0.5385	0.7387	0.200				
R_{12}	R_2	0.2949	0.8155	0.521				
R_{12}	R_8	0.2949	0.5650	0.270				
R_{13}	R_{12}	0.3289	0.6431	0.314				
R_{13}	R_6	0.3289	0.7387	0.410				
R_{14}	R_4	0.2622	0.5024	0.240				
R_{14}	R_{10}	0.2622	0.5808	0.319				

Table A.5 – Tripping times for coordinated configuration (Hybrid) - Distance / DOCR for 6-bus System - Part I

R_{main}	R_{backup}	Near-end			Far-end		
		t_{main}	t_{backup}	Δt	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.5384	NBA	NBA	0.3542	4.1116	3.757
R_1	R_8	0.3667	1.1819	0.815	0.3233	0.5536	0.230
R_2	R_3	0.2456	2.1845	1.939	0.1868	0.4203	0.234
R_3	R_{13}	0.3289	0.6983	0.369	0.2101	0.6035	0.393
R_3	R_{10}	0.4241	NBA	NBA	0.3804	0.5841	0.204
R_4	R_1	0.3641	0.8343	0.470	0.2578	0.5015	0.244
R_5	R_{12}	0.2945	1.5511	1.257	0.2093	0.4465	0.237
R_5	R_{14}	0.2622	NBA	NBA	0.3996	0.7197	0.320
R_6	R_3	0.3641	0.7168	0.353	0.2578	0.4956	0.238
R_7	R_2	0.2456	0.4980	0.252	0.1868	0.3886	0.202
R_7	R_{11}	0.2876	0.5584	0.271	0.2042	0.40601	0.202
R_9	R_4	0.3857	0.5914	0.206	0.3015	0.5231	0.222
R_9	R_{13}	0.3289	0.5327	0.204	0.2101	0.4470	0.237
R_{11}	R_6	0.3056	1.6001	1.294	0.3543	0.5899	0.236
R_{11}	R_{14}	0.2624	0.9322	0.670	0.3543	0.5547	0.200
R_{12}	R_2	0.2876	2.8662	2.579	0.2097	0.4098	0.200
R_{12}	R_8	0.3667	0.8258	0.459	0.2097	0.4705	0.261
R_{13}	R_{12}	0.2945	NBA	NBA	0.2102	0.4103	0.200
R_{13}	R_6	0.3056	0.7655	0.460	0.2102	0.5905	0.380
R_{14}	R_4	0.3857	3.7261	3.340	0.3896	0.5999	0.210
R_{14}	R_{10}	0.4241	1.3201	0.896	0.3896	0.6004	0.211
R_8	NBA	0.6153	NBA	NBA	0.5354	NBA	NBA
R_{10}	NBA	0.2714	NBA	NBA	0.2470	NBA	NBA

Table A.6 – Tripping times for coordinated configuration (Hybrid) - Distance / DOCR for 6-bus System - Part II

Near-end					Far-end			
R_{main}	R_{backup}	t_{main}	t_{backup}	Δt	Relay	t_{main}	t_{backup}	Δt
R_1	R_{11}	0.5384	0.8016	0.263	R_1	0.2578	0.5857	0.328
R_1	R_8	0.3667	0.5715	0.205	R_2	0.2042	0.8153	0.611
R_2	R_3	0.24566	0.7354	0.490	R_3	0.1868	0.7354	0.549
R_3	R_{13}	0.3289	0.5715	0.243	R_4	0.3015	0.7385	0.437
R_3	R_{10}	0.4241	0.6281	0.204	R_5	0.2204	0.4470	0.227
R_4	R_1	0.3641	0.5864	0.222	R_6	0.1765	0.5641	0.388
R_5	R_{12}	0.2945	0.6431	0.349	R_7	0.2876	0.6357	0.348
R_5	R_{14}	0.2622	0.7387	0.476	R_8	0.2833	0.4915	0.208
R_6	R_3	0.3641	0.5656	0.202	R_9	0.2470	0.6428	0.396
R_7	R_2	0.2456	0.8155	0.570	R_{10}	0.3804	0.7384	0.358
R_7	R_{11}	0.2876	0.8158	0.528	R_{11}	0.3012	0.5016	0.200
R_9	R_4	0.3857	0.5924	0.207	R_{12}	0.2093	0.5057	0.296
R_9	R_{13}	0.3289	0.5715	0.243	R_{13}	0.2101	0.8153	0.605
R_{11}	R_6	0.3056	0.7387	0.433	R_{14}	0.3896	0.5905	0.201
R_{11}	R_{14}	0.2622	0.7387	0.476				
R_{12}	R_2	0.2876	0.8155	0.528				
R_{12}	R_8	0.3667	0.5850	0.218				
R_{13}	R_{12}	0.2945	0.6431	0.349				
R_{13}	R_6	0.3056	0.7387	0.433				
R_{14}	R_4	0.3857	0.5924	0.207				
R_{14}	R_{10}	0.4241	0.6239	0.200				

A.2 System III: Eight Bus Network

A.2.1 DOCRs Only

Table A.7 – Tripping times for coordinated configuration - 8 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_6	0.4184	0.7186	0.300
R_2	R_1	0.8066	1.1062	0.300
R_2	R_7	0.8066	1.1066	0.300
R_3	R_2	0.7431	1.0433	0.300
R_4	R_3	0.6460	0.9459	0.300
R_5	R_4	0.5618	0.8617	0.300
R_6	R_{14}	0.5181	0.9967	0.479
R_6	R_5	0.5181	1.1376	0.620
R_7	R_{13}	0.6966	0.9967	0.300
R_7	R_5	0.6966	1.3994	0.703
R_8	R_9	0.5209	1.1066	0.586
R_8	R_7	0.5209	0.9782	0.457
R_9	R_{10}	0.5683	0.8683	0.300
R_{10}	R_{11}	0.6797	0.9797	0.300
R_{11}	R_{12}	0.7565	1.0564	0.300
R_{12}	R_{14}	0.8378	1.3994	0.562
R_{12}	R_{13}	0.8378	1.1376	0.300
R_{13}	R_8	0.4288	0.7288	0.300
R_{14}	R_1	0.6780	1.1062	0.428
R_{14}	R_9	0.6780	0.9782	0.300

Table A.8 – Tripping times for coordinated (Hybrid) configuration - 8 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_6	0.5006	0.9539	0.453
R_2	R_1	0.4075	1.0774	0.670
R_2	R_7	0.4075	0.7075	0.300
R_3	R_2	0.7774	1.0774	0.300
R_4	R_3	0.5542	1.0774	0.523
R_5	R_4	0.6539	0.9542	0.300
R_6	R_{14}	0.6445	1.0774	0.433
R_6	R_5	0.6445	0.9539	0.309
R_7	R_{13}	0.5101	1.0972	0.587
R_7	R_5	0.5101	1.0065	0.496
R_8	R_9	0.4275	0.7295	0.302
R_8	R_7	0.4275	1.0972	0.670
R_9	R_{10}	0.7055	1.0065	0.301
R_{10}	R_{11}	0.6469	1.0055	0.359
R_{11}	R_{12}	0.7053	1.0069	0.302
R_{12}	R_{14}	0.5980	1.0080	0.410
R_{12}	R_{13}	0.5980	1.0053	0.407
R_{13}	R_8	0.4978	0.7978	0.300
R_{14}	R_1	0.7972	1.0972	0.300
R_{14}	R_9	0.7972	1.0972	0.300

A.2.2 Distance and DOCRs

Table A.9 – Tripping times for coordinated configuration - Distance / DOCR for 8-bus System

R_{main}	R_{backup}	t^{OC}_{main}	t^{OC}_{backup}	Δt	t^{Z2}_{backup}	Δt
R_1	R_6	0.4338	0.7372	0.303	0.7364	0.303
R_2	R_1	0.8451	1.1468	0.302	1.2420	0.397
R_2	R_7	0.8451	1.1496	0.305	1.1478	0.303
R_3	R_2	0.7660	1.0660	0.300	1.0676	0.302
R_4	R_3	0.6458	0.9515	0.306	0.9511	0.305
R_5	R_4	0.5179	0.8320	0.314	0.8333	0.315
R_6	R_{14}	0.5491	1.1688	0.620	1.1696	0.620
R_6	R_5	0.5491	1.0471	0.498	1.0267	0.478
R_7	R_{13}	0.7237	1.1720	0.448	1.1697	0.446
R_7	R_5	0.7237	1.0471	0.323	1.0267	0.303
R_8	R_9	0.5447	1.1496	0.605	1.0350	0.490
R_8	R_7	0.5447	1.1496	0.605	1.1478	0.603
R_9	R_{10}	0.6679	0.9764	0.309	0.9702	0.302
R_{10}	R_{11}	0.7395	1.0480	0.308	1.0467	0.307
R_{11}	R_{12}	0.7806	1.0946	0.314	1.0832	0.303
R_{12}	R_{14}	0.8681	1.1688	0.301	1.1696	0.302
R_{12}	R_{13}	0.8681	1.1720	0.304	1.1697	0.302
R_{13}	R_8	0.4567	0.7620	0.305	0.7570	0.300
R_{14}	R_1	0.7334	1.1468	0.413	1.2420	0.509
R_{14}	R_9	0.7334	1.1496	0.416	1.0350	0.302

Table A.10 – Tripping times for coordinated (Hybrid) configuration - Distance / DOCR for 8-bus System

R_{main}	R_{backup}	t^{OC}_{main}	t^{OC}_{backup}	Δt	t^{Z2}_{backup}	Δt
R_1	R_6	0.5415	1.0693	0.528	1.1632	0.622
R_2	R_1	0.5070	1.1065	0.600	1.1693	0.662
R_2	R_7	0.5070	0.8070	0.300	0.9965	0.490
R_3	R_2	0.8065	1.1065	0.300	1.1065	0.300
R_4	R_3	0.5212	1.1065	0.585	0.8270	0.306
R_5	R_4	0.7693	1.0712	0.302	1.1065	0.337
R_6	R_{14}	0.5565	1.1065	0.550	1.0961	0.540
R_6	R_5	0.5565	1.0693	0.513	0.9212	0.365
R_7	R_{13}	0.4287	1.3993	0.971	1.088	0.660
R_7	R_5	0.4287	0.9965	0.568	0.9212	0.492
R_8	R_9	0.5818	0.8987	0.317	1.1632	0.581
R_8	R_7	0.5818	1.1632	0.581	0.9965	0.415
R_9	R_{10}	0.7432	1.0465	0.303	1.0432	0.300
R_{10}	R_{11}	0.7211	1.0432	0.322	1.0211	0.300
R_{11}	R_{12}	0.6460	1.0211	0.375	0.9460	0.300
R_{12}	R_{14}	0.7885	1.0940	0.306	1.0961	0.308
R_{12}	R_{13}	0.7885	1.0885	0.300	1.0885	0.300
R_{13}	R_8	0.5617	0.8617	0.300	0.9287	0.367
R_{14}	R_1	0.8632	1.1632	0.300	1.1693	0.306
R_{14}	R_9	0.8632	1.3993	0.536	1.1632	0.300

A.3 System IV: Nine Bus Network

A.3.1 DOCRs Only

Table A.11 – Tripping times for coordinated configuration - 9 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_{15}	0.2001	0.4129	0.213
R_1	R_{17}	0.2001	0.8567	0.657
R_2	R_4	0.2002	0.9051	0.705
R_3	R_1	0.1999	0.4512	0.251
R_4	R_6	0.2000	0.5036	0.304
R_5	R_3	0.2004	1.0736	0.873
R_6	R_8	0.1999	0.9203	0.720
R_6	R_{23}	0.1999	0.6885	0.489
R_7	R_5	0.2001	1.3476	1.147
R_7	R_{23}	0.2001	0.6885	0.488
R_8	R_{10}	0.2003	0.4123	0.212
R_9	R_7	0.2002	0.6767	0.477
R_{10}	R_{12}	0.2001	4.9914	4.791
R_{11}	R_9	0.2002	0.5026	0.302
R_{12}	R_{14}	0.1999	0.5266	0.327
R_{12}	R_{21}	0.1999	0.8247	0.625
R_{13}	R_{11}	0.2002	0.5829	0.383
R_{13}	R_{21}	0.2002	0.8247	0.624
R_{14}	R_{16}	0.2001	2.7886	2.588
R_{14}	R_{19}	0.2001	0.6922	0.492
R_{15}	R_{13}	0.2001	0.5539	0.354
R_{15}	R_{19}	0.2001	0.6922	0.492
R_{16}	R_2	0.2002	0.5959	0.396
R_{16}	R_{17}	0.2002	0.8567	0.657
R_{17}	R_{24}	0.2001	NBA	NBA
R_{18}	R_2	0.2001	0.5959	0.396
R_{18}	R_{15}	0.2001	0.4129	0.213
R_{19}	R_{24}	0.2000	NBA	NBA
R_{20}	R_{13}	0.2001	0.5539	0.354
R_{20}	R_{16}	0.2001	2.7886	2.588
R_{21}	R_{24}	0.2000	NBA	NBA
R_{22}	R_{11}	0.2006	0.5829	0.382
R_{22}	R_{14}	0.2006	0.5266	0.326
R_{23}	R_{22}	0.2000	NBA	NBA
R_{24}	R_5	0.2000	1.3476	1.148
R_{24}	R_8	0.2000	0.9203	0.720

Table A.12 – Tripping times for coordinated (Hybrid) configuration - 9 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_{15}	0.2635	0.5168	0.253
R_1	R_{17}	0.2635	0.5396	0.276
R_2	R_4	0.2393	0.4393	0.200
R_3	R_1	0.3317	0.5317	0.200
R_4	R_6	0.2846	0.4846	0.200
R_5	R_3	0.2896	0.4896	0.200
R_6	R_8	0.2688	0.4840	0.215
R_6	R_{23}	0.2688	0.4688	0.200
R_7	R_5	0.2043	0.4840	0.280
R_7	R_{23}	0.2043	0.4688	0.264
R_8	R_{10}	0.2536	0.4536	0.200
R_9	R_7	0.2525	0.4525	0.200
R_{10}	R_{12}	0.3415	0.5415	0.200
R_{11}	R_9	0.2108	0.4108	0.200
R_{12}	R_{14}	0.2094	0.5073	0.298
R_{12}	R_{21}	0.2094	0.5551	0.346
R_{13}	R_{11}	0.3551	0.5551	0.200
R_{13}	R_{21}	0.3551	0.5551	0.200
R_{14}	R_{16}	0.2395	0.5196	0.280
R_{14}	R_{19}	0.2395	0.5389	0.299
R_{15}	R_{13}	0.3389	0.5389	0.200
R_{15}	R_{19}	0.3389	0.5389	0.200
R_{16}	R_2	0.3396	0.5396	0.200
R_{16}	R_{17}	0.3396	0.5396	0.200
R_{17}	R_{24}	0.1526	NBA	NBA
R_{18}	R_2	0.3168	0.5396	0.223
R_{18}	R_{15}	0.3168	0.5168	0.200
R_{19}	R_{24}	0.1649	NBA	NBA
R_{20}	R_{13}	0.3196	0.5389	0.219
R_{20}	R_{16}	0.3196	0.5196	0.200
R_{21}	R_{24}	0.1703	NBA	NBA
R_{22}	R_{11}	0.3073	0.5551	0.248
R_{22}	R_{14}	0.3073	0.5073	0.200
R_{23}	R_{22}	0.1207	NBA	NBA
R_{24}	R_5	0.2840	0.4840	0.200
R_{24}	R_8	0.2840	0.4840	0.200

A.4 System V: Fifteen Bus Network

A.4.1 DOCRs Only

Table A.13 – Tripping times for coordinated configuration - 15 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt	R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_6	0.3108	0.5108	0.200	R_{20}	R_{30}	0.2750	0.4904	0.215
R_2	R_4	0.3029	0.7701	0.467	R_{21}	R_{19}	0.2652	0.5233	0.258
R_2	R_{16}	0.3029	0.6125	0.310	R_{21}	R_{17}	0.2652	0.5610	0.296
R_3	R_1	0.3216	0.9174	0.596	R_{21}	R_{30}	0.2652	0.4904	0.225
R_3	R_{16}	0.3216	0.6125	0.291	R_{22}	R_{23}	0.3004	1.4227	1.122
R_4	R_7	0.3451	0.5451	0.200	R_{22}	R_{34}	0.3004	0.5004	0.200
R_4	R_{12}	0.3451	0.6211	0.276	R_{23}	R_{13}	0.3260	0.5260	0.200
R_4	R_{20}	0.3451	0.6671	0.322	R_{23}	R_{11}	0.3260	0.6856	0.360
R_5	R_2	0.3495	1.0654	0.716	R_{24}	R_{21}	0.2868	0.9540	0.667
R_6	R_{10}	0.3628	0.5628	0.200	R_{24}	R_{34}	0.2868	0.5004	0.214
R_6	R_8	0.3628	0.5964	0.234	R_{25}	R_{15}	0.3406	0.7000	0.359
R_7	R_5	0.3964	0.5964	0.200	R_{25}	R_{18}	0.3406	1.3908	1.050
R_7	R_{10}	0.3964	0.5964	0.200	R_{26}	R_{28}	0.3741	0.5741	0.200
R_8	R_3	0.3881	0.5881	0.200	R_{26}	R_{36}	0.3741	0.6795	0.305
R_8	R_{12}	0.3881	0.6211	0.233	R_{27}	R_{25}	0.4340	0.6340	0.200
R_8	R_{20}	0.3881	0.6671	0.279	R_{27}	R_{36}	0.4340	0.6795	0.245
R_9	R_5	0.2996	0.5964	0.297	R_{28}	R_{29}	0.3880	0.8401	0.452
R_9	R_8	0.2996	0.5628	0.263	R_{28}	R_{32}	0.3880	0.5880	0.200
R_{10}	R_{14}	0.3018	0.5018	0.200	R_{29}	R_{19}	0.2916	0.5233	0.232
R_{11}	R_7	0.3263	0.5881	0.262	R_{29}	R_{17}	0.2916	0.5610	0.269
R_{11}	R_3	0.3263	0.5451	0.219	R_{29}	R_{22}	0.2916	0.5932	0.302
R_{11}	R_{20}	0.3263	0.6671	0.341	R_{30}	R_{27}	0.3380	0.5380	0.200
R_{12}	R_{13}	0.3159	0.6856	0.370	R_{30}	R_{32}	0.3380	0.5880	0.250
R_{12}	R_{24}	0.3159	0.5159	0.200	R_{31}	R_{29}	0.3032	0.5380	0.235
R_{13}	R_9	0.3414	0.5701	0.229	R_{31}	R_{27}	0.3032	0.8401	0.537
R_{14}	R_{11}	0.3096	0.5260	0.216	R_{32}	R_{33}	0.3225	0.5225	0.200
R_{14}	R_{24}	0.3096	0.5159	0.206	R_{32}	R_{42}	0.3225	0.7411	0.419
R_{15}	R_1	0.2652	0.9174	0.652	R_{33}	R_{23}	0.3446	0.9540	0.609
R_{15}	R_4	0.2652	0.7701	0.505	R_{33}	R_{21}	0.3446	1.4227	1.078
R_{16}	R_{18}	0.3074	1.3908	1.083	R_{34}	R_{31}	0.3656	0.5656	0.200
R_{16}	R_{26}	0.3074	0.5074	0.200	R_{34}	R_{42}	0.3656	0.7411	0.376
R_{17}	R_{15}	0.2775	0.7000	0.423	R_{35}	R_{25}	0.3440	0.6340	0.290
R_{17}	R_{26}	0.2775	0.5074	0.230	R_{35}	R_{28}	0.3440	0.5741	0.230
R_{18}	R_{19}	0.2904	0.5610	0.271	R_{36}	R_{38}	0.3256	0.5256	0.200
R_{18}	R_{22}	0.2904	0.5932	0.303	R_{37}	R_{35}	0.3640	0.5640	0.200
R_{18}	R_{30}	0.2904	0.4904	0.200	R_{38}	R_{40}	0.3985	0.5985	0.200
R_{19}	R_7	0.2971	0.5881	0.291	R_{39}	R_{37}	0.4067	0.6067	0.200
R_{19}	R_3	0.2971	0.5451	0.248	R_{40}	R_{41}	0.3616	0.5616	0.200
R_{19}	R_{12}	0.2971	0.6211	0.324	R_{41}	R_{33}	0.3196	0.5656	0.246
R_{20}	R_{17}	0.2750	0.5233	0.248	R_{41}	R_{31}	0.3196	0.5225	0.203
R_{20}	R_{22}	0.2750	0.5932	0.318	R_{42}	R_{39}	0.3713	0.5713	0.200

Table A.14 – Tripping times for coordinated (Hybrid) configuration - 15 Bus System

R_{main}	R_{backup}	t_{main}	t_{backup}	Δt	R_{main}	R_{backup}	t_{main}	t_{backup}	Δt
R_1	R_6	0.2631	0.4883	0.225	R_{20}	R_{30}	0.2458	0.4763	0.231
R_2	R_4	0.2350	0.4652	0.230	R_{21}	R_{19}	0.2378	0.4498	0.212
R_2	R_{16}	0.2350	0.4976	0.263	R_{21}	R_{17}	0.2378	0.4498	0.212
R_3	R_1	0.2976	0.4976	0.200	R_{21}	R_{30}	0.2378	0.4763	0.239
R_3	R_{16}	0.2976	0.4976	0.200	R_{22}	R_{23}	0.2676	0.5428	0.275
R_4	R_7	0.2879	0.5277	0.240	R_{22}	R_{34}	0.2676	0.4682	0.201
R_4	R_{12}	0.2879	0.5000	0.212	R_{23}	R_{13}	0.2487	0.5218	0.273
R_4	R_{20}	0.2879	0.5209	0.233	R_{23}	R_{11}	0.2487	0.4563	0.208
R_5	R_2	0.3239	0.5239	0.200	R_{24}	R_{21}	0.2682	0.6819	0.414
R_6	R_{10}	0.3145	0.5599	0.245	R_{24}	R_{34}	0.2682	0.4682	0.200
R_6	R_8	0.3145	0.5908	0.276	R_{25}	R_{15}	0.3375	0.7000	0.362
R_7	R_5	0.3234	0.5528	0.229	R_{25}	R_{18}	0.3375	0.5375	0.200
R_7	R_{10}	0.3234	0.5599	0.237	R_{26}	R_{28}	0.3185	0.5318	0.213
R_8	R_3	0.3000	0.5443	0.244	R_{26}	R_{36}	0.3185	0.5631	0.245
R_8	R_{12}	0.3000	0.5000	0.200	R_{27}	R_{25}	0.3631	0.6283	0.265
R_8	R_{20}	0.3000	0.5209	0.221	R_{27}	R_{36}	0.3631	0.5631	0.200
R_9	R_5	0.3174	0.5528	0.235	R_{28}	R_{29}	0.3418	0.5418	0.200
R_9	R_8	0.3174	0.5908	0.273	R_{28}	R_{32}	0.3418	0.6496	0.308
R_{10}	R_{14}	0.2833	0.4833	0.200	R_{29}	R_{19}	0.2498	0.4498	0.200
R_{11}	R_7	0.2831	0.5277	0.245	R_{29}	R_{17}	0.2498	0.4498	0.200
R_{11}	R_3	0.2831	0.5443	0.261	R_{29}	R_{22}	0.2498	0.4498	0.200
R_{11}	R_{20}	0.2831	0.5209	0.238	R_{30}	R_{27}	0.2867	0.5032	0.217
R_{12}	R_{13}	0.2825	0.5218	0.239	R_{30}	R_{32}	0.2867	0.6496	0.363
R_{12}	R_{24}	0.2825	0.4825	0.200	R_{31}	R_{29}	0.3032	0.5418	0.239
R_{13}	R_9	0.3201	0.5201	0.200	R_{31}	R_{27}	0.3032	0.5032	0.200
R_{14}	R_{11}	0.2563	0.4563	0.200	R_{32}	R_{33}	0.3180	0.5197	0.202
R_{14}	R_{24}	0.2563	0.4825	0.226	R_{32}	R_{42}	0.3180	0.5537	0.236
R_{15}	R_1	0.2652	0.4976	0.232	R_{33}	R_{23}	0.3428	0.5428	0.200
R_{15}	R_4	0.2652	0.4652	0.200	R_{33}	R_{21}	0.3428	0.6819	0.339
R_{16}	R_{18}	0.3073	0.5375	0.230	R_{34}	R_{31}	0.3537	0.6987	0.345
R_{16}	R_{26}	0.3073	0.5073	0.200	R_{34}	R_{42}	0.3537	0.5537	0.200
R_{17}	R_{15}	0.2601	0.7000	0.440	R_{35}	R_{25}	0.3318	0.6283	0.296
R_{17}	R_{26}	0.2601	0.5073	0.247	R_{35}	R_{28}	0.3318	0.5318	0.200
R_{18}	R_{19}	0.2286	0.4498	0.221	R_{36}	R_{38}	0.3259	0.5259	0.200
R_{18}	R_{22}	0.2286	0.4498	0.221	R_{37}	R_{35}	0.3439	0.5439	0.200
R_{18}	R_{30}	0.2286	0.4763	0.248	R_{38}	R_{40}	0.3987	0.5987	0.200
R_{19}	R_7	0.2758	0.5277	0.252	R_{39}	R_{37}	0.3732	0.5732	0.200
R_{19}	R_3	0.2758	0.5443	0.268	R_{40}	R_{41}	0.3617	0.5617	0.200
R_{19}	R_{12}	0.2758	0.5000	0.224	R_{41}	R_{33}	0.3197	0.5197	0.200
R_{20}	R_{17}	0.2458	0.4498	0.204	R_{41}	R_{31}	0.3197	0.6987	0.379
R_{20}	R_{22}	0.2458	0.4498	0.204	R_{42}	R_{39}	0.2774	0.4774	0.200