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ADVANCED SYSTEM RESTORATION AND LOAD MODELING IN MODERN POWER SYSTEM

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ADVANCED SYSTEM RESTORATION AND LOAD MODELING IN MODERN POWER SYSTEM

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A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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_____HOU Jia___(Name of student)

To my dear mom and dad

Abstract

This thesis deals with both system restoration and load modelling issues in modern power system. With increased penetration of renewables and upgrade of network complexity in modern grid environment, a resilient and efficient restoration strategy is increasingly desired to enhance system reliability. As one of the most important tasks for power system planning and operation, power system restoration is regarded as a multi-objective and multi-stage nonlinear constrained optimization problem involving a great number of generation, transmission, distribution and load constraints. For simplifying problem formulation, the process is usually divided into three stages: preparation, system restoration and load restoration, with emphasis on different restoration objective for each stage.

A restoration strategy is attained for dispatchers to start blackstart units, establish transmission path to crank non-blackstart units and pick up necessary loads. In existing methodologies, a strategy usually provides optimal starting timetable for all blackstart and non-blackstart units based on fixed time interval timeline in a way that the overall system generation capability is maximized. The insufficiency of this strategy is the inflexibility of the resultant restoration plan due to the assumption that the operation time for each transmission line and the whole restoration time horizon are preassigned fixed values. In modern power system environment, resilience and efficiency are critical and desirable features for electric power system recovery. Consequently, another variable factor of flexible transmission line operation time is taken into consideration while ensuring grid security at the same time, and a novel methodology named optimal efficiency oriented power system restoration has been

developed. The proposed efficiency oriented model consists of transmission path search module, operation time calculation module, startup constraints checking module and load pickup module. Particularly, the operation time calculation module is designed to generate a random time matrix T for modeling variable transmission line operation time which complies with beta distribution. Based on this time matrix, power system restoration is formulated as a permutation-based optimization problem. Different from traditional objective of maximizing available generation capability, the proposed novel optimization objective is to maximize available generation capability per unit time named as restoration efficiency for adapting flexible restoration period. Moreover, the optimization solution in terms of non-blackstart units startup permutation is solved through one optimization process for generator startup permutation and transmission restoration path. For practical application, a flexible restoration schedule is generated according to the optimal solution, and provides information of non-blackstart generator startup timing, charging path and corresponding available generation at each restoration stage. Another contribution is development of a tailored algorithm referred as advanced quantum-inspired differential evolutionary algorithm (AQDE) to solve the proposed permutation-based restoration model. It features with better population diversity and quicker convergence speed. The superior performance of AQDE has been benchmarked through comparison experiments with two other well established meta-heuristic techniques including QDE and GA. Consequently, the proposed AQDE method is successfully applied to solve the system restoration of IEEE 39 and 118 bus systems respectively.

The optimal efficiency oriented power system restoration methodology is also applied on load restoration stage after its validation on the aforementioned system restoration stage. Traditionally at load restoration stage, maximization of restored load becomes primary objective. When applying the proposed novel methodology, however, maximization of restored load per unit time is designed as the optimization objective. In order to reduce the impacts of service disruption on load loss, load prioritization should be taken into consideration in load pickup process. In general, electrical loads can be divided into three levels based on reliability requirements by customers. Load importance degree is defined according to properly ranking the prioritization of loads with reference to pre-signed contracts with customers, where the expected service quality has been specified. Based on the undirected power system topology model, a novel index P_s combining load prioritization and capacitance is proposed for searching optimal path. Finally, a flexible restoration schedule is obtained to provide information for generator startup and load pickup considering load prioritization. The proposed restoration methodology is applied on IEEE 39 and 57 bus systems respectively.

The second part of my research work is load modeling. It is an important issue due to the fact that load model significantly affects power system dynamic simulations. In modern power system, there is increasingly desire of delicate load model with respect to accuracy and computational efficiency. A delicate load model is called for to capture specific load characteristics of various load components. To catch these characteristics, a complete load model at distribution grid level consisting of equivalent capacitor, large motor and small motor is proposed. Furthermore, the other two models, namely the composite load model and dynamic load model at distribution grid level, are applied to assess the accuracy of the developed complete load model. The comparisons of simulation on case studies have demonstrated that the complete load model has superior performance in transient simulations at distribution grid level and capable to capture more accurate load characteristics than the other two models.

Acknowledgements

First of all, I would like to extend my sincere gratitude to my chief supervisor Dr. Zhao Xu, who has offered me kind support, great encouragement during the past four years in The Hong Kong Polytechnic University. I cannot thank him enough for his constructive suggestions, word-for-word scrutiny, and expert guidance. Without his painstaking instruction, the completion of the present thesis would not have been possible.

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List of Abbreviations

AQDE	Advanced quantum-inspired differential evolutionary algorithm
BS	Black start unit
CIGRE	International council on large electric systems
CR	Crossover factor
DE	Differential evolution algorithm
DFR	Digital fault recorders
DP	Dynamic programming
DR	Digital relay
EPRI	Electric power research institute
ES	Evolution strategy
GA	Genetic algorithm
IED	Intelligent electronic device
LOADSYN	Load model synthesis program package
LSE	Least square estimation
MILP	Mixed integer linear programming
MSE	Mean square error
NBS	Non-blackstart unit
NP	Non-deterministic polynomial time
PQ	Power quality monitor
PMU	Phase measurement unit
QDE	Quantum-inspired differential evolutionary algorithm
QEA	Quantum-inspired evolutionary algorithm

WAMS	Wide area measurement system
ZIP	Polynomial load model
T_{si}	generator unit i startup time
T_{stagej}	jth restoration stage time period
T_{total}	total restoration time from the beginning till the moment that the last hot startup
T_{ci}	generator unit i cranking period
T_{mi}	time period of unit i from ramp-start to reach the maximum output
T_{sj}	start time of NBS generator j
T_{hi}	maximum hot startup time limit of unit i
T_{ri}	minimum cold startup time limit of generator i
P_{mi}	maximum output of generator unit i
P_{rj}	required power of NBS generator j from T_{sj} to T
G_n	the number of on-state generator units
G_m	the number of on-state non-blackstart generator units
P_j	a set containing vertices of optimal restored path at j-th stage
W_{ij}	route cost value
C_{ij}	line charging capacitance
t_o	optimistic operation time
t_p	pessimistic operation time
t_m	most likely operation time
T_{ij}	operation time of transmission line between node i to node j
A_j	adjacency matrix
Q^t	Q-bit population at generation t
X^t	binary population at generation t
S^t	permutation population at generation t

B^t	global best best binary population at generation t
F^t	fitness function value population at generation t
Q_{best}^t	global best quantum population at generation t
X_{best}^t	global best binary population at generation t
S_{best}^t	global best permutation population at generation t
θ_{ij}	quantum rotating angle
$\lvert\alpha_{ij}\rvert^2$	probability of *j*-th qubit in '0' state
$\lvert\beta_{ij}\rvert^2$	probability of *j*-th qubit in '1' state
F	amplification factor
CR	crossover factor
$u_{i,G}$	trial vector at generation G
$v_{i,G}$	mutant vector at generation G
$x_{i,G}$	target vector at generation G
V_i	diversity of *i*-th bit
P_s	a novel index combining load importance degree and capacitance
R_s	stator winding resistance
X_s	stator leakage reactance
X_m	magnetizing reactance
X_r	rotor resistance
R_r	leakage reactance
S	motor slip
H	rotor inertia constant

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Publications from the Thesis

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[2] **J. Hou**, Z. Xu, Z. Y. Dong, “Measurement-based load modeling at distribution level with complete model structure," in *IEEE Power and Energy Society General Meeting*, San Diego, CA, Jul. 2012, pp. 1-6.

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1 *Introduction*

1.1 Scope of Research

1.1.1 System Restoration in Modern Power System

A severe blackout has significant impacts on the affected population such as the North America blackout of 2003 affecting 45 million people in eight states [1], and the India blackout of 2012 affecting over 620 million people across 22 states in Northern, Eastern, and Northeast regions [2]. Thus power system restoration is one of the most important tasks for system operation [3-5]. Furthermore, it is reported that the impacts of a blackout increase exponentially with the duration of the whole process, and an efficient power system restoration strategy capable of speeding the process is increasingly desired to enhance system reliability [6]. Therefore better system restoration methodologies and the associated decision support tools are studied and investigated in the thesis.

Power system restoration is a complex multi-objective nonlinear optimization problem involving a large number of generation, transmission and distribution, and load constraints [7-13]. For problem simplification, the process is usually divided into three stages: preparation, system restoration and load restoration with emphasis on different restoration objective for each stage [14-17]. In preparation stage, as time-critical nature of this stage, it is desirable that actions should be thoroughly planned for rapid implementation. These actions include evaluation of the post-disturbance system status, definition of the target system for restoration, selection of a strategy for rebuilding transmission network and steps to restart generation. At the second stage of system restoration, the overall goal is to rebuild the bulk electric network as a means to achieve the goal of next stage load restoration. During this period, skeleton transmission paths are energized, islands are resynchronized, and sufficient load is restored to stabilize generation and voltage. As for the third stage of load restoration, load restoration now becomes the dominant objective rather than control means. Minimization of the unserved load becomes primary goal, and load pickup scheduling is based on ability of available generation.

Many research efforts have been endeavored in this field in two aspects: novel theories introduction and traditional optimization tools improvements [18-26]. At first, novel theories introduction in system restoration have been reviewed. In [27], with the introduction of complex network theory, network configuration becomes an optimization problem to maximize the reconfiguration efficiency based on node importance degree. In [28], dynamic programming is applied to solve distribution restoration with state reduction, where the restoration process is divided into stages by equal time interval. Finally, a stage-by-stage feeder restoration sequence of minimum cost is calculated at a high computational burden exponentially proportional to the problem size. An ordered binary decision diagram (OBDD)-based system restoration methodology is presented by which determining proper splitting points in order to sectionalize the entire blackout area into several subsystems [29]. With introduction of scale-free networks and discrete particle, a skeleton-network reconfiguration methodology is proposed in which network reconfiguration efficiency is the objective to evaluate the restoration effect [30].

With respect to the improvements of optimization tools for system restoration, a two-step restoration model is proposed in [31] based on quasiconcave curves of generator capability. By segmenting the restoration horizon into equal time intervals, a step-by-step mixed integer quadratically constrained program is formulated to solve the startup sequence, of which the optimality can be guaranteed at each restoration step but not for the entire horizon. Similar to [31], [32] adopts equal time interval-based timeline and proposes a mixed integer linear programming (MILP) based model for solving both startup sequence and transmission path. In [33], a multi-agent approach of power system restoration is proposed. The system consists of several bus agents and a single facilitator agent. A suboptimal target configuration is developed by a BAG with other BAGs while FAG acting as a manager.

Existing methodologies are developed in traditional electric grid environment. Generally, power system operators rely on a predetermined restoration strategy to quickly pull system back to normal condition after a blackout. However, considering variable restoration time of transmission line, a predetermined plan can hardly be optimal and potentially results in extended blackout duration. In existing methodologies, power system operators usually rely on a restoration strategy based on equal time interval-based timeline. However when considering variable operation time of transmission lines, such a strategy lacks flexibility and therefore potentially resulting in extended blackout duration. In modern power system environment with increased penetration of renewables and the use of new technologies [34, 35], the requirements are strengthened with respects to efficiency and flexibility against potential uncertainties and risks [36-39].

1.1.2 Load Modeling in Modern Power System

It is a consensus that load model plays an important role in all kinds of power system analyses including stability analysis, dynamic simulations and system restoration as well [7, 40]. The model validity directly affects dynamic simulation results accuracy [14, 41-45]. With the increasingly complex grid and emergence of various load components, load modeling becomes an intractable task. Two approaches have been developed: the component-based approach [46, 47] and the measurement-based approach [47, 48]. Many research works showed that load model constructed by the measurement-based approach has better performance to reflect load characteristics in transient situations [49-51].

In measurement-based approach, load modeling is actually an identification process. It involves data collection and processing, model structure determination, parameter identification and load model validation. Many efforts have been dedicated to explore model structures and identification techniques. Load models could be roughly categorized into two classes: dynamic load model and static load model respectively. A composite load model consisting of ZIP and induction motor is commonly accepted in recent years by utilities for dynamic simulations which have better performance than static ones. Whereas, some research works indicated that load modeling based on the composite model at transmission level can't reproduce dynamic load behaviors at distribution level in some scenarios. In modern power system, the requirement for load model enhances correspondingly. A delicate load model is called for to capture specific load characteristics of various load components. Therefore, a complete model at distribution level with an equivalent capacitor, a large motor and a small motor is proposed [52]. The implication introduced by splitting the dynamic part into large and small motors. Corresponding case study is designed to demonstrate the accuracy of the delicate load model at distribution level through comparisons with the composite load model at transmission level and dynamic load model in PowerFactory.

1.2 Research Problem Motivation and Statement

1.2.1 Incentive of Optimal Efficiency Based Power System Restoration Methodology

With increased penetration of renewables and upgrade of grid complexity in modern grid environment, a resilient and efficient restoration strategy is increasingly called for in order to enhance system reliability. On the basis of the assumption that the entire restoration horizon is decomposed into equal time intervals, most existing methodologies convert system restoration into a step-by-step optimization problem. Finally an equal time interval-based system restoration strategy is obtained. Nevertheless, if in a situation where practical restoration time of transmission lines from blackstart unit to the first generator is smaller than the supposed starting time, this generator has to wait until the supposed starting time which reduces restoration efficiency. If practical restoration time is larger than the supposed starting time, corresponding constraint should be added and re-optimization should be conducted. The first situation waste time and the second situation increases computation burden. In order to deal with the conflict between predetermined time interval and practical restoration time of transmission lines, an optimal efficiency based power system restoration methodology is proposed. The restoration timeline of this novel methodology is flexible depending on practical restoration time of each stage.

Based on flexible timeline, traditional optimization objective of maximizing available generation capability alone is no longer reasonable. Novel index restoration efficiency P_e is proposed as the optimization objective, which measures available generation capability per unit time. Correspondingly, a novel efficiency oriented model is proposed. By utilizing it, power system restoration becomes an integral optimization problem rather than step-by-step optimization formulation. It is convinced that the resultant restoration plan by the novel methodology can reasonably resemble the reality better therefore providing a more valuable guidance to implement practical system restorations.

1.2.2 Incentive of Advanced Quantum-inspired Differential Evolutionary Algorithm

In optimal efficiency based power system restoration methodology, power system restoration is formulated as permutative combinatorial problem. It is NP hard problem. Constraints show up when applying traditional optimization methods in aspects of solution quality and convergence speed. In order to overcome the boundedness, a tailored advanced quantum-inspired differential evolutionary algorithm is developed based on quantum-inspired evolutionary algorithm (QEA). QEA is inspired from quantum computing [53] which features a large population diversity with a small population throughout the evolution. However, QEA cannot be directly applied on the permutation-based combinatorial optimization problem. That’s the motivation for developing advanced quantum-inspired differential evolutionary algorithm (AQDE). Combing merits of QEA and DE, AQDE features with large population diversity and fast convergence speed in handling permutation-based optimization problem.

1.2.3 Incentive of Complete Load Model Structure at Distribution Level

According to current load modeling practice [54], with several exceptions, standard load models are generally constructed at sub-transmission level (typically, 69kV to

138kV). For example, a typical bus load at transmission level contains transformers, distribution feeders, capacitors for compensation and various load devices.

Due to the complexity of bus load at sub-transmission level, composite load model is difficult to represent specific load dynamic performance. A major disadvantage of load modeling at sub-transmission level is reported that some dynamic phenomena at distribution level, such as motor stalling cannot be captured by such models in [52]. In order to capture accurate load characteristics at distribution level (typically 12.47kV and 13.8kV), a complete load model structure is proposed, in which induction motor and capacitor are separately modelled. For representing various loads characteristics at distribution level, induction motor is divided into large motor and small motor to better address the local power system conditions in details.

1.3 Primary Contributions

Both system restoration and load modeling in modern power system are addressed in this thesis. With respect to power system restoration, the major contribution is the development of an optimal efficiency based power system restoration methodology, which can largely enhance system reliability. In order to fit for the methodology, a tailored advanced quantum-inspired differential evolutionary algorithm is developed for solving permutation-based optimization problem. With respect to load modeling, primary contribution goes to the development of a complete load model at distribution level that can capture specific load characteristics of various load components.

1.3.1 Development of Optimal Efficiency Based Power System Restoration Methodology

Electric power system calls for effective and efficient solutions for all kinds of operation and planning tasks including system restoration, where optimal planning of restoration steps should account for variable operation time for transmission lines or generation units. An optimal restoration efficiency oriented system restoration methodology is proposed, where generator startup sequence and transmission recovery path are solved through a permutation-based combinatorial optimization process using an advanced quantum inspired differential evolutionary algorithm (AQDE). The restoration efficiency P_e, i.e. available generation capability per unit time, is modeled as the optimization objective. In order to solve this NP hard problem, AQDE with a novel encoding scheme is developed featuring better population diversity and quicker convergence speed. The proposed methodology is applied to the restoration of IEEE 39 and 118 bus systems respectively and compared with approaches using other solution methodologies. These results have demonstrated the superior performance of the proposed methodologies.

1.3.2 Development of Advanced Quantum-inspired Differential Evolutionary Algorithm

As power system restoration in this thesis is formulated as permutation-based combinatorial problem which is NP hard problem. Traditional optimization methods show constraints in aspects of solution quality and convergence speed. Therefore a tailored advanced quantum-inspired differential evolutionary algorithm is developed based on quantum-inspired evolutionary algorithm (QEA). The classical QEA is inspired from quantum computing [53]. As a meta heuristic algorithm, QEA can maintain large population diversity even with a small population throughout the evolution. It is designed based on Q-bit representation, observation process and update process by Q-gate to enable a superior balance between the exploration and exploitation of the evolution. Therefore QEA has proved to offer excellent performance for classical 0-1 knapsack problem compared with other conventional evolutionary algorithms. However, QEA cannot be directly applied for the permutation-based combinatorial optimization problem, which aims at finding an optimal permutation. Therefore, a novel advanced quantum-inspired differential evolutionary algorithm dedicated for permutation-based combinatorial optimization problem is newly proposed. Taking merits of QEA and DE, AQDE features large population diversity and fast convergence speed in handling the permutation based optimization problem.

1.3.3 Development of Complete Load Model at Distribution Level

Load modeling plays an important role in power system operation and control. With increasingly complex grid and emergence of various new load components, load modeling becomes an intractable task. In modern power system, the requirement for load model enhances correspondingly. A delicate load model is called for to capture specific load characteristics of various load components. Traditionally composite load model is established at sub-transmission level. Due to the complexity of bus load at sub-transmission level, composite load model is difficult to represent specific load dynamic performance. A major disadvantage of load modeling at sub-transmission level is reported that some dynamic phenomena at distribution level, such as motor stalling cannot be captured by sub-transmission level model in [52]. In order to capture accurate load characteristics at distribution level (typically 12.47kV and 13.8kV), a complete load model structure is proposed in which induction motor and capacitor are separately modeled. For representing various loads characteristics at distribution level, induction motor is divided into large motor and small motor to better address the local power system conditions in details.

Disturbance data is processed in advance through MATLAB programs according to the requirements of measurement-based approach. In case study, the measurements and simulated model outputs are demonstrated. For comparison purpose, three load models are used to access model accuracy, which are respectively complete load model at distribution level, composite load model at transmission level and dynamic load model in PowerFactory at distribution level. By contrast, the complete load model proved to have better performance in transient conditions. By splitting the induction motor into two parts, some issues are introduced at the same time. The generalization capability of this compete load model need further investigation.

1.4 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2 provides an overview of power system restoration procedure. State-of-the-art power system restoration methodologies have been reviewed. Summary of existing methodologies gives orientation for optimal efficiency based power system restoration methodology.

Chapter 3 introduces optimal efficiency oriented power system restoration methodology in detail. It contains four sections: a novel efficiency oriented model, optimization problem formulation, framework of efficiency oriented power system restoration methodology solved by AQDE and advanced quantum-inspired differential evolutionary algorithm for solving permutation-based optimization problem.

Chapter 4 presents the developed optimal efficiency oriented power system restoration methodology application on load restoration considering load prioritization. It contains three sections: load pickup in power system restoration, load prioritization introduction and definition, optimal efficiency oriented power system restoration methodology application on load restoration.

Chapter 5 presents research work on load modeling in modern power system. A complete load model at distribution level is proposed which is fit for future demand. This chapter contains four sections: basic concept and significance of load modeling, state-of-art load models, development trend and future demand in modern power system proposed load model fit for future demand.

Chapter 6 gives the overall conclusions of the present research work as well as future scope.

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2 Literature Survey on Power System Restoration

2.1 Power System Restoration Procedure

As illustrated in Figure 2.1, power system restoration process is typically comprised of three temporal stages. These stages are termed Preparation, System Restoration, and Load Restoration. Typically, the first stage lasts 1 to 2 hours, the second 3 to 4 hours, and the third extends to completion of the whole process, perhaps 10 hours [14]. The goal of each stage is according to the specific circumstance under which it pursues. In the first stage, time is critical hence many urgent actions must be taken quickly. During the second stage, the main task is to energize skeleton transmission paths and resynchronize islands. Essential load should be restored to stabilize generation and voltage as control way. At the third stage, maximization of restored load becomes the primary objective. One common thread linking these stages is the generation availability at each stage. More details of three stages are described as follow,

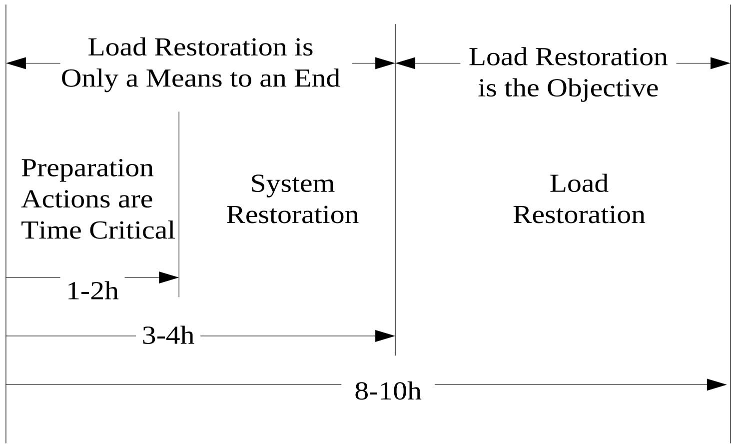

Figure 2.1 Typical restoration stages

Stage One-Preparation: As time-critical nature of this stage, it is desirable that actions should be thoroughly planned for rapid implementation. These actions include evaluation of the post-disturbance system status, definition of the target system for restoration, selection of a strategy for rebuilding transmission network and steps to restart generation.

Stage Two-System Restoration: The overall goal during this stage is reintegration of the bulk power network. Skeleton transmission paths are energized, islands are resynchronized, and sufficient load is restored to stabilize generation and voltage. Larger, base-load units will be under preparation for restart in the next stage. Reliable guidelines should have been prepared in advance.

Stage Three-Load Restoration: During this final stage, the load itself is restored as fully and rapidly as possible. Once the bulk power system has been reintegrated, restoration of system load now becomes the governing control objective rather than the control means. Minimization of the unserved load becomes the goal, and load pickup scheduling is based on ability of available generation.

2.2 Overview of State-of-the-art Power System Restoration Methodologies

For power system restoration, different methodologies have been proposed previously. Representative methodologies have been reviewed in this field concerning their merits and demerits in aspect of mathematical formulation.

2.2.1 Two-step Method Based Restoration Methodology

Due to the quasiconcave property of generation capability function, concavity-based optimization cannot be directly applied. Therefore, a “Two-Step” methodology is proposed to formulate generator startup as a mixed integer quadratically constrained programming problem [31]. For each unit, generation capability curve is divided into two segments. Each segment is a concave function. Subsequently, the critical step is to divide restoration horizon into equal time intervals ensuring that only one segment function is used for each unit at each time period. Therefore, at each time interval, the quasiconcave optimization problem is converted into a concave optimization problem. As a whole power system restoration becomes a step-by-step concave optimization problem within T_{total}. One implicit assumption of this problem formulation is that cranking period T_c of each unit must be integer multiple of fixed time interval t_e. If the assumption can’t be satisfied, this approach may fail. In a practical power system, the implicit assumption can’t always be satisfied depending on choice of t_e value and the characteristics of generator startup, which is a critical limitation of this approach. In addition, the operation time for each transmission path is neglected. In this case, it is assumed that all paths can be restored within the same time interval. From view of solution quality, optimality is only achieved for each time interval. Global optimality is not guaranteed in whole restoration time.

2.2.2 Mixed Integer Linear Programming Based Restoration Methodology

This methodology is developed based on the two-step methodology [32]. With introduction of binary decision variables and linear decision variables, the nonlinear combinatorial optimization power system restoration problem is transformed into a mixed integer linear programming problem. In this methodology, the time horizon is broken into equal time intervals which can be represented as [t_e , $2\,t_e$,…, $n\,t_e$]. Accordingly, the total restoration time of the whole process is also a constant value incorporated in the objective function. From whole restoration horizon point of view, it is a step-by-step MILP optimization problem. At each time interval dividing point, a solution is obtained indicating which non-blackstart (NBS) unit is on. Then transmission path module provides path and operation time T_0 from a blackstart (BS) unit to the target NBS unit. If T_0 is larger than time interval, the corresponding modified constraint is added into MILP problem. The MILP is resolved again. The optimization process ends until the total restoration time of the whole process is determined as a multiple of equal time interval. The constraints of transmission path operation time not only increase the computation burden, but also lead to the final solution hard to be globally optimal.

2.2.3 Dynamic Programming Based Restoration Methodology

In this methodology, radial system configuration is assumed in process of distribution system restoration [55]. The objective function is to minimize the unserved system energy. The whole restoration process is divided into stages represented again by equal time intervals. In each stage, all possible combinations of feeders are composed. One state in each stage is connected through arc with all states in next stage. The final strategy provides a step-by-step operation sequence of feeders. The DP model is constrained by the high dimensionality of problem decision variables. The computation time increases dramatically with the size of decision variable, which prevents the model from its application in practical power system restoration.

2.3 Summary

By far, most existing models shares one common property that the restoration process is regarded as a step-by-step optimization problem based on the decomposition of the entire restoration horizon into several equal time intervals, where the starting time of a non-blackstart unit is one time point belonging to the integer set [t_e, 2t_e,…, nt_e] as demonstrated in Figure 2.2.

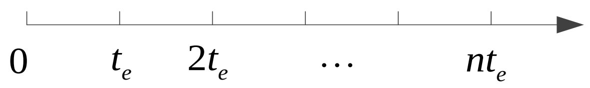

Figure 2.2 Restoration timeline with constant time intervals

The first generator is supposed to start at t_e, but if the practically needed operation time from blackstart to the first generator T_{g1} is smaller than t_e, the next operation step has to wait until the supposed time t_e, which reduces restoration efficiency. Alternatively, if T_{g1} is larger than t_e, corresponding constraint should be added and optimization has to be reconducted. The first situation causes waste of time in waiting but in first stage of restoration time is critical. The second situation causes reoptimization, which increases the computation burden. In order to overcome these drawbacks, a novel methodology named optimal efficiency based power system restoration methodology is therefore proposed which deals with the conflict between predetermined time interval and practical transmission line operation time. The restoration timeline of the novel methodology is flexible depending on practical operation time shown in Figure 2.3. T_{stage1} indicates generator startup time in restoration stage 1, which is determined by transmission line operation time from blackstart unit to the generator. T_{stage2} indicates generator startup time in restoration stage 2. The interval between stage 1 and stage 2 can be different from interval between stage 2 and stage 3, which accounts for possibly variations of operation time needed in each step.

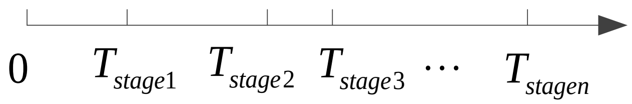

Figure 2.3 Restoration timeline with variable time intervals

Based on actual timeline considering variable operation time for different steps, the whole restoration period is the sum of practical operation time needed. Therefore traditional optimization objective of maximizing available generation capability alone is no longer reasonable anymore. Novel index restoration efficiency $\mathrm{P_e}$ is proposed as the optimization objective, which measures available generation capability per unit time. Meanwhile, it is also meaningful to optimize restoration sequence considering load priorities, which can further enhance the restoration efficiency and minimize the negative impacts due to service disruptions. Thus, a novel efficiency oriented model is proposed considering variable operation time for transmission lines. With the newly proposed model, power system restoration becomes an integral optimization problem rather than the step-by-step optimization formulation in most traditional models, which may lead to non-global optimal solutions. It is convinced that the resultant restoration plan by the novel methodology can reasonably resemble the reality better.

3 *Optimal Efficiency Oriented Power System Restoration Methodology Considering Variable Operation Time*

3.1 Introduction

This chapter contains four parts: a novel efficiency oriented model, optimization problem formulation, the framework of efficiency oriented power system restoration methodology and advanced quantum-inspired differential evolutionary algorithm for solving permutation-based optimization problem. As we known in practice, restoration time of transmission line is variable, accordingly the restoration timeline should incorporate this factor to allow for timely sequential restoration of transmission lines. A novel methodology referred as optimal efficiency oriented power system restoration has been developed. In this methodology, an efficiency oriented model is proposed consisting of transmission path search module, operation time calculation module, startup constraints checking module and load pickup module. In operation time calculation module, a random time matrix is generated to model variable transmission line operation time which complies with beta distribution. By utilizing it, power system restoration is formulated as a permutation-based optimization problem where generator startup permutation and transmission path are solved through one optimization process. Details of each part are presented in the following.

3.2 Novel Efficiency Oriented Model

A novel efficiency oriented model is proposed herein to optimize power system restoration efficiency considering variable operation time for transmission lines. Input of this model is a permutation or sequence of generators startup, and output is value of system restoration efficiency. With this model, power system restoration problem becomes a permutative optimization problem. As illustrated in Figure 3.1, this proposed model comprises four modules., including Transmission Path Search Module, Operation Time Calculation Module, Startup Constraints Checking Module, and Load Pickup Module, which are introduced in the following respectively.

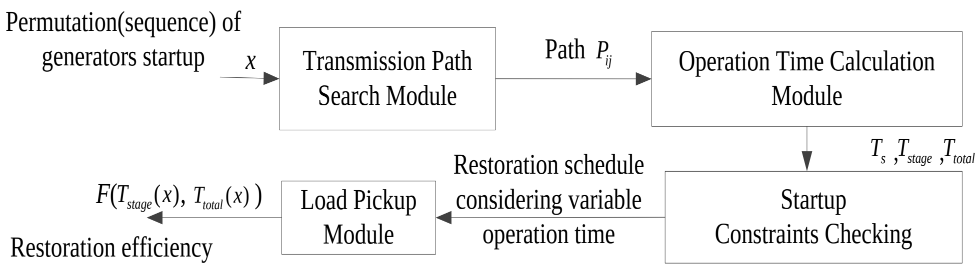

Figure 3.1 Novel efficiency oriented model

It is assumed that in a power system, there are totally n generators and m NBS generators (n>m).The input of Transmission Path Search Module is a permutation or sequence for generators to start up. The module aims at finding the optimal path in each restoration stage. In each restoration stage, path P_{ij} containing vertices of optimal path from node i to node j is found by optimal restoration path search algorithm. i is one of those restored nodes in previous restoration steps and j is the target NBS generator in this restoration step. With Operation Time Calculation Module, T_s , T_{stage} and T_{total} are attained. $T_s = [T_{s1}, T_{s2}, \ldots, T_{sn}]$, where T_{si} represents generator unit i startup time. $T_{stage} = \left[T_{stage1}, T_{stage2}, \ldots, T_{stagem}\right]$, where T_{stagej} indicates jth restoration stage time period. T_{total} indicates total restoration time from the beginning till the moment that the last warm startup generator is ready to reach maximum generation power in restoration process. T_s and T_{total} are sent into Startup Constraints Checking module to decide which generator can start within hot startup time limit while satisfying generator startup power constraints. Subsequently, a time schedule is tentatively provided to Load Pickup Module which decides load distribution to balance generation considering load prioritization. Finally, the objective function F (T_{stage}, T_{total}) is calculated value of which is used for evaluation in the optimization process. The following will firstly introduces the basics of generator characteristics in relation to system restoration, followed by details of each module of the proposed restoration method.

3.2.1 Generator Characteristic

Generators are divided into two groups: blackstart (BS) generator and non-blackstart (NBS) generator according to startup requirements. BS unit is a generating unit that is able to start by itself without any outside electrical supply while a NBS unit must be provided cranking power from available BS units [14]. Typical startup characteristic of a generator unit (BS or NBS unit) and characteristic of a NBS unit cranking power are illustrated in Figure 3.2 and Figure 3.3.

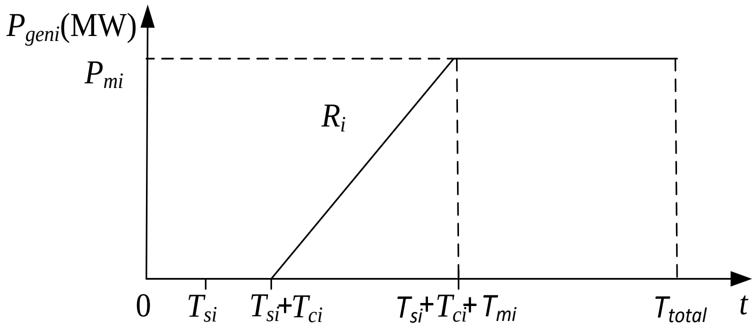

Figure 3.2 Startup characteristic of a generator

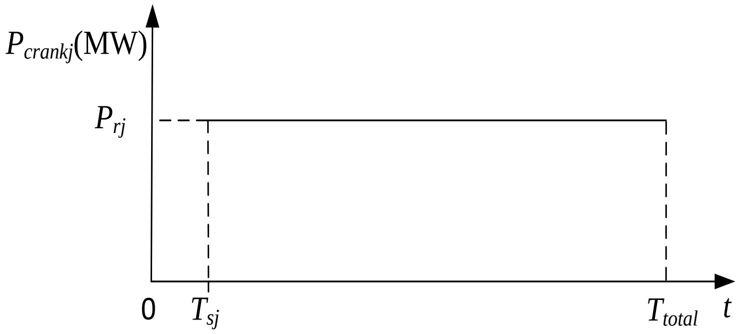

Figure 3.3 Characteristic of a NBS generator cranking power

In Figure 3.2, T_{si} indicates start time of generator *i*. T_{ci} is cranking period from start time to ramp up and parallel with system and T_{mi} is the time period from ramp-start to reach the maximum output P_{mi}. R_i represents the ramp-rate and T_{total} is the total restoration time from the beginning till the moment that the last hot startup. In Figure 3.3, T_{sj} is start time of NBS generator *j* and T_{total} is the total restoration time from the beginning till the moment that the last hot startup. P_{rj} indicates the required power of NBS generator *j* from T_{sj} to T_{total}. The startup characteristic of a generator can be described as $P_{geni}(t)$, and characteristic of a NBS generator cranking power can be described as $P_{crankj}(t)$. $i \in \{1, 2, \ldots, n\}$ and $j \in \{1, 2, \ldots, m\}$.

Equations of $P_{geni}(t)$ and $P_{crankj}(t)$ are illustrated as follows:

$$P_{geni}(t)=\begin{cases} 0 & 0 \le t < T_{si}+T_{ci} \\ R_i(t-T_{si}-T_{ci}) & T_{si}+T_{ci} \le t \le T_{si}+T_{ci}+T_{mi} \\ P_{mi} & T_{si}+T_{ci}+T_{mi} < t \end{cases} \tag{3.1}$$

$$P_{crankj}(t)=\begin{cases} P_{rj} & t \ge T_{sj} \\ 0 & 0 \le t < T_{sj} \end{cases} \tag{3.2}$$

After explanation of generator characteristics in equation, the physical property of blackstart or non-blackstart units in different restoration stages are further illustrated. In preparation stage, blackstart units are checked in order to prepare for cranking. And during transmission network reintegration stage, non-blackstart units are cranked using power provided by blackstart units. In the final stage of load restoration, available generation capability are mainly used to restore load as maximum as possible.

3.2.2 Transmission Path Search Module

The input of transmission path search module is a generator startup permutation x. Taking IEEE 39 as an example, one possible solution can be *x*=[34, 36, 37, 39, 38, 35, 30, 32, 31] which indicates 34 is blackstart unit and indexes afterwards indicates generator units start up sequentially. The output is restoration path $P=\{P_1,P_2,\cdots,P_n\}$, where P_j represents a set containing vertices of optimal restored path at *j*-th stage. The first node in P_j is one of those restored nodes in previous restoration stages and the last node is the target NBS generator in this present restoration stage. For instance, $P_2=\{33,19,20,34\}$ means that at the restoration stage 2, the optimal restoration path is $\{33\rightarrow19\rightarrow20\rightarrow34\}$, where Node 33 is already restored node to start and node 34 is the target NBS generator. In the next module of operation time calculation, T_s and

T_{total} are checked by startup constraints checking module to decide which generator can start within hot startup time limit while satisfying generator startup power constraints.

It is well known that the priority in the early stage of power system restoration is to ensure system security. Therefore, the optimal restoration path should ensure the minimum charging capacitance, along which the possibility of transmission line overvoltage is minimized. To achieve this, the physical power system network is abstracted into an undirected weighted graph **G=(V,E,W)** [56], where $V = \{V_i\}$ is a set of nodes representing electric power stations or transformer stations, and $\mathrm{E} = \{(i, j)\}$ is a set of edges representing high-voltage transmission lines. For each edge, there is a positive route cost value W_{ij}, and C_{ij} accounts for line charging capacitance,

$$W_{ij} = C_{ij} \tag{3.3}$$

In an abstract graph, this problem converts to searching the shortest cost path from start node to destination node. Dijkstra algorithm proved to be efficient for solving the single-source shortest path problem within a graph with nonnegative edge path costs [57]. To apply this algorithm to the path search of system restoration, several modifications has to be made including:

1) Transmission line reconfiguration is regarded as a staged optimization problem. In each stage, restoration can only be directed towards one non-blackstart generator. The optimization objective in each stage is to find the shortest path between the stage start node and stage end node.
2) In the first stage, the start node is a blackstart generator node.
3) Subsequently, the start node should be found in restored ones, and the end node is the non-blackstart unit.

3.2.3 Operation Time Calculation Module

In addition to security, efficiency is another critical factor in system restoration. For a practical system, restoration time of transmission line can be variable due to practical operation. To address this, restoration time of transmission line is estimated by sampling a beta distribution based on historical records according to [58, 59] for our case studies. The expected time t_{ei} and its standard deviation σ_i of line *i* can be calculated by Eq. (3.4). The optimistic, pessimistic, and most likely operation times t_o, t_p, and t_m can be obtained from historical operation records.

$$t_{ei} = \frac{t_o + 4t_m + t_p}{6} \quad \text{and} \quad \sigma_i = \frac{t_p - t_o}{6} \tag{3.4}$$

Without loss of generality, t_{ei} and σ_i are assigned 2min and 0.2min respectively according to historical data for simulation study. Thus for all simulations, an operation time matrix T is generated for modeling operation time of transmission lines, where n is the total number of generation units. T_{ij} indicates the operation time of transmission line between node *i* to node *j*.

$$\mathbf{T} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1n} \\ T_{21} & T_{22} & \cdots & T_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ T_{n1} & T_{n2} & \cdots & T_{nn} \end{bmatrix} \tag{3.5}$$

For each permutation x, P_j is obtained for each restoration stage. At each stage, P_j corresponds to an adjacency matrix A_j, which represents which vertices of a graph are connected to which other vertices. The non-blackstart generator startup time at the *j*-th restoration stage is equal to the total restoration time till the end of *j*-th restoration stage represented by T_{stagej}, expressed as,

$$T_{stagej} = T_{stage(j-1)} + A_j T \tag{3.6}$$

where $j \in \{1, 2, \cdots, m\}$. After calculating T_{stage}, T_s and T_{total} can be determined. $\mathbf{T_s} = [T_{s1}, T_{s2}, \cdots, T_{sn}]$ and T_{si} indicates the startup time of generator unit *i*. T_{total} is the total restoration time which is equal to T_{stagem}.

In a power system consisting of M NBS generators, the whole restoration process is divided into M stages of operation. For example in IEEE 39 bus system, generator 33 is the BS unit and there are 9 NBS units. If a permutation of generator startup is given like *x*=[34, 36, 37, 39, 38, 35, 30, 32, 31], an action-by-action strategy is determined. In stage one, unit 34 is supposed to start up. Path P_{33-34} from node 33 to node 34 is $\{33,\ 19,\ 20,\ 34\}$ determined by Transmission Path Search Module. Therefore T_{stage1} is the summation of all transmissions line operation time in P_{33-34}. In stage two, unit 36 is supposed to start up. The same calculation process proceeds. Path P_{19-36} is the optimal path from restored nodes to node 36. P_{19-36} is $\{19,\ 16,\ 24,\ 23,\ 36\}$. T_{stage2} is equal to T_{stage1} plus summation of all transmission lines operation time in P_{19-36}. T_{stagei} ($i \in \{1, 2, \ldots, \mathrm{M}\}$) can be obtained following the above method. Each transmission line is assigned a fixed operation time t_0=2. Finally $\mathbf{T}_{\text{stage}} = [T_{stage1}, T_{stage2}, \ldots, T_{stagem}]$ and corresponding $\mathbf{T_s} = [T_{s1}, T_{s2}, \ldots, T_{sn}]$ are obtained, which are used in objective function calculation.

3.2.4 Startup Constraints Checking Module

This module is to decide if one generator can satisfy the startup constraints based on T_s and T_{total} obtained from the operation time calculation module. A generator can only start when maximum hot startup time limit of unit *i* T_{hi} is larger than startup time of generator unit i T_{si} or startup time of generator unit i T_{si} is larger than minimum cold startup time limit of generator i T_{ri} .

3.2.5 Load Pickup Module

This module is to ensure the balance between the restored generation and load consumption at every time point. In network reconfiguration stage, system security is the major concern compared to the load restoration. Load threw-in aims at maintaining system stabilization, and therefore Eq. (3.7) must be satisfied during each restoration stage T_{stagek} as,

$$\sum_{k=1}^{m}\int_{T_{\text{stage}k}}^{T_{\text{total}}} P_{\text{load}k}(t)dt = \sum_{i=1}^{n}\int_{T_{si}}^{T_{\text{total}}} P_{\text{gen}i}(t)dt - \sum_{j=1}^{m}\int_{T_{sj}}^{T_{\text{total}}} P_{\text{crank}j}(t)dt \tag{3.7}$$

where P_{loadk} is threw-in load at k-th stage. With the load pickup, generator power outputs and bus voltages must satisfy the below constraints given as,

$$\begin{aligned} &\mathrm{P}_{Gi}^{\min} < P_{Gi} < \mathrm{P}_{Gi}^{\max},\ \mathrm{Q}_{Gi}^{\min} < \mathrm{Q}_{Gi} < \mathrm{Q}_{Gi}^{\max}, i = 1, 2, \ldots, \mathrm{m} \\ &\mathrm{U}_{j}^{\min} < U_{j} < \mathrm{U}_{j}^{\max},\ j = 1, 2, \ldots, n,\ \mathrm{P}_{r} < \mathrm{P}_{r\max}, r = 1, 2, \ldots, \mathrm{b} \end{aligned} \tag{3.8}$$

where m is the number of generator units, n represents power system node number, b is number of branches in a power system, and $P_{r\max}$ is the maximum power limit of branch r.

3.3 Optimal Efficiency Oriented Power System Restoration Methodology

3.3.1 Permutation-Based Optimization Problem Formulation

By utilizing novel efficiency oriented model, power system is formulated as permutation-based combinatorial optimization problem subjected to generator hot startup time, cranking power requirement and power balance constraints. The solution

x is the permutation of generator startup $x = \left(x_1, x_2, \cdots, x_m\right)$, which determines T_s, T_{stage} and T_{total}. The general expression of the optimization problem is formulated as Eq. (3.9)

$$\max \quad \mathrm{F}(T_{stage}(x), T_{total}(x)) \tag{3.9}$$

subjected to

Generator Hot Startup Time Constraint

Cranking Power Requirement

Power Balance

Due to variable restoration time of transmission line, the whole restoration time is according to practical operation. Therefore conventional objective of maximizing available generation capability during fixed whole restoration period is not reasonable anymore. Available generation capability per unit time is proposed as novel objective named restoration efficiency $\mathrm{P_e}$. It is given by Eq. (3.10)

$$\max_{x \in \mathrm{X}} f(T_s(x), T_{total}(x)) = \frac{\sum_{i=1}^{n} \int_{T_{si}}^{T_{total}} P_{geni}(t)dt - \sum_{j=1}^{m} \int_{T_{sj}}^{T_{total}} P_{crankj}(t)dt}{T_{total}} \tag{3.10}$$

where x is the permutation of m integer indicating startup permutation of non-blackstart generators, which determines T_s and T_{total}. T_{total} is the total restoration time counted from the beginning till the moment that the last hot startup generator is ready to supply power to the system during restoration process. $\mathbf{T_s} = [T_{s1}, T_{s2}, \cdots, T_{sn}]$, and T_{si} indicates the startup time of generator unit *i*. $P_{geni}(t)$ denotes generation capability of generator *i* at time t; $P_{crankj}(t)$ indicates the required cranking power for each generator *j* at t. X is a set of all possible permutations.

Because of equal time interval assumption, traditional methods of power system restoration are simplified to maximize the available generation capability alone during the full restoration period. Considering variable time involved in each step of practical operation, traditional system restoration methods obviously may not guarantee the best restoration efficiency. Instead, the efficiency oriented objective proposed in Eq. (3.10) pursues the best efficiency of the resultant restoration plan among all other alternatives subject to the following constraints, expressed as

1) Generator hot startup time constraint

$$T_{si} < T_{hi} \text{ or } T_{si} > T_{ri}, i = 1, 2, \cdots, m \tag{3.11}$$

where T_{hi} is the maximum hot startup time limit of unit *i*; T_{ri} is the minimum cold startup time limit of generator *i*. It means unit *i* can only restart after T_{ri} if it fails to do so within T_{hi}.

2) Cranking power requirement

$$\sum_{i=1}^{G_n} \int_0^{T_{stagek}} P_{geni}(t)dt - \sum_{j=1}^{G_m} \int_0^{T_{stagek}} P_{crankj}(t)dt > 0 \quad (k \in \{1, 2, \cdots, m\}) \tag{3.12}$$

where $\mathbf{T_{stage}} = [T_{stage1}, T_{stage2}, \cdots, T_{stagem}]$ indicating the total restoration duration at stage k determined by x. m is the number of restoration stages; G_n is the number of on-state generators and G_m is the number of on-state NBS units until T_{stagek}. Within each restoration stage T_{stagek}, the total system generation of on-state generators minus cranking power of on-state NBS units should be larger than 0 to satisfy this constraint.

3) Power Balance

$$\sum_{k=1}^{m} \int_{T_{stagek}}^{T_{total}} P_{loadk}(t)dt = \sum_{i=1}^{n} \int_{T_{si}}^{T_{total}} P_{geni}(t)dt - \sum_{j=1}^{m} \int_{T_{sj}}^{T_{total}} P_{crankj}(t)dt \tag{3.13}$$

During the restoration, generation should be equal to load consumption in order to maintain system balance and stability. The left side of Eq. (3.13) is load consumption at t, while the right side is available generation capability at t.

3.3.2 Framework of Optimal Efficiency Oriented Power System Restoration Methodology Solved By AQDE

The permutation-based optimization problem is solved by a tailored algorithm named advanced quantum-inspired differential algorithm (AQDE), which will be detailed in Section 3.4. The overall framework of optimal efficiency oriented power system restoration methodology solved by AQDE is given in Figure 3.4, including these following steps:

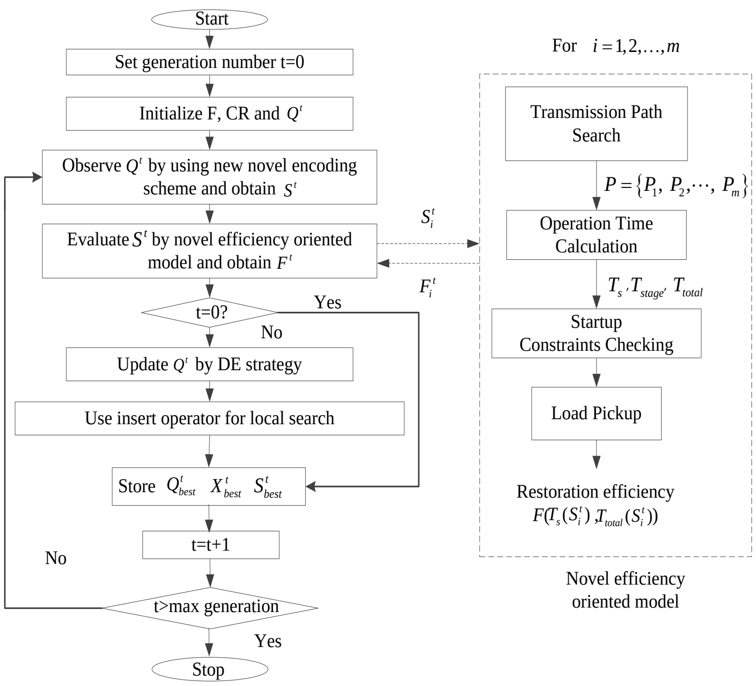

Figure 3.4 Framework of optimal efficiency oriented power system restoration methodology solved by AQDE

Step 1) Set generation number t=0.

Step 2) Initialize a population of Q^t with all θ values equal to $\frac{\pi}{4}$ and control parameters of F and CR of DE in update operator (F is amplification factor, CR is crossover factor).

Step 3) In the observation process, Q^t is converted to S^t by using a novel encoding scheme.

Step 4) Evaluate S^t based on fitness function and obtain F^t.

Step 5) If t=0, go to Step 8.

Step 6) Update Q^t by means of the update operator.

Step 7) Apply insert operator for local search.

Step 8) Compare F value among F^t and store Q_{best}^t, X_{best}^t and S_{best}^t.

Step 9) Set t=t+1.

Step 10) Terminate if t is larger than the maximum number of generations; else go to step 3.

In Figure 3.4 and above steps, Q^t represents a population of Q-bit individuals at generation t, S^t stands for permutation population at generation t by observing Q^t, and F^t is a vector of fitness function values at generation t corresponding to S^t. In Step 3, S^t is evaluated by novel efficiency oriented model which is presented in the dashed box.

3.4 Advanced Quantum-inspired Differential Evolutionary Algorithm for Solving Permutation-Based Optimization Problem

As power system restoration in this dissertation is formulated as permutation-based combinatorial problem, which is a NP hard problem. Traditional optimization methods show limitations in handling such problems in aspects of solution quality and convergence speed. Therefore a tailored advanced quantum-inspired differential evolutionary algorithm is developed based quantum-inspired evolutionary algorithm.

The classical quantum-inspired evolutionary algorithm (QEA) is inspired from quantum computing [53]. As a meta heuristic algorithm, QEA can maintain a large population diversity even with a small population throughout the evolution. It is designed based on Q-bit representation, observation process and update process by Q-gate to enable a superior balance between the exploration and exploitation of the evolution. Therefore QEA has proved to offer excellent performance for classical 0-1 knapsack problem compared with other conventional evolutionary algorithms. However, QEA cannot be directly applied for the permutation-based combinatorial optimization problem, which aims at finding an optimal permutation. Therefore, a novel advanced quantum-inspired differential evolutionary algorithm dedicated for permutation-based combinatorial optimization problem is newly proposed. Taking merits of QEA and DE, AQDE features large population diversity and fast convergence speed in handling the permutation based optimization problems.

3.4.1 Motivation for Developing Advanced Quantum-inspired Differential Evolutionary Algorithm

The classical quantum-inspired evolutionary algorithm can't directly be applied in solving the permutation-based optimization problems. This is because it was initially designed to solve general optimization problems, where the solution variable does not contain any permutation. To find an efficient way of converting a quantum chromosome into a permutation is a challenging task. In [60], random key representation was applied with weak link between original Q-bit and permutation chromosome established, which consequently prevents the search (exploration) of the algorithm from functioning well. A recent work on QDE for permutative problem reported in [61] provides another approach for conversion of quantum chromosome to permutation. The main demerit is that the permutation solution space is narrowed down after observation based on the used conversion rule.

To overcome aforementioned problems, a novel observation operator is proposed to convert a quantum chromosome to probabilistic superposition of permutations, meanwhile ensuring direct link between Q-bit and permutation chromosome and solution space integrity as well. Furthermore, a novel reset operator is developed as a supplement in order to increase the possibility of Q_{best}^{t} producing X_{best}^{t} when the probability is small. Therefore the developed AQDE distinguishes itself by large population diversity and quick convergence speed. AQDE takes advantage of superposition of states of quantum chromosome and updates chromosome using differential evolutionary algorithm.

3.4.2 Classical Quantum Evolutionary Algorithm

The classical QEA proposed by Han and Kim is based on the concepts of quantum mechanics [53]. Although QEA originated from quantum computing, it is a novel evolutionary algorithm, not a quantum one [62, 63]. An individual in QEA is represented by a string of Q-bits, which can provide a linear superposition of all the possible state combinations. Because of the property of the Q-bit individual, even with small population size, QEA can still well maintain the population diversity during the evolutionary procedure. A Q-gate is introduced as an evolution operator, which clearly directs the evolution and maintains the mutation probability concurrently which prevent the premature phenomena. Details of Q-bit representation and QEA procedure are briefed in the following.

1) Representation

A Q-bit individual *i* consisting of n qubits can be represented as

$$Q_i = \begin{bmatrix} \alpha_{i1} \Big| \alpha_{i2} \ldots \Big| \alpha_{in} \\ \beta_{i1} \Big| \beta_{i2} \ldots \Big| \beta_{in} \end{bmatrix} \quad \text{or} \quad [\theta_{i1}, \theta_{i2}, \ldots, \theta_{in}] \tag{3.14}$$

where θ_{ij} is the quantum rotating angle belonging to [0, π/2]. θ_{ij} satisfies $\cos^2\theta_{ij} = \alpha_{ij}^2$ and $sin^2\theta_{ij} = \beta_{ij}^2$, $j \in \{1, 2, \ldots, \text{n}\}$. Each qubit $\begin{bmatrix} \alpha_{ij} \\ \beta_{ij} \end{bmatrix}$ is the smallest unit of information. $|\alpha_{ij}|^2$ and $|\beta_{ij}|^2$ gives the probability of *j*-th qubit in '0' state and probability in '1' state respectively.

2) Classical QEA procedure

The procedure of QEA is described as below:

Begin t←0

initialize Q^t

observe Q^t and produce X^t

evaluate X^t

store the best solution among X^t into B^t

While (t<max generation) do, t←t+1observe Q^t and produce X^t

evaluate X^t

update X^t by using Q-gate

store the best solution among X^t and B^{t-1} into B^t

End

Initialization: Q^t represents a population of Q-bit individuals at generation t. $Q^t = [Q_1^t, Q_2^t, \ldots, Q_m^t]$ where m indicates the population size.

Observation: X^t is a population of binary solutions obtained by observing Q^t at generation t=0. In the while loop, X^t is determined by observing Q^{t-1}.

$X^t = \left[X_1^t, X_2^t, \ldots, X_m^t \right]$, where X_i^t is a binary solution and obtained by observing Q_i^{t-1}. $X_i^t = \left[x_{i1}^t, x_{i2}^t, \ldots, x_{in}^t \right]$ is obtained by determining 1 or 0 for each bit using $\left|\beta_i\right|^2$. A random number uniformly distributed between 0 and 1 is produced. If the random number is greater than $\left|\beta_i\right|^2$, x_{ij}^t is set to 0; otherwise, x_{ij}^t is set to 1.

Evaluation: After producing the solution X^t, the objective function value of each individual X_i^t can be evaluated. At generation t=0, the best solution in X^t is stored in B^t. In the while loop, the best solution among B^{t-1} and X^t is stored in B^t.

Updating: in while loop, after producing the solution X^t, an update mechanism to drive X^t towards a better solution is conducted. The Q-gate is used in the process as a variation operator as shown by Eq. (3.15),

$$\begin{bmatrix} \alpha_{ij}^t \\ \beta_{ij}^t \end{bmatrix} = \begin{bmatrix} \cos(\Delta\theta_{ij}) & -\sin(\Delta\theta_{ij}) \\ \sin(\Delta\theta_{ij}) & \cos(\Delta\theta_{ij}) \end{bmatrix} \begin{bmatrix} \alpha_{ij}^{t-1} \\ \beta_{ij}^{t-1} \end{bmatrix} \tag{3.15}$$

where $\Delta\theta_{ij}^t$ is a rotation angle, which determines the magnitude and direction of rotation. The value of $\Delta\theta_{ij}^t$ can be determined according to a pre-determined lookup table [53].

3.4.3 Differential Evolutionary Algorithm

Differential Evolution (DE) is a parallel direct search method. NP D-dimensional parameter vectors $x_{i,G}$, $i = 1, 2, \ldots, \mathrm{NP}$ is utilized as a population for each generation G. The initial vector population is chosen randomly which should cover the entire parameter space. In case a preliminary solution is available, the initial population might be generated by adding normally distributed random deviations to the nominal solution x_{nom0}. DE algorithm contains three operations which are respectively mutation, crossover, and selection. New parameter vectors are generated by adding the weighted difference between two population vectors to a third vector. This operation is named mutation. The mutated vector's parameters are then mixed with the parameters of another predetermined vector, the target vector, to yield the so-called trial vector of which the process is called "crossover" in the ES-community. The trial vector replaces the target vector in the following generation only when the trial vector yields a lower cost function value than the target vector. This last operation is called selection. Each population vector has to serve once as the target vector so that NP competitions take place in one generation.

More specifically DE's basic strategy can be described as follows:

1) Mutation

For each target vector $x_{i,G},\ i = 1,2,\ldots,\mathrm{NP}$, a mutant vector is generated according to

$$v_{i,G} = x_{r1,G} + F \cdot (x_{r2,G} - x_{r3,G}) \tag{3.16}$$

with random indexes *r1, r2, r3* $\in \{1,2,\ldots,\mathrm{NP}\}$, integer, mutually different and F > 0. *r1*, *r2* and *r3* are randomly chosen integers to be different from the running index *i*, so that NP must be greater or equal to four to allow for this condition. *F* is control parameter which is a real and constant factor $\in [0,2]$.

2) Crossover

Crossover operator is applied in order to increase the diversity of the perturbed parameter. To this end, the trial vector:

$$u_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, \ldots, u_{Di,G+1}) \tag{3.17}$$

is formed, where

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & if\,(randb(j) \le CR)\ or\ j = \mathrm{rnbr}(i) \\ x_{ji,G} & if\,(randb(j) \le CR)\ and\ j \ne \mathrm{rnbr}(i) \end{cases} \qquad (3.18)$$
$$j = 1, 2, \ldots, D.$$

In Eq. (3.18), *randb*(*j*) is the *j*th evaluation of a uniform random number generator with outcome $\in [0,1]$. CR is the crossover constant $\in [0,1]$ which has to be determined by the user. *rnbr*(*i*) is a randomly chosen index $\in 1, 2, \ldots, D$ which ensures that $u_{i,G+1}$ gets at least one parameter from $v_{i,G+1}$.

3) Selection

Greedy criterion is used to decide whether or not the trial vector should become a member of generation G+1. The trial vector $u_{i,G+1}$ is compared to the target vector $x_{i,G}$. If vector $u_{i,G+1}$ yields a smaller cost function value than $x_{i,G}$, then $x_{i,G+1}$ is set to $u_{i,G+1}$; otherwise, the old value $x_{i,G}$ is retained.

3.4.4 Advanced Quantum-inspired Differential Evolutionary Algorithm

Similar to QEA, Q-bit representation is adopted in AQDE for probabilistic observation. In order to convert a quantum chromosome into a permutation chromosome, a novel encoding scheme is proposed for the observation process. Differential evolutionary algorithm is employed as updating strategy in the evolution process.

1) Novel Encoding Scheme in Observation Process

In AQDE, Q-bit representation is still adopted according to Eq. (3.14). The observation and update processes in AQDE following the same procedure as in classical QEA. A novel encoding scheme is introduced in order to convert a quantum chromosome individual into a permutation through the probabilistic superposition.

The new encoding scheme can ensure the exact correspondence between a Q-bit and a permutation chromosome whiling maintaining the integrity of original solution space as well. The new scheme starts with calculating temporal information vector $V_i = [\sin\theta_{i1}, \sin\theta_{i2}, \ldots, \sin\theta_{in}]$ based on Q_i for observation. And two empty arrays *first*() and *last*() are initialized. A random number $\mu \in [0,1]$ is then produced. If $\mu < \sin\theta_{ij}$, $x_{ij} = 1$ and put *j* into first(); else $x_{ij} = 0$ and put j into *last*(). The larger θ_{ij} is, the larger possibility of x_{ij} being 1. Therefore there is a positive correlation between Q_i and V_i which can enhance algorithm evolution efficiency. Repeat the above steps until all Q-bits in Q_i are operated, and a binary chromosome X_i is then obtained. Subsequently, bits in *first*() and *last*() are sorted by the values of corresponding θ. Lastly a full permutation is determined by concatenating *first*() and *last*().The new coding scheme based observation process for converting a four dimension quantum chromosome to a permutation one is illustrated in Figure 3.5.

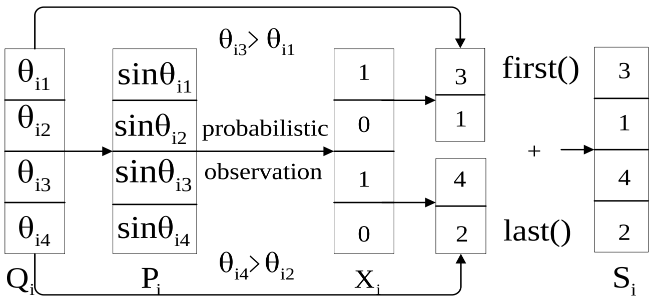

Figure 3.5 The observation process for a 4-bit individual in AQDE

The above probabilistic observation process is similar to that in QEA, but with a permutation resulted in the end. For example, given $Q_i = [0.7, 0.62, 1.51, 0.82]$, then $V_i = [0.64, 0.58, 0.99, 0.73]$. A random number μ =0.3<0.64 is generated, therefore '1' is assigned to *first*(). After all 4 Q-bits are observed, *first*()=[1, 3] and *last*()=[2, 4]. The permutation in *first*() should be [3, 1], because θ_3 =1.51> θ_1 =0.70. The permutation in *last*() should be [4, 2] because θ_4=0.82>θ_2=0.62. A full permutation [3, 1, 4, 2] is obtained by concatenating *first*() and *last*(). In this way, chromosome S_i can represent a candidate permutation, which will be input to the evaluation function $f(x)$. This novel encoding scheme leads to a strong logic correspondence between the quantum chromosome and the converted permutation chromosome compared to several other encoding methods, which will be discussed below.

In the Random Key Representation [60], a quantum chromosome is converted to a binary one and then to a corresponding decimal one. Finally, a permutation is obtained according to the sortation by decimal values. The length of binary chromosome increases rapidly with the increase of problem dimension. Besides, two conversion steps from Q-bit to binary, then to decimal chromosome can result in a weak logic correspondence between the original Q-bit and the permutation chromosome, which can consequently weaken searching capability of this algorithm.

With the conversion rule for QDE in [61], once Q_i is given, temporal information vector $V_i = [\cos\theta_{i1}, \cos\theta_{i2}, \ldots, \cos\theta_{in}]$ is determined. Subsequently two empty arrays *first*() and *last*() are initialized. A operation permutation-based observation process is conducted bit by bit based on V_i. For first bit, a random number $\mu \in [0,1]$ is produced. If $\mu > \cos\theta_{i1}$, bit information '1' is put in the first place in *last*(). Or '1' is put in the first place in first(). For second bit, another μ is produced. If $\mu < \cos\theta_{i2}$, bit information '2' is put in *first*() following previous numbers, or '2' is put in *last*(). After all Q-bits operation, *first*() and *last*() are obtained. And bits in *first*() and *last*() are already sorted during observation process. The permutation chromosome S_i is determined by concatenating *first*() and *last*(). According to this operation permutation-based conversion rule, the permutation solution space is narrowed down because S_i is restricted with operation permutation. As a result, genuine optimal solution can hardly be found within this reduced space. For instance, a permutation (2, 1, 4, 3) can never be generated. Because ‘2’ is before ‘1’, It indicates that *first*() contains (2) while *last*() contains (1, 4, 3). However, the 3rd bit of Q_i is observed before the 4th one, which indicates that ‘4’ can never be in front of ‘3’ in *last*(). Therefore, no matter how quantum chromosome updates, (2, 1, 4, 3) can never appear, and accordingly the loss of possible solutions is obvious, which potentially prevents the algorithm from finding the global best solution. In summary, this conversion rule can be detrimental to the population diversity, and cause searching space reduction for the permutation.

2) Update operator

DE mechanism is implemented as the updating strategy due to its excellent global search capability and convergence speed. DE is firstly proposed by Storn and Price based on real number encoding [64]. Suppose the population at generation t of m size is $Q^t = [Q_1^t, Q_2^t, \ldots, Q_m^t]$, each individual is $Q_i^t = \left[\theta_{i1}^t, \theta_{i2}^t, \ldots, \theta_{in}^t\right]$. For each individual, mutation, crossover and selection operators are applied successively for the evolution.

Mutation: classically one type of mutant vector V_i^t of a target vector Q_i^t is obtained by adding randomly selected vector Q_{r1}^t and a weighted differential vector $F(Q_{r2}^t - Q_{r3}^t)$, where *r1, r2, r3* and *i* are all distinct random numbers, and F is a real number between 0 and 2 which controls the amplification of the differential variation. In our approach, the DE/best/1/bin strategy [65] is adopted where Q_{r1}^t is replaced by

Q_{best}^{t} that is the best individual of generation t,

$$V_i^t = Q_{best}^t + F(Q_{r2}^t - Q_{r3}^t) \tag{3.19}$$

Crossover: a trial vector U_i^t is generated by comparing a random number between 0 and 1 with the crossover factor CR for each bit U_{ij}^t, and

$$U_{ij}^t = \begin{cases} V_{ij} & \text{otherwise} \\ Q_{ij}^t, & \text{if(rand<CR)} \end{cases} \tag{3.20}$$

Selection: The greedy strategy is adopted in the selection operation. If U_i^t generates a better fitness function value compared with the target vector Q_i^t, the target vector will be replaced by U_i^t in the next generation, or Q_i^t remains unchanged.

3) Insert operator

With the updated population at generation t by the DE algorithm, insert operator is used for local search which has been proved effective for permutation-based optimization [66]. In this case, the insert operator is applied to the global best permutation of each generation S_{best}^t in order to enhance the exploitation capability of the proposed AQDE. The procedure is illustrated below,

Initialize *k*=0, calculate fitness(S_{best}^t)

While fitness(S_{insert}^t)> fitness(S_{best}^t) and k<n

remove *i*-th number from S_{best}^t and obtained a partial chromosome S_{insert}^t

insert the removed number into the *j*-th position in S_{insert}^t ($j \neq i$)

End

Update $S_{best}^t = S_{insert}^t$ if fitness (S_{insert}^t)< fitness(S_{best}^t)

4) Novel reset operator

With the insert operation, Q_{best}^t, X_{best}^t and S_{best}^t are obtained. Due to the rule that the larger θ_{ij} is, the larger possibility of x_{ij} being 1, large θ_{ij} making x_{ij} 0 can be a small probability case. Therefore a novel reset operator is proposed to convert small probability case to large probability case. This step has been neglected in existing quantum-inspired algorithms[53, 67], which reduces the computing efficiency. Best binary solution X_{best}^t and the corresponding Q-bit individual Q_{best}^t performs the following detection and then is reset which are operated bit by bit,

$$\text{if} \quad \theta_{best,j}^t \geq \frac{\pi}{4} \;\&\; x_{best,j}^t = 0, \theta_{best,j}^t = \frac{\pi}{4};$$

$$\text{else if } \theta_{best,j}^t < \frac{\pi}{4} \;\&\; x_{best,j}^t = 1, \theta_{best,j}^t = \frac{\pi}{4}; \text{end} \tag{3.21}$$

when the above two small probability situations appear, $\theta_{best,j}^t$ is assigned a new value $\frac{\pi}{4}$ which drives small probabilistic representation towards large probabilistic one to ensure Q_{best}^t to produce corresponding X_{best}^t in next observation process.

5) Assessment Index

In our study, a variance-based population diversity index is applied to effectively measure and demonstrate the trend of population diversity and the convergence of AQDE and other algorithms for comparison purpose [68]. The diversity V_i of *i*-th bit is defined as follows:

$$V_i = \frac{\sum_{j=1}^{p} (\alpha_{ij} - \alpha_{avei})^2}{p} \quad \text{and} \quad V = \frac{\sum_{i=1}^{n} V_i}{n} \tag{3.22}$$

where $i \in \{1, 2, \ldots, n\}$ and $i \in \{1, 2, \ldots, p\}$. n is the dimension of the quantum chromosome. p is the number of population size. $\alpha_i = [\theta_{1i}, \theta_{2i}, \ldots, \theta_{pi}]^{\mathrm{T}}$, and

$\alpha_{avei} = \frac{\sum_{j=1}^{p} \alpha_{ij}}{p}$ is the average value of vector α_i.

6) AQDE Algorithm Procedure

The procedure of AQDE is illustrated in the following.

Begin t←0

initialize control parameters for DE

initialize Q^t

observe Q^t by novel observation operator and produce S^t

evaluate S^t

store Q^t_{best}, X^t_{best} and S^t_{best}

While (t<max generation) do, t←t+1

update Q^t by using DE algorithm

observe Q^t by novel observation operator and produce S^t

evaluate S^t

use **insert** operator for local search

store Q^t_{best}, X^t_{best} and S^t_{best}

use **reset operator** to modify Q^t_{best} used in DE update process

End

---

where Q^t represents quantum chromosome population at generation t, and S^t stands for permutation population at generation t by observing observing Q^t. Q^t_{best}, X^t_{best} and S^t_{best} represent best quantum chromosome, corresponding binary chromosome and corresponding permutation at generation t.

3.5 Numerical Results

The proposed restoration method is tested on IEEE 39 bus system and IEEE 118 bus system to find the optimal permutation of generators startup with the maximum restoration efficiency. Control parameters of AQDE including F, CR, and population size should be properly selected to ensure reasonable optimization performance. Therefore in Subsection A, parameter sensitivity analyses of AQDE performance on two test systems are conducted to identify appropriate control parameters. For comparisons, power system restoration of two test systems have also been solved by two other well established optimization techniques including QDE and GA. Notably for each studied algorithm, totally 10 trial runs are performed, and the resultant best fitness function value and mean fitness function value are used for performance assessment of applied algorithms. Subsection B provides the details of optimal solutions for IEEE 118 bus system and IEEE 39 bus system cases respectively, which include mainly a restoration schedule providing unit startup time, the charging path, and available generation capability or load pickup per restoration step. All algorithms are implemented in MATLAB 7.13 and executed on a PC with Intel Core of 1.8GHz and 3.73GB RAM.

3.5.1 Parameter Sensitivity Analysis of AQDE Performance

For IEEE 118 bus system case, there are totally 53 generators and unit number 69 is set as the blackstart unit. Therefore the dimension of this permutation-based optimization problem is 53. For IEEE 39 case, there are totally 10 generators, and unit 33 is the blackstart generator. The dimension of this case is accordingly 10. According to the proposed restoration model, AQDE aims at finding optimal restoration permutation for generators in order to maximize restoration efficiency, measured by available generation capability per unit time. In order to ensure algorithm performance, parameter sensitivity analysis of AQDE is conducted at first. For IEEE 118 case, effects of population size, differential variation F and crossover factor CR on AQDE are studied, where the maximum generation number is set to 100.

1) Impact of Population Size: In order to study effects of population size for IEEE 118 case, the population size varies from 5 to 25 when F and CR are set to 0.75 and 0.9 respectively. The simulation results are shown in Figure 3.6, which shows the population size of 5 is enough for obtaining optimal result.

2) **Impact of F and CR**: The population size is set to 5, and in order to enhance population diversity and prevent premature phenomenon, F can't be below 0.9. Figure 3.7 presents simulation results where CR is empirically fixed at 0.9, while F varies within [0.35, 0.95]. From Figure 3.7, it is noticeable that the optimal solution is obtained at F=0.75. Therefore the best combination is F =0.75 and CR=0.9 in terms of the resultant best benefit and mean benefit.

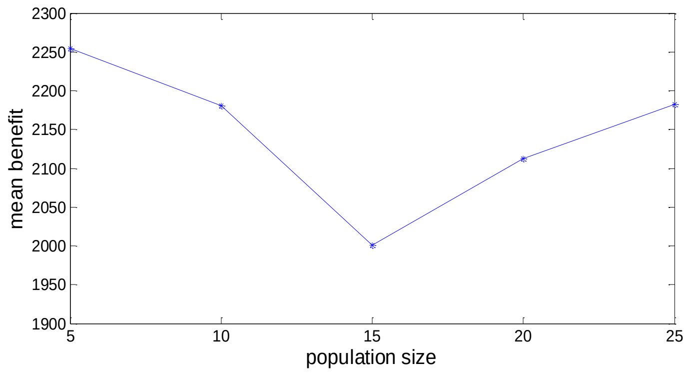

Figure 3.6 Effects of population size

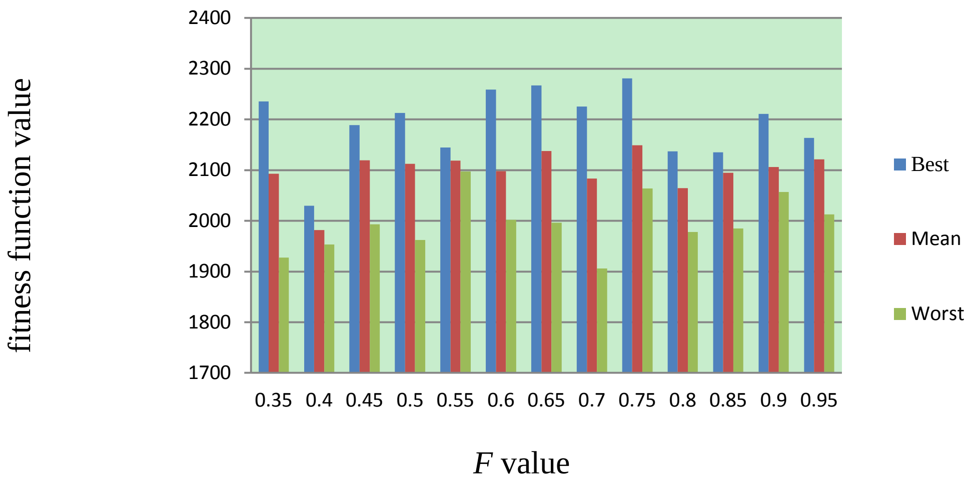

Figure 3.7 Impact of *F* on AQDE performance when *CR* at 0.9

For IEEE 39 case, similar parameter sensitivity analysis of AQDE has been repeated. Due to smaller dimension of this case, F, CR, and population size are found having little impacts on optimization results. Therefore in our case study the population size, F and CR are set to 5, 0.9 and 0.4 respectively for IEEE 39 case. After sensitivity analysis of control parameters, comparison experiments are conducted. Power system restoration cases for IEEE 118 and 39 systems are solved by AQDE, QDE and GA respectively using corresponding best control parameters. For AQDE and QDE, F= 0.75 and CR =0.9 is the best combination. Similarly sensitivity analysis has been done for GA correspondingly, and the best crossover and mutation probabilities are 0.9 and 0.03. For all three algorithms, the population size is 5 and maximum generation is 100 for fair comparisons. The simulation results are illustrated in Figure 3.8.

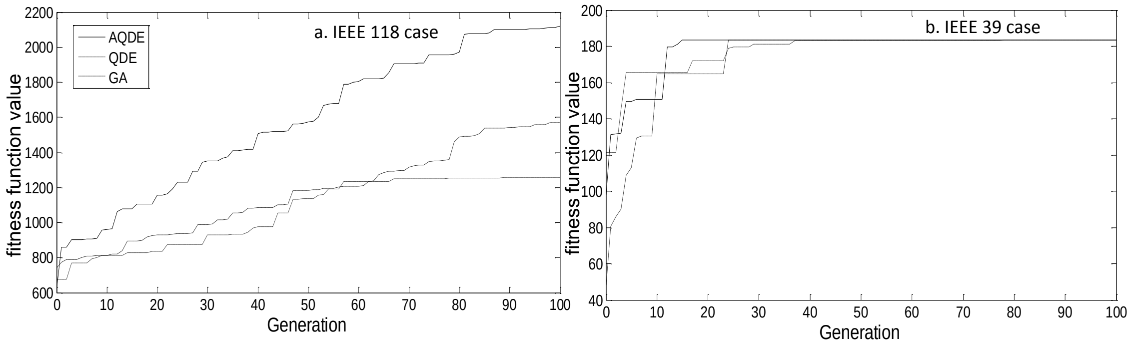

Figure 3.8 The optimization procedures of different power system cases by three algorithms: a. IEEE 118 bus system b. IEEE 39 bus system

It is easily observed in Figure 3.8 that in IEEE 118 bus system case, AQDE shows a better exploitation capability in the evolution process compared with QDE and GA. AQDE and QDE continue to improve solution quality until generation 100. In contrast, GA reaches optimal solution near generation 60 and remains nearly zero improvements afterwards. Obviously, AQDE can find a better solution than QDE and GA for this case. This best fitness value (corresponding to 2118.1MW available generation capability per unit time) outperforms that of QDE (1569.9MW available generation capability per unit time) by 34.9% and that of GA (1256.3MW available generation capability per unit time) by 68.6%. For IEEE 39 bus system case, even though all three algorithms reach the same optimal solution (183.1MW available generation capability per unit time), AQDE obviously converges faster than QDE and GA. In above studies, the reason why AQDE can obtain a better solution and quicker convergence speed can be analyzed due to not only the enhanced exploitation capability, but also the greater exploration capability. Enhanced exploitation capability is due to difference vector of DE which is automatically adaptive to fitness function value, and superior exploration capability is based on development of QEA principle. To further validate superior exploration capability of AQDE, the population diversity index V for solving the IEEE 118 case is calculated and illustrated by a boxplot in Figure 3.9.

Figure 3.9 presents the quartiles of V values in solving IEEE 118 bus system by three algorithms, where the center line in a box indicates median value, while values between 25% and 75% are enclosed by the box, and tips are the maximum and minimum ones respectively. Figure 3.9 shows, during the evolution, median value of population diversity V begins with 80 and gradually evolves towards 70 for AQDE, while the range of V also converges well along the way, indicating a stable optimization performance. For QDE, V begins with 67 and oscillates around 65 after generation 20, while its range diverges along the way, indicating an unstable performance. For GA, no obvious trends for V are observed, and its median value varies between 15 and 57 all along the evolution. In terms of median value, AQDE obviously can maintain highest V during the evolution, followed by the QDE, and then by GA with lowest V. It can therefore be concluded that AQDE demonstrates a superior population diversity in the whole evolution process, which justifies its superior exploration capability over QDE and GA.

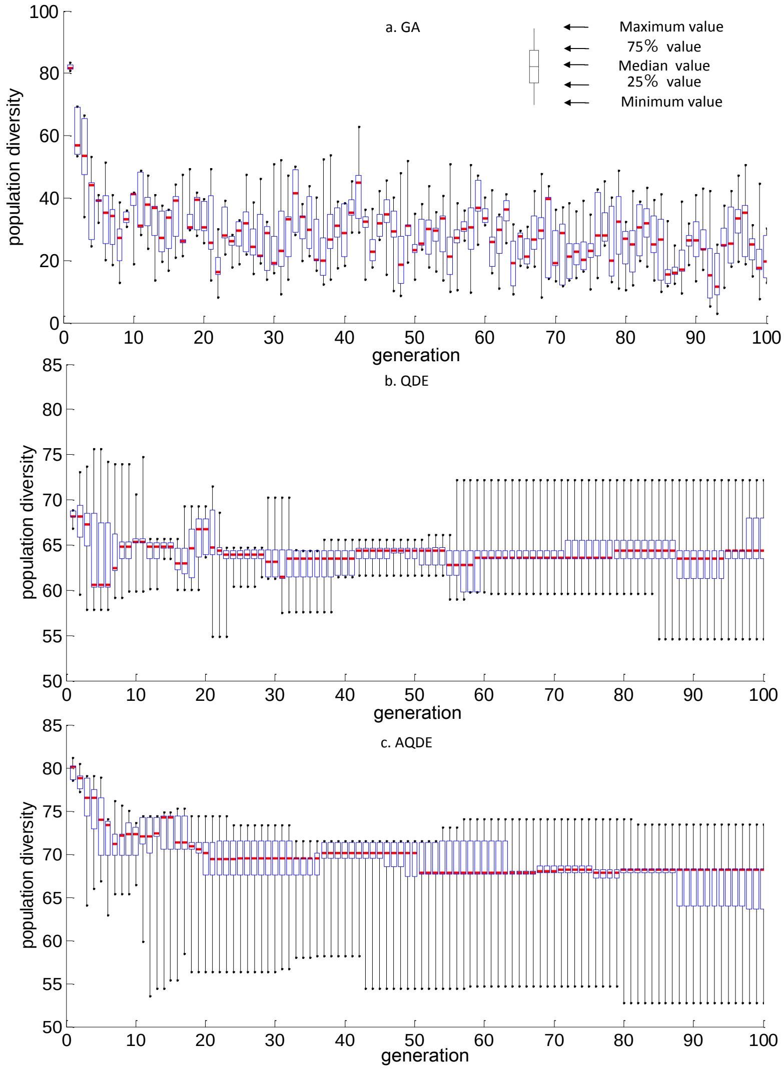

Figure 3.9 The population diversity for IEEE 118 bus system case by different algorithms: a. GA b. QDE c. AQDE

3.5.2 Case of IEEE 39 Bus System

The proposed methodology is applied on IEEE 39 bus system using optimal control parameters of AQDE identified in the preceding section. For this case, there are totally 10 generators, and unit 33 is the blackstart generator. Detailed data of IEEE 39 bus system generator characteristics is presented in Table A.1 of Appendix. The obtained optimal restoration schedule is demonstrated in Table 3.1. And the corresponding optimal objective function value is 183 available generation capability per unit time.

Table 3.1 IEEE 39 bus system restoration schedule

Sequence	Node	Path	T_{stage} (min)	Generation(MW)
1	33	33→33	0	0
2	34	33→19→20→34	3	4.2
3	36	19→16→24→23→36	10	18.8
4	35	23→22→35	14	27.7
5	38	16→17→27→26→29→38	22	84.0
6	32	16→15→14→13→10→32	32	172.5
7	30	17→18→3→2→30	37	211.0
8	37	2→25→37	40	can't start in T_{h37}
9	31	13→12→11→6→31	46	can't start in T_{h31}
10	39	2→1→39	50	392.3

Table 3.1 provides optimal time schedule for non-blackstart generator units' startup, charging path and generation capability. The first column represents restoration stage. The second column is bus node number where startup generator locates at each stage. The third column provides the obtained optimal charging path, and T_{stage} is the corresponding generator startup time at each restoration stage. The final column shows available generation capability stage by stage. With generators hot startup time limit checking, unit 33, 34, 36, 35, 38, 32, 30 and 39 are feasible in this plan, while units 37 and 31 are excluded. Due to variable restoration time of transmission line, T_{stage} in Table 3.1 is variably increasing along the whole restoration timeline, which distinguishes from the results by other traditional methods considering constant time interval.

The generation capability curves for IEEE 39 and 118 cases are depicted in Figure 3.10, where two curves are observed smoothly increasing and these two dashed lines represent restoration efficiency of the whole restoration period respectively.

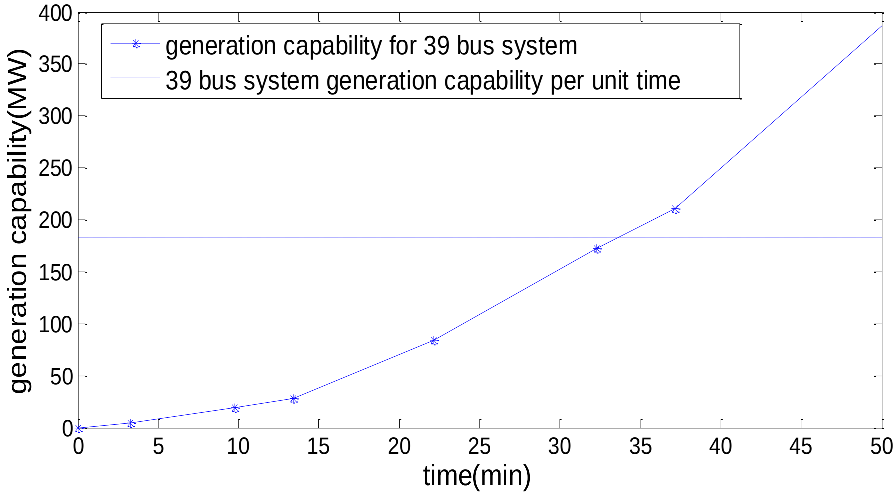

Figure 3.10 Generation capability curves for 39 bus systems

3.5.3 Case of IEEE 118 Bus System

Another case study is applied on IEEE 118 bus system, which has 53 generators and much more transmission lines and generator 69 is the blackstart unit. Detailed data of IEEE 118 bus system generator characteristics is presented in Table A.3 of Appendix. The corresponding optimal restoration schedule is provided in Table 3.2. The corresponding optimal objective function value is 2281.1 available generation capability per unit time.

Table 3.2 IEEE 118 bus system restoration schedule

Sequence	Node	Path	T_{stage} (min)	Generation(MW)
1	69	69→69	0	0
2	66	69→49→66	3	3.1
3	49	49→49	3	0.9
4	80	69→77→80	6.2	5.3
5	77	77→77	6.2	2.6
6	100	80→98→100	9.1	16.2
7	103	100→103	10.3	23.5

8	104	103→104	11.3	32.3
9	111	103→110→111	13.2	48.0
10	110	110→110	13.2	46.8
11	62	66→62	14.2	56.5
12	61	62→61	15.4	71.5
13	91	100→92→91	18.3	121.9
14	59	61→59	19.3	141.9
15	89	92→89	21.5	193.9
16	90	91→90	22.5	222.0
17	105	104→105	24.3	279.0
18	92	92→92	24.3	276.5
19	107	105→107	25.5	310.7
20	112	110→112	27.4	370.3
21	70	77→75→70	29.5	445.6
22	26	70→24→23→25→26	35.3	712.4
23	25	25→25	35.3	709.9
24	24	24→24	35.3	708.6
25	55	59→55	37.4	808.3
26	56	55→56	39.2	902.3
27	54	56→54	40.3	960.3
28	73	70→71→73	43.0	1109.4
29	116	69→68→116	46.0	1299.4
30	74	75→74	48.2	1430.9
31	46	49→47→46	51.7	1662.0
32	87	89→88→85→86→87	85.9	3660.9
33	32	23→22→21→20→19→18→17 →31→32	87.7	3731.3
34	40	19→15→33→37→40	93.6	3935.2
35	85	85→85	95.3	3988.9
36	6	19→15→14→12→7→6	98.3	4086.8
37	19	19→19	104.5	4325.7
38	34	15→33→37→34	106.4	4399.6
39	15	15→15	111.6	4618.2
40	99	100→99	114.7	4746.3

Table 3.2 provides optimal time schedule for NBS’s startup time, charging path and generation capability. The first column represents restoration stage. The second column is bus node number where startup generator locates at each stage. The third

column provides the obtained optimal charging path, and T_{stage} is the corresponding generator startup time at each restoration stage. The final column shows available generation capability stage by stage. With generators hot startup time limit checking, only 40 units are available to be involved in the restoration, while the remaining units are excluded due to the reason that generator can't start in corresponding hot startup time limits.

The generation capability curves for IEEE 118 case is depicted in Figure 3.11, where curve is observed smoothly increasing and dashed lines represent restoration efficiency of the whole restoration period respectively.

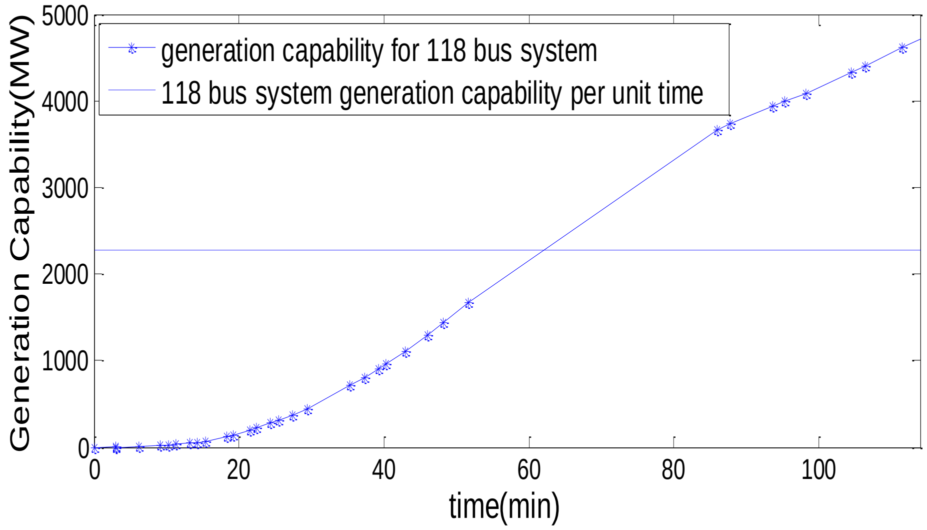

Figure 3.11 Generation capability curves for 118 bus systems

3.6 Summary

A novel power system restoration methodology is developed considering variable restoration time of transmission lines referred as optimal efficiency based power system restoration. Distinguished from most existing methods, in this methodology power system restoration is formulated as a permutation-based combinatorial optimization problem of which restoration efficiency is the objective. Restoration efficiency (i.e., available generation capability per unit time) is proposed to adapt to flexible restoration time period. In order to solve this problem, an advanced quantum-inspired differential evolutionary algorithm with a novel encoding scheme has been developed. Using appropriate control parameters, system restoration cases of IEEE 39 and IEEE 118 bus systems have been successfully solved by AQDE. The significant merits of AQDE include the enhanced population diversity and fast convergence demonstrated through comparisons against QDE and GA. An optimal restoration schedule with maximum restoration efficiency is achieved, and information of non-blackstart generator startup time, charging path and generation capability at each restoration stage is provided.

4 *Optimal Efficiency Oriented Power System Restoration Methodology Considering Load Prioritization*

4.1 Introduction

Application of optimal efficiency oriented power system restoration methodology on load restoration is presented in this chapter. In this novel methodology, under the premise of ensuring electric grid security the influence of service disruption on load loss should be minimized to the greatest extent. In order to evaluate load loss influence, load importance degree for each load node is defined according to ranking the prioritization of loads with reference to pre-signed contracts with customers where the expected service quality has been specified. When searching optimal charging path in restoration process, a novel index P_s is proposed relating load importance degree with grid security in power system topology model. Instead of maximization of restored load, maximization of restored load per unit time is formulated as optimization objective. Case Studies are conducted on IEEE 39 and 57 bus systems respectively. Finally as optimization result, a flexible restoration schedule is obtained providing information for restored load node, optimal charging path and restored load capacity at each stage.

4.2 Load Pickup in Power System Restoration

At the third stage of power system restoration, load restoration becomes the objective rather than a control means in previous two stages as illustrated in Figure 4.1. Once the initial priority objectives have been achieved, and the bulk power system has been reconfigured, load should be restored as fully and rapidly as possible. The scheduling of load pickup will be based on response rate capabilities of available generators. The effective system response rate and the responsive reserve increase with the combined capacity of the online generators, and load restoration can be accomplished in increasingly larger steps [69-75].

In practical operation, transmission path restoration is interconnected with load restoration in the same process. Therefore Load prioritization, as one of the key factor influencing load loss, should be taken into consideration in path search process. Generally, electrical loads are classified into three grades according to reliability regulations by the utility. The first level load refers to significant loads interruption of which causes massive economic, political or military loss, such as loads of hospitals, airports and broadcasting station. The second level load includes some industrial loads, interruption of which may cause loss to a certain extent. The interruption of third level load has small influences on public. Based on the above classification, load pickup priority can be predefined.

Under the basic principles mentioned before, there are several guidelines provided for establishing load restoration procedure [13]:

1) The priority load pickup must be predefined keeping in mind that the balance between generation and load.
2) The maximum amount of power in each priority load pickup for each geo-electrical area must be predefined.

3) It should consider extreme load configurations such as maximum and minimum (heavy and light loads) to ensure that the restoration process can be carried out at any time.
4) To avoid overvoltage during outages, capacitor banks are to be de-energized and transformer taps are operated in such a way as to minimize this risk.

The utilities are responsible for the load pickup subject to predefined considerations and this procedure can only begin after the following requirements are met: nonexistence of equipment overload; frequency stabilization; compatible voltage levels.

4.3 Load Prioritization Introduction and Corresponding Path Search Algorithm

This section contains three portions: power system topology model, Load prioritization introduction based on load importance degree and corresponding optimal restored path search algorithm.

4.3.1 Power System Topology Model

In the process of charging transmission line in preliminary stage of power system restoration, the capacitance will lead to overvoltage at the end of a transmission line. For security consideration, the path with minimum capacitance has the minimum possibility of overvoltage. Therefore the line charging capacitance value is used as edge weight in the proposed power system topology model, which can then be formulated as an undirected weighted graph G=(V,E,W), where $V = \{V_i\}$ is a set of nodes representing electric power stations or transformer stations; $E = \{(i, j)\}$ edges represent high-voltage transmission lines. For each edge, there is a positive route cost value W_{ij}, which accounts for line charging capacitance. For disconnected nodes, W_{ij} is set infinite. Figure 4.1 presents IEEE 14 bus system topology model. Generator nodes demonstrate with G and black nodes indicate load nodes.

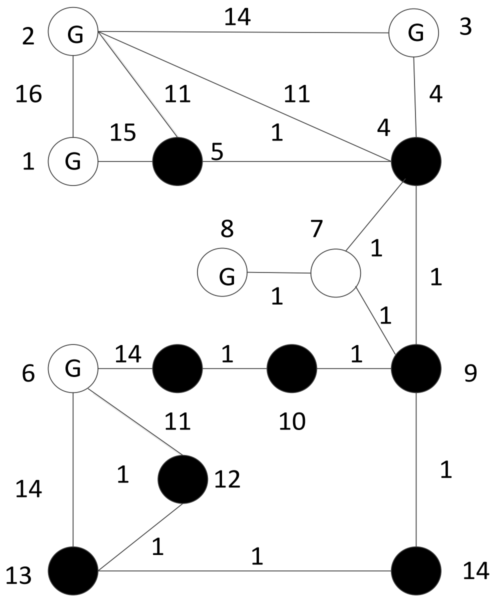

Figure 4.1 IEEE 14 bus system topology model (where G nodes stand for generators, and black nodes stand for substations)

Traditionally, the optimal path from node i to node j is the minimum cost path searched by using the Dijkstra method [66], along which the possibility of transmission line overvoltage is minimized. Besides the capacitance impacts on system restoration security, load importance degree is another factor need to be considered in path restoration. Consequently, a new index P_s is proposed combining load importance degree and capacitance for optimal path search optimization.

4.3.2 Load Prioritization Introduction Based on Importance Degree

In general, electrical loads can be divided into three levels based on reliability requirements by customers. The first level load refers to significant loads interruption of which causes massive economic, political or military loss. Load of hospitals, airports and broadcasting station belongs to the first level. The second level load includes some industrial loads interruption of which cause a certain extent loss. The interruption of third level load has small influence on public. There are three predetermined values I_1, I_2 and I_3 indicating three levels of load. I_1=1, I_2=0.5 and I_3 =0.1. In power system topology model, importance degree of load node L_i is given based on load prioritization. If node 1 is the third level load, $L_1 = I_3$.

4.3.3 Corresponding Optimal Restored Path Search Algorithm

Based on power system topology model and assigned load importance degree, a new index P_s is proposed combining load importance degree and capacitance for optimal path search optimization. Figure 4.2 provides a four-node case for optimal restored path search illustration. P_s is defined as $P_s = \frac{\sum W}{\sum L}$. $\sum W$ is summation of weights of edges in a path. $\sum L$ is summation of load importance degree of all load nodes along a path. The larger $\sum L$ is, the smaller P_s is. The smaller $\sum W$ is, the smaller P_s is. Therefore path with minimum P_s value is regarded as optimal path which reflecting balance between system security and load prioritization. In the four-node case, there are two paths from node 1 to node 4. Path 1 is $\{1,\ 2,\ 3,\ 4\}$. Path 2 is $\{1,\ 3,\ 4\}$. L_1=0.5, L_2=1, L_3=0.1, L_4=0.5. $\sum W$ of path 1 is 5 and $\sum W$ of path 2 is 5. $\sum L$ of path 1 is 2.1 and $\sum L$ of path 2 is 1.1. Therefore P_{s1}=2.38 and P_{s2}=4.54. Therefore path 1 is the optimal path P_{14} from node 1 to node 4.

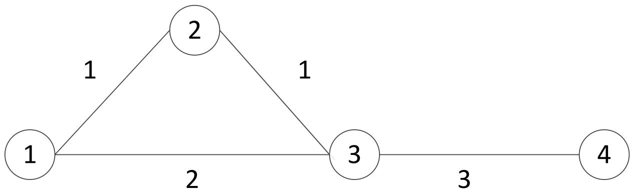

Figure 4.2 Four-node case for optimal restored path search

The modified dijkstra method is proposed to find path with minimum P_s from vertice V_0 to all other nodes. The procedure of the modified dijkstra is described as following steps:

Step1: V indicates all nodes in a graph. Initially S contains only source node V_0. Initially $S=\{V_0\}$. *U*=*V*-*S* which contains all nodes except V_0.

Step2: Calculate all P_s from node V_0 to every node V_u in *U*. Choose node k from *U* ensuring minimum P_s of path from node V_0 to V_k.

Step3: Add V_k in *S* and regard V_k as middle node and modify P_s of every node in *U*. If P_s of path from node V_0 to V_u (across node V_k) is smaller than P_s of precalculated P_s of path from node V_0 to V_u (not across node V_k), P_s of path from node V_0 to V_u is modified based on new path.

Step4: Repeat step 2 and step 3 until all nodes are contained in *S*.

4.4 Optimal Efficiency Oriented Power System Restoration Considering Load Prioritization

By utilizing novel efficiency oriented model, power system restoration is formulated as a permutation-based combinatorial optimization problem subjected to generator hot startup time, cranking power requirement and power balance constraints.

The solution x of this problem is permutation of generator startup which determines T_s, T_{stage} and T_{total}. With consideration of load prioritization, the objective becomes maximization of the restored load per unit time named as load restoration efficiency. The general expression of the optimization problem is formulated as Eq. (4.1)

$$\max \quad \mathrm{F}(T_{stage}(x), T_{total}(x)) \tag{4.1}$$

subject to

Hot Startup Time Limitation

Cranking Power Requirement

Power Balance

4.4.1 Objective Function

Due to T_{total} is depending on different generator startup permutation in this methodology, exclusive maximization of total restored load during the entire restoration period is not meaningful. Therefore maximization of restored load per unit time is proposed as optimization objective. T_{stagej} is *j*-th restoration stage time period. T_{total} is total restoration. $P_{loadi}(t)$ represents the restored load at stage *i*.

$$\mathrm{F}(T_{stage}, T_{total}) = \frac{\sum_{i=1}^{m} \int_{T_{stagei}}^{T_{total}} P_{loadi}(t)dt}{T_{total}} \tag{4.2}$$

4.4.2 Constraints

1) Generator hot startup time constraint

$$T_{si} < T_{hi}, i = 1, 2, \ldots, m \tag{4.3}$$

where m is number of NBS generator units, T_{hi} is the maximum hot startup time limit of unit i, which means unit i can only start within the hot startup period, or it fails.

2) Generator cranking power requirement

$$\sum_{i=1}^{Gn}\int_{0}^{T_{stagek}} P_{geni}(t)dt - \sum_{j=1}^{G_m}\int_{0}^{T_{stagek}} P_{crankj}(t)dt > 0 \quad (k \in \{1, 2, \ldots, m\}) \qquad (4.4)$$

where $P_{geni}(t)$ is the generation capability of generator unit *i* and $P_{crankj}(t)$ is cranking power function of NBS unit *j*. T_{stagek} indicates restoration period at stage k. m is the number of restoration stages. G_n is the number of on-state generators and G_m is the number of on-state NBS generators until T_{stagek}. Within each restoration stage T_{stagek}, the total system generation of on-state generators minus cranking power of on-state NBS generators should be larger than 0 to satisfy this constraint.

3) Power Balance

$$\sum_{k=1}^{m}\int_{T_{stagek}}^{T_{total}} P_{loadk}(t)dt = \sum_{i=1}^{n}\int_{T_{si}}^{T_{total}} P_{geni}(t)dt - \sum_{j=1}^{m}\int_{T_{sj}}^{T_{total}} P_{crankj}(t)dt \qquad (4.5)$$

This constraint is established that available generation must be equal to restored load.

4.5 Numerical Results

The proposed restoration methodology is applied on IEEE 39 bus system and IEEE 57 bus system to find the permutation of generators startup in order to obtain optimal load restoration efficiency. The power system restoration of these two test systems have been solved by AQDE. Finally, a flexible restoration schedule is attained providing information for generator startup and load pickup considering load prioritization. Since the parameters of AQDE including the population size can affect the performance of optimization very, optimal selection of these parameters has been conducted in relation to the studied cases. According to parameter analysis, optimal population size is 5 and F= 0.75 and CR =0.9 is the best combination. All algorithms are implemented in MATLAB 7.13 and executed on a PC with Intel Core of 1.8GHz and 3.73GB RAM.

4.5.1 Case of IEEE 39 Bus System

For IEEE 39 bus system case, unit 33 is the blackstart unit. Table 4.1 provides the optimal load restoration strategy demonstrated with a timetable. It provides information of non-blackstart generator units' startup time, charging path and restored load capacity at each stage. The corresponding optimal objective function value is 97.4 restored load capacity per unit time.

Table 4.1 IEEE 39 bus system restoration schedule

Stage	Node	Path	T_{start} (min)	Restored load (MW)
1	33	33→33	0	0
2	34	33→19→20→34	6	10.2
3	36	19→16→24→23→36	14	can't start within T_{h36}
4	35	23→22→35	18	can't start within T_{h35}
5	38	16→17→27→26→29 →38	28	87.8.
6	32	16→15→14→13→10 →32	38	(can't start within T_{h32})
7	30	17→18→3→2→30	46	178.5
8	37	2→25→37	50	(can't start within T_{h37})
9	31	13→12→11→6→31	58	(can't start within T_{h31})
10	39	2→1→39	62	(can't start within T_{h39})

The first column indicates restoration stage. The second column indicates startup generator node number at each stage. Path provides the determined optimal charging path and T_{start} is the corresponding generator startup time. The final column indicates restored load capacity by T_{start} . With generators hot startup time limit checking, units 30, 34, 33 and 38 are available. Figure 4.3 shows restored load curve for IEEE 39 bus system and the dashed line indicates restored load capacity per unit time.

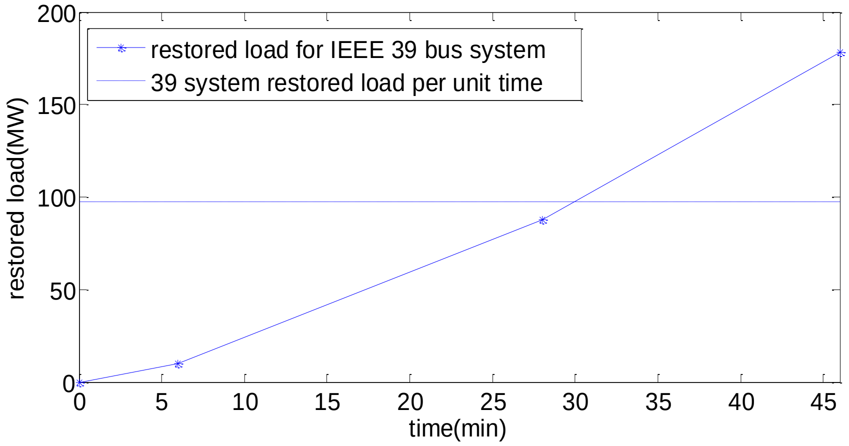

Figure 4.3 Restored load curve for IEEE 39 bus system

4.5.2 Case of IEEE 57 Bus System

IEEE 57 bus system has seven generators and much more transmission lines, and generator 3 is regarded as the blackstart unit. Table A.2 of Appendix provides detailed data of IEEE 57 bus system generator characteristics. The optimal load restoration schedule is provided in Table 4.2. And the corresponding optimal objective function value is 58.1 MW restored load capacity per unit time.

Table 4.2 IEEE 57 bus system restoration schedule

Stage	Node	Path	T_{start} (min)	Restored load(MW)
1	3	3→3	0	0
2	2	3→2	2	0.3
3	1	2→1	4	2.35
4	8	3→4→18→19→20→21→22→38→37→36→35→34→32→31→30→25→24→26→27→28→29→7→8	48	(not start within T_{h8})
5	9	29→52→53→54→55→9	58	(not start within T_{h9})
6	6	7→6	60	102.4
7	12	38→49→50→51→10→12	70	124.6

The first column indicates restoration stage. The second column indicates startup generator node number at each stage. Path provides the determined optimal charging path and T_{start} is the corresponding generator startup time. The final column indicates restored load capacity by T_{start}. With generators hot startup time limit checking, units 8 and 9 are unavailable. Figure 4.4 shows restored load curve for IEEE 57 bus system and the dashed line indicates restored load capacity per unit time.

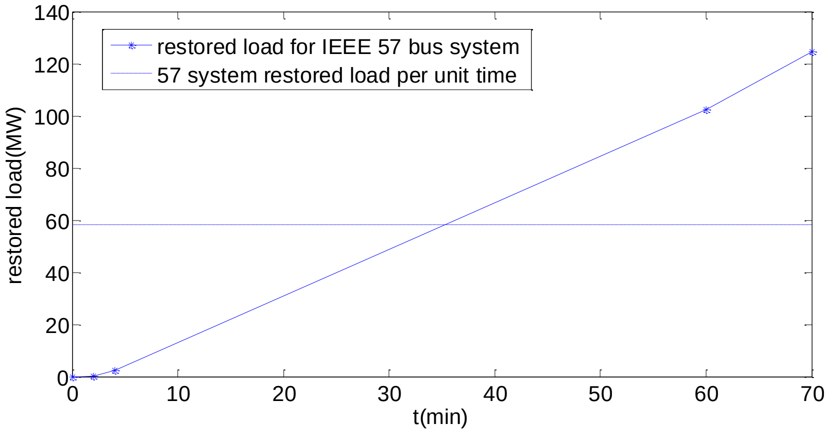

Figure 4.4 Restored load curve for IEEE 57 bus systems

4.6 Summary

This chapter focuses on power system restoration considering load prioritization with emphasis on the third stage. Traditionally at load restoration stage, maximization of the served load becomes the primary objective after electric grid reconfiguration. Based on the research work in previous chapter, the objective becomes maximization of restored load per unit time named as load restoration efficiency when applying the novel optimal efficiency based power system restoration methodology. By utilizing it, power system restoration is formulated as permutation-based optimization problem. In practical operation, transmission path restoration is interconnected with load restoration in the same process. Therefore when determining pickup load, there should be a balance between system security and load prioritization which is another distinguished part of this research work. A novel index P_s is proposed combining load prioritization and capacitance for guiding optimal path search. The corresponding modified dijkstra method is proposed to find path with minimum P_s from vertice V_0 to all other nodes. Similarly as previous work, advanced quantum-inspired differential evolutionary algorithm is chosen to solve the permutation-based optimization problem due to its successful application before. Using appropriate control parameters, system restoration cases of IEEE 39 and IEEE 57 bus systems have been successfully solved. Finally an optimal restoration schedule with maximum restoration load efficiency is obtained. The information of non-blackstart generator units' startup time, charging path and restored load capacity at each stage is provided.

5 General Overview of Load Modeling Practice

5.1 Introduction

In addition to load prioritization identification, issues of frequency control, cold load pickup and under-frequency load shedding are involved in load restoration. As we known, load model plays an important role in these dynamic simulations. The model validity directly affects simulation results accuracy. In modern electric grid, new challenges emerge in aspects of large-scale integration of renewable energy resources, expansion of transmission system and long time operation. A delicate load model is increasingly desired with enhanced accuracy and computational efficiency in order to capture specific load characteristics of various load components. Firstly, this chapter provides a general overview of load modeling practice in previous research work. It contains load modeling basic concepts and significance, load modeling methodologies, state-of-the art load models and load model development trend and future demand. And next chapter provides research work on advanced load modeling in modern power system.

There are two major load modeling methodologies: component-based approach and measurement-based approach. In the component-based approach load models are constructed from information on its constituent parts while the measurement-based approach makes use of field measurements to identify parameters of a chosen load model. For each methodology, the process consists of three procedures: data collection, load aggregation and load model validation. Prevailingly, measurement-based approach is the dominant methodology for load modeling. The existing load models for measurement-based approach include static load model, dynamic load model and composite load model. An international survey of load modeling on industrial practice is provided by CIGRE. The ZIP model occupies one third, 30.9%. Then the second most popular load model is the constant PQ type with 19.6%. The third frequently used load models are respectively exponential model and composite model (ZIP + induction motor) each with 18.6%. Based on current load modeling practice, load model development trend and future demand are discussed lastly to provide research direction in chapter 6.

5.2 Load Modeling Basic Concepts and Significance

5.2.1 Load Modeling Basic Concepts

Basic definitions and concepts for those terminologies that are frequently encountered in the field of load modeling are explained in this section [43, 76].

1) Load

The term "load" can have several meanings in terms of power system engineering, including:

- A device, connected to a power system that consumes power.
- The total power (active and/or reactive) consumed by all devices connected to a power system.
- A portion of the system that is not explicitly represented in a system model, but rather is treated as if it were a single power-consuming device connected to a bus in the system model.
- Equivalent representation of the aggregate effect of many individual load devices.

- The power output of a generator or generating plant.

In load modeling, the term “load” usually refers to the third definition. In cases where the meaning of load is not clear, specific term will be used to indicate the intent, such as “load device”, “system load”, “bus load” or “generator load”.

As illustrated in Figure 5.1, the following terms will be used when describing the composition of the load.

2) **Load Component**

A load component is the aggregate equivalent of all devices of a specific or similar types, for example, resistive heat, room air conditioner, incandescent lighting.

3) Load Class

A load class is a category of load, such as residential, commercial, or industrial. For load modeling purposes, it is useful to group loads into several classes, where each class has similar load composition and characteristics.

4) Load Composition

Load composition is the fractional composition of the load by load components. This term may be applied to the bus load or to a specific load class.

5) Load Class Mix

Similar to load composition, load mix is the fractional composition of the bus load by load classes.

6) Load Characteristic

Load characteristic is represented through a set of parameters, e.g., power factor and partial derivatives of P and Q respect to voltage magnitude and frequency. This term can be applied to a specific load device, a load component, a load class or a bus load.

The terminology introduced in the following part will commonly used in describing the load modeling process or different types of models.

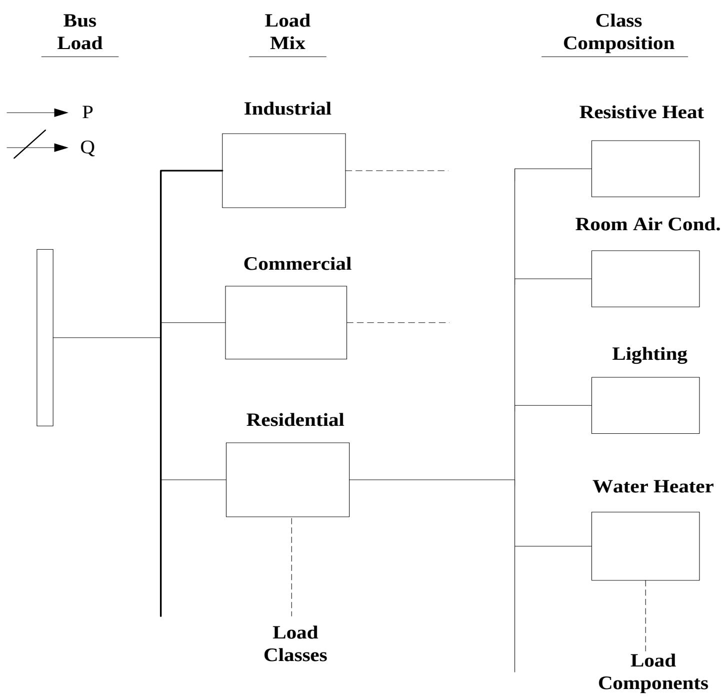

Figure 5.1 Terminology for component-based load modeling

7) Load Model

A load model is a set of algebraic and possibly differential equations, which describe the relationship between a bus voltage (and/or frequency) and the load (active power and/or reactive power). In most cases, researchers only consider the voltage dependency of the load due to its significant impacts as well as the ease of modeling work. Although the frequency dependency of load is important, only a few works have been done in this field.

8) Static Load Model

A static load model describes the relationship between a bus voltage and the load (active power and reactive power) at the same instant. A static load model is not only used to represent static load components, e.g., resistive load, but also as an approximation of dynamic components such as induction motor. However, the approximation is not always sufficient for studies, especially in stability studies [77]. The fact that inaccurate load models may lead to complete wrong results are forwarding the replacement of static load models by dynamic ones [78].

Generally, there are two forms of static load model: Polynomial Load Model (also known as ZIP Model) and Exponential Load Model [43, 44, 79].

9) Dynamic Load Model

Different from static load model, a dynamic load model expresses the load at any instant as a function of the bus voltage (magnitude and frequency) at past and present instants. From literature surveys, dynamic load models can be expressed by two kind representations: differential equations and difference equations [14, 80].

10) Composite Load Model

A composite load model is a combination of static and dynamic load models. It is expected to be used in stability studies which require more accurate dynamic representation than power flow studies. According to different research purposes and simulation programs, composite load models have various load model structures [81, 82].

5.2.2 Load Modeling Significance

The benefits of a delicate load model are difficult to quantify. But it is easy to see the effects of an inaccurate model on dynamic studies. The following will discuss how load models affect transient and small signal stability analyses for frequency and voltage.

1) Transient Studies

A voltage dip is normally during the first swing after a fault. The power calculated by an inaccurate load model will lead to the generation-consumption imbalance, which therefore further influences the magnitude of the angular excursion and the system transient stability during this period.

2) Small Signal Damping Studies

The inter-area oscillations involving many generators distributed over the system will usually result in significant changes of voltage and frequency. If a constant impedance load model is used to estimate the damping, the results turn out pessimistic. The result is more than twice as the results produced by using an accurate model [43].

3) Voltage Stability Studies

Voltage stability studies have a stronger dependency on the load models. A study of the impacts of the loss of one of the transmission lines in Ottawa area was conducted. The results show that there is a significant difference existing between results obtained from static models and dynamic models. The static load models lead to totally wrong results [77, 83].

Static load models are proved not adequate for voltage stability studies. Even though there is no consensus on the choice of load models suitable for voltage stability studies, dynamic models rather than static models produce more reliable outcomes.

5.3 Load Modeling Methodology

There are two main methodologies utilized in practice: “component-based approach” [42, 84] and “measurement-based approach” [48, 80, 85, 86]. The component-based approach which is a traditional approach develops load model from information on its constituent parts as illustrated in Figure 5.1. The measurement based approach uses field measurements to identify parameters of a chosen load model.

This section will introduce these two different methodologies. In order to make it clear when describing the process of load modeling and show the difference between the two methods, the process is divided into three sections: data collection, load aggregation and load validation [23].

5.3.1 Data Collection

1) Data for Component-based Approach

Three types of data are required in component-based approach: load characteristics, load composition and load class mix. They can be divided into two categories: predefined data and uncertain data.

Load characteristics data are predefined data which can be obtained by theoretical analysis and laboratory measurement. Once determined, they will be used by all power utilities. Many data have already been determined and documented by EPRI Projects [84, 87]. However, it needs update when new load types emerge or load devices redesign. Typical load component characteristics are demonstrated in [43, 88].

One critical question encountered in determining load characteristics should be noted. The diversity in some load components, e.g., identical induction motors with different aging time, will represent different load characteristics. It is necessary to conduct more surveys to assess the effect of load characteristics diversity on load modeling.

Load composition data and load class mix data at a specific bus are both uncertain data which need be calculated depending on the bus load consumption information while the load component characteristics data can be used directly.

They vary with time, season and location. It is difficult to identify them with great certainty compared with load characteristics data.

Load composition data is the fractional composition of the load by load components, e.g., resistance heating, room air conditioner. To obtain this data, data on capital stocks and utilization factors are required [43]. The capital stock refers to the total inventory of a load component. And the utilization factor indicates the percentage of what is being on to the total. Useful data sources for estimating load composition include load research data, census and billing data etc. Typical load composition data for several load classes, locations, seasons can be found in EPRI Load Modeling Manual. Typical data can be used as reference at first. To get more specific load compositions, guidelines can be found in [47].

Load class mix data, which is the fractional composition of the bus load by load classes, vary from bus to bus. Besides that, the data are also affected by location, season, weather and other factors. Therefore they are uncertain data which can be deduced from bus load consumption information using methods described in [84].

Gathering load composition data and load class mix data is an arduous task which is a disadvantage of component-based approach. To ease the problem, further attention should be focused on developing general procedures for collecting this data.

2) Data for Measurement-based Approach

Data for measurement-based approach are measured by devices installed at the bus where loads are to be aggregated. With development of communication and computer technologies, different types of microprocessor-based devices applied for load modeling emerge, e.g. Power Quality monitors (PQ), Digital Fault Recorders (DFR), Digital Relays (DR) and Phase Measurement Units (PMU), the most prevailing instrumentation. These microprocessor-based devices are generally called intelligent electronic devices which can send or receive data and provide for control of station devices. For load modeling, such devices must record the voltage and frequency and the corresponding active power and reactive power. The data measured can be generally sorted into two categories: data in steady state and disturbance measurements. The data under steady state can be used for small signal load modeling purposes. And the disturbance data are good resource for building up load models used in transient stability studies [89]. Many utilities have developed data acquisition systems to collect data suitable for load modeling purposes [80, 90]. For obtaining suitable data for load modeling, EPRI conducted a careful investigation of current IEDs and identified desirable attributes of devices with an accepted range which are suitable to obtain available data for load modeling. The choice of devices determined the exact attribute value. Except that, the choice of measurement location is crucial to the accuracy representation of load. Guidelines for selecting an appropriate location can be found in [47].

5.3.2 Load Aggregation

Load aggregation is the most critical part in load modeling. The aggregation method directly affects the accuracy of load model. There are two aggregation forms: theoretical aggregation and identification aggregation corresponding to component-based approach and measurement-based approach.

1) Theoretical Aggregation

Theoretical aggregation means lumping similar loads based on the load type analytically and then using pre-defined values for each parameter of the load. Several methods are applied to aggregate static and dynamic load model using information on load class mix and load compositions [42, 84, 88]. Generally, the load composition data are regarded as weight factors. In order to construct a general load model, the sensitivity factors of load model should be a weighted average of individual ones.

EPRI has developed Load Model Synthesis Program Package (LOADSYN) using load mix, load composition and load characteristics data to determine load parameters suitable for power flow and transient stability programs. LOADSYN is comprised of two main programs: GLDMOD and SLDMOD. GLMOD can generate general load model while SLDMOD can turn the general load model into the specific one with required detail level.

2) Identification Aggregation

In measurement-based approach, load models are aggregated through identification based on field measurements [91, 92]. In fact, it is a system identification process which involves finding a suitable load model structure and parameters for the structure. A flowchart of the process is illustrated as Figure 5.2 which can be described as three steps:

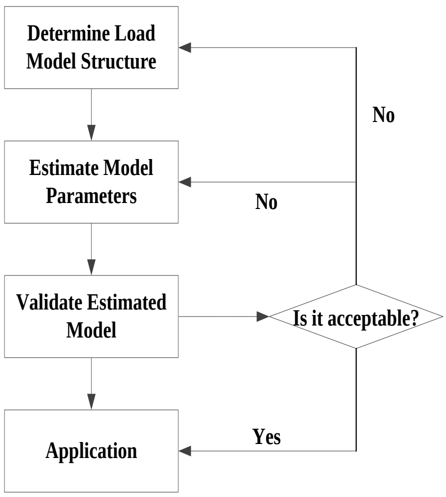

Figure 5.2 Flow chart of system identification

- Determine the load model which describes the system input output behavior.
- Determine an appropriate parameter estimation technology.

- Validate the estimated load model. If the model is acceptable, then apply it in practice. If it is not, then repeat the identification process until find the fit model.

5.3.3 Load Model Validation

After obtaining all the parameters of the chosen load model structure, the load modeling process has not yet finished. The model generated from specified datasets should be tested by using new, unseen data. The model will be validated if the model simulation results can best fit the test data. That is to say, a valid model should have strong generalization capability.

Therefore, we have to evaluate the model's generalization ability. A cross-validation method is used to estimate the generalization capability of a composite load model in [82, 93, 94]. In a recent study for validating measurement-based composite load model shows that the load composition does have significant influence on the load validity [82]. The further the actual composition of the load deviates from the one used for construct load model, the larger discrepancy will be between the model simulation results and the field measurements. Thus a recommendation for load characteristics clustering before the validation is put forwarded. A validating method for computing an accuracy index and its confidence interval is provided in [95].

5.4 State-of-the-art Load Models

Load models can be roughly sorted into two classes: static load model and dynamic load model. This section introduces some existing load models for dynamic simulations. A summary of prevailing load models for dynamic simulations is presented. A more detailed summary can be found in [14, 23, 78].

5.4.1 Static Load Model

A static load model is a representation which describes the relationship between a bus voltage and the load (active power and reactive power) at the same instant. Generally, there are two forms: polynomial load model (also known as ZIP Model) and exponential load model.

1) Constant Impedance Load Model

A constant impedance load model is a static load model of which power varies directly with the square of the voltage magnitude.

2) Constant Current Load Model

A constant current load model is a static load model of which power corresponds directly to voltage magnitude.

3) Constant P-Q Load Model

A constant P-Q load model is a static load model which is irrelevant to voltage. In practice, many loads are considered as constant P-Q load. But for some devices, such as electronic devices, constant P-Q can't represent the load behavior below a specified voltage. Therefore, constant P-Q load model are not adequate to replicate dynamic load behavior under contingency situations.

4) Polynomial Load Model

Polynomial load model is a combination of constant impedance, constant current and constant power. It is also called ZIP model. The mathematical representation of ZIP load model is in the following form:

$$P = P_0[a_p(\frac{V}{V_0})^2 + b_p(\frac{V}{V_0}) + c_p] \tag{5.1}$$

$$Q = Q_0[a_q(\frac{V}{V_0})^2 + b_q(\frac{V}{V_0}) + c_q] \tag{5.2}$$

The parameters of the load model are a_p, b_p, c_p, a_q, b_q, and c_q. P_0 and Q_0 are nominal load power.

5) Exponential Load Model

Exponential load model is a static load model which describes the relationship between power and voltage as an exponential function. In some cases, the dependency between reactive power and voltage is more than quadratic where the ZIP model loses physical meaning. The mathematical representation is expressed in the following form:

$$P = P_0(\frac{V}{V_0})^{p_v} \tag{5.3}$$

A frequency-dependent load model is a static load model which represents the frequency dependency of the load. It is usually represented by multiplying either a polynomial or exponential load model as a factor of the following form:

$$\left[1 + a_f\left(f - f_0\right)\right] \tag{5.4}$$

where f is the frequency of the voltage, f_0 is the nominal frequency and a_f is the frequency sensitivity parameter of the model.

In many dynamic performance analysis studies, the frequency-dependent model is ignored. But when describing the correct effects on damping of oscillations, the frequency model is required.

6) Component-based representation

Component-based model is an aggregation of individual components which is used in LOADSYN program which has physical meaning. The load is divided into some categories: residential, industrial, commercial, agricultural and so forth. And the individual component characteristics are predefined. The component-based representation can be obtained through theoretical aggregation. But in dynamic studies, the sum of their contributions is not equal to the combination responses.

5.4.2 Dynamic Load Model

A dynamic load model expresses the load at any time instant as a function of the bus voltage (magnitude and frequency) at past and present instants. From literature review, dynamic load models can be expressed by two kinds of representations: the one based on induction motor differential equations, and the other based on transfer function difference equations [96, 97].

1) Induction Motor Model

Induction motor is a critical component in power system. The induction load model based on physical characteristics of an induction motor can represents the dynamic response which static load model can not under contingency conditions.

Induction motor model has several forms. Generally, the third order model is enough for transient stability studies. The equivalent circuit is shown in Figure 5.3.

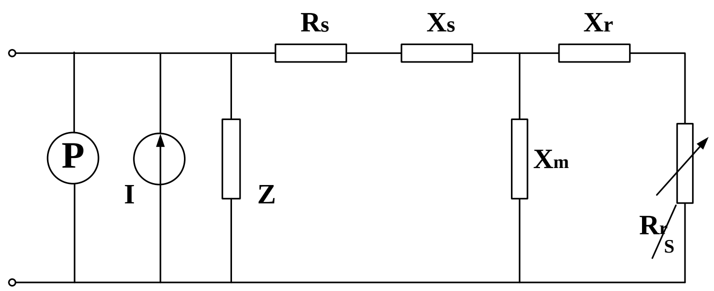

Figure 5.3 Equivalent circuit of the composite load model

R_s is stator winding resistance. X_s is the stator leakage reactance. X_m is the magnetizing reactance. X_r and R_r separately represent the rotor resistance and leakage reactance. S is the motor slip.

2) Difference Equation Model

Unlike induction motor, difference equation model is a dynamic model with no physical meanings. The second order difference equation is showed as below:

$$\begin{aligned}\Delta P(k) = a_{p1}\Delta P(k-1) + a_{p2}\Delta P(k-2) + c_{p0}\Delta V(k) + c_{p1}\Delta V(k-1) \\ + c_{p2}\Delta V(k-2) + g_{p0}\Delta f(k) + g_{p1}\Delta f(k-1) + g_{p2}\Delta f(k-2)\end{aligned} \tag{5.5}$$

$$\begin{aligned}\Delta Q(k) = a_{q1}\Delta Q(k-1) + a_{q2}\Delta P(k-2) + c_{q0}\Delta V(k) + c_{q1}\Delta V(k-1) \\ + c_{q2}\Delta V(k-2) + g_{q0}\Delta f(k) + g_{q1}\Delta f(k-1) + g_{q2}\Delta f(k-2)\end{aligned} \tag{5.6}$$

5.4.3 Composite Load Model

Composite load model incorporates static load model and dynamic load model [98]. There are four general types proposed by EPRI, considering the industry requirements [47]. As mentioned before, the static load model types include ZIP model and exponential model. And the dynamic load model involves induction motor model and difference equation [99]. It should be noted that ZIP model and induction motor both have physical meaning while other two types do not. These four composite load model structures are as follows:

- ZIP + Induction Motor (third state model)
- ZIP + Difference Equation(second order model)
- Exponential + Induction Motor (third state model)
- Exponential + Difference Equation(second order model)

5.4.4 Survey on Current Load Modelling in Utility Practice

A summary of prevailing load models in this field for dynamic simulations is illustrated as in Figure 5.4 according to CIGRE international surveys on industrial practices on load modeling.

As seen from Figure 5.4, the ZIP model occupies one third, 30.9%, of practical implementations, which is not a surprise. Then the second most popular load model structure is the constant PQ type with 19.6%. These two model structures account for 50.2% out of all industrial practices. The third frequently used load model structures are respectively exponential model and composite model (ZIP + induction motor) each with 18.6%. It is easily found that in industrial practice, about 70% utilities use static load model structures for dynamic simulations. Even though composite load model proved to have better performance according to many research works, traditional static load models are still applied due to their more simple forms. The reason why power utilities have been unwilling to change traditional load modeling practice is the fact that good models with complexity can only be obtained from good data. Therefore, there is strong incentive for advanced load model which can be used for general practice in utility.

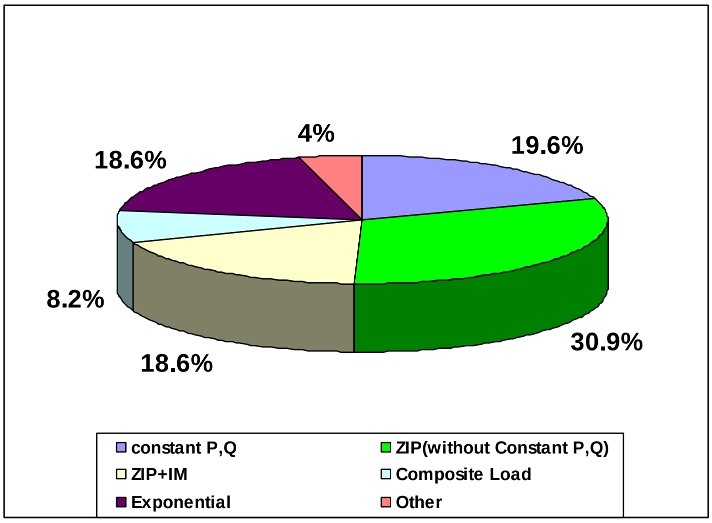

Figure 5.4 Prevailing load model types for dynamic simulations

5.5 Parameter Estimation Technology Determination

After determining load model, the next procedure is parameter estimation. Parameter estimation approaches are in fact a collection of techniques which aim at extracting a mathematical model of a given process by analyzing relations between the input and output quantities of the process[96]. In load modeling, the input data are measured voltage (magnitude and frequency), and the output data are the active and reactive power. The aim of parameter estimation is to find the suitable model parameters so that the simulated results can best fit the field measurements. There are numerous parameter estimation approaches. No evidence proves that one approach is better than others. In some cases, an approach may produce more reliable results than another one. But this approach can not be proved suitable for any condition. For a more detailed discussion of different approaches, see [97]. This section only provides a review of current existing parameter estimation techniques. There is no comparison presented.

Different parameter estimation approaches all involve two aspects: an estimation criterion and an appropriate algorithm. Approaches for linear model have been well developed while parameter estimation for nonlinear system needs more future research. Generally, approaches for nonlinear system can be sorted into three types:

1) Analytical Based Approach: The analytical approach proposed in [23] is a simple parameter derivation method for an induction motor load. This approach is usually used in special tests.

2) Statistical Based Optimization Approach In optimization based approach, the objective function is defined as the sum of square error between the simulated results and the measured outputs (P and Q). The main aim of optimization based approach is to minimize the objective function. Traditional algorithms are listed as follows:

- Least Square Based Parameter Estimation Approaches
- Weighted Least Square Based Parameter Estimation Approaches
- Generalized Least Square Based Parameter Estimation Approaches

- Gradient Based Parameter Estimation Approaches
- Instrument Variable Based Parameter Estimation Approaches

3) Advanced System Identification Approaches

There are several advanced optimization approaches as follows:

- Neutral Network based Parameter Estimation Approaches
- Genetic Algorithm Based Parameter Estimation Approaches [86]
- Fuzzy Logic Based Parameter Estimation Approaches [91, 100, 101]
- Trajectory Sensitivity Based Parameter Estimation

5.6 Load Model Development Trend and Future Demand in Modern Power System

5.6.1 Load Model Development Trend

The future development of modern electric power grid is smart grid. It brings about new challenges and requirements for power system planning and operation. One of the new challenges is the large-scale integration of renewable energy resources. New load components emergence requires corresponding load models to represent accurate dynamic performance.

Besides that, expansion of transmission system and long time operation impose more and more stress on power system which requires the system operating limits are as close as possible to the real system capability. For solving problems in practice, utilities usually depend on dynamic simulations. According to research surveys, simulation results significantly depend on load model types and parameter values. A delicate load model which can replicate system response under contingency is necessary for dynamic simulations.

5.6.2 Future Demand in Modern Power System

According to surveys regarding industry practice and research, ZIP model is the most popular model in power utilities for power flow programs while the composite model (ZIP + induction motor model) is widely applied in existing software tools for dynamic studies.

Future demand for a load model usable in modern power system is discussed as follows:

- Generalization ability
- High Flexibility (user-defined feature)
- Simplified form

A model in simplified form can provide more flexibility rather than a high complexity model with many parameters. In a specific situation, a high complexity model may be more accurate rather than a simplified model. But the parameters of a high complexity model may not be proper for other different conditions while a simplified model represents strong generalization ability. In practice, there always exists a tradeoff between simplicity and accuracy of a load model.

5.6 Summary

This chapter provides the whole process of load modeling in detail. It provides a general overview of load modeling practice in previous research work, including load modeling basic concepts and significance, load modeling methodologies, state-of-the art load models, load model development trend and future demand. This work prepares preliminary knowledge for the next chapter.

6 Load Model Development and Verification Study in Modern Power System

6.1 Introduction

In traditional way load model is established at transmission voltage level or high voltage level. Nevertheless a load model established at distribution voltage level can satisfy the demand of modern power system to greater extent with respect to accuracy and efficiency. Therefore there is increasingly desire of a delicate load model to capture specific load characteristics of various load components. As load model established at transmission voltage level can not fit for the data accuracy of measurement at distribution voltage level, in order to compensate data accuracy difference, a complete load model at distribution voltage level with equivalent capacitor, large motor and small motor is proposed. For demonstrating the complete model efficiency, comparison experiments of three load models are conducted. They are respectively the proposed complete load model at distribution voltage level, PowerFactory built-in dynamic load model at distribution voltage level, and composite load model at transmission voltage level which are all established in DIgSILENT PowerFactory. This chapter consists of four sections: data collection and processing, three identification load models established in DIgSILENT PowerFactory, load model parameter identification and case study. This chapter provides research work on load model development and verification at distribution voltage level.

6.2 Data Collection and Processing

For our study, historical disturbance data from Western Power Corporation in Australia is used as measurement data for load modeling. All the following analysis is based on these disturbance data under different fault conditions. The provided event data are all saved in the format of COMTRADE file. In each COMTRADE file, there are groups of voltage signal, current signal, phase angle signal and frequency signal from different terminals or transformers which are around the load point to be identified. The pre-processing of each COMTRADE file requires three steps:

1) Select out the voltage signal, current signal and corresponding phase angle signal from the raw COMTRADE file of the load point at the distribution voltage level or transmission voltage level.
2) The calculation of the active power and reactive power is realized by MATLAB code using the selected signals. The main process of dealing with data at the distribution voltage level is demonstrated as follows:

$$P_a = |U_a| \cdot |I_a| \cdot \cos(\theta_{va} - \theta_{Ia})$$
$$P_b = |U_b| \cdot |I_b| \cdot \cos(\theta_{vb} - \theta_{Ib}) \tag{6.1}$$
$$P_c = |U_c| \cdot |I_c| \cdot \cos(\theta_{vc} - \theta_{Ic})$$

$$Q_a = |U_a| \cdot |I_a| \cdot \sin(\theta_{va} - \theta_{Ia})$$
$$Q_b = |U_b| \cdot |I_b| \cdot \sin(\theta_{vb} - \theta_{Ib}) \tag{6.2}$$
$$Q_c = |U_c| \cdot |I_c| \cdot \sin(\theta_{vc} - \theta_{Ic})$$

$$P = P_a + P_b + P_c \tag{6.3}$$

$$Q = Q_a + Q_b + Q_c \tag{6.4}$$

While dealing with data at transmission voltage level, the corresponding calculation of Eq. (6.1) and Eq. (6.2) are modified as follows:

$$P_a = |U_a| \cdot |I_a|_1 \cdot \cos(\theta_{va} - \theta_{Ia1}) + |U_a| \cdot |I_a|_2 \cdot \cos(\theta_{va} - \theta_{Ia2})$$

$$P_b = |U_b| \cdot |I_b|_1 \cdot \cos(\theta_{vb} - \theta_{Ib1}) + |U_b| \cdot |I_b|_2 \cdot \cos(\theta_{vb} - \theta_{Ib2}) \tag{6.5}$$

$$P_c = |U_c| \cdot |I_c|_1 \cdot \cos(\theta_{vc} - \theta_{Ic1}) + |U_c| \cdot |I_c|_2 \cdot \cos(\theta_{vc} - \theta_{Ic2})$$

$$Q_a = |U_a| \cdot |I_a|_1 \cdot \sin(\theta_{va} - \theta_{Ia1}) + |U_a| \cdot |I_a|_2 \cdot \sin(\theta_{va} - \theta_{Ia2})$$

$$Q_b = |U_b| \cdot |I_b|_1 \cdot \sin(\theta_{vb} - \theta_{Ib1}) + |U_b| \cdot |I_b|_2 \cdot \sin(\theta_{vb} - \theta_{Ib2}) \tag{6.6}$$

$$Q_c = |U_c| \cdot |I_c|_1 \cdot \sin(\theta_{vc} - \theta_{Ic1}) + |U_c| \cdot |I_c|_2 \cdot \sin(\theta_{vc} - \theta_{Ic2})$$

3) Along with the calculated power value, the voltage signal, the frequency signal are altogether to store in a new processed COMTRADE data file which is used directly in load modeling parameter identification. In order to take into account the effect of 3 phases, we use the average voltage value of 3 phases as the voltage playback to the load point terminal during the following identification. The whole process is accomplished by MATLAB program. With these three steps, available data for parameter identification have been prepared. In summary, these 3 steps of data pre-processing can be demonstrated as Figure 6.1.

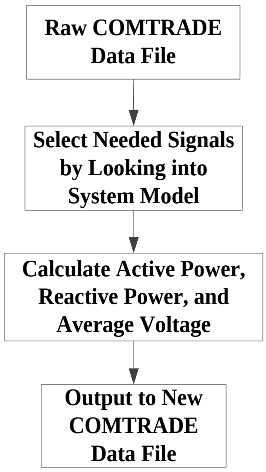

Figure 6.1 Disturbance Data Pre-processing Procedure

6.3 Three Identification Load Models Established in DIgSILENT PowerFactory

Three identification load models are established in DIgSILENT PowerFactory for comparison experiments in case study. They are respectively the proposed complete load model at distribution voltage level, dynamic load model at distribution voltage level, and composite load model at transmission voltage level.

6.3.1 The Proposed Complete Load Model at Distribution Voltage Level

In order to capture accurate load characteristics at distribution voltage level, a complete load model is proposed in which induction motor and capacitor are separately modeled. The induction motor is divided into large motor and small motor to better address the local power system conditions in details. As mentioned before, the complete load model at distribution voltage level is proposed which is illustrated in Figure 6.2. It contains a substation transformer, and a distribution feeder with an equivalent capacitor, an equivalent ZIP model, a large and small motor respectively.

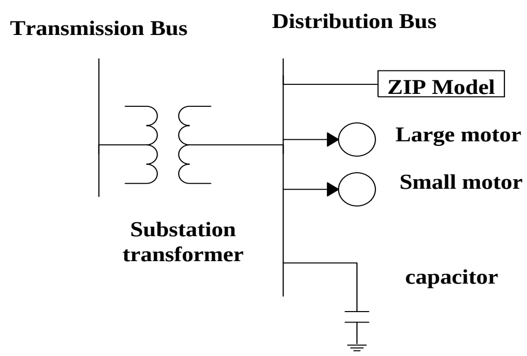

Figure 6.2 Complete load model at distribution voltage level

Based on local power system conditions, information about substation transformer and equivalent capacitor can be determined. The critical issue is how to identify parameters for the large and small motors. Induction motor parameters include R_r, X_r, X_m, X_s, R_s, *S*, *A*, *B* and *H*. Based on researchers' work [99, 102], parameters of induction motor can be divided into two subsets. One subset contains R_s, R_r and X_r which significantly affect reactive power and active power. Another subset contains the rest parameters which are X_s, X_m, *A*, *B* and *H* with small trajectory sensitivities. Therefore, the second subset's parameters are excluded from the parameter identification process and in advance determined based on typical large and small motor parameters [44]. Besides the first subset, there are other parameters of composite load model to be identified including the percentages of large and small motors, and the proportion of constant impedance, constant current and constant power models.

The complete load model can reflect the load composition in details but involve additional complications. Due to the use of large and small motors, the parameters to be identified are doubled. Considering negligible effects on active and reactive power consumptions, typical motor parameter values can be directly used for some parameters to save the modeling efforts in some extent.

6.3.2 PowerFactory Built-in Dynamic Load Model at Distribution Voltage Level

There are two types of PowerFactory built-in load models: General Load Model and Complex Load Model. For this study, a combination of General Load Model and Complex Load Model is used as dynamic load model which is established at distribution voltage level. General load model is sufficient for dynamic stability studies while the Complex Load Model has better capability of describing industrial load with a large portion of induction motors. The structure of DIgSILENT General

Load Model follows the composite load model proposed by EPRI as a standard load model for utility applications. 'General Load Model' can be used in most cases to sufficiently model the static and dynamic load characteristic for load-flow and dynamic simulations. And the 'Complex Load Model' is a complex synthetic model which considers the characteristics of different load models, including static load, dynamic load, induction motor load. Detailed equations of these two models can be found in user manual of DIgSILENT PowerFactory.

6.3.3 Composite Load Model at Transmission Voltage Level

The composite load model in our study is established at transmission voltage level shown as Figure 6.3. It is a combination of ZIP and Induction Motor (third state model). A third order induction motor model is sufficient for dynamic simulations considering mechanical dynamics as well as rotor flux dynamics.

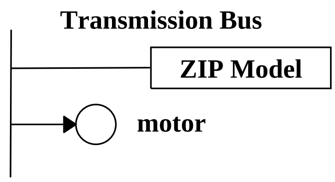

Figure 6.3 The composite load model at transmission voltage level

The corresponding mathematical equation is described as follows:

$$\begin{cases} \dfrac{dw}{dt} = -\dfrac{1}{2H}\left[\left(Aw^2 + Bw + C\right)T_0 - \left(E'_d I_d + E'_q I_q\right)\right] \\ \dfrac{dE'_q}{dt} = -\dfrac{1}{T'}\left[E'_q - \left(X - X'\right)I_d\right] + \left(w-1\right)E'_d \\ \dfrac{dE'_d}{dt} = -\dfrac{1}{T'}\left[E'_d + \left(X - X'\right)I_q\right] - \left(w-1\right)E'_q \end{cases} \tag{6.7}$$

$$
\begin{cases}
I_d = \dfrac{1}{R_s^{\ 2} + X'^2}\left[R_s\left(U_d - E'_d\right) + X'\left(U_q - E'_q\right)\right] \\
I_q = \dfrac{1}{R_s^{\ 2} + X'^2}\left[R_s\left(U_q - E'_q\right) - X'\left(U_d - E'_d\right)\right]
\end{cases} \tag{6.8}
$$

where $T^{'} = (X_r + X_m)/R_r$, $X = X_s + X_m$, $X^{'} = X_s + X_m X_r / (X_m + X_r)$; H is the rotor inertia constant; A, B, and C are coefficients in load torque representation in terms of motor speed which satisfy A+B+C=1.

6.4 Load Model Parameter Identification

In measurement-based approach, load modeling is actually a mathematical identification process. For a load model, inputs are voltage and frequency. Outputs are active power and reactive power which can be obtained from measuring devices. The aim of parameter identification is to find appropriate load model with the smallest errors between measured outputs and simulated outputs. The system identification process involves finding a suitable load model, parameters identification and load model validation.

Once the load model is determined, parameters can then be determined based on field measurements by using identification algorithms. These algorithms usually include e.g. the linear square error method[91], the fuzzy regression method [100, 101], the genetic algorithm and advanced pattern recognition methods. Nonlinear LSE method is chosen as the identification technique due to its easy implementation and proved effectiveness.

After identification, the model should be validated according to criteria. As defined Eq. (6.9), the mean square error (MSE) between the model output data and the measured can be applied as criteria for model validation[93],

$$\mathrm{MSE} = \frac{1}{\mathrm{N}}\sqrt{\sum_{i=1}^{N}\left(y_{meas} - \hat{y}_{sim}\right)^2} \qquad (6.9)$$

where N is the number of sampling points. y_{meas} is the field measurements data. $\hat{y}_{sim}$ is the simulated outputs of the load mode. Obviously, the smaller the MSE, the better the identification results will be.

6.5 Case Study

In measurement-based approach, load modeling is actually a mathematical identification process. For a load model, inputs are voltage and frequency. Outputs are active power. The voltage dynamics in one disturbance is demonstrated in Figure 6.4. It is clearly seen from the figure that the voltage begin to dip close to 10s and the sag is about 10%. It lasts for about 0.2s. Then it goes back to the nominal value. For comparison purpose, three load models are used to access modeling accuracy. They are respectively the proposed complete load model at distribution voltage level, PowerFactory built-in dynamic load model at distribution voltage level, and composite load model at transmission voltage level which are all established in DIgSILENT PowerFactory.

The comparison of simulated outcomes between three models can be seen from Figure 6.5 to Figure 6.10. The complete load model contains equivalent capacitor, large motor and small motor. The composite load model consists of motor and ZIP. And the PowerFactory built-in dynamic load model is a combination of General Load Model and Complex Load Model. Solid lines represent measurement data while dash lines represent simulation results.

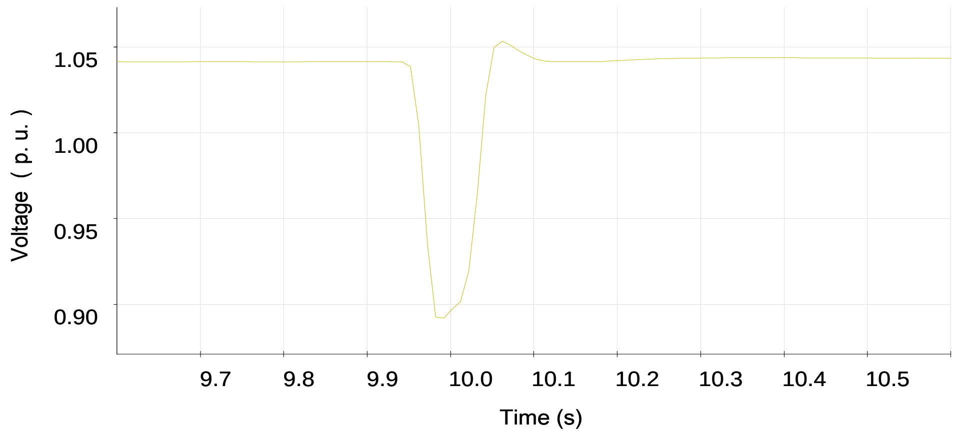

Figure 6.4 Bus voltage dynamics

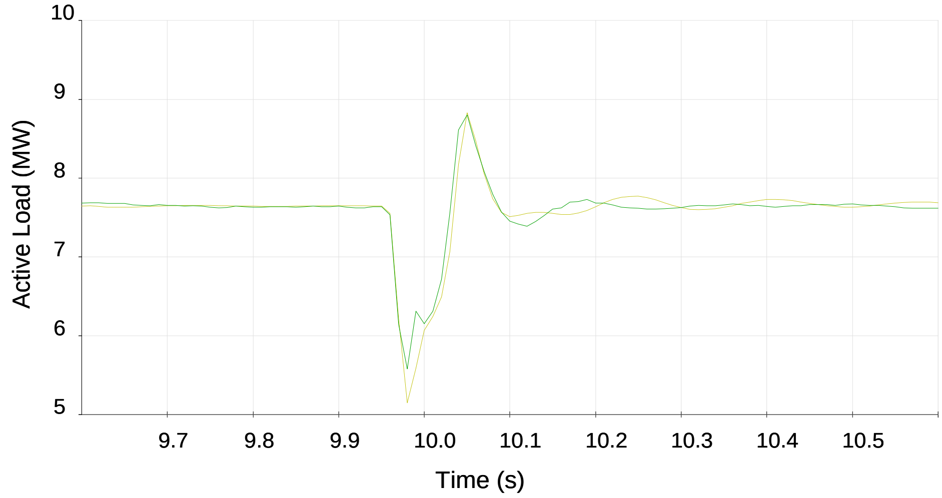

Figure 6.5 Measured and simulated active load of complete load model at 22kV

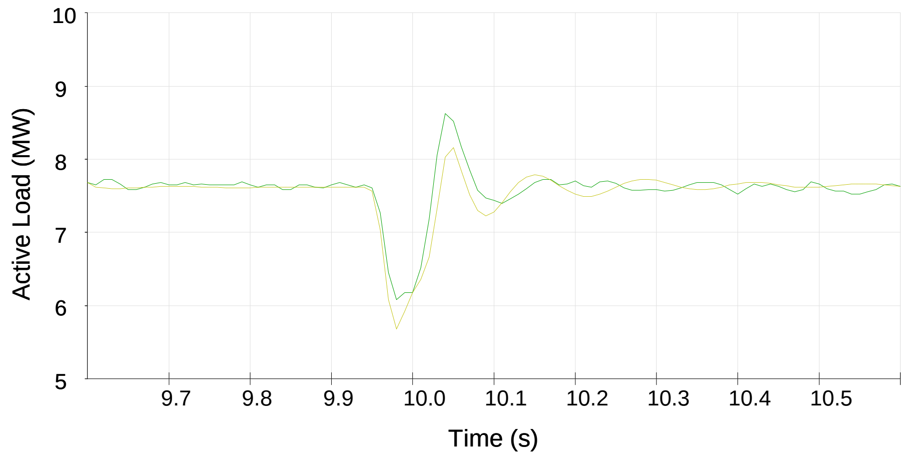

Figure 6.6 Measured and simulated active load of composite load model at 132kV

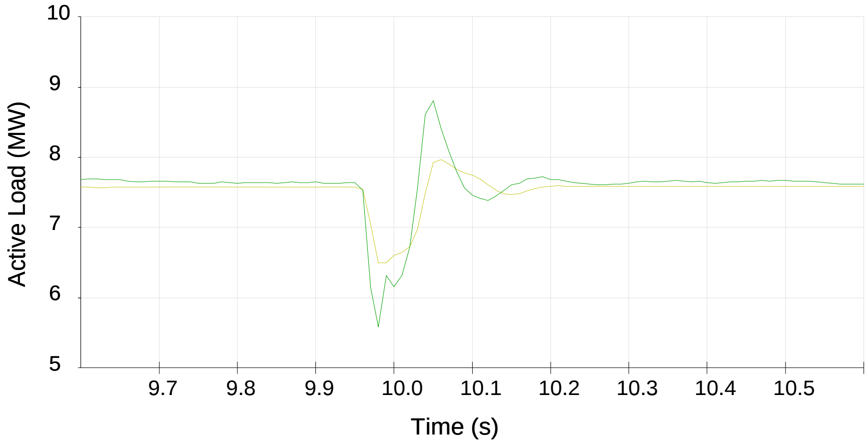

Figure 6.7 Measured and simulated active load of dynamic load model at 22kV

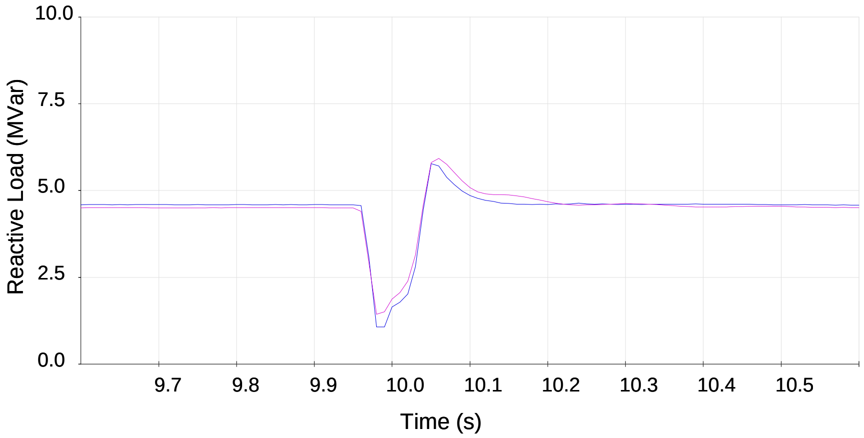

Figure 6.8 Measured and simulated reactive load of complete load model at 22kV

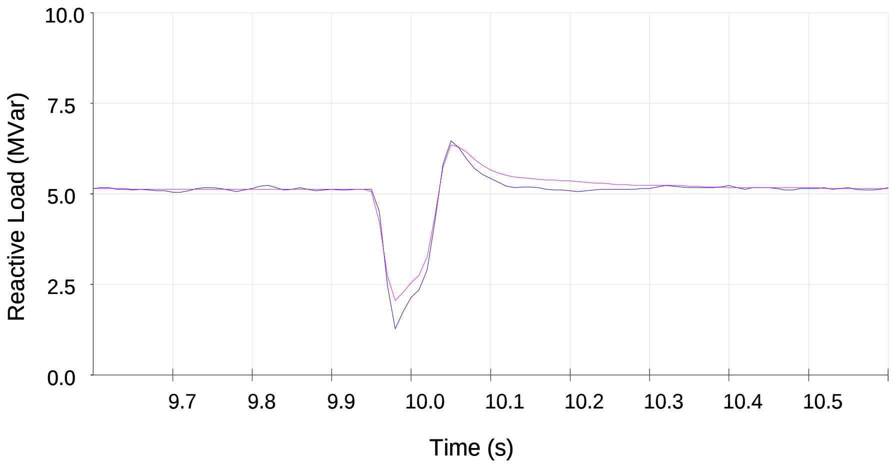

Figure 6.9 Measured and simulated reactive load of composite load model at 132kV

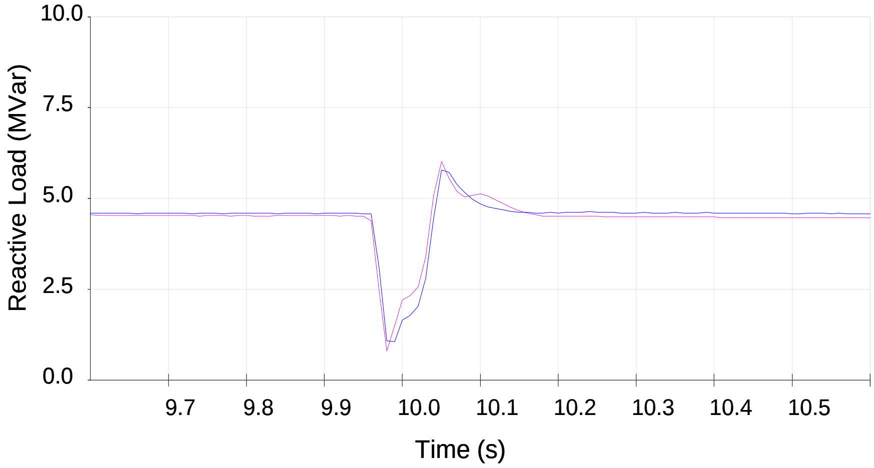

Figure 6.10 Measured and simulated reactive load of dynamic load model at 22kV

From the above figures, it is clearly seen that the complete load model at distribution level gives best fit between simulated outputs and measured active power and reactive power. The dynamic load model at 22kV gives poor description about active load behavior while an acceptable performance of reactive load behavior. The simulation outputs of the composite load model at 132kV level roughly fit the measurement data obtained at 132kV.

Through comparison, it can be found that an appropriate load model is the foundation to obtain good results. The complete load model performs better than composite load model without reactive compensation and dynamic load model. Besides, load modeling at distribution level gives specific description of load behavior. The deviation between simulated outputs and measurement data is the smallest of the three models. However, the nonlinear LSE parameter identification method heavily relies on model parameter initial values. More advanced identification methods such as differential evolution can be applied in future study.

6.6 Summary

This chapter provides research work of load model development and verification study in modern power system. In order to compensate data accuracy difference between measurement at transmission voltage level and measurement at distribution voltage level, a complete load model at distribution voltage level with equivalent capacitor, large motor and small motor is proposed. For validating this novel model efficiency, comparison experiments of three load models are conducted. They are respectively the proposed complete load model at distribution voltage level, PowerFactory built-in dynamic load model at distribution voltage level, and composite load model at transmission voltage level which are all established in DIgSILENT PowerFactory. From comparison experiments results, it is clearly demonstrated that the complete load model has superior performance than two others of capturing load dynamic characteristics.

7 Conclusions

7.1 Summary of Dissertation

Power system restoration is regarded as one of the most important tasks for system operation. With modern power system development, many variable factors have been introduced due to increased penetration of renewables and upgrade of grid complexity. Correspondingly system restoration strategy should accommodate these variable factors to ensure system flexibility and efficiency. As for another topic load modeling, in modern power system environment, there is increasingly desire of delicate load model to fit for accuracy updating of measurement data collected at distribution voltage level. Specifically speaking, the primary contributions of this thesis can be summarized as the following three aspects:

1) *Development of a novel methodology referred as optimal efficiency oriented power system restoration methodology*

   In addition to system security, variable operation time of transmission line is considered correspondingly in the efficiency oriented model. By utilizing it, power system restoration is formulated as a permutation-based combinatorial optimization problem. The optimization objective becomes maximization of restoration efficiency which is defined as available generation capability per unit time. As permutation-based problem is NP hard, advanced quantum-inspired differential evolutionary algorithm (AQDE) with a novel encoding scheme has been exploited. With appropriate control parameters, AQDE has been successfully applied on cases of IEEE 39 and IEEE 118 bus systems. In order to verify AQDE, comparison experiments are conducted with QDE and GA. Finally an optimal restoration schedule with maximum restoration efficiency is obtained, and the information of non-blackstart generator startup time, charging path and generation capability at each restoration stage is provided.

2) *Development of optimal efficiency oriented power system restoration methodology considering load prioritization*

After validation of this methodology, it is applied on load restoration stage. The optimization objective is to maximize load restoration efficiency which is defined as restored load per unit time. In load pickup process, the impacts of service disruption on load loss should be minimized in premise of ensuring electric grid security. Therefore Load prioritization, as one of the key factor influencing load loss, should be taken into consideration in path search process. In practice, transmission path restoration is interconnected with load restoration in the same process. For guiding optima path search, a novel index P_s is proposed combining load prioritization and capacitance. The corresponding modified dijkstra algorithm is proposed to find path with minimum P_s from vertice V_0 to all other nodes. Similarly as previous work, advanced quantum-inspired differential evolutionary algorithm is chosen to solve the permutation-based optimization problem due to its successful application before. The effectiveness of the proposed restoration methodology is validated on case studies of IEEE 39 and IEEE 57 bus systems. Using appropriate control parameters, system restoration cases of IEEE 39 and IEEE 57 bus systems have been successfully solved. Finally an optimal restoration schedule with maximum restoration load efficiency is obtained providing information of non-blackstart generator units' startup time, charging path and restored load capacity at each stage.

3) *Development of a complete load model at distribution voltage level with equivalent capacitor, large motor and small motor*

The load modeling is another important research topic investigated in this thesis. In modern power system, there is an increasing desire of delicate load model with respect to accuracy and computational efficiency for dynamic simulation of power systems. Traditionally, load model is established at transmission voltage level or high voltage level due to the fact that collection of measurement data at distribution voltage level or low voltage level is difficult to obtain. However load model established at transmission voltage level can not fit for the data accuracy of measurement at distribution voltage level as measurement at distribution voltage level captures more accurate load dynamic characteristics. In order to compensate data accuracy difference, a complete load model at distribution voltage level with equivalent capacitor, large motor and small motor is proposed. In order to demonstrate the complete model efficiency, comparison experiments of three load models are conducted. They are respectively the proposed complete load model at distribution voltage level, PowerFactory built-in dynamic load model at distribution voltage level, and composite load model at transmission voltage level which are all established in DIgSILENT PowerFactory. From comparison experiments results, it is clearly demonstrated that the complete load model has superior performance than two others of capturing load dynamic characteristics.

7.2 Future Research Scope

The thesis deals with two essential research topics including system restoration and load modelling in modern power system. Based on the achievements achieved in this thesis, several aspects are considered worthy of further research in the future, including:

1) Even though optimal efficiency oriented power system restoration strategy has been successfully applied on cases of IEEE 39 bus and IEEE 118 bus systems, an in-depth investigation of comparison experiments with existing power system restoration methodologies should be conducted to demonstrate the superior performance of this novel methodology.
2) In aspects of convergence speed and solution quality, advanced quantum-inspired differential evolutionary algorithm still can be enhanced. Moreover the novel encoding scheme should be modified to convert a quantum chromosome individual into a permutation in a direct way to enhance algorithm efficiency.
3) For developing better load model, data collection is the basic work. In measurement-based approach, the quality of measurement data is one of the critical factors affecting results. Thus more efforts for choosing representative monitoring locations and collecting available data should be paid. In parameter estimation procedure, the initial parameter values have important effects on the results. If they are set inappropriately, identified results are local optimum. Therefore, a sensitivity study involving impacts of initial parameter values setting on identification results is required.
4) The generalization capability of the complete load model needs further investigation due to the fact that load model complexity increases by splitting the

induction motor into large motor and small motor. Another research direction is development of efficient optimization methods in order to find optimal parameter values ensuring faster convergence.

Appendix

A. Data of power system generator characteristics

Table A.1 Data of IEEE 39 bus system generator characteristics

Gen	T_c (min)	T_h (min)	T_r (min)	R (MW/hr)	P_r (MW)	P_m (MW)
G30	8	60	120	160	15	1040
G31	4	12	Inf	130	8	646
G32	5	35	Inf	165	9	725
G33	0	Inf	0	132	0	652
G34	3	8	60	124	3	508
G35	4	15	Inf	134	8	687
G36	3	10	60	128	7	580
G37	3	8	60	126	6.5	564
G38	6	40	120	144	10	865
G39	8	60	120	164	15.5	1100

Table A.2 Data of IEEE 57 bus system generator characteristics

Gen	T_c (min)	T_h (min)	T_r (min)	R (MW/hr)	P_r (MW)	P_m (MW)
G1	5	60	120	85	3	575
G2	1	35	Inf	15	1	100
G3	0	Inf	0	21	0	140
G6	1	35	60	13	1	100
G8	5	45	60	82	1	550
G9	1	35	Inf	13	2	100
G12	4	60	60	61	0	410

Table A.3 Data of IEEE 118 bus system generator characteristics

Gen	T_c (min)	T_h (min)	T_r (min)	R (MW/hr)	P_r (MW)	P_m (MW)
G1	8	56	Inf	2	3	100
G4	6	24	120	3	1	100
G6	4	26	93	2	4	100
G8	5	45	Inf	2	2	100
G10	5	39	158	2	4	550
G12	8	15	Inf	2	5	185
G15	4	35	111	2	3	100
G18	5	46	Inf	2	3	100
G19	4	33	104	3	4	100
G24	4	46	Inf	2	5	100
G25	6	56	Inf	2	3	320
G26	6	40	133	2	1	414
G27	7	13	141	2	1	100
G31	8	32	147	2	3	107
G32	6	30	86	2	1	100
G34	4	38	94	2	5	100
G36	4	48	Inf	2	3	100
G40	5	35	89	3	3	100
G42	3	35	Inf	2	4	100
G46	4	55	91	2	3	119
G49	3	23	131	3	5	304
G54	8	53	132	2	1	148
G55	4	39	92	3	4	100
G56	5	39	145	2	1	100
G59	7	37	Inf	3	2	255
G61	6	53	138	3	1	260
G62	6	27	135	3	2	100
G65	8	13	101	2	4	491
G66	6	24	Inf	2	4	492
G69	0	Inf	0	2	0	805
G70	4	58	118	3	3	100
G72	8	16	Inf	2	2	100

G73	6	46	126	3	2	100
G74	6	59	134	3	3	100
G76	6	40	126	2	2	100
G77	8	20	134	3	2	100
G80	4	32	84	3	3	577
G85	4	13	92	2	3	100
G87	5	41	82	3	2	104
G89	5	45	146	2	3	707
G90	7	59	133	2	1	100
G91	3	48	Inf	2	2	100
G92	8	48	Inf	2	1	100
G99	5	47	113	2	4	100
G100	7	47	Inf	2	1	352
G103	8	16	155	2	2	140
G104	3	16	109	2	2	100
G105	5	27	115	2	3	100
G107	4	39	140	2	3	100
G110	7	41	132	2	4	100
G111	3	17	105	2	1	136
G112	6	33	103	2	4	100
G113	5	28	Inf	2	4	100
G116	6	58	134	3	2	100

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