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OPTIMIZAÇÃO DE ESTRATÉGIAS DE DESLASTRE FREQUENCIMÉTRICAS ATRAVÉS DO USO DE REDES NEURONAIS E DE ALGORITMOS GENÉTICOS

"OPTIMIZATION OF UNDER-FREQUENCY LOAD SHEDDING STRATEGIES THROUGH THE USE OF A NEURAL NETWORK AND A GENETIC ALGORITHM"

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Abstract

This thesis describes the approach developed to identify optimal load shedding strategies, with its objective being to minimize the total amount of load being shed, subject to three constraints, to be applied through remotely setting system UFLS relays, for a given operating condition and disturbance. This thesis is solely for analyzing the feasibility of the procedure developed within this work. Defining a complete definition for UFLS relay settings for all system disturbances is considered out of the scope of this work. The procedure utilizes neural networks and genetic algorithms.

The procedure can be broken down into two parts, first, the prediction of a power system's dynamic frequency response during a perturbation, and second, the determination of optimal load shedding strategies in order to achieve a set of system goals.

The neural network was used to make quick and accurate prediction of the dynamic response of a power system during an under-frequency load shedding scenario. Emergency actions in a power system due to loss of generation typically calls for under-frequency load shedding measures to avoid potential collapse due to the lack of time in which to correct the imbalance via other means. Due to the slow and repetitious use of dynamic simulations, the need for a fast and accurate procedure is evident when trying to determine optimal load-shedding strategies. A neural network (NN) seems to be an ideal solution for a quick and accurate way to replace standard dynamic simulations. The steps taken to produce a viable NN and corresponding results are discussed.

The genetic algorithm is used to determine optimal under-frequency load shedding (UFLS) strategies for each type of system operating condition and a given disturbance. In the past under-frequency load shedding has relied on general predetermined schemes to arrest falling system frequency for all system operating points. These schemes were typically not optimal due to their generality and abidance to the same stepped shedding procedure. Within this paper a genetic algorithm (GA) is used to produce the optimal load shedding strategies, according to current system operating conditions, to be implemented afterwards remotely via adaptable UFLS relays. The steps taken to produce this GA and corresponding results will be discussed.

The Terceira Network was utilized for testing and evaluating the procedures developed within this work.

Resumo

Esta dissertação descreve uma metodologia desenvolvida para identificar estratégias optimizadas de deslastre de cargas, para cada condição de operação e perturbação do sistema eléctrico de energia, tendo como objectivo a minimização do valor total de carga a deslastrar e sendo sujeito a três restrições As estratégias identificadas são aplicadas remotamente a partir dos parâmetros de entrada de relés UFLS (*under-frequency load shedding*). Esta dissertação analisa a viabilidade da metodologia desenvolvida no âmbito deste trabalho. A realização de uma definição detalhada para os parâmetros de entrada dos relés UFLS para todas as perturbações do sistema, é considerado fora dos objectivos deste trabalho. A metodologia desenvolvida utiliza redes neuronais e algoritmos genéticos.

A metodologia pode ser dividida nas seguintes duas partes: na previsão da resposta dinâmica da frequência do sistema na sequência de uma perturbação, e na determinação de estratégias optimizadas de deslastre de cargas de modo a atingir um conjunto de objectivos para o sistema.

As redes neuronias (NN) foram utilizadas para obtenção de previsões rápidas e precisas da resposta dinâmica do sistema. Os cenários avaliados consistiram em situações em que são realizados deslastre de cargas na sequência do abaixamento da frequência do sistema. As acções de emergência utilizadas em sistemas eléctricos quando ocorre perda de geração, tipicamente baseiam-se em deslastre de cargas, uma vez que outras medidas levariam ao colapso do sistema por terem acção mais lenta. Sendo os processos analíticos convencionais de simulação dinâmica do sistema de elevado peso computational, tornasse evidente a necessidade de recorrer a outros métodos, que sejam rápidos e precisos, quando se pretende determinar estratégias optimizadas de deslastre de cargas. Por esta razão se utilizaram as redes neuronais. Neste documento são discutidos os passos tomados para obter uma NN viável e respectivos resultados obtidos.

Os algoritmos genéticos (GA) foram usados para determinar as estratégias optimizadas de deslastre de cargas em condições de abaixamento de frequência, para uma dada condição de operação e perturbação. No passado, o deslastre de cargas em condições de abaixamento de frequência baseava-se em esquemas genéricos, pré-determinados de forma a travar o abaixamento da frequência para todos os pontos de operação do sistema. Estes esquemas eram tipicamente não optimizados devido à sua característica de generalização e devido a manterem sempre os mesmos procedimentos de deslastre. No trabalho apresentado, são utilizados algoritmos genéticos (GA) para obter estratégias optimizadas de deslastre, de acordo com as condições actuais de operação do sistema. As acções de deslastre obtidas podem ser implementadas remotamente através de relés UFLS adaptáveis. Este documento descreve os passos realizados para produzir os GA e respectivos resultados obtidos.

A metodologia desenvolvida no âmbito do trabalho apresentado, foi testada e avaliada na rede eléctrica da ilha da Terceira do arquipélago dos Açores (Portugal).

Resumé

Cette thèse présente une méthode développée pour faire l'identification des stratégies de délestage de charges, avec l'objective de minimiser le total de charge à délester, soumis à trois contraintes, et de façon a être appliquée à travers dune fixation périodique, à la distance, des consignes des relais de délestage par minimum de fréquence, pour chaque ensemble de condition de opération du réseau e pour chaque perturbation considérée importante.

La procédure développée peut être divisée en deux étages principales: la première, ou on fait la prédiction de la réponse dynamique du système en termes de fréquence pendant la perturbation, et la deuxième concernant la détermination de la stratégie optimale de délestage.

Un réseau neuronal à été utilisé pour faire la prédiction rapide de la réponse en fréquence du système électrique après la perturbation et après l'application d'une séquence de délestage. Des actions d'émergence sont nécessaires en cas de perte de production et notamment le délestage de charge, de façon à éviter le collapse du système. Une fois que la simulation pas-à-pas est un procédure qui demande beaucoup de temps de simulation, il faut chercher l'utilisation des outils qui permettent obtenir des résultats très rapidement et de façon exacte. Un réseau neuronal est justement la méthode idéal pour remplacer la simulation dynamique complète. Les pas nécessaires à adopter pour cette méthode sont présentés dans la thèse.

Un algorithme génétique a été utilisé pour faire la détermination optimale des stratégies de délestage par minimum de fréquence. Jusqu'à présent le délestage par minimum de fréquence a utilisé une philosophie ou les consignes des relais sont fixés, d'après des études de planification, et reste comme ça pendant des longues périodes, jusqu'à que ont actualise les études. Ces schémas ne sont pas optimales et peuvent mener à des délestage en surplus. Dans cette thèse les algorithmes génétiques ont été utilisés pour déterminer les „*feeders*" à couper, en tenant compte de sa localisation, sa nature en termes de comportement dynamique et de la valeur de la charge elle même. Les pas nécessaires à utiliser par cette méthode sont discuté dans la thèse.

Le réseau électrique de l'île *Terceira* a été utilisé comme ambiance de teste pour la méthode développé dans dette travail de recherche.

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Chapter 1 Introduction

1.1 Initial Remarks

The work being reported within this Master thesis addresses the issue of finding optimal under-frequency load shedding strategies through the use of neural networks (NN) and genetic algorithms (GA). This new approach will be developed to address the remote setting of UFLS relays, as applied to isolated systems with large shares of wind power production.

Throughout the world there are numerous medium size isolated networks, especially on islands, but also in some continental regions where, due to economic reasons, it is not feasible to have interconnections. In some of these systems, the contribution of wind power is playing a more significant role as it provides a cheaper and independent way of producing electricity. However, in these cases, the vulnerability of the system may increase if large penetrations of wind power are foreseen.

Following a system disturbance, such as a loss of a production facility, the identification of effective emergency control measures that prevent system collapse are most important. In the case of a generation-load imbalance, leading to a negative deviation in system frequency, the disturbance must be quickly and effectively compensated by generator frequency regulators, assuming enough spinning reserve is available. If system frequency reaches a given threshold, even for a short amount of time, power stations may trip off resulting in further load imbalance which may lead to a global system collapse, as seen in figure 1-1. When there is a rapid decline in frequency, simple governor response may be neither sufficient nor quick enough to stop the frequency excursion before it reaches the protection threshold of frequency relays in some power plants. Thus, there is a need for a complementary emergency action, namely load shedding, in order to assure that the declining frequency is stopped before reaching this threshold, again as seen in figure 1-1.

The development of this thesis involves research in two domains; prediction of the systems dynamic behavior, and the identification of optimal load shedding solutions.

In regards to the first domain, the dynamic behavior analysis of an electrical network after a disturbance is a very time demanding task. Thus in recent years a large effort has been made toward developing fast approaches to deal with the prediction of system dynamic behavior, using namely neural networks [1], decision trees [2], and regression trees [3]. In this thesis, a NN is proposed to predict the systems dynamic frequency response through the final motivation of trying to identify optimal load shedding strategies.

The need to determine and evaluate the dynamic frequency response of a system during an under-frequency load shedding scenarios is of the utmost importance. Establishing an effective under-frequency load shedding scheme typically hinges on knowing what to expect from a given disturbance, especially in regards to the maximum negative and positive frequency deviations, the residual (resting) frequency, along with the rate of frequency change of the first negative swing. Prediction of these values can be done using machine learning techniques as described in [4]. Obtaining knowledge about the system behavior after a shedding scheme, following a given disturbance will also help in deciding between potential load shedding schemes.

In situations where many evaluations of the system dynamic behavior are needed, like in this case of planning a load shedding scheme, the time taken by full dynamic simulators to perform complete frequency evaluations is overwhelming. Therefore, machine learning techniques are well suited to deal with this problem. NNs are particularly appropriate to do so, due to their ability to map a non-descriptive function (like the one associated with the system dynamic behavior) and to provide a fast response with sufficient accuracy. Their success when dealing with similar problems, for example the prediction of the operation of under frequency load shedding relays [5] is well known.

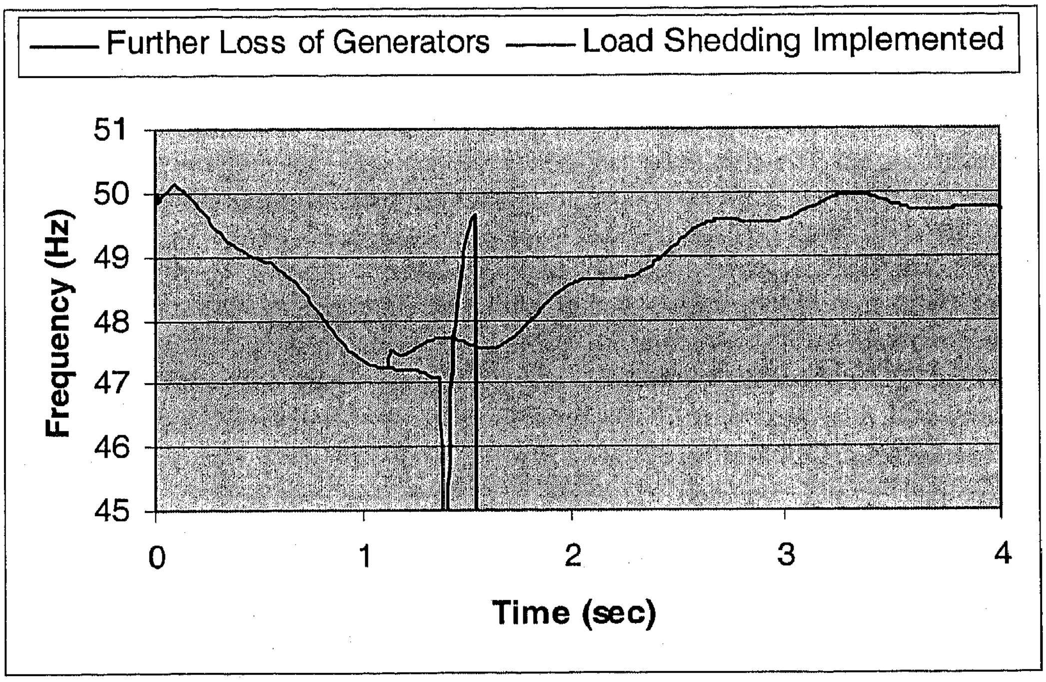

Figure 1-1. System Frequency Response to Generation load Imbalance

Addressing the second domain and main motive of this dissertation, the identification of optimal load shedding strategies takes long man-hours of off-line planning and testing to analyze the system response through a step-by-step simulation, in order to obtain a well-suited comprehensive plan. Due to the overwhelming number of potential shedding schemes the use of a GA approach is an ideal choice to help eliminate most of the time taken to create and evaluate these potential schemes.

Typically load shedding schemes are developed following the same basic design, in which under-frequency relays, at the feeder level, are set to operate at different triggering frequencies and time delays, in order to arrest falling system frequency [6,7,8,9,10,11].

Analyzing the operating conditions and disturbances that may be encountered throughout the system is the first step in developing successful load shedding strategies. After a thorough understanding of the system is attained, the amount of system overload for which the load shedding scheme will be designed needs to be selected. Next an acceptable value for the post-shedding residual frequency threshold of the system needs to be established. This value is of great importance since it not only affects the amount of shedding to plan for but it also influences the potential for further intervention, by manual or automatic system devices.

Since system load and generation are constantly changing to meet new consumer demands, the use of stepping schemes and different relay settings to stop declining frequency "seem" best suited [12]. However, with this type of strategy, once fixed the settings are kept until a new assessment is made and it is determined that a different and "better" scheme is required in order to fulfill new system security and reliability needs. With the onset of a more competitive power market and the need for better system reliability, reliance on these pre-determined load shedding schemes may not be satisfactory. Namely, step type schemes do not consider current system conditions or new topologies, due to growth in system size, nor do they optimize the load shedding selection, assuming instead a worst-case scenario. Therefore, actual scenarios frequently lead to excess load shedding. Utilities would like to minimize the amount of load to be shed therefore the load shedding scheme should change according to the system operating conditions. This means that investigation is needed in the field of defining remotely the settings of UFLS relays.

In order to deal with the optimization of shedding schemes, a one step shedding scheme produces a better frequency response than a stepping scheme, due to its one time bulk shed versus cascade shedding [13]. In this thesis a new approach will be developed to address the remote setting of UFLS relays, as applied to an isolated systems with large shares of wind power production. In this approach two frequency settings are considered, such that the first setting is optimized through the use of the procedure developed within this work and remotely defined. Using the proposed methodology the relays will be sent new settings, "from time to time" according to the new system topologies and loading levels, thus making these UFLS relays adaptable depending on system conditions. The second is kept pre-defined and is to be used as final resource to save the system if the first measures fail. The overall approach can be illustrated in figure 1-2.

The identification of the new optimal relay settings must be done quickly and effectively; thus two new tools working in parallel are needed. The first, a NN, should be able to assess and predict system behavior in these conditions and therefore replace the conventional dynamic simulation. The second, the GA approach, should be able to determine optimal load shedding strategies for any given operating condition, thus eliminating the need for extensive manual load shedding evaluations.

This work done within this thesis has been applied to the Terceira Island (Archipelago of Azores-Portugal). This isolated system provides the needed diversity, with respect to the inclusion of renewable energy resources, and simplicity, with respect to its size, required by this research.

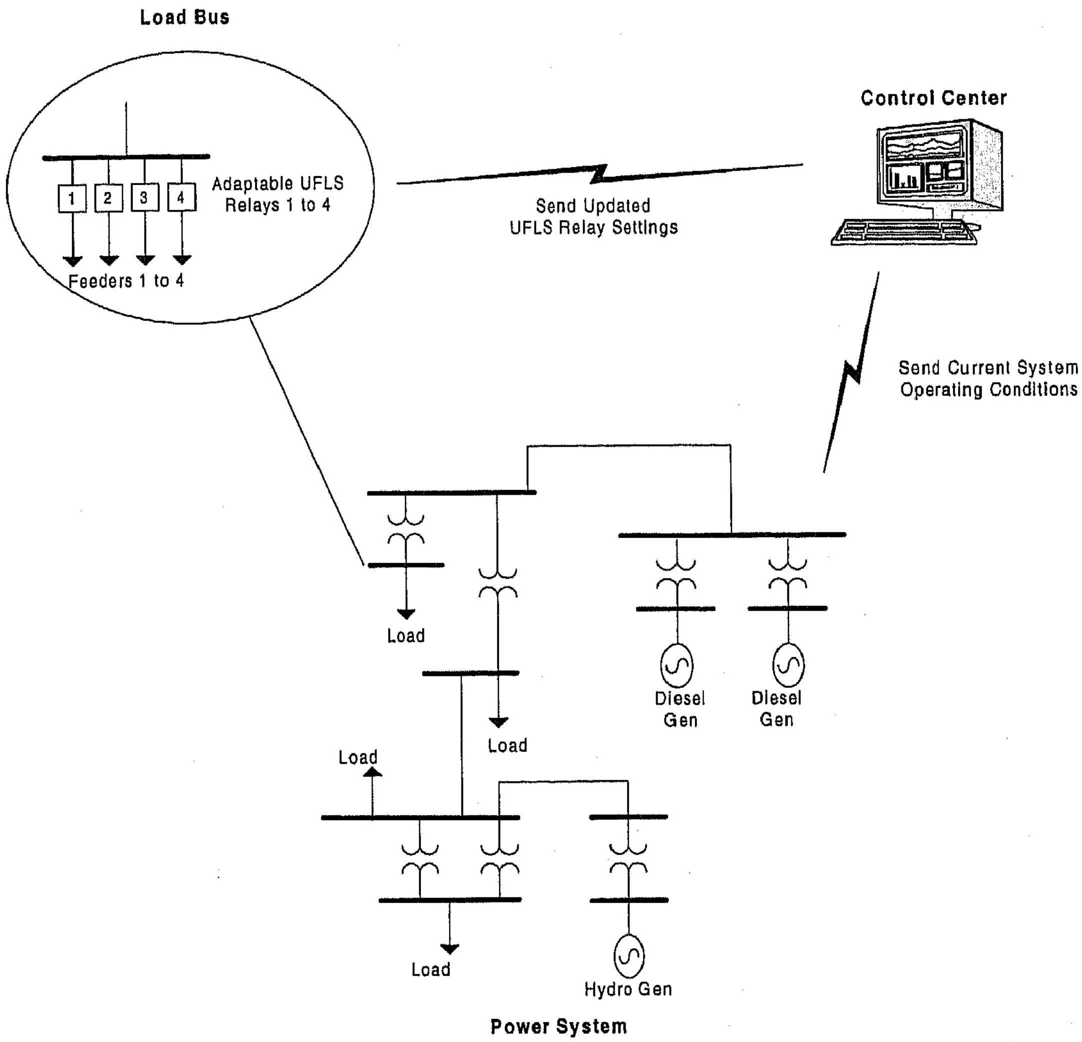

Figure 1-2. System Illustration

1.2 Structure of the Thesis

The work done in this thesis is laid out as follows. Chapter 2 refers to the background and current technologies used in today's power systems in regards to load modeling, load shedding, and the operation of a large isolated system with wind penetration. Due to the dynamic nature of the work done within this thesis, the understanding of how load modeling influences the optimal load shedding selection process is of value. Likewise, understanding the diversity associated with the operation of an isolated system also plays a vital role toward the complete comprehension of the work being performed. Lastly, a firm grasp on the procedures followed in emergency load shedding scenarios is of the greatest importance.

Chapter 3 addresses the new approach that is being developed within this thesis. This chapter also mentions the problems associated with the current procedures used in load shedding and the means in which to improve and modify them through the use of NNs and a GA approach.

Chapter 4 provides detailed information regarding the process used to develop a NN, including input/output variable identification, generation of a data set, architecture selection, and NN evaluation process, in order to generate a NN with the capabilities to accurately predict the dynamic response of a power system during an emergency load shedding situation.

Chapter 5 illustrates the steps taken in determining the appropriate GA, in terms of chromosome representation, operator selection, parameter assignments, and the objective function for calculating the optimal load shedding strategies.

Chapter 6 will discuss the system model used and numerical results obtained throughout this work. This chapter is divided into three sections, Terceira Power System model, NN results and GA results. In regards to the NN results, four comparison evaluations were made to validate the accuracy of the NN. The first comparison was made to determine the effectiveness of NN training utilizing data from each of the two potential data set generators. The second comparison was made with respect to the training and testing procedure of the NN. The third and fourth comparisons evaluate the prediction and generalization accuracy with respect to actual dynamic simulations.

With respect to the GA results, three more analyses were performed. The first evaluation analyzing the GA convergence ability, to assure that the GA can accurately identify the global solution optimal and avoid getting "stuck" in local optima. The second, associates the type of load selected for shedding and its influence on the resulting system response, and hence load shedding criteria. Lastly, an overall load shedding scheme assessment is made to appraise the selection of load shedding strategies created by the GA.

The work done within this thesis is expected to provide logical, extensive, and positive results in all of the aforementioned areas of analysis. Specifically with respect to the NN it will show its capabilities to accurately produce the dynamic response of a power system during emergency load shedding scenarios for any potential operating condition within the Terceira network. In regards to the GA approach, it is expected to produce logical and globally optimal load shedding solutions. Lastly, the advantages and disadvantages different load types have on the system dynamic frequency response will be revealed.

Finally chapter 7 will draw conclusions about the work that was performed and the potential for future work within this area.

Chapter 2 System Modeling and Current Technologies

In order to ensure a full understanding of the work described in this thesis it is important to be familiar with the background, current technologies, and procedures being used in power systems. Since this thesis is addressing a dynamic problem, a complete dynamic model, representative of all system components is needed. This implies that generators, AVRs, governors, and loads need to be included in this model. Since this thesis is centrally developed around load shedding and its procedures, it is of the utmost importance that load modeling is given special attention. Therefore, the first section of this chapter will address current load models, the development of these models, their potential applications in power system studies, and what is needed from these load models in terms of their use within this work.

Selection of an appropriate power system model for this thesis was made according to its size, component simplicity, independence, ease of perturbation implementation without the potential of other problems, and evaluation of its dynamic response. Hence, an isolated power system with wind power production was selected as the model to be used within this work. However, since isolated systems and systems with renewable energy resources involve different operating strategies than conventional interconnected systems, a complete understanding of its operation is needed, in terms of generator dispatching, steady-state operation, power quality, and dynamic behavior.

Lastly, since the focus of this work is on developing optimal load shedding strategies, it is imperative that the procedure is fully understood. Hence, a close look at load shedding objectives, schemes, and requirements will be taken.

The following sections will provide background information on the current technologies in regards to load modeling, load shedding schemes, and the operation of an isolated network with wind power production. Each section will give a brief description of the relevant information available.

2-1 Load Modeling

When preparing studies for dynamic system response the type of models to be used for system devices needs to be taken into serious consideration. In past years, loads have not been given the attention toward accurate representation like other system devices, such as generators and transmission systems [14], due to the difficulty in having a good realistic picture of the system load components. The complexity in classifying a given load into one specific load type has proven to be challenging for many reasons, some of which are the following [15,16].

- Stochastic nature in time;
- Large number of diverse load components at a given bus;
- Uncertainties regarding the characteristics of many load components, particularly for large voltage or frequency variations;
- Ownership and location of load devices in customer facilities not directly accessible to the electric network;
- Changing load composition with time of day, week, seasons, weather, or through time in general;
- Computational and man effort availability.

Another issue addressed in the literature is the exact definition of the term "load" itself. In [14], the author states that an accurate description of a *busload* needs to take into account the effect of tap-changing-under-load transformers, load dynamics (restoration, asynchronous motors, and protections), shunt compensation, along with the variability in available loads to be shed. From this definition it is understood that the load comprises the elements from the distribution level to the load component. The IEEE Task Force on Load Representation for Dynamic Response, states that depending on the level of analysis the term load can include all components from the transmission bus to the consumer, including the substation step-down transformer, sub-transmission feeders, primary distribution feeders, secondary distribution feeders, shunt capacitors, voltage regulators, customer wiring, transformers, and capacitors [16]. As from the two previous definitions the level of detail can be very deep, thus the need exists for an enhanced "relative" load model, according to the problem or system under analysis.

The voltage sensitivity if loads are typically lumped into constant MVA, constant impedance, or constant current loads [15,16,17,18]. Regardless of which of the three voltage dependent models was used they are all only valid for a given range of voltage levels, usually from 0.8 to 1.2 p.u. Outside of this range under- and over-voltage relays are usually activated and the load is lost. The use of these load models indicates that some attention has been devoted toward modeling the voltage dependencies they portray within a limited range. However, very little work has been done regarding load frequency dependencies. Some authors [18] assumed a linear relationship of a one-percent change in real power for every 1 percent changing in frequency, in a frequency dependent load. It has been shown that these load representations create unrealistic phenomena in dynamic simulations and therefore worsen case scenarios in stability studies. For example, purely constant MVA modeled loads cause amplification of voltage oscillations, and, purely constant impedance loads can cause a damping effect on voltage oscillations, which can be a false representation of an actual system response [18]. Thus, the need for a model to more effectively represent system busloads exists.

Since most busloads have more than one type of load connected to them, a collective type of modeling can give a more accurate and realistic view of actual system load. The ZIP model is the most generally used model that takes into consideration the composition of constant MVA, current, and impedance loads but lacks the ability to represent non-constant load types. Evolving this idea further a voltage exponential model can not only mimic the ZIP model but also takes into consideration voltage exponents other than those considered by the ZIP model. Once again, this type of load model is limited to voltage dependencies and does not address frequency dependencies; therefore a voltage and frequency dependent load model is needed. Although these type of models are comprehensive they do not address the presence of motor or thermostatically controlled loads.

In order to get a complete busload representation each of these load types needs to be considered when developing an aggregated busload model. With increased computational abilities and enhanced understanding of load behavior the development of this type of aggregate busload models is the next step to superior system load representation.

One such technology adopted today to determine the appropriate load model is EPRI's LOADSYN software, which has the capabilities to represent real and reactive loads as functions of voltage and frequency [14]. Although EPRI software was used for most of the computational procedures used in this work LOADSYN was unavailable. However, EPRI's Extend Transient Mid-term Stability Program (ETMSP) program provides an ample load model representation. As will be seen the ETMSP load model is comprised of the needed components for accurate load representation in this work. Along with this load model, and its respective components, attention will be given to two methods for determining the load models and their respective coefficient values, component based load models and measurement based load models.

2-1.1 Load Models

2-1.1.1 ZIP Models

A polynomial load expression, commonly known as the ZIP model, takes into consideration the sum of constant MVA, current, and impedance type loads [14,16]. The ZIP model provides a real and reactive power level for busloads, by considering the weighted conglomeration of each of these types of load, as seen in Equations 2-1and 2-2.

$$Ptotal = P_o\left(a1\left(\tfrac{V}{Vo}\right)^2 + a2\left(\tfrac{V}{Vo}\right) + a3\right)$$ **Equation 2-1**

$$Qtotal = Q_o\left(b1\left(\tfrac{V}{Vo}\right)^2 + b2\left(\tfrac{V}{Vo}\right) + b3\right)$$ **Equation 2-2**

Here P_o and Q_o are the original real and reactive loads respectively;

V and V_o are the actual and rated (initial) bus voltages respectively;

a1, a2, a3, b1, b2, and *b3* are percentages coefficient of each load type.

The coefficients for these equations are assigned such that their total needs to sum to 100 percent, for the entire load at the bus to be represented. Although they are highly used in many applications they still lack the needed dependency on voltage and frequency variations to be considered complete models. However, it does establish a base from which further development can begin.

2-1.1.2 Exponential Models

Recognizing the need to consider voltage dependencies when modeling busloads, other than those used in the ZIP model, variable exponential load models were developed [15,18]. This type of load model, as seen in equations 2-3 through 2-6, can not only represent any one of the ZIP modeled loads, but it can also take into consideration loads that have exponents of values other the 0, 1, or 2.

$$Ptotal = So * kp * \left(\tfrac{V}{Vo}\right)^{np}$$ **Equation 2-3**

$$Qtotal = So * kq * \left(\tfrac{V}{Vo}\right)^{nq}$$ **Equation 2-4**

Here S_o is the loads apparent power (VA) at the rated voltage;

V_o is the rated voltage;

kp is the load power factor;

$kq = (1-kp^2)^{1/2}$;

np and *nq* are the voltage exponents for the real and reactive power respectively.

$$Ptotal = Po * \left(\tfrac{V}{Vo}\right)^{np} \qquad \textbf{Equation 2-5}$$

$$Qtotal = Qo * \left(\tfrac{V}{Vo}\right)^{nq} \qquad \textbf{Equation 2-6}$$

Here P_o, Q_o are the real, reactive power consumed at rated voltage;

V_o is the rated voltage;

np, *nq* are voltage exponents for the real, reactive power respectively.

Again, although these types of models take into consideration voltage dependencies, there is no mention of the much needed frequency dependency some loads exhibit.

2-1.1.3 Frequency Dependent Models

In order to completely represent system load, frequency dependency needs to be taken into account. Frequency dependency on active and reactive power is usually represented in static models as in equation 2-7 [15,18].

$$P(V, f) = P(V) * (1 + Kpf * \Delta f) \qquad \textbf{Equation 2-7}$$

Where *P(V)* a voltage dependent power equation

K_{pf} is the frequency coefficient

$\Delta f = f - fo$

$fo = \frac{\partial \theta}{\partial t}$ with θ being the voltage phase angle at each bus.

This type of general equation can be added to any load model currently being used to make it frequency dependent. With this type of equation composition, determined as being the most representative of all types of loads and their respective dependencies, there becomes a need for a standard load model. The same IEEE task force has generated a standard for load models in power flow and dynamic simulation [19]. A standard load model allows the ability to exchange data between users of different production-grade simulators [19]. With a standard in mind the committee proposed the use of a ZIP model along with two frequency and voltage dependent terms for real and reactive powers as seen in equation 2-8 and 2-9 respectively.

$$\frac{P}{Po*Pfrac} = Kpz\left(\tfrac{V}{Vo}\right)^2 + Kpi\left(\tfrac{V}{Vo}\right) + Kpc + Kp1\left(\tfrac{V}{Vo}\right)^{npv1}\left(1+npf1\Delta f\right) + Kp2\left(\tfrac{V}{Vo}\right)^{npv2}\left(1+npf2\Delta f\right)$$

Equation 2-8

$$\frac{Q}{Qo*Qfrac} = Kqz\left(\tfrac{V}{Vo}\right)^2 + Kqi\left(\tfrac{V}{Vo}\right) + Kqc + Kq1\left(\tfrac{V}{Vo}\right)^{nqv1}\left(1+nqf1\Delta f\right) + Kq2\left(\tfrac{V}{Vo}\right)^{nqv2}\left(1+nqf2\Delta f\right)$$

Equation 2-9

Here P and Q are the consumed real and reactive powers at the load;

Po and Qo are the initial real and reactive powers;

$Pfrac$ and $Qfrac$ are the real and reactive fractions of busload represented by this model;

Kpz and Kqz are the real and reactive percent of busload represented by constant impedance;

Kpi and Kqi are the real and reactive percent of busload represented by constant current;

Kpc and Kqc are the real and reactive percent of busload represented by constant power (MVA);

$Kp1$, $Kp2$, and $Kq1$, $Kq2$ are the real and reactive percent of bus load represented by exponential and frequency dependent power of type 1 and type 2;

$npv1$, $npv2$ *and* $nqv1$, $nqv2$ are the real and reactive voltage exponents to the voltage dependent power;

$npf1$, $npf2$ *and* $nqf1$, $nqf2$ are the real and reactive frequency coefficients to the frequency dependent power.

Δf is the change in frequency calculated as $\Delta f = f - fo$

Where $fo = \dfrac{\partial\theta}{\partial t}$

θ is the voltage phase angle at each bus.

The only constraint that applies to this model is that equation 2-10 and 2-11 must be satisfied for real and reactive power respectively.

$$Kpz = 1 - \left(Kpi + Kpc + Kp1 + Kp2\right)$$ **Equation 2-10**

$$Kqz = 1 - \left(Kqi + Kqc + Kq1 + Kq2\right)$$ **Equation 2-11**

With this type of load model established as an industry standard, all studies that are being done using this model can more easily be compared and evaluated. As mentioned in equations 2-8 and 2-9 this type of model may only contribute to part of the bus load, which means that other models can also be included at the bus level to create an aggregate bus load of other types as well.

2-1.1.4 Other Load Types Modeled

The previous formulations consider all but two major components still present in system loads, which are dynamic motor loads and thermostatically controlled loads. Both have a noteworthy effect on the systems dynamic performance depending on the model used. However, since they are not used within this work only a short description of each will be given.

Dynamic motor loads, whether they are induction or synchronous motors, can be modeled in a number of different ways depending on the study to be performed and software capabilities. The difficulty in modeling dynamic motors with an accurate aggregated model is that these models require significant information about the motor(s) under consideration. Typically the simplest induction motor model that can be used is of the first order, which represents the rotor values, armature values, magnetizing inductance, and slip, as seen in figure 2-1.

It is important that the slip be represented in the model in order to take into consideration the motor's dependence on frequency, since slip is calculated as bus frequency minus motor speed [16,19]. In contrast, if synchronous machines are used a second, or even third order model, should be used in order to cover their d- and q-axis, since they also have an effect on the power consumed by this type of machine [20], as seen in figure 2-2.

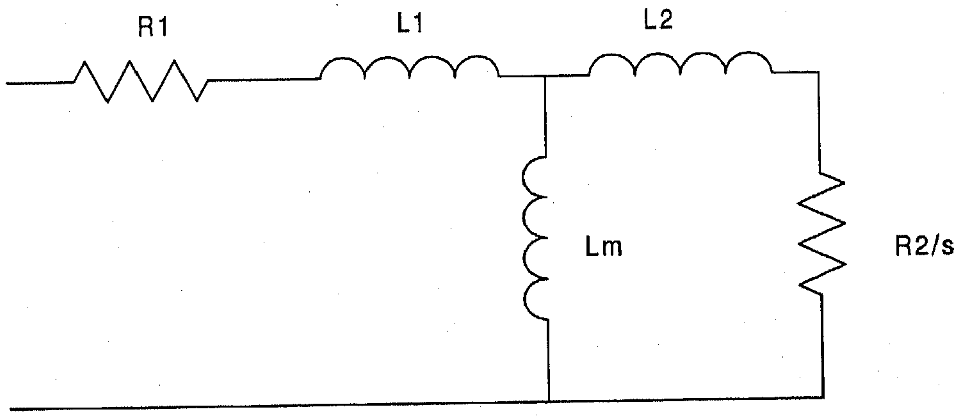

Figure 2-1. Induction Motor Model

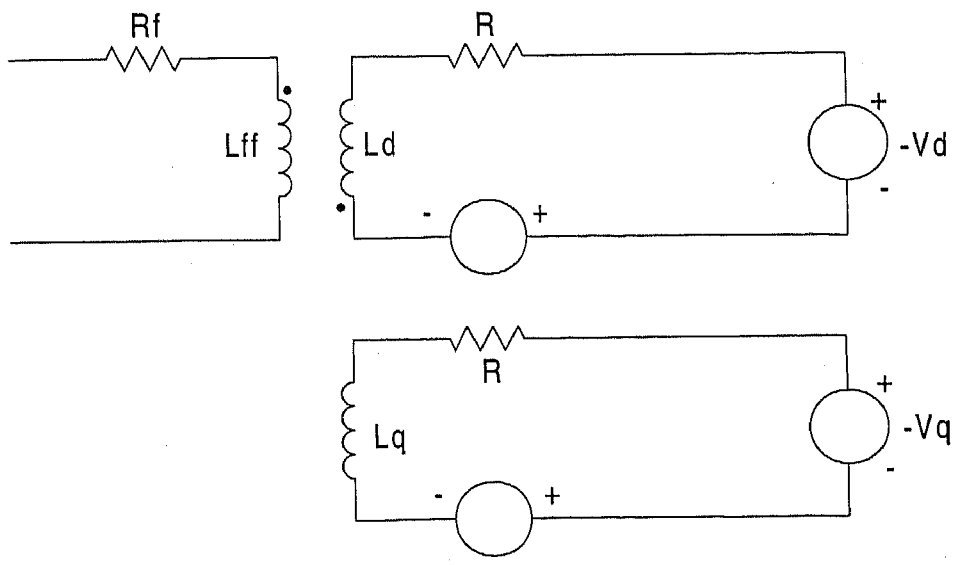

Figure 2-2. Synchronous Motor Model

In regards to thermostatically controlled loads, like space heaters, molding, packing, and soldering machine, are considered constant impedance in short term analyses. This is due to the fact that a rapid change in power does not affect the temperature of the resistive element enough to give it any dynamic characteristics in short term analysis. However, following a sudden voltage drop thermostatically controlled loads sense the change in voltage, consequently the "on" state of the load is extended due to the lower voltage levels, in order to draw the same power. With this type of phenomena the load is typically represented with a differential equation [16].

2-1.1.5 Typical Load Representation

Although it is desirable to get the most accurate representation of all system loads, it is impractical to represent them all in the greatest detail. However, dedicating time to accurate representation of certain loads over others is yet another caveat in the quest for better load modeling. The authors of [21] propose a method that ranks loads into modeling priority, so those loads with the greatest influence on the phenomenon being studied are most accurately represented. In regards to loads that are not of the highest priority, a best estimate as to the type of load they are, is still needed. In order to grasp what type of assumptions are being made in relation to the way specific loads are being represented in power systems a brief description will be made in regards to each below.

Lighting:

System lighting, although numerous in types, can be sufficiently generalized into two categories, discharge lighting or incandescent lighting.

Discharge lighting, makes up almost 20 % of residential and commercial loads due to its widespread use in street lamps. Typically, many different load models represent these types of lighting, however, regardless of the source they all typically represent this type of lighting as an exponential model with active power exponents in the range from 1 to 2 and the reactive power as voltage to the 4^{th}.

Incandescent lights are often assumed to have constant resistive characteristics due to filament structure. However, due to the large temperature swing that occurs in the filament, the active power usually varies at 1.55 power of voltage (half way between constant current and constant impedance) [16]. As can be seen the value of the coefficients associated with lighting is quite varied, thus it is difficult to accurately determine a single coefficient value that considers all of these types.

Motors:

System motor loads, whether induction or synchronous, have sufficient influence on the systems dynamic response. Two elements, which play a vital role in determining active and reactive power responses to voltage and frequency fluctuations are motor inertia and rotor flux [16]. These variables need to be present in the motor load model, to accurately capture their true dynamic behavior. However, detailed motors models are seldom available in dynamic stability software, and a worst case scenario is often used to represent motor loads as constant MVA [19].

Thermostatic Controlled:

The proper modeling for these types of loads can be a difficult task for many reasons. First, they are usually dependent upon the weather and time of day, however, they are typically represented by one of two worst case scenarios depending on the type of study being performed. For long term analysis they are often represented by a constant MVA, otherwise they are usually represented as constant impedance. It is important that some sort of representation is used to model them since they typically make up 20 to 40% of system load [16].

Other equipment:

Although the range of equipment addressed here, as "other equipment", is great, only a simple overview is provided to fill in the gaps. Electronic drives such as computers, microwaves, and TVs typically have DC power supplies and are represented by constant MVA down to 90% voltage. Adjustable speed drives, also shut down at around 90%, and are effectively constant MVA, due to their frequency independent real power part, which usually results in a negative contribution to system damping. For loads with frequency dependence it was found that standard linear models for active and reactive load power [14,16,19] could represent them. Some types of industrial equipment like dryers and heat pumps can be considered constant impedance loads [14].

2-1.2 Component Based Approach

As mentioned earlier, there are two ways to determine the load models and their respective coefficients. The first is the component-based approach, which determines the load model and its respective coefficients. This is achieved by taking into consideration the dynamic behaviors of all individual load components that can be found at a given load bus [22,23] and making an aggregate model that represents all those taken into consideration. Before further comments are made, a few definitions are provided to avoid confusion between terms. The following terms have been defined from [16].

- Load Characteristic- a set of parameters, such as, power factor, variation of P with V, etc. that characterize the behavior of a specified load.
- Load Component- the aggregate of all devices of a specific or similar type, such as, a water heater, a room air conditioner, or fluorescent lighting.
- Load Type – a classification of load components, such as, constant MVA, constant impedance.
- Load Class- a category of load, such as, residential, commercial, or industrial.
- Load Class Mix- a fractional composition of the busload by load classes.

Specific load classes are usually established to aid in the classification of this component based approach. Combining system load components into one of three possible classes, residential, commercial, or industrial, helps pinpoint the overall class load models. Due to the relative consistency of load types found in a given class, these class identifications can more accurately categorize actual system load. For example, discharge lighting comprise much of a residential area due to its use in street lamps. From here, busload feeders can then be composed of a load class mix. However, this type of approach relies on the assumption that individual load components already have a load model. For example, discharge light can be studied to determine its load characteristics and an appropriate model can be assigned. Once each load component has a settled load model the aggregation of each of these models can take place and a total load bus model can be developed.

2-1.3 Measurement Approach

Another way to accurately represent loads is by installing measuring devices at buses where loads are to be modeled [15,16,17,22,23,24] to take actual system measurements. This measurement approach provides valuable information regarding load reaction to given changes in voltage and frequency. Currently some utilities have been developing methods to gather this data [25,26]. The devices used to collect system data are commonly referred to as "disturbance monitors" [16]. These monitors observe bus voltages and currents continuously with a central computer storing the data for future use. Among other potential uses, this data is used to form accurate model structures and estimate their respective parameters, which provides an inherent advantage to this method since the real system data is used to determine load model structures and parameters. However, there are some drawbacks, for one, these parameter values can only be applied to loads that are considered similar, therefore with diverse load components many different models would be needed. Second, the consideration as to a wide range of actual frequency and voltage deviation may be impractical, and "time" factors are also neglected [16]. Some studies have been done on voltage drops of over 25% to 75% to study load response and within this study loads were modeled as aggregated load classes [27].

2-1.4 System Modeling

Once all applicable load components are assigned a given load type model, and categorized into a resulting load class model, an overall load class mix model can be given to the busload from the resultant combination of these classes. This can be achieved by using equations 2-12 and 2-13 [14].

$$Kj = (Xaj * A + Xbj * B + Xcj * C)/100$$ **Equation 2-12**

Here, K_j is the percentage of load type j;

X_{aj} is the percentage of load type j in the a load class;

A is the percentage of the respective load class;

X_{bj} is the percentage of load type j in the b load class;

B is the percentage of the respective load class;

X_{cj} is the percentage of load type j in the c load class;

C is the percentage of the respective load class.

$$Xz = \sum_{j=1}^{N} (PFj * Bj * Yzj)/100$$ **Equation 2-13**

Here, X_z is the coefficient for the aggregate load in the class;

PF_j is the power factor of load type j;

B_j is the percentage of load type j;

Y_{zj} is the coefficients for the load type j.

Using equation 2-13 each load component can be aggregated into a load class. Likewise, equation 2-12 can be used to determine the coefficients of the overall busload, equation 2-8, from these load classes. From this aggregate bus load model a complete load modeling scheme can be developed for the entire system to accurately reflect its dynamic response.

2-2 *Load Shedding in Power Systems*

It is inevitable that for one reason or another any power system will need to take emergency action in order to avoid system collapse. One such action taken by power systems today in order to avoid collapse from declining frequency is load shedding. Under-frequency load shedding can be simply defined as:

> *An emergency action, which removes system loads in an attempt to restore the generation-load balance, in order to arrest falling system frequency and ideally recapture the nominal system frequency.*

The following are some examples of load shedding and the resulting outcome.

- In the summer of 1981, England's power system was islanded caused by inadequate tree clearance, resulting in a cascading line tripping. Load shedding was implemented after a fall to 47.3 Hz in order to recover the frequency decline and save the system from collapse.
- In Brazil in 1996 (60 Hz nominal frequency), a bus differential protection misoperation led to a cascade of line tripping, activating an emergency scheme that created an island within the system. Within this island, frequencies reached 55.25 Hz, thus activating load shedding schemes in order to return the island frequency to 58 Hz. However, the load shedding within this island caused an over voltage, tripping transformers and generator groups, which culminated into a system collapse after 12 minutes.
- In Italy, in 1994 the southern area was importing 2000 MW from the North-Center and 300 MW from Sicily. Two of the four lines between the North and South were lost due to a short circuit. Load shedding was implemented but lower than expected, thought to be caused by low voltage and hence a blackout resulted from this inadequate shedding.
- In Malaysia, in August of 1996 a stuck breaker pole led to generation losses and a frequency drop of .9 Hz in 3 seconds. Gas turbines with "free governor" picked up rapidly but tripped out due to temperature limits or "flame out" causing further loss of generation to 2143 MW. When an insufficient scheme shed only 1580 MW a blackout occurred within 16 seconds of the initial incident.

The previous examples illustrate a few cases in which under-frequency load shedding was implemented due to a system disruption. Typically under-frequency load shedding is needed when a power system disruption creates a generation-load imbalance resulting in a frequency decline, in order to avoid system collapse. The effect that declining frequency has on the system, the way in which the system influences the declining frequency, and the way in which load shedding schemes are created and implemented is the focus of the sections that follow.

2-2.1 The Need for Load Shedding

Even before system collapse, a lot is at stake should the continuation of less than nominal frequency occur throughout the system. The frequency level of the system affects all system devices. However, system generators are the reasons why load shedding is needed, and, is addressed in this section.

2-2.1.1 Pre-Load Shedding

In order to clarify the terms used within the next section, the following definitions will be made in reference to frequency.

- Nominal frequency - is simply defined as the systems steady state operating frequency, typically 50 Hz or 60 Hz.
- Residual frequency - can be defined as the frequency at which the system rests at after a load shedding scheme has been implemented. Note that this may not be the nominal operating frequency.
- Maximum frequency swing - is defined as the maximum negative, or positive, frequency excursion experienced by the system following a disturbance.

Following a loss of active power generation, system frequency will begin to decline until proper system action occurs in order to arrest the falling frequency. In large power systems, small isolated islands can appear with swift frequency decays, along with decreases in voltage at buses where generation loss has occurred, due to reactive power deficiencies. These voltage excursions can further affect the rate of frequency decay and hence the load shedding scheme [6]. In large interconnected systems the need to know the location of the disturbance is imperative to ensure that correct measures are taken. Therefore, voltage measurements can be taken in order to help identify where the disturbance has occurred. Extensive interconnected power networks have shown that a disturbance can set up a frequency wave which takes seconds or more to progress from one extreme to the other [7].

The derivative of system frequency is also greater in areas closer to the disturbance than in areas further away. Therefore, the rate of frequency decay can also be used to determine the severity and location of the system disturbance [9]. However, due to the relatively close proximity of all devices in isolated networks the rate of frequency decay as well as the frequency can be considered uniform throughout the network.

If the frequency reaches a given threshold, even for a short amount of time, UFLS relays at the power station may open resulting in further disruption, which could lead to system collapse. Sometimes, because of the rapid decline in frequency, simple governor response is neither sufficient nor quick enough to stop the frequency excursion before it reaches this threshold. When the system is operated at less than nominal frequency, generators operate under strained conditions. First, generators begin to decrease their speed, thus, not only contributing to further decline in system frequency but also decreasing their ability to handle thermal loading, due to lack of cooling abilities associated with this decrease in generator speed. Even if the decline is halted, it may still be the case that AGC alone might not be able to return to nominal frequency due to governor limits for certain units. Thus the need for means of correction to ensure that the resulting residual frequency be sufficient in magnitude in order to avoid additional problems.

Another problem seen by generators is the potential for over-excitation, caused by a decrease in system voltage, which usually are closely coupled to falling frequency. However, this type of disruption is unlikely as a result of the "usual" installation of over-excitation limiter within the generator exciter controller. These limiters not only prevent over-excitation problems, but also tend to limit generator current, thus limiting thermal excursions above rated values.

Lastly, the decrease in frequency can lead to loss of generator and turbine life caused by vibrations. As seen from figure 2-3, we can see that generators can take a limited exposure to decreased frequency [28] (for machines operating at 60 Hz nominal frequency).

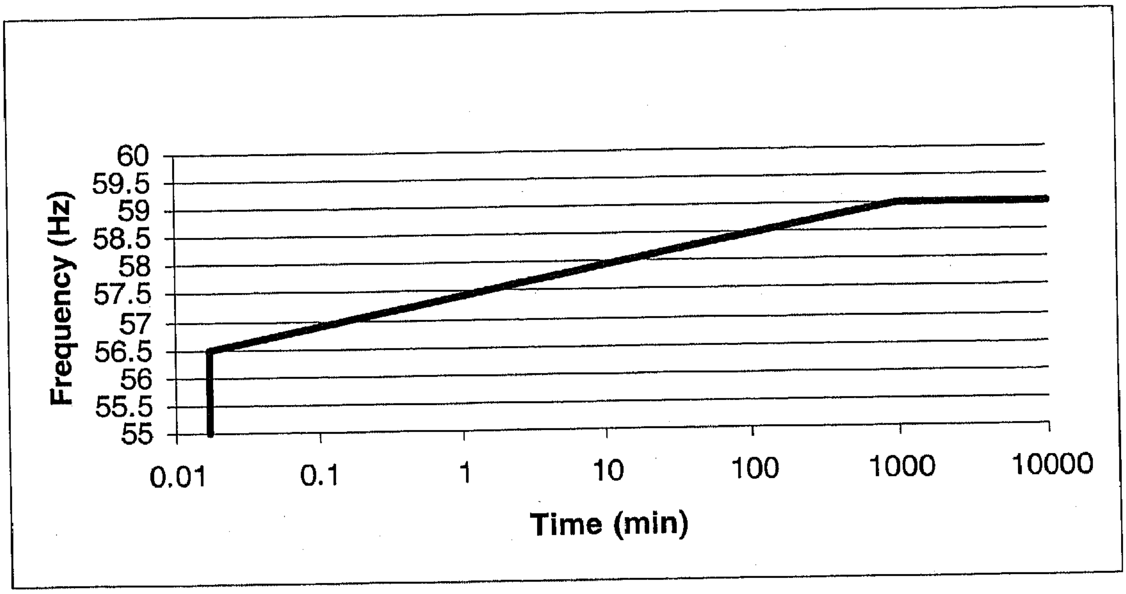

Figure 2-3. Frequency vs. Turbine Life

From this figure it can be seen that generator units can operate at a residual frequency of 58.5 Hz for a limited time, in this case ten minutes or less. However, tests have shown that the power plant only reduces power output for frequencies below 53-55 Hz, [6,9,10,11]. From each of these effects comes a potential for over-excitation, over-thermal, or under-frequency relays to be activated causing further system disruption that may lead to system collapse. Thus, the importance of an efficient, effective, and swift load shedding scheme can be seen.

When disturbances are large in magnitude the speed at which the frequency declines is too great to wait for a response from Energy Management Systems (EMS) and therefore a prompt shedding scheme needs to be available to arrest frequency before further disruption or potential collapse occurs [7]. This also implies local independent UFLS actuation on the basis of local frequency values.

2-2.1.2 *Post Load Shedding*

The need for load shedding in power systems in order to avoid the aforementioned problems along with the preservation of system security is quite obvious. Although load shedding is usually effective, problems can arise due to ineffective shedding, which can lead to a system collapse anyway [6]. Some of these problems are listed below:

- Insufficient load disconnection by under-frequency relays in an island;
- Non-uniform shedding throughout the system, leading to high line flows and voltage problems;
- High voltage due to inherent drop of reactive load;
- Excessive load shedding causing inconvenience to the consumers;
- Oscillatory behavior following shedding;
- Unnecessary shedding during a power swing or similar disturbance;
- Load shedding not occurring in the desired sequence;
- Load shedding leaving a slight imbalance, keeping frequency below nominal and leading to loss of equipment life.

These issues need to be considered when developing an effective load shedding scheme, along with the ones already mentioned, in order to avoid further system generation losses. With respect to the last point in the list above, it may be the goal of the system planners to perform load shedding such that the residual frequency will only return to a planned threshold less than nominal. In which case, the corresponding power system will need to have sufficient spinning reserve available to compensate for the imbalance and return the residual frequency to nominal. Another issue to consider after a disturbance and load shedding has occurred is that the generator be operated via governor control and not manually controlled [11,12]. This is due to the fact that if the post disturbance residual frequency is less than 50 (or 60Hz) then it is imperative that manual action does not take place to try and restore generator frequency to nominal, to avoid conflict with AGC control settings or emergency governor control settings. It should be noted that during a perturbation, emergency settings should be used to determine generator output, since economically determined AGC settings may not provided the needed output from a given generator. This relates to the fact that since the power plant is essentially blind to the rest of the system at this point, with respect to other unit set points and their course of action toward frequency correction, therefore an unadvised change in generator frequency can lead to potential cascading and system collapse due to the following reasons [11]:

- Increased power output of unit attempting to re-establish frequency;
- Decrease power output from other units under governor control;
- Consumption of spinning reserve of a unit being regulated by AGC;
- Transfer power on the transmission lines;
- Possible automatic transmission line re-closer in areas that are nearing synchronism;
- Possible automatic load restoration.

As it can be seen by the previous list, it also imperative that following a shedding scenario generator control should be performed by their respective governors.

2-2.2 System Parameter Response and Influence to Declining Frequency

As already mentioned, when a loss of generation occurs in a power system, for any reason, the need to restore the load generation balance is paramount to system operation. The response of the power system to a frequency decline needs to be understood in order to judge how these influences will affect the steps taken in preparing a load shedding scheme. System factors that affect the way in which the system responds are:

- System topology;
- Size and location of the disturbance;
- System stiffness;
- System inertia;
- Gain and time constants of primary frequency controllers;
- Load damping coefficient.

System topology plays a significant role in power system response for any type of disturbance. Determining where the system may separate when disturbances occur is one key that aids load shedding planners to determine the best schemes. Where there exist islands that are unable to provide the needed amount of generation to correct the imbalance in time before a total collapse, load shedding is an essential tool for saving the power system from collapse due to large frequency excursions.

When considering a loss of generation disturbance the amount and location of this generation loss greatly influences the systems response and potential need for load shedding. If a generation loss is small in magnitude the maximum frequency swing will be quite small and the slope of this swing will be relatively flat. Therefore the resulting dip in frequency will typically not be enough to activate system under-frequency relays, and governor response can typically restore the load-generation balance, provided that spinning reserve is available. However, when generation losses increase in size the related rate of frequency decline and maximum dip also increases, thus leading to a direct correlation between frequency swing and initial frequency slope to the disturbance magnitude.

The location of a disturbance plays an important role only in large interconnected systems. In large interconnected systems, frequency declines takes time to propagate throughout the entire interconnected system. The time delay associated with this propagation can be referred to as system stiffness or transmission elasticity. Within an interconnected system there are many tie lines that provide power to all parts of the system. The amount of energy "stored" within these lines at any moment is considered to be transmission elasticity. This stored amount of energy in the tie line can provide a delay in the declining frequency propagation from the disrupted area of the system to areas not yet affected by the disturbance [7]. System stiffness can also include the generator turbine shaft, which also exhibits a stiffness coefficient [29], however this is not within the scope of its meaning taken within this text. This elasticity phenomena, is best seen with a two area example.

Consider that area 1 and area 2 are adjacent areas and part of a vastly interconnected power system, each having multiple generation facility and load sites. Should a disturbance occur in area 1 the frequency would decline more rapidly within its physical area boundaries. The frequency within area 2 would also start to decline due to their interconnection but at a slower rate, again due to the physical distance from the disturbance. Assume that the disturbance is great enough in magnitude to warrant an emergency load shedding action. Since the frequency falls faster in area 1 the shedding scheme within this area would be activated first. Again assuming that this shedding is great enough to arrest the frequency, however, due to the slow propagation of frequency the effects of this scheme may not be seen in area 2 until after it has already initiated its load shedding scheme to arrest the frequency decline which it sees. Therefore an overlapping of shedding has occurred resulting in over-shedding. The need to avoid this phenomenon is one reason why interconnected systems must have good planning coordination. In an isolated or islanded system, location of the disturbance plays almost no role toward the frequency effects, due to the close proximity of all devices to one another, thus creating an instantaneous propagation of frequency [7,9,10,11,28,30].

Power system inertia is one of the biggest factors that need to be taken into consideration when observing system frequency response. Power systems with large amounts of inertia take longer to respond to frequency fluctuations due to their "heaviness" in nature. Therefore, they tend to reduce the maximum frequency excursion. However, they also require greater control action to arrest frequency declines. Systems with small amounts of inertia can more quickly adapt to changing frequency and make the needed alterations to correct system frequency, although they are more prone to greater frequency deviations [28,29].

With the inclusion of governor action in power systems some declines can be handled more easily by the available spinning reserve than other larger disturbances. The ability for a generator to increase its output power, in order to aid in the correction of falling frequency, depends on the amount of spinning reserve that generator has, control setting sensitivity (speed droop), load variation, and the system energy time constant [9]. When a generator's governor senses a frequency decline, the appropriate recourse is taken to attempt to stabilize and restore the frequency to nominal. Usually the generator set points are determined by the system AGC [12], however, during an emergency condition, governor control should not be economically determined, thus supplemental control should take over [9]. The authors in [9] suggest that the influence of spinning reserve and governor action able omitted when developing load shedding schemes, since spinning reserve tends to reduce the amount of excess-load. However, its inclusion provides a more realistic view of the power system response.

The governor's droop influences how much the generator will contribute to the correction of the frequency decline. Although the droop setting has an effect on the frequency swing and resting frequency it should be noted that it has no influence on the initial rate of decline, due to its delay in actuation. However, changing the values of the droop characteristic can have a significant influence on the system frequency. Droop settings are usually in the range of 0.05 to 0.1. Considering these setting values, it has been shown [28] that increasing the droop from 0.05 to 0.1 not only increases the maximum frequency swing but also lowers the resting frequency. In isolated systems, another factor that influences governor action is its integral time constant, which contributes to the speed at which the generator converges to zero deviation in residual frequency. Increasing this parameter influences the time in which the governor responds to the frequency decline [28]. However, in interconnected or large isolated systems, governors are under AGC control and therefore the integral time constant is not used locally.

System damping is another consideration to take into advisement when planning a load shedding scheme. This system coefficient influences the amount of load change for a given amount of frequency change. This is best seen by equation 2-14. [28]

$$\Delta P_L = D\Delta\omega \qquad \textbf{Equation 2-14}$$

Here, ΔP_L is the change in system load;

D is the system damping coefficient;

$\Delta\omega$ is the change in system frequency.

This damping coefficient is also representative of the generator and turbine influence. Performing a simple mathematics manipulation of this equation it can be seen that the greater the damping factor the less the change in system frequency when a changing load disturbance occurs.

2-2.3 Load Shedding Schemes

In the past load shedding schemes have been integrated as a last ditch effort to keep the system from collapsing during a frequency decline. These shedding schemes have relied on general predetermined scenarios to arrest falling system frequency for all types of system operating conditions. Deciding which scheme is best for the systems emergency situation takes long hours of planning and testing to develop a well suited comprehensive plan. For an under-frequency load shedding scheme to be most effective, the location and magnitude of all generators and load is needed, however, during emergency situations there is not enough time to access all of this information and make manual or even central EMS decisions. When developing load shedding schemes the following points need to be taken into consideration [6,15,28]:

- Compatibility with adjacent systems and their respective shedding schemes in order to spread the shedding equally among them;
- Recognition of potential islanding in an interconnected power system;
- Self effective scheme, should the area be isolated from the remaining system
- Fast activation, in a period of cycles in order to provide a rapid response;
- Minimum permissible frequency in the island, usually determined by thermal generator units;
- Avoid any over-shedding in order to limit over-frequency operating conditions, which could in turn cause further disruption;

Typically load shedding schemes are developed following the same basic design, as will be described in steps 1 thru 4.

1. Conditions and disturbances that may be encountered throughout the entire system, and any post-disturbance island that may form, are examined in which load shedding may be required. This can be a difficult task since system generation, loading, spinning reserve, and renewable energy penetration, are constantly changing for a given scenario. Defining these scenarios helps decide the second step in the procedure.

2. Determine the amount of system overload the load shedding scheme will be designed to handle [7,9,30]. This is needed in order to estimate the amount of load to be shed. One of the following equations, 2-15 or 2-16 [9], can be used to determine the system overload.

$$\%Overload = \frac{Load - \sum Unit\_Loading}{\sum Unit\_Loading} * 100 \qquad \textbf{Equation 2-15}$$

$$\%Overload = \frac{Generation\_Loss}{\mathrm{Re}maining\_Generation} * 100 \qquad \textbf{Equation 2-16}$$

3. The residual frequency the system should return to after shedding, needs to be established. This value is of great importance since it not only influences the amount of shedding to plan for, but it also influences the potential for further intervention, by either the system (automatically) or by its operators (manually). Many utilities determine this value in accordance with the expected time of activation and amount of spinning reserve.

4. Lastly, since system load and generation are constantly changing to meet new consumer demands it is difficult to have one optimal set point for all potential disturbances [12]. Therefore, the use of stepping schemes (different relay settings) to stop declining frequency is best suited, since it is more likely to closely match the amount of load shed to the size of the disturbance being experienced. Determining the number of steps and the range of frequency settings needs to be established. As mentioned earlier, the size of a disturbance directly influences the maximum frequency deviation. In order to determine these frequency settings, a few calculations need to be made prior. First the expected total amount of load to be shed needs to be concluded, as seen by equations 2-17 and 2-18 [7]. Equation 2-17 assumes that there is sufficient spinning reserve to meet the remaining system load and losses, while equation 2-18 does not.

$$\sum P_{LS} = \Delta P_G - K\Delta f_{SS} \qquad \textbf{Equation 2-17}$$

Here $\sum P_{LS}$ is the required amount of load shed;

ΔP_G is the generation lost;

K is the systems stiffness;

Δf_{SS} is the desired steady state frequency after load shedding.

$$\sum P_{LS} > (\Delta P_G - SR) + (\Delta P_G - K\Delta f_{SS}) \qquad \textbf{Equation 2-18}$$

SR is the amount of spinning reserve.

After the total amount of load to be shed is settled, the number of steps and the corresponding frequency settings and delays needs to be fixed. Determining the number of steps and when to activate them is the most important step in developing these schemes. One of two positions can be taken. Either shed large amounts in few steps, or shed small amounts in more steps. Each has its advantages and disadvantages. Regardless of which method is adopted, there are a few considerations common to both procedures that need to be addressed.

First, it is important that the steps are far enough apart to avoid overlapping, as mentioned in the multi-area example. This can be achieved by intentional or inherent time delays in the relays or by sufficient gaps in the frequency setting [8]. The rate of change of the frequency decline is often used to determine the delays used for the shedding relays [10,12] and gives an indication as to the size and location of the disturbance being experienced. Therefore as mentioned prior, sharp declines in frequency indicate larger magnitudes of imbalance and close proximity to the disturbance, thus the need for rapid action. Implementing relay time delays dependent on the rate of change of frequency increases the speed of relay operation. A low rate of change in the frequency decline would increase the delay in relay operation in the hopes that shedding could be avoided by some other means of system intervention, such as governor response.

Second, in regards to the frequency setting of the first relay, the sooner the shedding is initiated, the faster the declining frequency will be arrested. However, if the frequency setting is too close to nominal it may cause undue shedding in times of severe frequency swings, yet not substantial enough to be considered emergency conditions where shedding is warranted [8]. Typically the initial frequency setting is in the range of 59.5 to 59 Hz [28], for systems with 60 Hz nominal frequency. Sufficient time delays can also be employed to avoid undesired tripping in severe but not emergency situations.

Returning now to the advantages and disadvantages inherent to step size and number. First, bearing in mind that in accordance with the initial frequency setting the faster the needed amount of shedding is implemented the faster the frequency will recover.

With this in mind the advantage that fewer large steps have over many small steps can be evaluated. Since fewer large steps activate shedding in larger amounts this makes for rapid recovery of frequency. Larger amounts of load and fewer steps also require less hardware to utilize, lowering the cost as well. However, the disconnection of large amounts of load in fewer steps has a drawback, because there is a greater potential for over-shedding.

Smaller amount of loads spread throughout more steps leaves more room for better matching the load shed to loss of generation. However, the more steps needed to shed the required amount of load, the greater are the maximum frequency swing and the more delay in frequency restoration. In addition implementing a higher number of steps requires higher cost associated with the installation of relays.

In view of all the aforementioned information it seems that a combination of the two schemes would be most beneficial. Using larger steps will quickly halt frequency decline and using small steps will minimize loads to be shed and aid in stabilizing the system. Most systems employ 3 to 5 steps, designed to that the amount of load shed on the first step is less than any other step [9]. However, typically these values are partially determined by utility pool agreements, system operating rules, settings of large generating units within the system, etc. Other points to be addressed, which play significant roles in determining the shedding scheme, are the post-shedding state of the power system and the selection of loads to be shed. An optimal load shedding scheme will find the best steady-state stable operating point for a post-fault system with minimum amount of load to be curtailed [31]. In regards to load selection, as mentioned in the previous section, extensive load modeling has been neglected and therefore its influence on the shedding scheme does not currently play a role in shedding selection. Rather loads to be shed are determined on economic and priority reasons alone. However, as will be pointed out in chapter 6, this is not the case within this work. Once all of these values are determined a viable load shedding scheme can be designed.

The type of procedure just discussed, in steps 1 to 4, works well for most load shedding cases and will be referred to as the "standard" procedure. However, there are a few situations where this type of procedure lacks sufficiency. One of which is in regard to returning the system frequency back to nominal, in the case of non-nominal residual thresholds values. However, as mentioned prior it may be the design of the scheme to only return to a given threshold and allow other system devices to make the final residual frequency correction. The main objective of the standard procedure is to stop the declining frequency before it reaches dangerous levels, and not bring frequency back to nominal values. Leaving the power system at values other than nominal for extended periods of time is as equally dangerous to system devices as a harsh frequency excursion. Therefore some systems adopt additional procedures to address the issue of returning frequency to nominal. One such procedure implements EMS to shed the exact amount needed for the given disturbance along with the location of the disruption [7].

Another way in which system return frequency to nominal following disruption, is through manual intervention to initiate more generation, through cold or hot start-up, or more load shedding if the system has an inadequate spinning reserve. As is the case with some of the scenarios addressed within this work.

The second situation, which causes difficulty for the standard procedure, is in the case of multiple losses of generation at different times, usually due to delayed operation of power plant breakers when falling frequency occurs. During the first drop, load is shed according to the predetermined settings of the standard procedure. Once this occurs the frequency will begin to recover and the rate of change of the frequency (df/dt) value will become positive. If subsequent action occurs, the relays will not operate until after the frequency falls below the already tripped settings causing a slower system recover. The authors of [12] have proposed a procedure that adapts the relay settings, so quicker action can be taken in multiple outages situations. When additional drops are found, relay settings are reset based on the difference between the last frequency local maximum and local minimum. With their proposed scheme, the relays that have not been tripped will be reset to update values and when subsequent frequency decline occurs the relays remaining will activate quicker to establish a faster system response [12]. These authors also propose a parallel operation of under frequency governor control that sets the governors to their maximum output to quickly initiate the needed spinning reserve in an under frequency situation.

However, step type schemes do not consider current system conditions or new topologies due to growth in system size, nor do they optimize the load shedding selection but rather assume worst case scenarios and thus excess loads may be shed. With the onset of a more competitive power market and the need for better system reliability reliance on these pre-determined step load shedding schemes will not be satisfactory. Utilities would like to minimize the amount of load to be shed, therefore the load shedding scheme should change according to the system operating conditions. This means that investigation is needed in the field of defining remote settings of UFLS relays.

In order to deal with the minimization of the load curtailment, a one step shedding scheme produces a better frequency response than a stepping scheme, due to its one time bulk shed versus cascade shedding [13]. The identification of the new relay settings must be done in a fast way, thus a new tool able to assess and predict system behavior in these conditions must replace the conventional dynamic evaluation.

2-3 *Isolated Power Systems with Renewable Energy Resources*

Throughout the world, electrical power is an essential need for the development of any society. Isolated power systems are stand-alone networks that are too distant, typically due to rough terrain or sea, making it too expensive to set up transmission lines in which to fully integrate into a larger network and need to be handled with awareness.

With the current concern regarding the depletion of fossil fuels, the need for an alternative energy source has become a major focus of research in industry today. One of the most attractive forms of energy production is through the use of nature's natural forms of energy like wind, solar, and hydro. Although some forms of renewable energy production are mature enough and have been integrated into power systems today, they still need complementary research in the areas related with the integration and operation.

Isolated power systems are naturally weak systems and need to be treated with care due to increased complication with planning and operation. Since isolated power systems usually employee gas or diesel generating units their operating costs are typically high, due to the need to import fuel [32,33]. When considering these two issues, the need for other efficient and cost effective forms of energy production is a must. Isolated power systems seem to be an ideal place for the use of renewable energy resources. However, with the inclusion of such renewable energies into the isolated system the onset of new circumstances arises. Some renewables, such as wind energy, provide highly volatile sources for production of energy and therefore make it difficult to accurately predict their intended power supply. Other renewable supplies, such as, hydro and bio-mass, can be more accurately predicted due to their long term storage of resources for production.

Within this work the addition of both a wind park and a hydro plant have been considered. Although the use of hydro plants can induce potential problems in regards to operation and planning, its role will be considered to be like that of any other regular unit (diesel). A brief description about the assumptions used toward the operation of the hydro unit will be made.

It is assumed that the river or reservoir that supplies the hydro unit has an ample and unlimited supply of water due to sufficient rain or melt-off in the time period prior to use. With this assumption, not only can the hydro produce power at any point throughout its capable range of operation but it can also provide potential spinning reserve, due to the inclusion of a governor and exciter.

Unlike the hydro unit in the system being modeled, there are some problems that are introduced into an isolated system due to the insertion of wind parks, namely dispatching and scheduling of generation, power quality problems, and dynamic behavior problems [4,32]. Each of these will be discussed in the sections that follow.

2-3.1 Dispatching of Generation

The problems regarding dispatching and scheduling system generators in an isolated system are due to the uncertainties regarding the production of energy from the connected wind park. Although the variation in power output by the wind parks due to wind fluctuations are typically efficiently compensated by the diesel generator's governor control [34], this may not always be the case and sufficient steps need to be taken to ensure that nothing negative could result. When dealing with dispatching and scheduling three points need to be taken into consideration.

- Unit commitment possibilities in order to supply the needed demand;
- Spinning reserve requirements;
- Potential security issues.

In regards to the unit commitment of dispatchable energy, the amount of power that is being efficiently supplied by the wind park must be understood so that the best economic dispatch scheme by non-renewable production can be determined accordingly. Determining the level of power expected from renewable energy sources is a difficult task. Prediction methods can typically provide somewhat reliable information for short periods of time just prior to use. However, due to the volatile nature of the source, only a rough estimate can be used to determine the remaining amount of energy that should be supplied by diesel units. When determining the best economic dispatch for a given power requirement, the limits placed on generators need to be observed and taken into consideration so that only feasible solutions are considered.

Another concern when planning dispatch schemes is the amount of spinning reserve available. Unlike an interconnected system that can simply import emergency power from adjacent systems in time of need, isolated systems do not have this option. Instead they rely on individual unit governors, which are typically run on a closed loop integral control and not by AGC, to compensate for decreases in system frequency. However, this is typically the case when dealing with small isolated system, since large systems, like Crete and Madeira, do employ AGC[1].

A very conservative policy can be adopted, thus increasing the amount of spinning reserve required. In contrast, systems can operate at a higher "risk", in which a limited amount of spinning reserve is scheduled, thus the need for a shedding strategy that can return the residual frequency to nominal, due unavailability of backup real power. Regardless of the risk involved the spinning reserve requirement may trigger an increase in the number of units needed for commitment causing them to run at lower levels and hence lower efficiency. As mentioned prior, the cost associated with the operation of diesel or gas generators is typically high, and any increase in the number of units or any decrease in unit efficiency could bring about an increase in operating costs and could potentially offset the financial advantage of using renewable energies [35]. Another point to consider when dealing with commitment is the use of units with

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[1] Knowledge obtained through conversations with CARE team members

low inertia. Typically units that are needed for quick spinning reserve are units with low levels of inertia so they can quickly provide the needed power. However, this has a counter effect when operating in parallel with wind parks. Since wind speeds vary greatly, the power production likewise varies greatly. This variability in wind power production can cause low inertia units within the system to also vary in power production. This causes higher maintenance costs among these units.

2-3.2 Power Quality

The connection of a wind park to a network, whether it is isolated or not, brings about the concern as to the quality of power the wind park is injecting into the network. Since wind parks are typically not managed by utilities, they are not continually under close supervision by network operators. Rather they are under the supervision of promoters who want to sell as much power as possible. This motivates the need for strict connection guidelines for power injections made by the wind park in order to maintain the quality of power being distributed by the utility. Power quality problems to be considered when addressing the quality of power injected into the network by the wind park are the following:

- Shortage of Reactive Power;
- Voltage Flicker;
- Harmonics.

The type of generator used by wind parks determines whether or not there is a need to connect additional means in order to produce reactive power. This need for reactive power comes from not only the excitation needed by the generator itself, but it may also be that legally the wind park must sometimes inject reactive power into networks. [36,37], as inferred by the Portuguese law. When wind parks are built with induction type machines, this creates a need for reactive power production from an external source. Typically capacitor banks are added to supply this need [36]. Another option wind parks have is to buy reactive power from the utility, however, this may cause additional problems for the utility. During times of light load, reactive power consumption by the wind parks is usually quite high, thus causing difficulties in the operation of generation units with a load below minimum technical limits [32].

2-3.3 Dynamic Behavior

In order to have a good understanding of how wind parks influence the dynamic behavior of an isolated system, it is important that each mode of operation is evaluated. A wind park is always in one of three modes of operation.

- Startup and Synchronization;
- Fixed Pitch or Variable Pitch operation;
- Normal Shutdown and Cutout.

Each of these modes of operation creates different responses within the system, and they will be discussed in the sections that follow.

The startup of a wind park requires that the wind speed be within an acceptable range for a given period of time, in order for the turbine to gain sufficient speed and the generator voltage to match the phase and voltage of the system. If out of phase synchronization were to occur, then serious power and voltage transients would follow. Thus, it is of the utmost importance that proper synchronization occurs [34]. Another point to consider during startup is the current surge associated with the connection of an induction type machine. In order for these unwanted currents to be depressed, a startup power electronic device is used in parallel for the first few moments of connection.

Wind park shutdown is usually initiated when wind speed is out of the normal range of operation, either too high or too low. The pitch of the blade is slowly decreased in order to bring the output power from the turbine down slowly, thus avoiding any unwanted side effects from lingering currents within the park. If these currents are significant, potential voltage transients can occur [34].

During normal operation there are a few points to be considered, depending on the mode of operation the turbine is in. When the turbine is in the fixed pitch mode, the power output of the turbine is uncontrolled and hence varies as a square of the input power. This variability in output power causes equal swings in the conventional diesel units, which in turn can cause damage to the units if this occurs for too long.

Three other points to be considered during normal modes of operation, whether fixed or variable, are the potential for fault currents, frequency excursions, and voltage collapse. The voltage collapse and fault current problems are not addressed here, but rather, the following section focuses on frequency excursions as this point is more closely tied to this work

As mentioned earlier, the variation in the wind speed creates a corresponding deviation in wind park power output. These power changes instigate fluctuations in system frequency, and if severe enough may lead to the disconnection of the wind park from the network [36]. This disconnection could initiate an even larger swing in system frequency and/or voltage, creating security issues if plans for this type of occurrence has not made. If the characteristics of the conventional units within the system are not tuned properly to the inclusion of the wind parks the potential of voltage and frequency transients is present due to wind fluctuations [36].

Speed governing characteristics of the system determine the way in which the power frequency control is realized at any given unit [15]. Over speed limiters are used to help prevent over speed tripping of the turbines. Location with respect to the disturbance, along with fuel, boiler, and turbine types influence the generator ability to release its stored energy and respond to power increase demands. AGC cannot play a role in limiting the magnitude of a frequency deviation. Most control areas require suspending AGC when frequency deviations exceed a given threshold. Following a disturbance, the mode of operation for units is typically changed from AGC-based to emergency-based to allow increased output from available units [12]. Also during large deviations some control center switch off control signals deriving from the center and activate local frequency control loops. The reasons for this are as follows:

- To avoid undesirable effects due to the centralized power frequency control acting on a network area, which is no longer in their control;
- To restore the rated frequency value on the island in order to assure good island operation quality level;
- To set the frequency value equal to the rated value for subsequent resynchronization.

With all these points considered, it can be easily understood that the operation of an isolated power system with wind parks needs to be performed with careful operational and security planning, as was done with the CARE project [38].

Many types of behavioral analysis are needed for major frequency disturbances. Some of these include the ability of a power plant to ride through frequency disturbances, coordination of protective systems, examination of emergency procedures, proper operator training, and evaluation of under-frequency load shedding practices [15]. Although the scope of this thesis is to deal with frequency disturbances, it should be noted that voltage fluctuations also have a direct relation with large frequency disruptions.

2-4 Conclusions

This chapter on current technologies used in today's power systems has provided the needed information to understand the techniques and areas of improvement to justify the work being done in this thesis. Each of the sections presented within this chapter will be addressed in the following paragraphs.

Considering the first section, on load modeling, the techniques that have been applied to system models in the past have been provided along with the development of a complete and accurate load model adopted for use within this work. This is of the utmost importance due to the treatment of dynamic problems preformed in this work.

With respect to section two, load shedding, information in regards to the need for it, the procedure it follows, and restrictions used for its application were presented. The deficiencies that were discovered throughout the examination of current load shedding techniques have given rise to the approach used within this work, namely in terms of the problems related with isolated systems.

Lastly, section three, presented the relative information needed to understand the diversity presented to system operation with the inclusion of renewable energy resources, namely, wind power. The way in which these diversities are addressed within this work will be considered in the remaining part of this thesis.

Chapter 3 New Approach

3-1 The Problem being solved

The purpose of this chapter is to describe a new approach to deal with load shedding, taking into consideration the needed amount of load to be disconnected. As seen from the literature, load shedding procedures usually rely on complex schemes in which under-frequency relays, at the feeder level, are set to operate at different triggering frequencies and time delays in order to arrest falling system frequency. At times this procedure, centered around the principle "if it gets this bad then shed," does minimize the amount of load to be shed, however, these schemes are usually prepared for general worst case situations and often lead to excess shedding. Another concern is the settings, once fixed, are permanent until a new assessment is made and it is determined that a different "better" scheme is needed, in order to fulfill new system security and reliability needs. This is typically the case with growing power systems.

As was mentioned prior, the quicker load shedding is initiated the better the frequency response. Hence, the need for a procedure to create optimal strategies that can shed the needed amount of load in one step in order to arrest the falling frequency swiftly, for any operating condition and a given disturbance. Implementing this type of procedure would need to utilize an adaptable UFLS relays. This could be achieved by remote setting of the UFLS relays from time to time, according to the current system conditions and calculated optimal shedding scheme. A secondary level of relays will also be used to provide backup and prevent system collapse should the first scheme fail.

Determining optimal load shedding strategies is a time intensive task, as mentioned prior, and these strategies are difficult to assess. In the case where only one shedding step is used this issue is even more critical. The primary objective of all load shedding schemes is to minimize the overall amount of load shed, while maintaining system security. There are times when the load shedding scheme minimizes the amount of load being shed, however at the cost of other system variables being sacrificed. For instance most shedding schemes losing only minimal load can arrest the frequency from falling further but do not take into consideration that post shedding system frequency is less than nominal, and hence rely on operator intervention to adjust the frequency accordingly, assuming spinning reserve is available. Therefore, the formulation of an optimal load shedding scheme needs to consider many system variables, depending upon the guidelines of the shedding scheme. Within this work it was concluded that the following three restrictions must be considered in order to formulate an effective, efficient, and swift shedding scheme that does in fact minimize the amount of load to be shed:

- Stopping and minimizing the frequency deviation;
- Returning the system to threshold residual frequency;
- Minimizing or avoiding the disconnection of certain high priority loads.

The inclusion of all three of these concerns into an optimization problem ensures system security, reliability, and economics. The reason for each of the constraints will be addressed in the paragraphs that follow.

As mentioned prior, if system frequency reaches a given limit, it may provoke the disconnection of some generators due to the activation of their under-frequency protection relays, leading to further system losses which could send the system into a downward spiral toward total system collapse. Therefore, stopping the frequency decay is the most important priority of a load shedding scheme. Minimizing these deviations also play an important role with respect to the time it takes the system to return to nominal frequency, assuming all system characteristics are equal.

Once the frequency decay is arrested, focus can be turned toward re-establishing the threshold frequency. Within this thesis it was assumed that the isolated system accepted a high risk operating strategy and therefore utilized a large amount of wind energy with low levels of spinning reserve, for economical benefit. Therefore due to the minimal amount of available reserve, the excess time associated with AGC control for new governor set points, and the increased time associated with cold-startup of generators the implementation of a shedding scheme that returns the frequency to nominal value is needed. By utilizing this type of shedding strategy the risk of system operation at less than nominal frequency is limited and the speed of initiating and completing the restorative stage of the disturbance cycle is greatly increased.

Once the two aforementioned criteria have been satisfied, i.e. the scheme will effectively save the system from further disruption and the system frequency will be restored, the issues with respect to load priority can be considered. This restriction addresses the desire to shed certain system loads with low priority over other loads with a higher priority, due to contractual agreements, potential advantageous effect on system frequency response, or a more closely matched amount of load to be shed.

Considering these restrictions the problem can now be mathematically formulated as seen in equation 3-1.

$$\begin{aligned} \textbf{Min} \quad & \Sigma\,(\textit{Load to be Shed}) \\ \textbf{Sub:} \quad & f_{min} > F_{threshold} \\ & f_{residual} = F_{res\_thres} \\ & \Sigma\, L_{priority} = 0 \end{aligned} \qquad \textbf{Equation 3-1}$$

Where f_{min} is the minimum system frequency;

$f_{residual}$ is the residual frequency after load shedding;

$F_{threshold}$ is the maximum allowable negative frequency deviation;

F_{res_thres} is the system residual frequency threshold (nominal in this work);

$L_{priority}$ is the load priority level.

This optimization problem is very non-linear, due to its dependence on system behavior in the time domain, and the control variables are discrete, as they are in feeder load and generator levels. Due to the overwhelming number of potential solutions, this is also a combinatorial problem. Thus the use of a GA to solve this problem seems most appropriate.

3-2 *General Overall Procedure*

Due to the non-linear, combinatorial nature of this problem a GA is best suited to calculate the optimal load shedding schemes, due to its ability to evaluate numerous potential solutions and make informative decisions about their respective performance.

The scope of this section is to give a brief description of a newly adapted GA used for optimizing load shedding strategies. The goal of this methodology is to minimize the overall load being shed subject to the aforementioned restrictions, which aim at minimizing the maximum frequency excursion by arresting decaying frequency swiftly, restoring system frequency to nominal, and minimizing the shedding of high priority loads. These goals can be achieved by producing a tailored optimal load shedding scheme that sheds the required amount of load for a given operating point in one step with minimal time delay. Due to the use of a one step shedding scheme, it may happen that the shedding strategy may need to change with respect to the changing operating conditions, which include the following.

- Generators in operation;
- Available spinning reserve;
- Wind power production;
- Feeder load levels;
- Changing climatic factors that influence dispatch schemes.

As was mentioned prior, the determination of load shedding strategies in the past relied on numerous evaluations of potential strategies, which used full dynamic simulation to assess the system dynamic behavior for each potential shedding scheme. Using a GA approach in parallel with a trained NN avoids using full simulation techniques and therefore, load shedding scheme assessment becomes fast and easy. Figure 3-1 illustrates how the overall procedure is laid out. As seen from the figure the process begins with a database of operating conditions in order to imply full system coverage. However, a full database covering the breadth of a given operating system does not need to be used.

Starting with a desired operation scenario, out of a database or not, the process begins by determining if the given operating scenario passes load flow simulations. This step is only used to assure that scenarios passed to the algorithm are indeed feasible operating points, since the NN used for this process was trained with only feasible operating points. Once convergence is achieved the operating point is then passed to the GA to determine the optimal load shedding strategy. As mentioned previously load shedding will take place at the feeder (distribution) level and hence increases the number of potential schemes. Within the 5 bus Terceira model, as it can be seen in chapter 6, each of these buses has been considered to have 4 feeders, thus creating 20 different loads that could be shed and hence 2^{20} potential shedding schemes. For the problem being addressed within this work (loss of wind production, due to transmission line loss from a short-circuit) several possible solutions will be tried through the GA approach, in order to determine the best overall solution, for the given operating point. The GA approach can be broken down into the following steps, and can be seen in figure 3-2.

- Codification/De-codification;
- Operators and program evolution;
- Fitness evaluation.

Each of these steps will be addressed in detail in chapter 5.

As seen from this figure, the GA uses a NN to calculate the system frequency response for a given operating point and corresponding load shedding scheme. This procedure was adopted from Peças Lopes et al. [13] and modified to include the use of a NN [39]. The procedure for training this NN will be discussed in the next chapter. After the GA has assessed the best viable load shedding solution the scheme is then written to a database of strategies to be referenced in similar situation or future work. It should be mentioned that the GA platform exploited in this research was developed at INESC Porto within the framework of other projects, and was modified to address additional issues related to this thesis work.

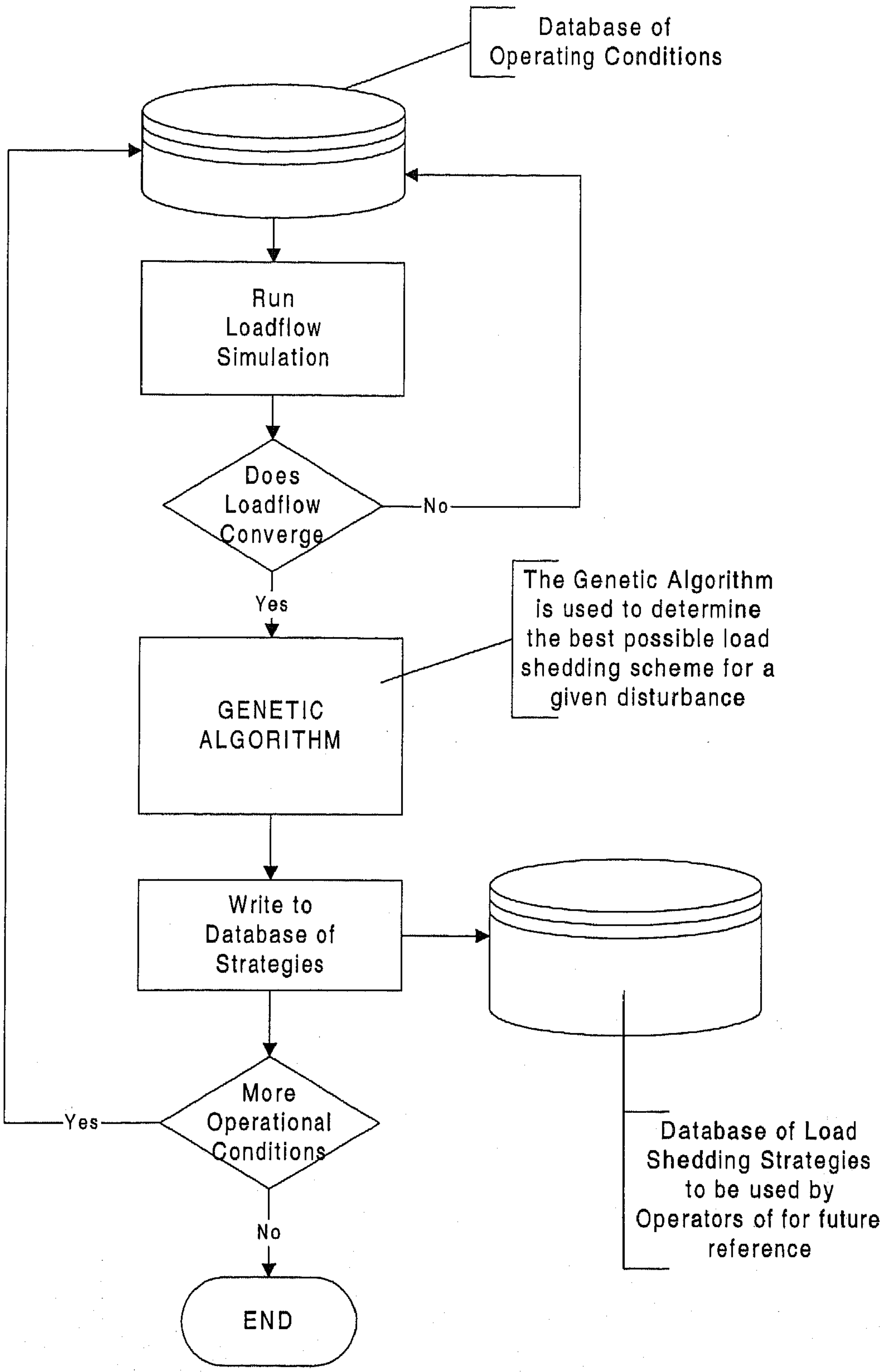


Figure 3-1. Overall Procedure

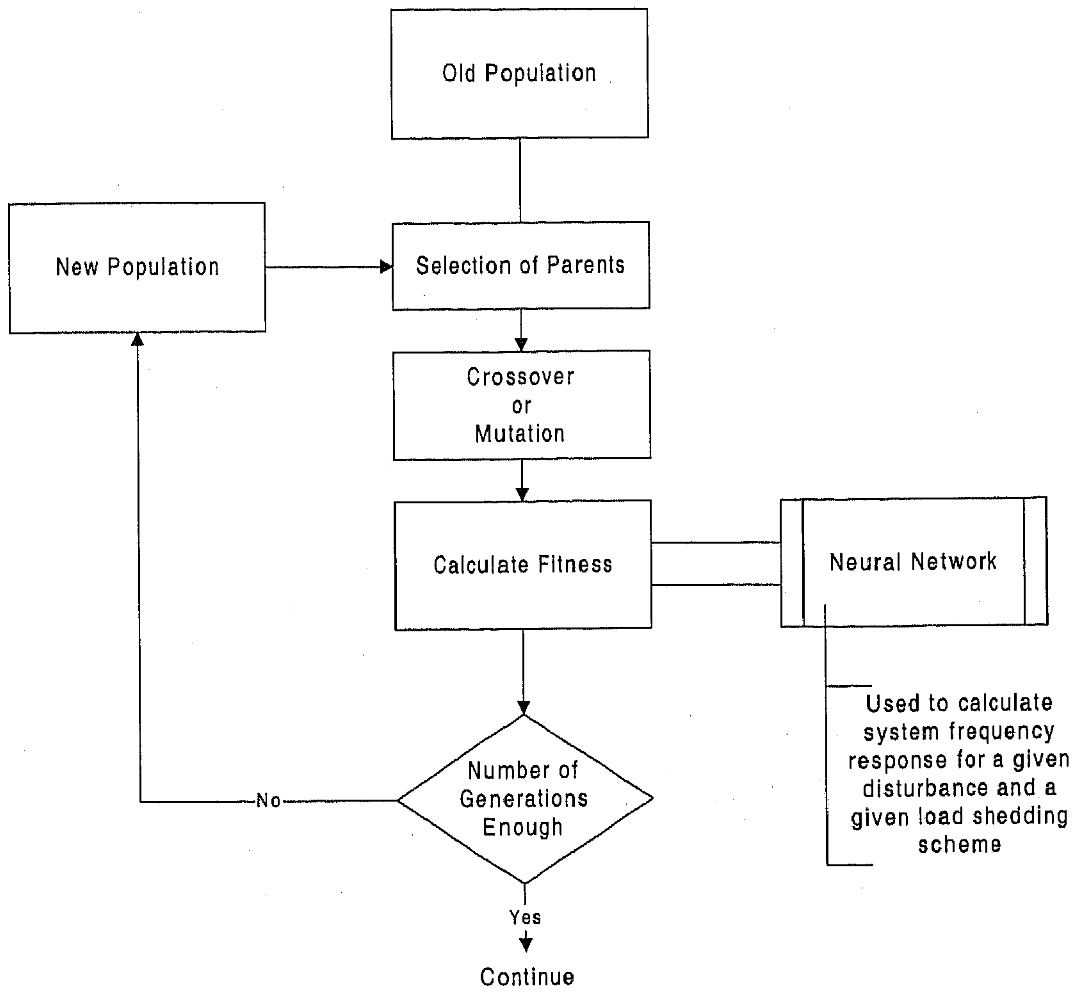


Figure 3-2. Genetic Algorithm Procedure

3-3 Conclusions

As was described in this chapter the generation of optimal load shedding strategies is a very complex problem due to its non-linear nature, the need for numerous evaluations of potential schemes, and the demanding restrictions imposed onto these schemes.

The application of a GA and a NN are well suited to solve this problem, due to their combinatorial ability to assess non-linear problems, evaluate numerous potential schemes, and address all the restrictions imposed onto the problem, all achieved in a timely, efficient, and accurate manner.

Chapter 4 Development of the Neural Network

In this chapter a closer look will be taken at the steps needed to create a viable NN for dynamic frequency response prediction. It is critical that the NN be able to provide accurate dynamic system response for a given set of operating conditions and load shedding schemes, if applicable, so that the overall load shedding strategy database, created by the overall approach, is accurate. The procedure used to generate this NN involves the following main steps:

- Identification of NN input and output variables;
- Data Set Generation;
- Splitting the data sets into training and test set data;
- Design of the NN;
- Performance evaluation of the resulting NN.

In the sections that follow a closer look will be taken into each of these steps along with the power system models that were used.

4-1 Identification of Neural Network Input and Output Variables

The identification of the variables that are going to characterize a given operating scenario is an important stage for the successful application of a NN approach. In the case of simple functions with x variables only those x inputs are selected, thus the function being modeled derives the decision in regards to the inputs needed. However, if the function is non-linear and complex, such as the one that is being modeled within this work, then potential inputs need to be closely studied and their inherent properties evaluated. Sometimes a pre-processing stage is needed to select the most relevant variables to be used as inputs of a NN. In this work, a set of meaningful variables was selected, using engineering judgment, considering the following issues:

- Availability from SCADA;
- Direct physical meaning towards the phenomenon;
- Potential controllability.

A good starting point to determine which of the numerous system variables satisfy all of these constraints is to include all variables which might play an important role in calculating the outputs. From here, inputs can be eliminated according to some of the following rules. First, inputs whose value remain constant throughout the training set can be omitted, no matter how relevant it may seem, since they aren't providing the NN with any new changing information. Second, inputs may be combined into total values, such as total system real load for example, instead of 6 individual real loads. However, when doing this the input individuality may be lost, such as unit spinning reserve, when dealing with generator real power input. Having this in mind, the variables seen in table 4-1 have been selected as inputs to the NN.

First, in regards to the system generation, only the actual and available real powers were needed, since frequency excursions are byproducts of real power mismatches. These generator variables provide the NN with the information to make the needed correlation between the dynamic frequency response and system generation and effective spinning reserve levels. It should also be mentioned that keeping the generators separated instead of lumping them into one unit is due to the different way each generator may contribute to the system frequency changes.

Table 4-1. NN Input Variables

Number	Selected Variable
1 to 15	Generator "i" Available Real Power
	Generator "i" Actual Real Power
16	Total Real ZIP Load
17	Total Real Exponential 1 Load
18	Total Real Exponential 2 Load
19	Total Real Load Shed
20	Percentage of Exponential 1 Load Shed
21	Percentage of Exponential 2 Load Shed

With respect to system loading levels and having in mind the characteristics of isolated systems (single dynamic area), individual loading levels are not needed. However, since a complex load model is being used within this work and each load type has its own profound influence on the systems frequency response it is critical that each load type is used separately as an input to the NN, so it can produce more accurate conclusions. Thus load level inputs to the NN can be broken down into total real ZIP (constant impedance, constant current, constant power types), exponential 1, and exponential 2 load types.

Finally the total amount of real load shed so that the NN can make a proper correlation between the amount of generation imbalance and the load shed. Second, the percentage of exponential type 1 and 2 loads were needed so that the NN knows how much of each type of load is being lost in this particular shedding scheme. As mentioned earlier three types of load present in the system need to be represented, however, since the NN can make the implicit calculation of the other value only two are needed. Percentages are used instead of real values for simplicity reasons alone. Taking into account the structure of the Terceira network, namely the number of connected generators, there are a total of 21 inputs to the NN that will deal with the problem for this system (see Chapter 6 and Annex I).

The need to determine and evaluate the dynamic frequency response of a system during an under-frequency load shedding scenario is of the utmost importance. Establishing an effective under-frequency load shedding scheme typically hinges on knowing what to expect from a given disturbance, especially in regards to the maximum negative and positive deviations, the residual frequency, along with the slope of the first negative swing. Prediction of these values can be done using machine learning techniques as described in [4].

Obtaining knowledge about the system behavior after a shedding scheme, following a given disturbance will help in deciding between potential load shedding schemes. In regards to specific frequency information, a summary of the knowledge that can be acquired is described in table 4-2.

Table 4-2. Dynamic Response Knowledge

Frequency Variable	Knowledge Acquired	
Maximum Negative Deviation	determines amount of load needed to be shed in order to, minimize initial frequency swing and insure that the residual frequency will be close to nominal	determines the first relay's frequency setting and time delays, in order to insure a quick response
Maximum Positive Deviation	helps minimize over-shedding thus avoiding the activation of any over-frequency protection devices, thus contributing more losses to the disturbance	
df/dt	assesses the severity and location of the disturbance	determine the time delays needed, or what delays to expect from df/dt sensitive relays
Residual Frequency	determines the amount of load to be shed, in order to insure that the residual frequency is above the desired threshold	determines if any other system intervention will be needed to recapture nominal frequency

In reference to the output variables, and as mentioned before, the interest in knowing the maximum negative and positive frequency deviation, the final system resting frequency, and the slope of the first negative swing lead to the selection of these 4 variables as outputs of the NN.

4-2 Generation of Operating Points

In this section the procedure used to generate a data set of operating scenarios is discussed. The objective of the NN used within this thesis is to replicate the dynamic frequency response of a power system during a load shedding scenario. As mentioned earlier, the overall effectiveness of the approach to load shedding developed in this thesis hinges on the capabilities of this NN to create accurate results. Knowing that the replication of a given power system response by the NN can only be as good as the data it is trained with, it is imperative that this data be the most accurate and realistic representation of the power system. Optimally the generation of a database would include all possible system scenarios, however this would require infinite computational capabilities and even more unrealistic man-hours. Therefore the scope of this, like any other data generation technique, is to capture the breadth of the systems operating conditions while limiting computational and human efforts. The process used to generate this data set was adopted from McCalley et al. [40] and modified to address additional issues.

One such modification made to this program was in regards to the boundary searching technique that was used by McCalley. In this work [40] the objective of the NN being trained was boundary classification and hence needed a high concentration of operating points around this system boundary, in order to create a training set for a NN with sufficient accuracy. Since this work is not concerned with boundaries of operation this technique was removed from the process. Another adaptation made to this process was for the purpose of localizing operating point scenarios in order to limits their number, yet maintain their effectiveness in representing the operating region. A load curve operation was established in order to generate points according to a predicted system load. This type of point generation decreases the need for a complete coverage of a load range and instead focuses point generation on areas of the range that are most probable in actual system conditions. The learning set generator, as seen in figure 4-1, is divided into three main modules, Structured Monte Carlo Sampling Module, Constraint and Unit Commitment Evaluation Module, and finally an Economic Dispatch Module. A closer look at each of these modules will be taken in the following sections.

4-2.1 Structured Monte Carlo Sampling[2]

Creating a wide variety of operating conditions to cover the breadth of the system is the main objective of a learning set generator. How this is achieved can greatly affect the final results produced by the NN. The data set generator within this work implements a Structured Monte Carlo sampling technique to efficiently produce a wide and probable set of operating conditions. The difference between a Simple Structured operating point generator and a Structured Monte Carlo operating point simulator can be seen in figure 4-2. From this figure it can be seen that points generated by the Simple Structured sampling technique limits the number of different values to 3 over the entire range for each parameter. As seen from the Structured Monte Carlo sampling technique there are 9 different values for each parameter, thus increasing the overall comprehensiveness of the training set in comparison to the simply structured technique. The next step in creating a viable training set database is to understand which parameters provide the greatest influence on the training sets "target" value(s), or expected NN output(s). It is of the utmost importance to have parameters that have a significant influence on the target in order to establish controllability of this target. With appropriate control the input parameters can be varied in order to vary the target value and hence produce a large range of target values. With a larger range of outputs we can then train a NN with equally large output capabilities, thus having a vast coverage of system dynamic response for the given disturbance. The text that follows will first explain parameter types along with the procedure of generating data.

[2] Also referred to as "Latin Hypercube Sampling"

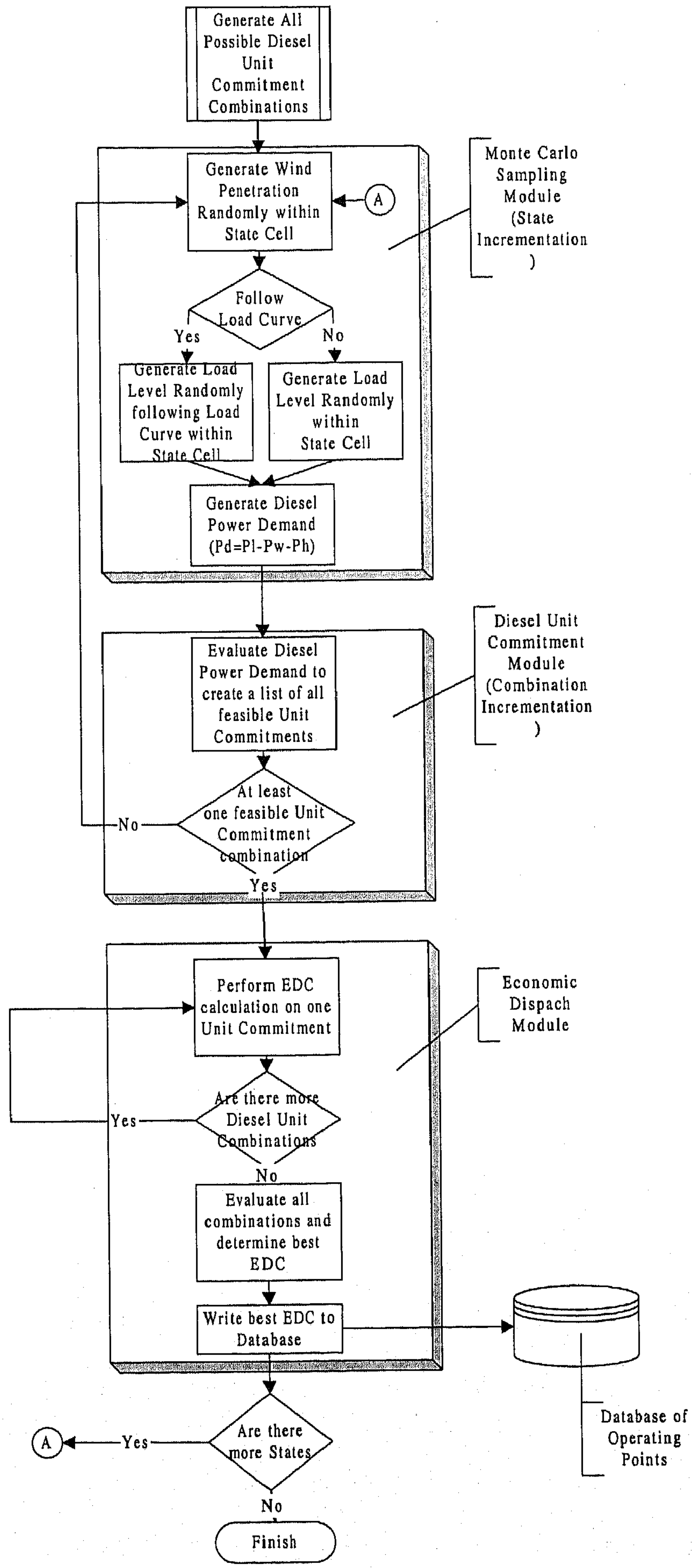
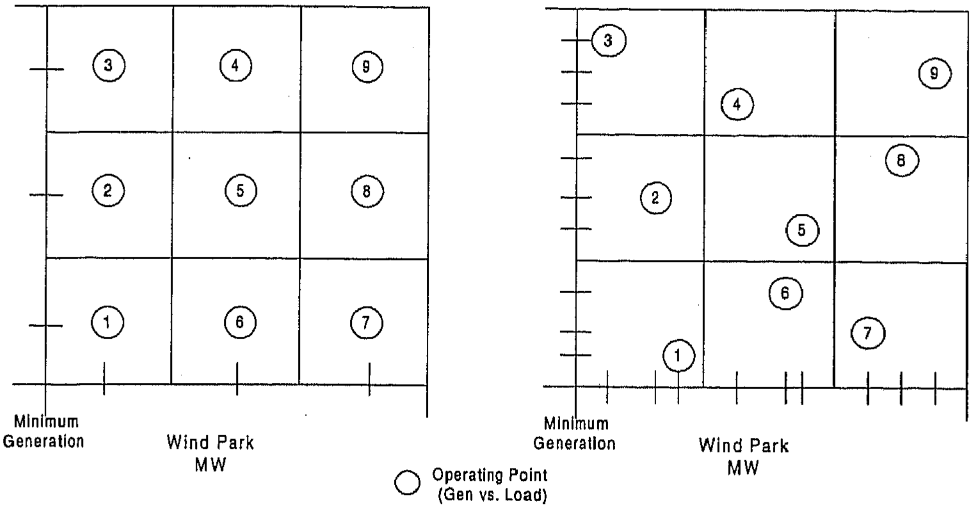


Figure 4-1. Operating Point Generator



Structured Sampling Technique Monte Carlo Sampling Technique

Figure 4-2. Structured Sampling vs. Monte Carlo Sampling

4-2.1.1 Parameter Type and Influence on the Data Set

For a given training problem, system parameters need to be classified according to their relative influence. Using engineering judgement we can classify these parameters into one of three categories, Independent Critical, Independent or Dependent Secondary.

4-2.1.1.1 Parameter Independence

The independence of a system parameter is simply determined by whether it can be controlled in real life system operation or not, such as injected real and reactive power at PQ buses and bus voltage at PV buses. Although loads may be considered uncontrollable due to their random demand, in these scenarios we have classified load levels as a controllable entity. This is done since system load is one of the most influential parameters on these NN outputs. All other system values have been considered dependent parameters since they can only be evaluated as a product of a load flow simulation.

4-2.1.1.2 Critical and Secondary Parameters

The difference between critical and secondary parameters is determined for a given training set objective. A critical parameter can be defined as a parameter with significant influence on the target value. This significance is left up to the engineer to decide, and usually takes some study to determine the best set of critical values in order to maximize "state" efficiency. A state can be defined as set of system operating parameters that describes the current point of system operation. Furthermore a hyper-cube is then defined as an n-dimensional representation of the power system with each dimension of this hyper-cube being a critical parameter. Therefore in this respect, increasing the total number of critical parameters, or dimensions in the hyper-cube, actually increases the total number of operating points created for the training set database for the NN. As previously mentioned it is undesirable to have too many operating points in the training set in order to avoid over training problems and added computational efforts. Each dimension of the hyper-cube has a range of actual operating conditions, within which the training set creates values. This range of operation is divided into "cells" (states) of the hyper-cube as seen, comparatively with two-, three-, and n-dimensional systems, in figure 4-3.

The critical parameters, with the most influence on the target, are divided into more segments thus creating more cells, and hence more states, therefore increasing the overall number of points in the training set and the greater time required to run the data generator. Determining the number of states required to accurately capture all of the system operating possibilities is again left up to engineering judgement.

Since dependent parameters are products of a load flow simulation, these values can not be pre-determined in order to vary them via the procedure below, therefore they can not be considered as critical independent parameters. Parameters that have some influence on the target value but not enough to increase the state number are called secondary independent parameters. Secondary parameters too have a range of operation, such that their values stay within it to accurately mimic system operation. The following section looks at how we advance through this hyper-cube and how values for each parameter type are selected.

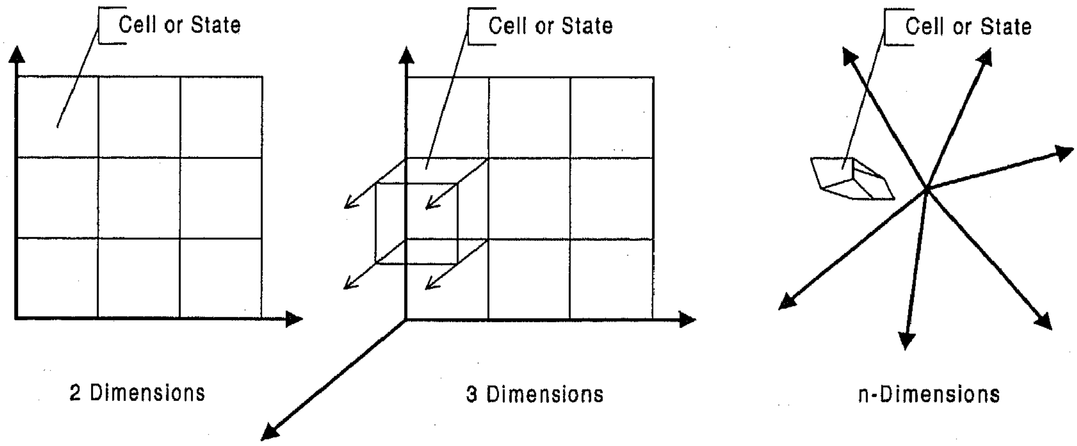


Figure 4-3. Cell (State) Representation with System Dimension

4-2.1.2 *Procedure of State Trajectory*

State trajectory is the process of advancing through each of the cells of a given hyper-cube dimension, in order to create a full set of operating parameters that covers the breadth of the operating system. Each of the critical parameters are varied one at a time in order to create all possible combinations of the operating conditions. For a given cell in the hyper-cube each parameter value is selected randomly within in its cell range. This process allows for a more diverse selection of operating parameter values within the given cell range and hence overall range, as seen previously in figure 4-3. The secondary parameter values are also selected randomly but within their entire range of operation. The total number of states can be calculated by equation 4-1.

$$TS = \prod_{i=1}^{N} Si$$ **Equation 4-1**

Here, *TS* is the total number of states;

Si is the number of divisions over the entire range of parameter *i*;

N is the total number of critical independent parameters.

Thus, with this type of approach we are assuring that the breadth of system operation is being covered. We use random values since the exact operation of the system is never known, due to loading conditions, wind penetration, and other unforeseen occurrences in the system.

4-2.1.3 *Load Curve Modeling*

Many of today's power systems follow a forecasted load curve model to accurately commit the needed amount of generation and satisfy security constraints. Although load forecasting can only be accurately performed for a short time ahead, say 10 minutes, historical data can be utilized to give a rough approximation of "common" daily or seasonal load, or what ever time period of operation is under consideration. Via this historical data a general system load curve can be developed. Using this generic load curve the critical load parameters can be varied accordingly, as seen in figure 4-4.

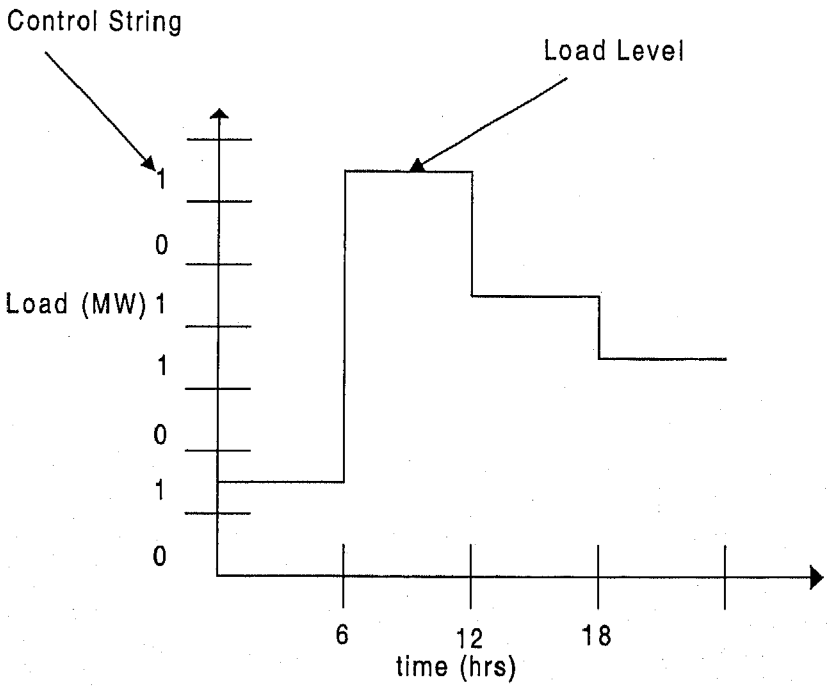


Figure 4-4. Load Curve Model

From the load curve it is observed that certain levels of load are never attained by the system. Therefore these load values are not included in the training set database. This type of operating point generation limits the required range of the given critical parameter, hence shortening operating point run time. Due to the unavailability of load curve data for the network we are modeling, an estimated load curve was generated for each load bus in the system.

Although power systems generally follow load curves there still is the possibility of a load to fall within this, untrained range. Should this happen it is important that the NN has good generalization capabilities, in order to avoid lowering the NN ability to provide an overall accurate representation of the system's dynamic response. In order to avoid this a second database was created which did not follow a predicted load curve, but rather simply varied its operating point values over the entire range. Although this requires a much broader operating region to sample, it improves the NN generalization capabilities. A numerical comparison between the two procedures will be discussed in the result section. Taking into consideration the points made above within this work a combination of the two data sets into one larger focused set was used to train the final NN. This was to ensure complete system coverage and also NN accuracy in highly anticipated areas of operation.

4-2.2 Constraint and Unit Commitment Evaluation

When creating any learning set it is crucial that only feasible system operating conditions are generated and unfeasible operating points are avoided. This part of the procedure is used to ensure that such conditions are met. Since the actual number of system constraints can be overwhelming, only selected constraints will be applied to the corresponding system parameters. Also addressed in this section is the determination of feasible unit commitment possibilities for every given operating condition. For the Terceira system only units 1 through 4 of the Belo Jardim Power Station will be considered in the unit commitment assignment process. Since unit 5 is being used as the swing bus it can not be put out of service for commitment purposes. Although unit 6 could be considered for unit commitment assignments, it was determined that, due to its size, keeping it in service would lessen the spinning reserve requirement imposed on the other 4 units (see Chapter 6 and Annex I for system details). After a unit commitment possibility has passed all applied constraints it is then passed on to the EDC module. The following section will take a closer look at the constraints that are to be applied to this work.

4-2.2.1 Generator Limits

In normal system operation it is impractical to run a generator above its rated capacity, in order to avoid shortened life expectancy of the unit. In order to avoid these harmful effects limits of operation are applied to keep generators in their desired range of operation. Thus the need arises to assure that our data set too accurately captures this full available range of generation. Applying these generator limits to our data set minimizes the number of feasible unit commitments for any given diesel power demand. This constraint is easily achieved by giving each generator a maximum and minimum generating value, as it can be seen in table AI-1 in Annex I.

For a given load level, wind penetration, and other generation units there is a need for diesel generation, as calculated by equation 4-2.

$$Pdd = Pl - (Pw + Pg) \qquad \textbf{Equation 4-2}$$

Here, Pdd is Power demand of the diesel units (MW);

Pl is Load demand of the system (MW);

Pw is the Wind power production (MW);

Pg is the Power generated by other units in the system (MW).

With this value of diesel demand, each unit commitment possibility can be evaluated and determine whether they are feasibility according to these generation limits. The following example is provided to help clarify the application of this constraint. Suppose the system diesel demand is 10 MW, as calculated by equation 4-2, and that each unit in the system has a maximum generating level of less then 10 MW. Then from this constraint any solution with only one unit committed can be eliminated since it will not satisfy the needed demand alone.

4-2.2.2 System Maintenance

Throughout any year of operation there are times when a given unit may be unavailable for operation and hence any unit commitment strategy must account for maintenance needs. In most power systems only one unit is taken off line for maintenance reasons at any given moment in order to avoid commitment problems. So in order to capture this aspect of system operation a randomly generated outage, or no outage, is employed. Since maintenance is usually performed once a year on each unit the amount of time any unit is off line is relatively small compared to total operation time. Therefore a small percentage of time is arbitrarily selected to model each of these outages and the remainder of time is set for no maintenance outages. First a large percentage of the time is allocated to no maintenance outages. Next we divide the remaining percentage of time equally between all other units, thus giving us a percentage of outage time per generator. Table AI-1 gives the numerical percentages applied for use in this thesis.

As can be seen only 80% to 100% are given within this table, this implies that 80% of the time there are no maintenance constraints on the system. Once these percentages are determined, only once per data generation, a new random percentage is selected corresponding to one of the possible maintenance constraints. The following example will help clarify this constraint. Suppose that if the number 93 (%) was generated randomly, using the maintenance values from table AI-1 the maintenance constraint corresponding to unit 2 out of service would be applied. Therefore any unit commitment possibility that included committing unit 2 would be infeasible according to this constraint.

4-2.2.3 Spinning Reserve Criteria

When a system has a potential for high penetration of renewable resources it is critical that enough spinning reserve be available should there be a sudden decrease in the renewable production level. However at the same time it is not cost affective to leave too many units on line in order to achieve 100% coverage, since the probability of complete renewable failure is very low. In order to determine the needed amount of spinning reserve and assure that a given unit commitment can satisfy this criterion we employ equation 4-3.

$$SR = Pl * LM + Pw * WM$$ **Equation 4-3**

Here, *SR* is spinning reserve (MW);

Pl is system load (MW);

LM is load margin;

Pw is wind power production (MW);

WM is wind margin.

The load and wind margins selected can be varied according to their forecast uncertainties. Due to the limited amount of data known about the loading characteristics in the Terceira network common margins of 0.4 and 0.1 were applied respectively [32]. It should be noted that although spinning reserve is available for use, the disturbance selected produced severe and rapid enough frequency decline that a load shedding scheme is still required to prevent system breakdown. Therefore the system spinning reserve will be applied to tune the final point of operation after the shedding as occurred. This may be to increase generation if the new post-shedding generation load balance is generation heavy, or may be to cut some generation if the mismatch is in the other direction.

4-2.3 Economic Dispatch and Unit Commitment

Once all feasible unit commitments are determined, via the previous module, we can proceed with individual generator production levels. In order to accurately model system operation we need to employ an economic dispatch module to determine generation levels for each unit commitment scheme. A Lagrange multiplier method was used to calculate the EDC problem [41]. Therefore a quadratic cost curve was used for diesel units, as can be seen in equation 4-4.

$$Cost = Ax^2 + Bx + C \qquad (\$ / \text{h})$$ **Equation 4-4**

Here, *A*, *B*, and *C* are generator cost curve coefficients;

x is the level of power generation (MW).

For a given set of wind and load levels, we can have a wide range of unit commitment possibilities, from 1 to all of them. The cost associated with each economic dispatch assignment is used to determine which dispatch scheme is the best. Since each one of these commitments adds an operational point to our learning set, in order to limit the size of the learning set only the best scheme is written and saved into the database of operating points that will be passed on to the next procedure. Only the best scheme will be used since this is the most likely course of action to be taken by actual system operators.

4-2.4 Results of Operating Points Generated

With all of the above points taken into consideration an analysis of points generated by this procedure can take place. From the Terceira model, as can be seen in chapter 6, it has been determined that the 5 load buses will be the only critical parameters selected for this data set generator. System load has the most influence on the frequency response in a load shedding scheme analysis. Other parameters of influence on the training set's target are generation values throughout the system, however they have not been deemed critical for a couple of reasons. Of the 8 generators in the Terceira network, 4 are unit commitment determined variables and their respective real powe is calculated via economic dispatch. Therefore they are dependent on system load, wind power production, and cost equation constants. This dependency prevents their generation levels from being selected via the structured Monte Carlo sampling technique.

Of the remaining four generators in the system two of them are renewable energy resources and hence produce power randomly dependent on their particular source of power. This randomness can best be implemented using them as secondary independent parameters. Of the remaining two units left for selection one of them has been selected as the swing bus, thus again making it a by-product of the load flow simulation. Although it is a by-product of the load flow simulation it can still be employed as a secondary independent parameter by limiting it's overall range of operation in order to account for added system losses. The last unit could be selected as a critical parameter but its influence on the target becomes minimal due to the total amount of generation from the other units. So its inclusion would only increase the total number of states and cause need for longer run time, therefore it too will be selected as a secondary parameter. Table 4-3 lists each system parameter and its roll in the operating point generator for the particular case of the Terceira Network.

Table 4-3. Role of Operating Point Parameters

Parameter	Load	Load	Load	Load	Load	D.Gen	D.Gen	W.Gen	H.Gen
Bus #	10	20	30	40	50	5	6	7	8
Type	CI	CI	CI	CI	CI	SI	SI	SI	SI
Step Size	4	4	4	4	4	1	1	1	1

Here *CI* is a critical independent parameter;

SI is a secondary independent critical parameter;

D.Gen is a diesel generator;

W.Gen is a wind generator;

H.Gen is a hydro generator.

Using equation 4-1 the total number of states has been calculated as follows:

$$ST = \prod_{i=1}^{9} Si = 4*4*4*4*4*1*1*1*1 = 1024$$

The actual number of points passed on to the next step, in this procedure, may be less than this calculated value. This is due to the fact that some states may not have any acceptable unit commitments due to the randomness of parameter value selection with each hyper-cube cell. Even though this may occur the operating point generator is robust enough to still provide an ample amount of points.

4-3 Neural Network Training and Test Set Generation

Figure 4-5 shows an overall state diagram that is followed to generate the remaining data needed to create a complete NN data set. Beginning with a database of system operating scenarios[3], produced by the procedure just described, the operating scenario feasibility, actual system generation including losses, all the needed relay schemes, and the resulting dynamic frequency responses can be calculated. In order to determine this information the following steps are used. First a load flow program is run to ensure operating point feasibility and determine actual swing bus generation due to system losses. Next a relay file is created with all possible load shedding schemes for a given operating point. Finally the dynamic simulation is run and the results are stored in a database with the corresponding operating point parameter values and shedding scheme. Each of these will be discussed in greater detail in the sections to come.

[3] The reason for creating an initial database of operating points, instead of one full length procedure, was due to operational constraints related with the software used (ETMSP software was resident at Iowa State University).

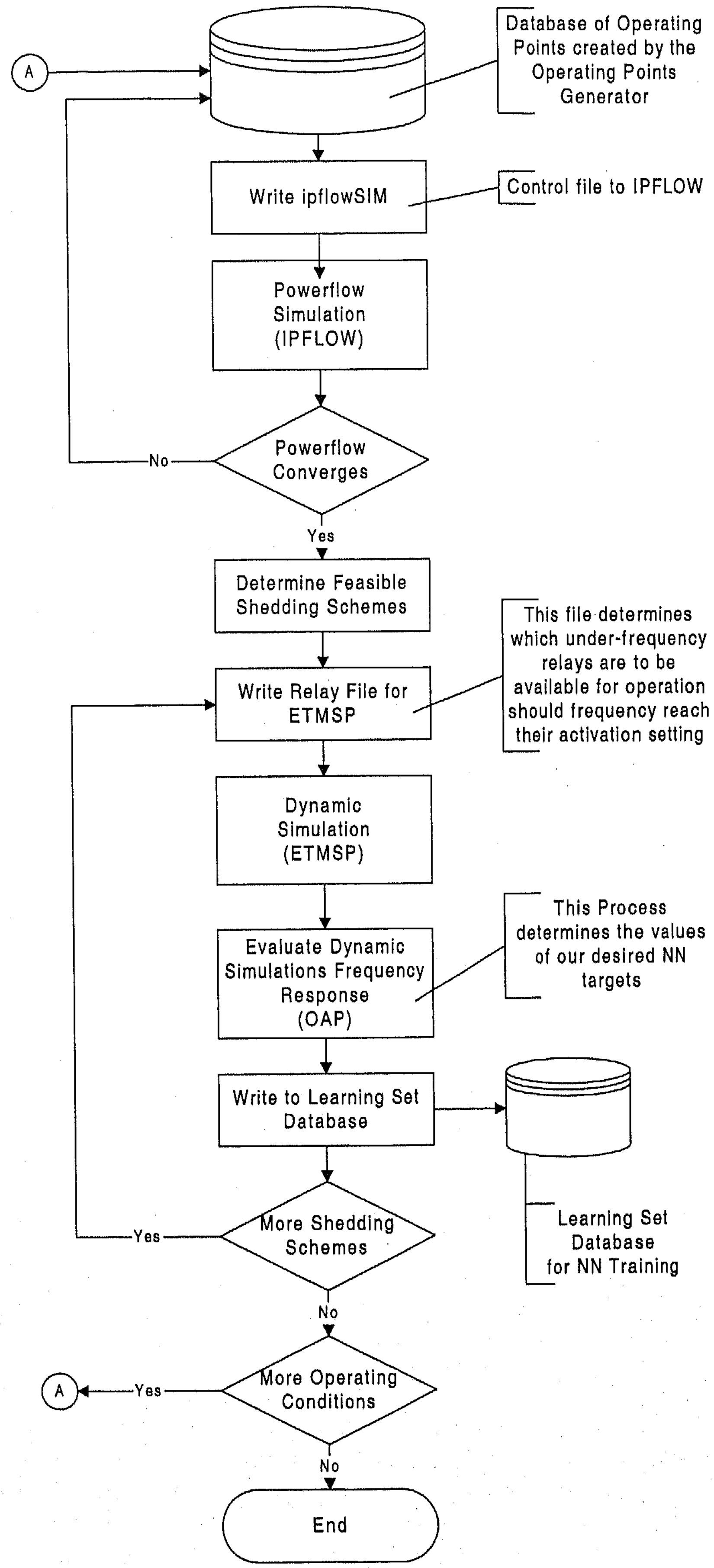


Figure 4-5. Neural Network Training Set Generator

4-3.1 Load Flow

After a complete system set of operating points is generated as seen previously we can then continue with the procedure illustrated in figure 4-5. Although the operating point generator insures balance supply and demand of real power, an evaluation of the system operation feasibility is needed. Taking one operating point out of our database at a time, it is run through a load flow simulation to see if the system conditions converge, hence solving the power flow equation. In this thesis Newton-Raphson followed by an automatic solution is used to calculate the power flow equation. The software used to perform the power flow evaluation was EPRI's IPFLOW.

In order to keep this procedure 100% automated a control file was needed to automatically change and control the power flow scenarios. Since the format of the database is not in any of IPFLOW's acceptable formats a small program was written to take one system operating point and write it and the appropriate control commands into IPFLOW. Points that do not pass the power flow convergence test are not desired, since they are not realistic operating points. Once power flow convergence is reached the next step of the procedure can be performed.

4-3.2 Relay and Shedding Schemes

Since the scope of this learning set generator is to take into consideration the effects load shedding has on the power systems dynamic performance, it is crucial that all potential load shedding schemes are analyzed via a dynamic simulation. So for one given operating point there may be a number of different potential load shedding schemes, depending on amount of generation that is lost and bus load levels.

Within the Terceira model, as will be described in chapter 6, there are 5 load buses each with 4 feeders, therefore there is a maximum potential of 2^{20} or 1,048,576 different shedding schemes that are possible. As seen in figure 1-2 the busloads are a composite aggregation of the four individual feeder loads. With this aggregation model any one of the four feeder loads is a part of the composite busload level. Therefore by producing shedding schemes at the busload level we are inherently taking into consideration the shedding scheme at the feeder level, so long as the total load shed at the feeder level equals the same amount at the busload level.

An example will help clarify this point. Suppose that 10 MW of load is to be shed. If buses 10 and 20 have a load level that together equal this 10 MW then they will be shed. The same holds true at the feeder level, if 6 feeders have a sum of 10 MW then they will be shed. Whether it's the same 6 feeders at buses 10 and 20 or if its 2 from bus 10, 3 from bus 20 and one from bus 30 the needed 10 MW will be shed.

This assumption can be made due to the fact that frequency is the same at any given moment at all buses in the system. This does however limit the ability to represent these types of aggregate representations to location independent zones of a power system. Meaning, as mentioned earlier, areas in a power system where a perturbation has occurred experience instantaneous frequency propagation and any load shedding within this area would likewise be felt instantaneously, hence load location has no positive or negative effect on the system frequency response. With the number of schemes reduced to a maximum 2^5, as described above, the training procedure becomes feasible. However, of these 32 potential schemes some may still be considered unfeasible. For instance if some of the 32 possible schemes were activated they would shed too many loads and cause an over-frequency situation due to the reverse imbalance. A shedding constraint has been applied in order to avoid such occurrences, as seen in equation 4-5

$$Shed\max = Ploss + Ploss * buffer$$ **Equation 4-5**

Here *Shed max* is the maximum allowable load to be shed;

Ploss is the amount of generation lost;

Buffer is the percentage of extra load to be considered for shedding.

An example will help clarify this. Suppose that for a given operating condition 4.5 MW of generation is lost, an additional 20% buffer amount is also added. Therefore Shed max is calculated to be 5.4 MW, hence any load shedding scheme that does not exceed this amount is considered feasible.

Since it may happen that the system can be operated at less than nominal frequency levels for short periods of time, as can be planned for when determining the residual frequency threshold, load shedding schemes that do not shed enough load are still considered feasible. Keep in mind that a base frequency response needs to be established for a given operating condition in order for the GA to see intent for shedding, hence no load shedding is also an acceptable load shedding scheme. However, the scope of this thesis is to purpose strategies that will not only arrest falling frequency but also return the systems frequency to near nominal without manual intervention. Typically this involves matching the amount of load shed to the amount of generation that was lost in the disturbance. However, due to the minimal contribution of available spinning reserve and the influence of load type being shed has on the systems frequency, it could feasible that an amount less then the generation lost adequately brings the resting frequency back to nominal. Therefore all scheme less than Shed max will be considered. Once all feasible load shedding schemes are calculated they are addressed one at a time to get their respective system dynamic response.

Each load shedding scheme can be translated into potential relay operations, therefore the appropriate relays need to be set accordingly. Each of the appropriate bus relays, for a given scheme, is set with the same triggering frequency of 49 Hz and a delay of operation of 3 cycles. As mentioned prior this type of relay setting produce the best frequency response, because it produces a bulk one time shed versus cascade shedding. The back-up relay setting used was 47.5 Hz, to allow sufficient delay for the system frequency to be corrected before reaching the critical threshold were generator under-frequency relays are set to activate, and lead to a potential collapse.

4-3.3 Dynamic Simulation

Once the operating point reaches this stage it has passed all possible system constraints and requirements. Therefore the next step can be taken, which is to create the target values for the given operating point. As mentioned earlier, the 5 load bus level model is used to perform this part of the work. The scope of this module is to run the actual dynamic simulation to determine the four target values; maximum positive frequency swing, maximum negative frequency swing, derivative of initial frequency swing, and resting frequency. These outputs were selected since they provide the necessary information to the GA in order for it to make correct assessments about which schemes are the best. The frequency swings are needed so that the GA can assess if the scheme in question will arrest the frequency in time so that other system protections are not activated. The derivative of the initial frequency swing is used to provide the GA with the severity of the disturbance and hence the need for quick action. Finally the resting frequency is needed in order for the GA to assure proper measures have been taken and the frequency indeed has been restored to an acceptable level.

EPRI's, Extended Transient-Mid-Term Stability Program (ETMSP) is used to perform the dynamic simulation, along with EPRI's, Output Analysis Program (OAP) for numerical analysis. The dynamic simulation used here replicates the system response for the disturbance being evaluated. In this case a loss of wind park generation is being simulated, due to a short circuit in an adjacent transmission line. Since ETMSP does not have the capabilities to represent asynchronous generators a reactive load was added to bus 7 to simulate the reactive power needed for wind generator operation. Therefore, the disconnection of this fictitious load needs to takes place simultaneously with the generator. The time sequence of this disturbance is laid out as follows. First the three-phase fault of the transmission line occurs at 0.0 seconds. At time 0.01 the wind parks capacitor banks is removed, followed by the disconnection of the wind park's reactive load at 0.015 seconds. At 0.02 seconds the wind park's generator is disconnected followed lastly by the clearing and disconnection of the transmission line at time 0.1 seconds. A total simulation time of 30 seconds is used to assure that the frequency has settled following the disturbance.

4-4 The Neural Network

In recent years the use of NNs in power systems applications has become increasingly popular and well studied [1,5,42,43]. Hence only a brief description will be given regarding its technology and its development within this work.

4-4.1 Architecture

The key aspect of using a NN is determining an architecture that is best suited to produce good results. The idea is to use the simplest architecture while maximizing performance. As commonly known, a NN consists of three types of layers, input, output, and n hidden layers. Each layer of the NN contains m number of nodes, each of which are connected to all of the nodes in the previous and next layer of the NN. Deciding the number of layers and nodes is just one of the caveats associated with the use of NN. Unfortunately there is no formula for determining network architecture, and, it is therefore left up to the engineer to determine what is best.

Determining the number of input and outputs nodes is done using the approach just mentioned. In regards to the number of hidden layers typically the more complex the function the greater need for more layers and nodes. However, when developing a NN used for mapping a non-descriptive function it is best to use a simple architecture of one or two hidden layers, as was employed within this work. It was concluded after a few trials that an internal architecture of 2 hidden layers, the first with 14 nodes and the second with 10 nodes, was best suited for this application. This architecture with 21 inputs and 4 outputs is illustrated in figure 4-6

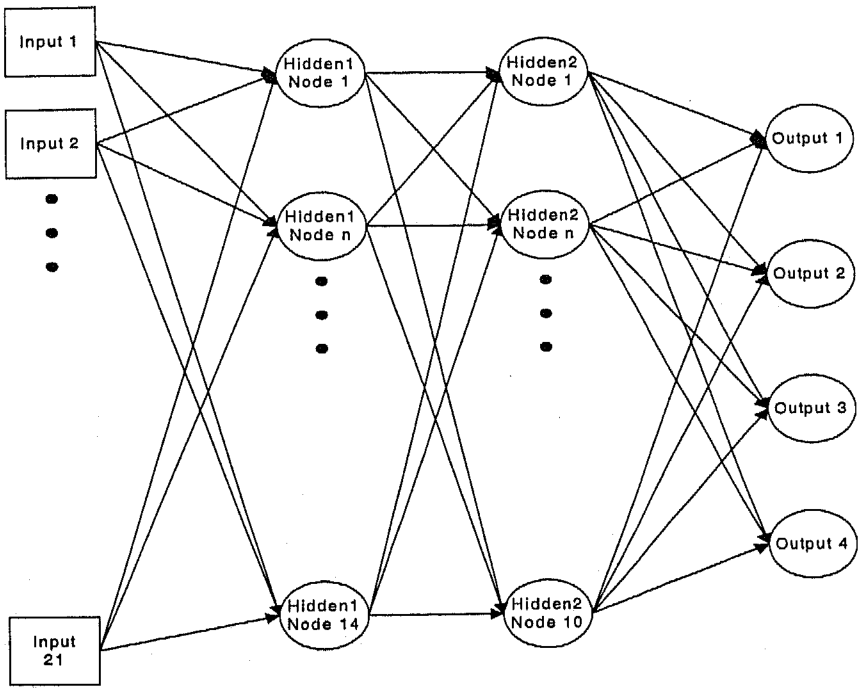


Figure 4-6. Neural Network Architecture

4-4.2 Activation Function and Normalization

Once the overall NN architecture is understood a closer look at what happens within each node of the network is needed. The input layer is simply one complete training pattern, with its associated values. The need to change these values into a normalized range of values not only simplifies the activation function as will be discussed shortly but also speeds up the overall convergence of the NN as a whole [42]. Normalizing the inputs such that they have a mean of zero and a variance of one is the general course of action. After the inputs have been normalized then NN training commences.

Like the NN in its entirety each individual network node is presented with a normalized input in order to generate a corresponding output. This is achieved within each node by performing two actions. The first is to sum the total node inputs and the second is to apply this value to an activation function to generate an output, as seen in equation 4-6 and 4-7 [42].

$$net_j = \sum(w_{ij}x_i)$$ **Equation 4-6**

$$O_j = f(net_j)$$ **Equation 4-7**

Here, w_{ij} is the weight between nodes i and j;

x_i is the input from node i;

O_j is the node output.

The activation function can be linear, step, sigmoid, or other non-linear varieties [42, 43]. Within each node there is sometimes a bias "weight" that is added to the equation, as seen in equation 4-8, in order to move the origin of the activation function [42].

$$O_j = f(net_j + \theta_j)$$ **Equation 4-8**

Here, θ_j is the bias;

All other variables are as indicated in equation 4-7.

4-4.3 Back-Propagation, Adaptive Learning, Momentum Rate

The procedure followed to create a viable NN consists of taking the developed architecture and giving it a set of training points in which to compute the weights of the architectures. Once the weights are determined an independent test set is presented to the trained NN and an evaluation is performed. If the NN fairs well against the test set, then the trained neural network is sufficient for use in the desired application for which it was created. Weights can be changed in one of two ways, they can either be adapted after each pattern in the training set, or they can be altered after the entire training set has been presented. Typically the first is selected, since it takes less overall CPU time. Most NNs used today are trained with back-propagation techniques. Back-propagation consists of calculating and minimizing the overall network performance error throughout its training cycle in order to achieve the most accurate network feasible as seen in equation 4-9 [42].

$$E = \tfrac{1}{2}\sum(T_k - O_k)^2$$ **Equation 4-9**

Here E is the NN performance error;

T_k is the target output provided by the training data;

O_k is the actual NN output.

However, the equation used for network performance calculations can be whatever the user desires. Once the performance error is calculated for a given iteration the change in network weights can then take place. This is done using the partial derivative of the error with respect to the weight multiplied by a learning rate. This learning rate helps focus and speed up the search for the optimal network weights [42, 43]. The learning rate determines the size of the step taken by the change of a weight from one iteration of the training cycle to the next, as seen in equation 4-10 [42].

$$\Delta w_{kj} = -\eta \frac{\partial E}{\partial w_{kj}}$$ **Equation 4-10**

Here Δw_{kj} is the change in weight connecting node k to j;

η is the learning rate;

$\frac{\partial E}{\partial w_{kj}}$ is the partial derivative in performance error with respect to the weight k to j.

Back propagation techniques can also take advantage of yet another variable, the momentum rate, to help speed up the convergence of the NN. The momentum rate is similar to the learning rate in regards to its efforts to speed up network convergence. However, its contribution is dependent on the previous change in weight rather then the size of the error itself, as is seen in equation 4-11 [42].

$$\Delta w_{kj}(n+1) = -\eta + \alpha \Delta w_{kj}(n)$$ **Equation 4-11**

Here Δw_{kj} is the change in weight connecting node k to j;

η is the learning rate;

α is the momentum term;

n is the iteration number.

Throughout each iteration of the training cycle, the weights are updated until the overall network performance error is within tolerance. Since this type of searching technique relies on the gradient of the solution space it important that the values of the momentum and learning rates are chosen carefully. As mentioned earlier these variables increase the speed of network convergence, and they also help in preventing getting stuck in one of the solution spaces local optima. Although larger values for these variables increase the speed of convergence they may also increase the likelihood of oscillations of a weight due to the proximity of a local optima in the solution space. Therefore, the learning and momentum terms are usually positive and less than one [43].

4-4.4 Neural Network Techniques used within this work

The techniques used in network training, within this work, are similar to those just discussed, but with slight modifications to increase performance. An adaptive back propagation technique was used to train the NN [44]. This consists of the same routine as typical back propagation with the exception that, instead on one learning rate for all the network nodes, a learning rate was assigned to each of the nodes in order to speed up convergence and improve overall performance. A momentum term was also used here but only one overall value for all the nodes. The activation function used within this work was a hyperbolic tangent function and the inputs were normalized to have a mean of zero and a variance of 1. It should also be noted that the tool used to obtain the weights of the NN for this research was developed by INESC Porto [42].

4-5 Neural Network Evaluation

In order to get an idea for what kind of performance is to be expected from a NN architecture, a preliminary evaluation is needed of its capabilities. The "training set" data, typically composed of ¾ of the OPs from the overall data set, is used to teach the NN and give a relative inclination as to its suitability for that particular application. The "test set," which is comprised of the remaining data, is used to evaluate the prediction capabilities and generalization performance of the structures.

If the training set provides good results, in terms of accuracy, and the test set does not, this generally indicates over fitting in the learning stage and/or that the current NN structure is too complex and needs to be simplified. On the other hand, if the training set and test set provide comparable results, but not satisfactory ones regarding the user this generally implies that a more complex structure should be tried or more data is needed. Once desirable results are attained from both the training and test data, a comparative evaluation can be made with the dynamic simulator.

4-6 Conclusions

This chapter has provided the needed support to demonstrate the capabilities of a NN to accurately predict the dynamic frequency response of a power system during a load shedding situation. More specifically, topics with respect to the identification of NN input variables were discussed, focusing on the relevant and most needed inputs to assure that the NN was provided with the necessary information to perform its prediction and generalization tasks. Next the procedure used to generate the data sets for training and testing the NN was outlined. Finally the structure of the NN was discussed, along with the needed evaluations for determining the NNs usefulness. The results that were achieved from all of the aforementioned procedures will be addressed in Chapter 6.

Chapter 5 Development of the Genetic Algorithm Based Approach

In this chapter a description is given of the procedure that the GA takes in route to identifying the optimal load shedding scheme for a given point of system operation. In this chapter a description of how the GA was developed, including the potential solution representation, the selection of it's operators, it's evolution, it's respective evolutionary parameters, and finally it's fitness function.

5-1 Solution Representation

In every GA it is crucial that the potential solution be encoded in such a way that the fitness function can make precise assessments and produce meaningful results. There are numerous ways in which solutions can be represented as GAs, anywhere from simple binary strings to complex trees. In this work, a simple 1 dimensional binary string is used for chromosome representation. Since load shedding consists of simple yes or no to the, "do we shed this load" question, only a 1 or 0 is used for potential solution representation. In this case a 1 indicates the load is to be shed, and likewise a 0 means it is to be kept in service. With this type of representation, each feeder within the system can be represented by one bit in the overall system chromosome, as seen in figure 5-1.

Bus Load:	1	•••	5
Chromosome:	1 0 0 1	•••	1 0 1 1
Feeder Number:	1 2 3 4	•••	1 2 3 4

Figure 5-1. Chromosome Representation

The amount of load present at each feeder is determined by an additional input file, which describes all the needed feeder information.

5-2 GA Operators

Within any GA there are two types of operators, crossover and mutation [45]. Crossover refers to the mating of two parent chromosomes to create two new child chromosomes. There are three types of crossover that can occur in a GA depending on the scope of the work and the preference of the user. For this work a uniform bit crossover was selected as the mating process of choice. The reason for this selection is that uniform bit crossover is not limited in its crossover pattern. Whereas the other two types have limitation, if optimal bits are located in certain locations. This point is illustrated in the figures that follow. [46].

Two schemata that One-Point Crossover Cannot Combine

Chromosome 1: **1** 1 **0** 1 1 0 0 1 0 1 1 0 1 **1**

Chromosome 2: 0 0 0 1 0 1 1 0 1 1 1 1 1 0

Figure 5-2. One-Point Crossover

Two-Point Crossover Can Combine the Schemata

Chromosome 1: 1 1 **0** 1 | 1 0 0 1 0 1 | 1 0 1 1

Chromosome 2: 0 0 0 1 | **0** 1 1 0 **1** 1 | 1 1 1 0

Chromosome 1: 1 1 **0** 1 **0** 1 1 0 **1** 1 1 0 1 1

Chromosome 2: 0 0 0 1 1 0 0 1 0 1 1 1 1 0

Figure 5-3. Two-Point Crossover

First consider that the bits that are in bold text are the optimal genome for that particular bit in the overall string. As seen in figure 5-2 it is impossible to include all the optimal bits in one string via one-point crossover, due to their locations. And likewise if either of these chromosomes were altered it may be for the worse. With respect to two-point crossover, performed in figure 5-3, within this figure it can be seen that the optimal bits of the chromosome can be exchanged creating an optimal child. However this scheme also has its limitation as seen with the one point crossover. For example, suppose that two optimal bits are located on both sides of the crossover point. Uniform bit crossover can be seen in figure 5-4 [46].

Uniform Crossover

Parent 1: 1 0 0 1 0 1 1

Parent 2: **0 1 0 1 1 0 1**

Template: 1 1 0 1 0 0 1

Yields

Child 1: 1 0 **0** 1 **1 0** 1

Child 2: 0 **1** 0 **1** 0 1 1

Figure 5-4. Example of uniform crossover

From figure 5-4 it can be seen how uniform crossover is performed. The template is used to indicate which bits are to be switched. The bits of the second parent are in bold text so that the origin of the bits in the resulting chromosomes of the children can be determined. With the use of uniform crossover the potential limitation of crossover are avoided and hence the resulting GA is free to mate and crossover in an unlimited possibility of success.

The second type of operator used within a GA is mutation. Mutation allows for irregularities to be introduced into children that did not originate within the parents. Single bit flip mutation is used within this work. This type of mutation can be seen within figure 5-5 [46].

Child 1:	1 0 1 0 0 1 1
Bit to be mutated:	0 0 0 1 0 0 0
	Yields
Child 1a:	1 0 1 **1** 0 1 1

Figure 5-5. Example of single bit flip mutation

From the figure we can see that one of the bits within the child was selected for mutation and thus was flipped.

These two types of operators allow the GA to evolve to an optimal solution. The crossover operator helps the GA converge to the local optima, which may in fact be the overall optimal. The mutation operator not only helps the GA in convergence but it also helps in getting it out of local optima, and advancing toward the global solution optima.

5-3 *Evolution of the Genetic Algorithm and it's Parameters*

In this section the solution population, the operator probabilities, and the process termination identifier are described. These variables and their respective values will be addressed as they are encountered throughout the evolutionary cycle, described next.

In the first evolution of the GA the population of solutions must be initialized. Within this work this is achieved via random individual generation. After this initialization the sequence of the GA evolution follows the cycle described in the following sections. First, the GA selects a set of parents for mating. There are many types of selection techniques that can be used for parent selection, within this work a roulette wheel selection is performed. This type of parent selection though random in nature tends to select parents with higher fitness values, thus producing children with high fitness as well. This type of selection technique can be seen in figure 5-6 [46] and the following example.

Chromosome:	01	02	03	04	05	06	07	08	09	10
Fitness:	08	02	17	07	02	12	11	07	03	07
Running Total:	08	10	27	34	36	48	59	66	69	76

Figure 5-6. Roulette Wheel Selection

First a number is generated randomly from 0 to total running fitness, 76 in this example. Suppose for this example that number 50 was generated randomly. Therefore, the first chromosome having a running total greater than or equal to the random number generated, 50 in this case, is the one selected for mating. In this example it can be seen that the running total of 59 is the first value greater than 50, therefore chromosome number 7 would be selected. The greater the chromosome fitness, the larger the gap between each chromosomes running total. This increased gap allows for a higher probability of selection. Therefore a chromosome with a small fitness value, and hence smaller running total gap, is less probable for selection.

After a set of parents has been chosen for mating, another random number is generated to determine if crossover will take place. This determination is done via simple probability values; should the value of the random number be less than or equal to the probability value assigned to the crossover operator then crossover will take place, otherwise it will not occur, and the resulting children will be clones of the parents.

After the mating process as been completed each of the two resulting children will be given a chance to mutate. Again random numbers are generated, one number for each of the child's bits. Should the bit random number be less than or equal to the probability value of mutation, then that corresponding bit will be mutated. Within this work a trail and error experiment observing the GA's convergence properties was performed. It was determined, via trial and error simulations that the values of 0.2 and 0.001 were to be used for the crossover and mutation probabilities. These values provide a good rate of convergence toward the optimal solution and also provide ample chances of jumping out of local optima as will be seen in the result section.

After mating and mutation have occurred the new population needs to be established. The term population simply refers to the number of solutions kept between each cycle (evolution) of the GA process. Within this work a population size of 300 individual chromosomes was used.

The new population consists of all the new children created in the mating process. However, even though some parents were selected for mating, this does not necessarily mean that crossover of chromosomes took place, as mentioned prior, therefore the resulting children could simply be just clones of their parents. Using this type of population helps prevent the GA from getting stuck in local optima. However, there is a greater risk of losing the best solution. This can occur if the optimal solution was created in an early evolution and not selected for mating, therefore leaving it behind. One technique adopted to prevent the optimal solution from being lost is "Elitism". This technique identifies the best ever-encountered solution and automatically passes it to the next evolution regardless of its selection for mating. This ensures that the best chromosome is not lost. Some of the optimal solution that are included in the result set might be produced in early generations. However, it may also be the case that some of the "would be" top solution, not the "elitist", may be lost. This loss can be attributed to these "would be" top solutions not being selected for reproduction, due to randomness. This type of population also has a greater likelihood of reproducing the same chromosomes again, since there are no means to ensure that identical chromosomes are not re-introduced in the population.

Finally, the last step needed in completing the GA is the termination identifier. Typically one of two types of termination are used in GAs, either a convergence term or a maximum number of generations. A convergence term utilizes the best solution error achieved by the GA so far, and compares this error with a given tolerance, if the error is less than this tolerance the process is stopped. Another scheme used for stopping the GA is the maximum number of generations that are to be performed by the GA. Within this work, the maximum generation terminator was used with a maximum generation count of 500. Again, like with the reproductive probabilities, the values of the population size and number of generations were determined via trial and error simulations.

5-4 Fitness Function

The fitness function of the GA is used to determine overall chromosome fitness with respect to the "objective" at hand. Optimizing the overall value of this function is the goal of the GA. This function can be as simple or as complex as the user desires, depending on the application. The GA has one of two options when it comes to evaluating the results of the objective function. It can either maximize the value of the objective function or minimize it, again dependent on the application. Within the scope of this work the goal of the GA is to minimize the value of the fitness function.

The fitness function is broken up into four distinct objects, each having its own weight to indicate its importance to the overall fitness function value, as can be seen in equation 5-1. Each of the objects in the fitness function represents a restriction imposed in equation 3-1, with the fourth object representing the overall minimization objective of the total load to be shed. Each of these objects and the role they take in determining the optimal solution is discussed below.

$$FF = MFD * w1 + RF * w2 + PEN * w3 + LS * w4$$ **Equation 5-1**

Where *MFD* is the maximum frequency deviation object;

RF is the steady-state resting frequency object;

PEN is the load penalty object;

LS is the load shedding object;

w1 to w4 are the object weights

First the maximum frequency deviation object is as its name applies the maximum frequency deviation of the particular chromosome. However, the value of the MFD is not a straightforward deviation in frequency value, but instead it is a step function as seen as in equation 5-2.

$$MFD = \begin{cases} 100{,}000 & \textit{if}\ \text{mfd} > 3.0 \\ e^{|mfd|*mfmore} & \textit{if}\ \text{mfd} <= 3.0 \end{cases}$$ **Equation 5-2**

Where *mfd* is the maximum frequency deviation;

mfmore is a constant.

These are two characteristics of the MFD object. The first characteristic is, in order to avoid frequency excursions that reach magnitudes of 3 Hz for more than 1 second (due to harmful affects on the generator's turbine), thus ensuring that the GA will only purpose solutions that have a maximum frequency deviation of less than 3 Hz. Thus solutions that do not minimize the maximum deviation to a value less than 3.0 Hz will be severely penalized with a value of 100,000 to the object, which will most assuredly keep them from achieving a good overall fitness value. The second characteristic of the MFD object is if the solution has an mfd less than 3 Hz then a simple exponential function will be used to calculate its object value. Since the goal of the shedding scheme is to return the frequency to nominal as quickly as possible, the greater the deviation in frequency the greater length of time it will take the frequency to recover. Since the relative change in maximum deviation between potential solutions is usually small, an exponential function is used to increase the difference and hence the overall value this object will have in the final calculation of fitness. An exponential is also used to give greater "penalty" to solutions that are further from zero frequency deviation. The inclusion of the mfmore constant in equation 5-2 is used to tailor the influence that maximum deviation has on the potential solutions. The higher the mfmore value the greater the difference between close solutions and thus the overall fitness function final value.

Like the MFD object the resting frequency object is not a straightforward frequency value but rather can be determined via equation 5-3.

$$\text{RF} = \begin{cases} e^{|50-rf|*rfmorepos} & \textit{if} > 50.0\ \text{Hz} \\ e^{|50-rf|} & \textit{if} >= \text{resting threshold} \\ e^{|50-rf|*rfmoreneg} & \textit{if} < \text{resting threshold} \end{cases}$$ **Equation 5-3**

Where *rf* is the resting frequency;

rfmorepos and *rfmoreneg* are constants.

This is the most important object of the fitness function due to the fact that the overall goal of the load-shedding scheme is to return the frequency back to or close to the threshold (nominal in this case). Again like the MFD object a step function was used to help focus the solution to the most desirable according to the overall objective. The use of a resting frequency threshold was used in order to tailor the resulting solution to a threshold should it be something other than nominal, depending again on the objective of the shedding scheme. Also the use of an exponential function is used to give more of a separation between close values, and to give more benefit to solutions that vary less from the desired resting point. The two constants rfmorepos and rfmoreneg are used so as to give more worth to potential GA solutions.

The third object in the fitness function is the load penalty object. This object associates the priority a load has in the system with a penalty factor, should the GA select that particular load for shedding. The use of a penalty factor in this objective function is to mimic the actual systems priority schemes. The equation used to calculate the penalty object can be seen in equation 5-4.

$$PEN = pen / pnmore$$ **Equation 5-4**

Where *pen* is the sum of all the load penalties for a given solution;

pnmore is a constant.

The constant pnmore is used so that the penalty object can be adjusted to increase or decrease the penalty objects value.

Finally, the fourth object in the fitness function is the load shed object. This object is used to indicate to the fitness function the total amount of load being shed for a particular solution. Typically an objective of a load shedding scheme is to minimize that amount of load being shed however, this generally is at the cost of other system variables. For instance most shedding schemes losing only minimal load can arrest the frequency from falling further but do not take into consideration that steady-state system frequency is less than nominal, and hence rely on operator intervention to adjust the frequency accordingly. The equation for the load shedding object used within this work can be seen in equation 5-5.

$$LS = ls^{lfmore}$$ **Equation 5-5**

Here, *ls* is the amount of load shed for a given solution;

lfmore is the value of the exponent.

The GA uses an n-powered function so as to give a greater value to schemes that shed more loads and hence makes them less attractive for selection. The GA objective function coefficients used in this research were obtained after several tests, using engineering judgment, and can be seen in table 5-1.

Table 5-1. GA objective Function Coefficient Values

Coefficient	w1	w2	w3	w4	mfmore	rfmorepos	rfmoreneg	pnmore	lfmore
Value	0.7	1	0.5	0.3	1	20	5	2	0.6667

5-5 Conclusions

This chapter has described the approach to create optimal load shedding strategies through the use of a GA. More explicitly, the objective function outlined in chapter 3 has been manipulated into a viable fitness function needed by the GA to evaluate potential shedding scheme [47]. The GA construction also has the ability to logically and successfully perform the needed evaluations, such that optimal solution convergence is achieved in a timely manner. The results that were obtained throughout this chapter will be addressed in chapter 6.

Chapter 6 Numerical Results

This chapter presents the necessary information to support the work performed in this thesis. The chapter begins with the presentation of the system model used for this work and the disturbance selected for the simulation. Next the chapter presents the results obtained with respect to the NN, in terms of operating point generation, performance evaluations, and comparisons made with a dynamic simulator. Finally the presentation of the GA results will be discussed, in terms of optimal solution convergence, load type influence on system dynamic performance, and the overall success with respect to selecting logical and optimal load shedding schemes.

6-1 Terceira Model

6-1.1 Terceira System Network

In this work a model similar to the Terceira Island Network (Terceira is one of the islands of the Azores Archipelagos – Portugal) has been selected for the applications within this thesis. As seen in section 2-3 an isolated system model allows for compact, simple, and precise system analysis. Figure 6-1 shows the one line diagram used for the Terceira Network. This power system was adopted from [48] and modified for simplicity. The modifications that were made to the system will be described as they are encountered throughout this section.

In order to make quick bus type assessment the system was numbered with the following schema:

1-9	are generator buses
10-99	are load buses
100-999	are transmission buses

As can be seen from figure 6-1 the power system is composed of 6 voltage levels and 4 transmission buses, 5 actual load buses and 1 hypothetical load bus, and 8 generator buses. The transmission and transformer impedance data can be seen in table AIII-1 of Annex III. A description of the buses is provided in what follows.

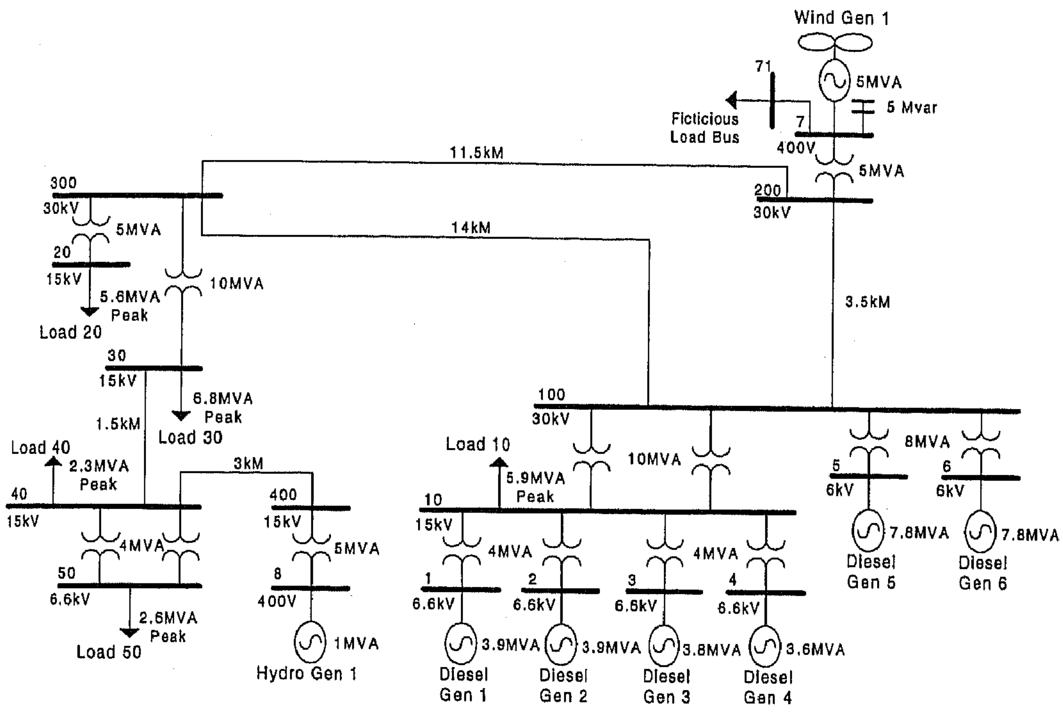


Figure 6-1. Terceira System Model

6-1.2 Generation

As mentioned prior, the Terceira Power system is comprised of eight generator buses, each bus containing only one generator. Of these eight generators, two of them use renewable energy resources. One of their is a hydro station (bus 8), which is a standard synchronous machine, and the other generator is an asynchronous wind park (bus 7). One modification that was made to the Terceira network was the aggregation of the two foreseen wind parks, for representative simplicity, in the actually network to only one wind park at bus 7. Although due to IPFLOW program limitations the wind generator, at bus 7, will be modeled as a synchronous machine plus an additional reactive load.

Within the scope of this thesis only the diesel station contributes to the systems dynamic response. Since the wind park will be disconnected from the power system due to the disturbance selected, its generator dynamics were neglected. The other 6 units within the power system are diesel-powered units, each of which are represented by a synchronous machine model like the one seen previously in figure 2-2. The model used to represent the generators is a two axis model.. The synchronous machine base ratings,and inertia constant are also included into the model. Each of the diesel generators, along with the hydro unit in the system participates in speed and voltage regulation. The models for the voltage exciter and speed governor were also adopted from EPRI's ETMSP built in data block library. All of the generator models and dynamic data can be seen in Annex I.

Using these types of generator models gives a more realistic system representation, and hence a better picture of the true dynamic response. However, as seen from the governor model there is a lack of integral control over individual units. Therefore it was assumed that governor set points are established by AGC operation, and thus once established are maintained until reset by a new operating condition. As was mentioned prior the real power generation heavily utilizes the wind power production.

6-1.3 Load

The load composition of the network representation adopted for the Terceira system consists of five load buses spread throughout the system. Each of the load buses was further considered to be divided into four feeders, each containing five potential load types; constant MVA, constant impedance, constant current, exponential one, and exponential two. The total load real and reactive powers can be calculated from equations 2-8 and 2-9 respectively. Using these equations, two different levels of load representation were used for the work in this thesis.

Within the framework of the NN training a composite busload model was used to represent all the four feeders found at each given bus into one composite load, achieved using the procedure seen in section 2-1.4. The resulting busload model's real and reactive power load coefficients and exponents, which are the same in all cases, can be seen in table AII-1 and table AII-2 respectively in Annex II. Using this process ensures an accurate bus level representation of all the feeders. The purpose of using this composite load model at the bus level was to decrease the overall size of the data set for the NN. If a four-feeder load representation were to be used, the size of the resulting database would be enormous and therefore infeasible to create using the procedure discussed in the following section. It should be noted that although load location plays an important role in a large interconnected system, due to the close proximity of loads within an isolated network, it has negligible influence on the dynamic frequency response.

The second type of load representation used within this work is the actual power system, and will be for the GA application. Since load shedding is performed at the feeder level, it is imperative that the GA makes comparisons between actual load shedding schemes. The NN only needs total load shedding values and total load values, as was described in section 4-2, to produce the resulting dynamic response, hence enabling the GA to evolve to an optimal feasible solution. A feeder level system model was created, with each feeder using the load model described previously. The resulting feeder load model real and reactive power exponents are the same as those used in table AII-2. These feeder load model coefficients can be seen in tables AII-3 through AII-7 in Annex II. The load minimum and maximum values can be seen in table AII-8.

As it can be seen from the tables in Annex II some of the coefficients are less than or greater than the values used for the busload model, seen in the total column. Since the NN was not trained with values in this range, it may seem to pose a problem for the NN's prediction capabilities in cases where the NN is presented with schemes utilizing these "out of range" feeders. However, the capability of the NN to make generalizations can overcome this problem, as will be addressed in the result section.

6-1.4 Transmission and Distribution Network

The Terceira transmission network is small and is only composed of three buses at 30 kV level each and three lines interconnecting them. Each of the buses is then stepped down to distribution levels with Under Load Tap Changers (ULTC). There are a total of seven ULTC's within the system, three of which step the voltage down for connection with generation facilities, and the remaining four are used to step the voltage down to load buses. Fixed tap transformers are also used within this system to further step the voltage down to other load buses.

6-1.5 Disturbance Selection

Having in mind the particularity of the network under analyses, namely that the wind park in the network constitute its weak point, a loss of wind power generation was simulated to replicate the needed generation-load imbalance disturbance, due to its high severity and probability if occurrence. This was achieved via a symmetrical three-phase fault on the transmission line connecting buses 200 and 300 as seen in figure 6-1. The resulting consequence of this fault is the disconnection of not only the transmission line but the wind park as well. A thermal overload check was performed to evaluate the potential of overloading the resulting system configuration. The result of this analysis has shown that the system does not violate any thermal limits due to the loss of this transmission line. For this disturbance the GA will assess the current system operating conditions and determine what the best load shedding scheme would be for this scenario. Other system disturbances can be used to train the NN too in order to replicate the systems dynamic response for these cases.

6-2. Neural Network Results

The results regarding the NN obtained in this work can be broken down into three areas. The first includes scatter plots of the system load and generator data created for the NN data set. The second, with respect to the NN a performance result, illustrates the NN training and testing procedures. The third provides a comparison between the NN and a dynamic simulator results. Each of these will be addressed in the sections that follow.

The graphs of the loads below in figures 6-2 to 6-6 show the wide range of allowable parameter coverage this operating point generator provides.

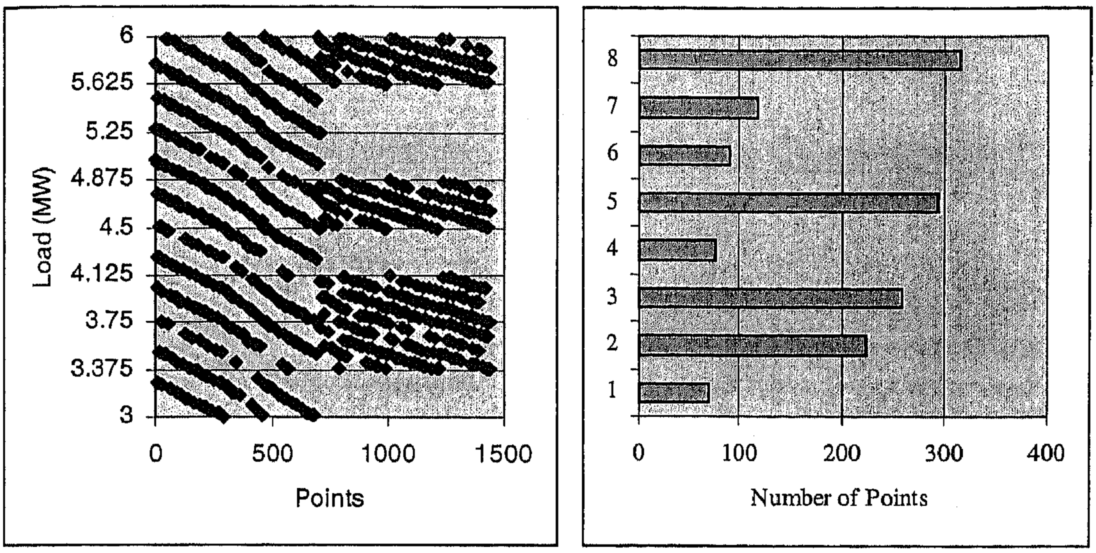


Figure 6-2. Load 10 Scatter Plot

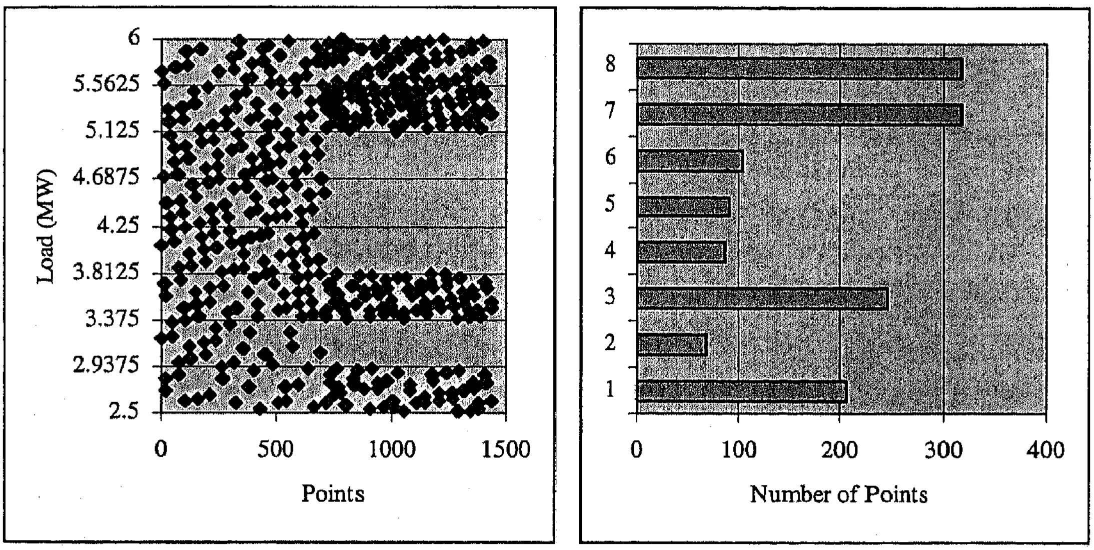


Figure 6-3. Load 20 Scatter Plot

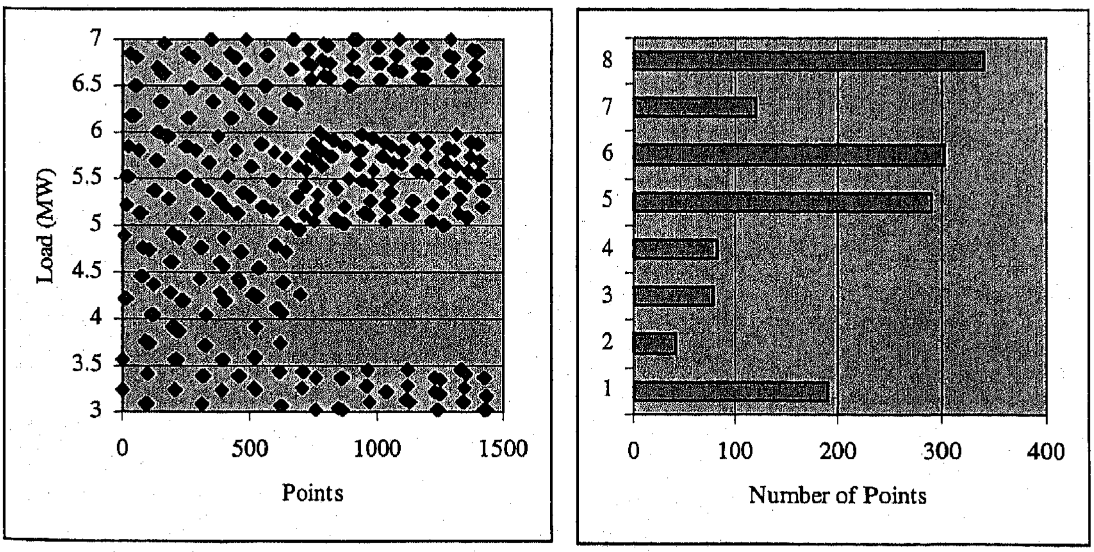


Figure 6-4. Load 30 Scatter Plot

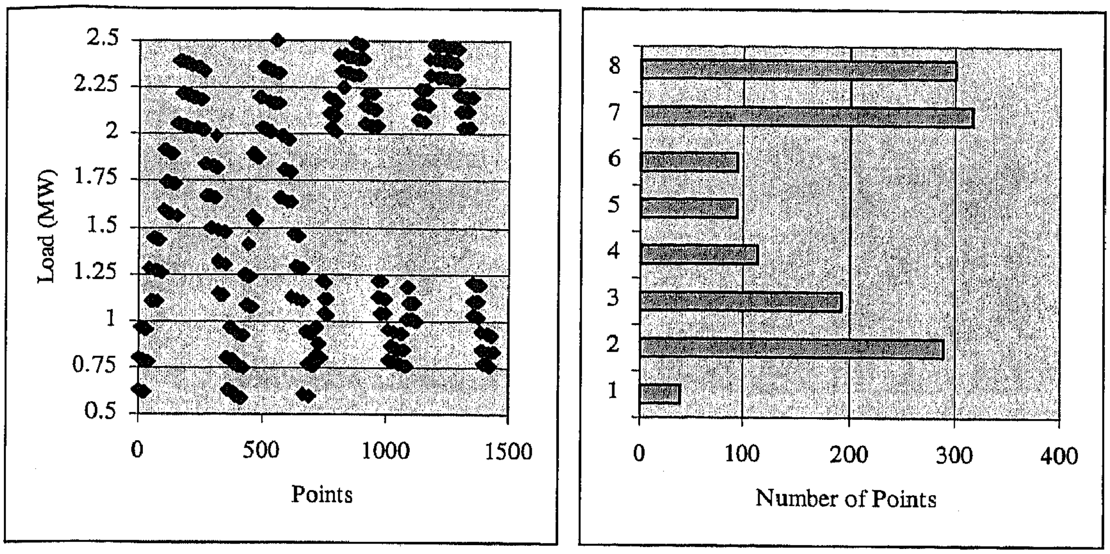


Figure 6-5. Load 40 Scatter Plot

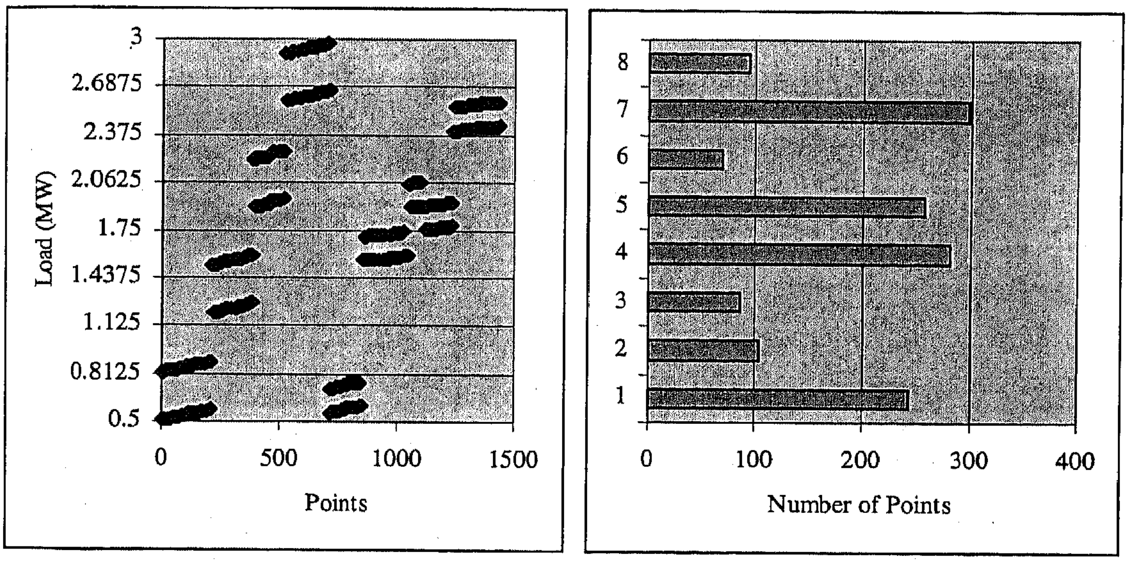


Figure 6-6. Load 50 Scatter Plot

As can be seen from the load bus scatter plots, the plots are comprised of two distinct sections. The first section of the plot shows the generation of operating points throughout the entire range of the load, later referred to as the MC data, and the second section of the plot follows the load curve model, later referred to as the LC data. From these plots two points can be addressed with respect to data coverage and its potential advantage. Considering the first section of the plot, it can be seen that the plot gives a complete coverage of the entire range of operation, thus alleviating the potential for bad generalization in areas not covered by the load curve model. With respect to the second section of the plot, it can be seen that the load curve model has a greater density of points in each respective area (1 to 8), therefore creating the potential for better NN accuracy within that area. Since both breadth and depth are desired from a NN data set, the combination of these two databases seems the logical choice for a complete data set.

Four different comparisons were made in order to get a full "data potential" assessment, each utilizing one of two NNs. The first NN was trained with simple Monte Carlo (MC) operating points over the entire operating range. The second NN was trained with the Load Curve (LC) operating points, as described earlier. Each NN was then tested with two data sets, one consisting of points from the MC operating set and the other containing points from the LC operating set. A numerical comparison, as seen in tables 6-1 to 6-4, between these two methods was performed in order to show the aforementioned potentials of the two training methods, thus leading to the combination of methods.

Table 6-1. NN performance Evaluation of MC vs. MC

Case MC vs. MC	Mean Abs. Error	RMS Error	Abs. Deviation	RMS Deviation
Max. Pos. Deviation (Hz)	0.04003	0.092848	0.050834	0.117907
Max. Neg. Deviation (Hz)	0.027272	0.048286	0.015421	0.027302
First Neg. Swing df/dt (Hz/s)	0.052045	0.110024	0.047719	0.100878
Residual Frequency (Hz)	0.025534	0.067229	0.000513	0.00135

Table 6-2. NN performance Evaluation of LC vs. LC

Case LC vs. LC	Mean Abs. Error	RMS Error	Abs. Deviation	RMS Deviation
Max. Pos. Deviation (Hz)	0.036505	0.083333	0.045749	0.104435
Max. Neg. Deviation (Hz)	0.025531	0.055663	0.01426	0.03109
First Neg. Swing df/dt (Hz/s)	0.052851	0.120398	0.045265	0.103116
Residual Frequency (Hz)	0.020052	0.060988	0.000403	0.001224

Table 6-3. NN performance Evaluation of MC vs. LC

Case MC vs. LC	Mean Abs. Error	RMS Error	Abs. Deviation	RMS Deviation
Max. Pos. Deviation (Hz)	0.054403	0.108332	0.069086	0.137569
Max. Neg. Deviation (Hz)	0.047476	0.074619	0.026844	0.042192
First Neg. Swing df/dt (Hz/s)	0.086191	0.174754	0.079026	0.160227
Residual Frequency (Hz)	0.035992	0.082963	0.000723	0.001666

Table 6-4. NN performance Evaluation of LC vs. MC

Case LC vs. MC	Mean Abs. Error	RMS Error	Abs. Deviation	RMS Deviation
Max. Pos. Deviation (Hz)	0.048924	0.098236	0.061313	0.123112
Max. Neg. Deviation (Hz)	0.04023	0.069742	0.02247	0.038953
First Neg. Swing df/dt (Hz/s)	0.070968	0.154776	0.060781	0.132559
Residual Frequency (Hz)	0.027723	0.070468	0.000556	0.001415

From these tables the previously mentioned data set potentials can be seen. With respect to table 6-1 and 6-2, the NN trained with the LC data provides more accurate results than the NN trained with only the MC data, as was expected, due to a greater point density around the load curve model. However, when evaluating the crosscomparisons, tables 6-3 and 6-4, two issues need to be addressed. First, it can be seen that the NN trained with the MC data provides better results than the one trained with the LC data. This is due to the absence of points in areas of the load range that were not modeled by the load curve. Second, the NN trained with the MC data set has a poorer accuracy than either of the previous tests, tables 6-1 and 2. This last point indicates that the MC data set alone is insufficient with respect to a NN accuracy. Therefore, a combination of the two data sets will be employed and the resulting performance will be analyzed in the next section.

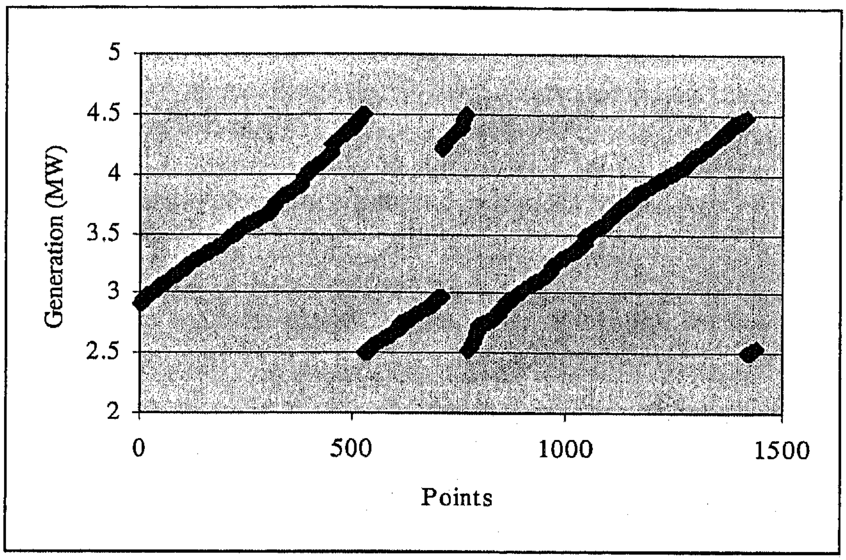


Figure 6-7. Generator 5 Scatter Plot

The scatter plot in figure 6-7 shows the values generated for a secondary independent parameter, in this case generator 5. Since all scatter plots of secondary independent parameters look the same, generally speaking, they are not included in order to avoid redundancy. The final training set will have more than 1024 due to the fact that for each of these potential operating points there will be potentially more than one load shedding scheme and therefore possibly more than one simulation will be necessary for each operating condition.

6-2.1 NN Performance Results

After the design of the NN (adopting the architecture described before), a performance evaluation stage was implemented, as mentioned prior. The results obtained can be seen in table 6-5. As can be seen from this table the NN's training performance, in terms of accuracy, was quite satisfactory and provided a good predictability with respect to the test set.

Table 6-5. NN Performance Results

Frequency Variable	Mean Abs. Error		RMS Error		Abs. Deviation		RMS Deviation	
	Train	Test	Train	Test	Train	Test	Train	Test
Max. Pos. Deviation (Hz)	0.037	0.041	0.089	0.101	0.0475	0.0503	0.1130	0.1235
Max. Neg. Deviation (Hz)	0.029	0.029	0.0547	0.058	0.0161	0.0163	0.0307	0.0325
First Neg. Swing df/dt (Hz/s)	0.055	0.059	0.108	0.153	0.0488	0.0518	0.0957	0.1355
Residual Frequency (Hz)	0.023	0.024	0.064	0.074	0.0005	0.0005	0.0013	0.0015

Thus it was assumed that the NN has the capabilities to predict the dynamic frequency response of the power system during an under-frequency load shedding scenario, hence a comparison is needed.

6-2.2 NN Comparison with a Dynamic Simulator

Three comparisons were made with a dynamic simulator, ETMSP, in order to see how well the NN can predict system dynamic frequency response for two system models. The first comparison uses the busload system model, which was the model used to generate the training data, while the second and third comparisons utilize the feeder load system model, which is the actual system model. The first comparison simulates the loss of 7.9 MW of wind power production and a subsequent shedding of 7.8 MW. The numerical results obtained from the dynamic simulator and the NN can be seen graphically in figure 6-8 and numerically in table 6-6. As was expected, it can be seen that the NN provides results that match quite well in comparison with the ones obtained from full dynamic simulation given through ETMSP.

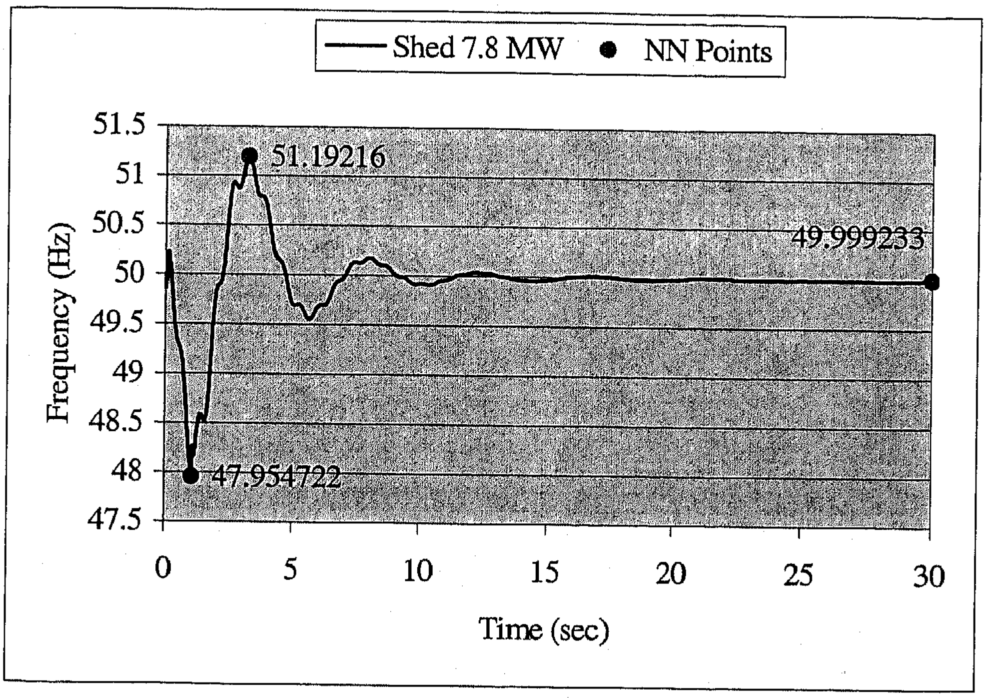


Figure 6-8. NN vs. Dynamic Simulator Comparison 1

Table 6-6. NN vs. Dynamic Simulator Numerical Comparison 1

Frequency Variable	Shed 7.8 MW		
	Dyn. Sim.	NN	Abs. Diff.
Max. Pos. Deviation (Hz)	0.23586	0.29807	0.06221
Max. Neg. Deviation (Hz)	2.18452	2.146897	0.037623
df/dt (Hz/s)	1.356845	1.37481	0.017965
Residual Frequency (Hz)	49.43389	49.46745	0.033555

Demonstrating that the NN has the capabilities to produce precise results for the actual power system model is crucial to the further development of this work. Therefore a second and third comparison was needed to exhibit the accuracy of the NN under actual system scenarios. In regards to actual system scenarios two types of load data are of a concern. As mentioned prior a composite busload model was used for training the NN, thus there is a potential for some feeder loads to have values out of the aggregate model range. Therefore the second comparisons will be made for feeder loads that have values within the training range and the third will be made in for feeder loads outside of the training range, in order exhibit the NN generalization capabilities.

The second comparison simulates the loss of 4.2 MW of wind power production and a subsequent shedding of 4.46 MW. The numerical results obtained from the dynamic simulator and the NN can be seen graphically in figure 6-9 and numerically in table 6-7. Again as expected the NN provides comparable results with the dynamic simulator. These results show two significant points. First, the NN has the capabilities to accurately predict the dynamic response of a power system during a disturbance. Secondly, the aggregation of feeder loads into one busload for the purpose of reducing OP generation sufficiently characterizes the system load. Thus from this point on the NN can be used solely for further dynamic frequency response evaluations.

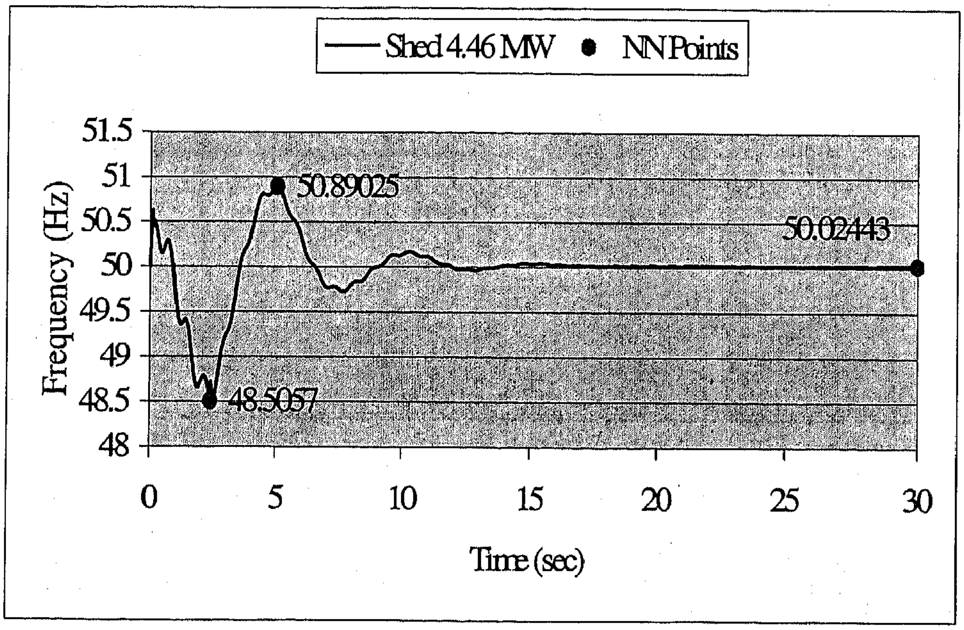


Figure 6-9. Frequency Response and Corresponding NN Point Prediction

Table 6-7. NN vs. Dynamic Simulator Comparison 2

Frequency Variable	Shed 4.46 MW		
	Dyn. Sim.	NN	Abs. Diff.
Max. Pos. Deviation (Hz)	0.89025	0.9368	0.04655
Max. Neg. Deviation (Hz)	1.4943	1.480065	0.014235
df/dt (Hz/s)	0.620041	0.69299	0.072949
Residual Frequency (Hz)	50.02443	50.00568	0.01875

The third comparison simulates the loss of 7.6 MW of wind power production and a variable amount of shedding, from six different load shedding schemes. Each of these load shedding strategies focused on presenting the NN with feeder loads that had load model coefficients outside of the training range. Each of the shedding schemes that were tested can be seen in table 6-8. It can be seen that some of the schemes had more than one of the three load modeling coefficients outside of the training range.

Table 6-8. Load Shedding Schemes

High Exponential Type 1

Scheme HE1	11	12	53	Total %	Shed (MW)
ZIP	62	49.5	48	55.8	1.52
EXP 1	31	31	47	33.2	
EXP 2	7	19.5	5	11	

High Exponential Type 2

Scheme HE2	10	12	24	42	51	Total %	Shed (MW)
ZIP	77	49.5	55	72	63	66.1	2.7
EXP 1	11	31	30	8	25	19.4	
EXP 2	12	19.5	15	20	12	14.5	

High ZIP

Scheme HZ	30	40	Total %	Shed (MW)
ZIP	85	92	86.1	0.98
EXP 1	10	3	8.9	
EXP 2	5	5	5	

Low Exponential Type 1

Scheme LE1	40	Total %	Shed (MW)
ZIP	92	92	0.16
EXP 1	3	3	
EXP 2	5	5	

Low Exponential Type 2

Scheme LE2	13	20	21	25	30	33	40	41	50	53	Total %	Shed (MW)
ZIP	77	80	66	76	85	77	92	82	72	48	76.3	6.99
EXP 1	21	16	30	21	10	20	3	13	23	47	20.4	
EXP 2	2	4	4	3	5	3	5	5	5	5	3.32	

Low ZIP

Scheme LZ	11	12	24	52	53	Total %	Shed (MW)
ZIP	62	49.5	55	62	48	56.3	2.2
EXP 1	31	31	30	26	47	31.9	
EXP 2	7	19.5	15	8	5	11.8	

The results from the comparisons can be seen in table 6-9, with the mean average in table 6-10.

Table 6-9. NN vs. Dynamic Simulation Comparison 3

Frequency Variable	HE1			HE2		
	Dyn. Sim.	NN	Abs. Diff.	Dyn. Sim.	NN	Abs. Diff.
Max. Pos. Deviation (Hz)	0.15126	0.299959	0.148699	0.16084	0.193247	0.032407
Max. Neg. Deviation (Hz)	2.36818	2.394459	0.026279	2.0901	2.146879	0.056779
df/dt (Hz/s)	1.426614	1.532506	0.105892	1.290185	1.626939	0.336754
Residual Frequency (Hz)	49.31918	49.34044	0.021259	49.46821	49.46203	0.006181

Frequency Variable	LE1			LE2		
	Dyn. Sim.	NN	Abs. Diff.	Dyn. Sim.	NN	Abs. Diff.
Max. Pos. Deviation (Hz)	-0.03479	0.254451	0.289241	1.1722	1.080704	0.091496
Max. Neg. Deviation (Hz)	2.58802	2.528127	0.059893	2.04452	2.048746	0.004226
df/dt (Hz/s)	1.522365	1.55123	0.028865	1.928792	1.937358	0.008566
Residual Frequency (Hz)	49.16614	49.19919	0.033048	49.94404	49.94181	0.002226

Frequency Variable	HZ			LZ		
	Dyn. Sim.	NN	Abs. Diff.	Dyn. Sim.	NN	Abs. Diff.
Max. Pos. Deviation (Hz)	0.06907	0.271102	0.202032	0.21492	0.291736	0.076816
Max. Neg. Deviation (Hz)	2.4391	2.422589	0.016511	2.24336	2.290391	0.047031
df/dt (Hz/s)	1.451845	1.52016	0.068315	1.367902	1.47453	0.106628
Residual Frequency (Hz)	49.26177	49.28912	0.02735	49.4012	49.412	0.010795

Table 6-10. Mean Average of table 6-9 Results

Frequency Variable	Mean Abs. Error
Max. Pos. Deviation (Hz)	0.140115167
Max. Neg. Deviation (Hz)	0.035119833
df/dt (Hz/s)	0.109169754
Residual Frequency (Hz)	0.016809833

Again as expected the NN provides comparable results with the dynamic simulator. Although some of the errors are a bit higher than those obtained form scenarios that have shedding scheme with load type values within the training range, the two most important variables, max. neg. deviation and residual frequency, had errors quite comparable with those obtained in simulation comparison 2. In regards to the variables with higher errors, specifically max. pos. deviation and df/dt, one point need to be considered, regarding the max. pos. deviation. The value from the NN was always an overestimate, thus giving more pessimistic results, and hence no negative outcome from under-planning could occur.

Thus the results obtained from the third comparison shows the ability of the NN to make accurate generalizations, which is important to the overall effectiveness of the NN. Thus from this point on the NN can be used solely for further dynamic frequency response evaluations.

6-3. Genetic Algorithm Results

In regards to the results obtained with respect to the GA process three different evaluations were performed in order to show the quality of the work being done within this thesis. The first evaluation shows the ability of the GA to converge to acceptable solutions. The second evaluation is with respect to the influence load types have on load shedding schemes. Lastly the overall results obtained from the GA optimal load shedding strategies, in terms of this thesis objective will be discussed.

6-3.1 GA Convergence Evaluation

Throughout the evolution of the problem under study, the GA may come across solutions that are situated in local optima. The ability of the GA to overcome these local optima and evolve to a better, or best solution is of the utmost importance. The crossover and mutation rates influence this ability, therefore the tuning of these parameters is of great importance. Rate of convergence evaluation helps identify whether the GA has the capabilities to surmount these local optima and evolve to the best solution, which is paramount to the overall performance of this method. Figure 6-10 shows the rate of convergence of the GA for one particular case.

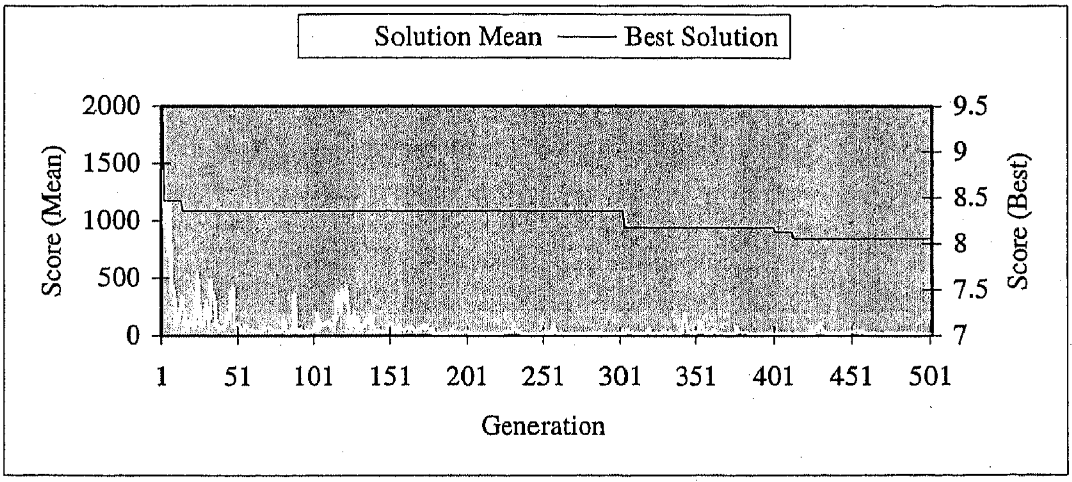


Figure 6-10. GA convergence

From the figure it can be seen that the mean value of the GA follows an exponential-like curve toward the optimal solution. The first hundred generations have a higher mean value, which generally indicates the GA is evaluating a wider area of solution space. Another feature to notice within this figure is that there are places throughout the evolution of the GA that the mean value spikes, showing the influence of chromosome mutation, in an effort to jump out of potentially local optima. This is an important aspect of the GA, which ensures that the GA does not prematurely converge to local optima.

6-3.2 Load Modeling Influence of Selected Load Shedding Schemes

In regards to the loads being modeled it is prudent to show how load type selection affects the resulting dynamic frequency response and resulting load shedding scheme. Again a loss of 7.9 MW of wind production was simulated and the resulting frequency response to 7 different load shedding strategies was observed. Each of the 7 shedding strategies, as seen in figure 6-11, implements a different level of load types to be shed, yet all maintain the same shedding value of 7.8 MW, due to the one-step shedding scheme being utilized in this work. This is critical so that the comparison is between load types and not the amount shed. For this evaluation scheme 1 will be used as a control scheme, in order to make a proper assessment of the outcome. The results obtained from the NN are shown in figure 6-12 to 6-14 and numerically in table 6-11. From the figures the "Additional from Base" marking refers to the additional or lesser amount, in reference to the control scheme (1). For example, from figure 6-12, feeder 3 has additional influence on the frequency, where as feeder 2 has lesser influence.

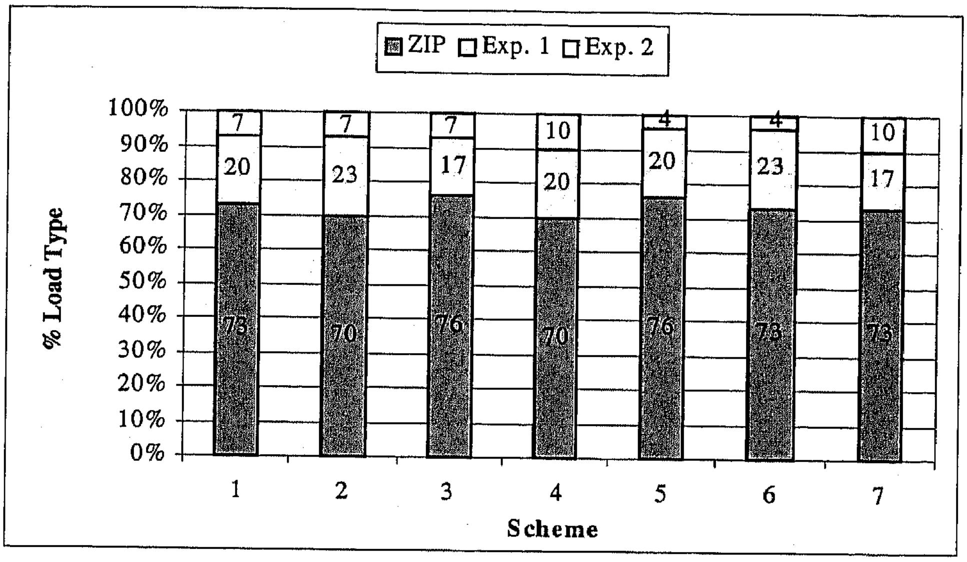


Figure 6-11. Load Type Composition

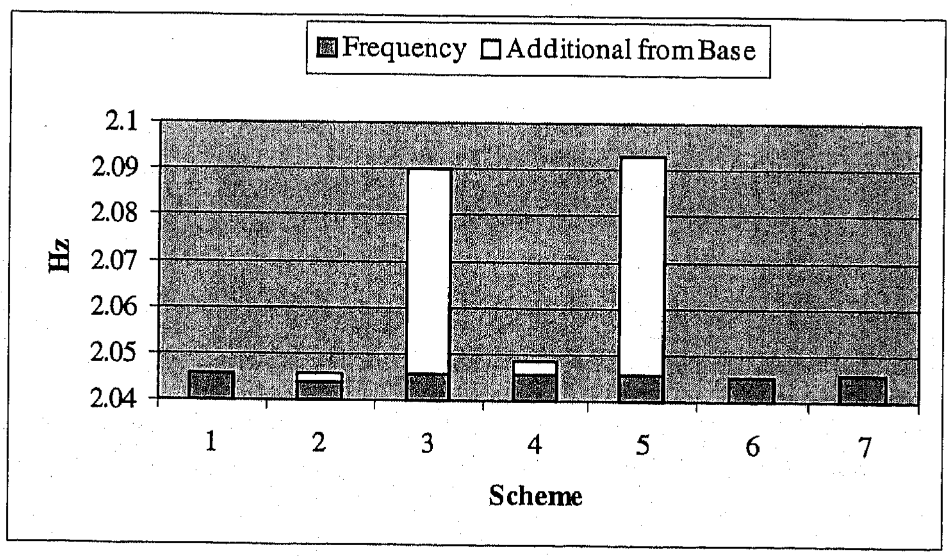


Figure 6-12. Comparison of Maximum Negative Deviation

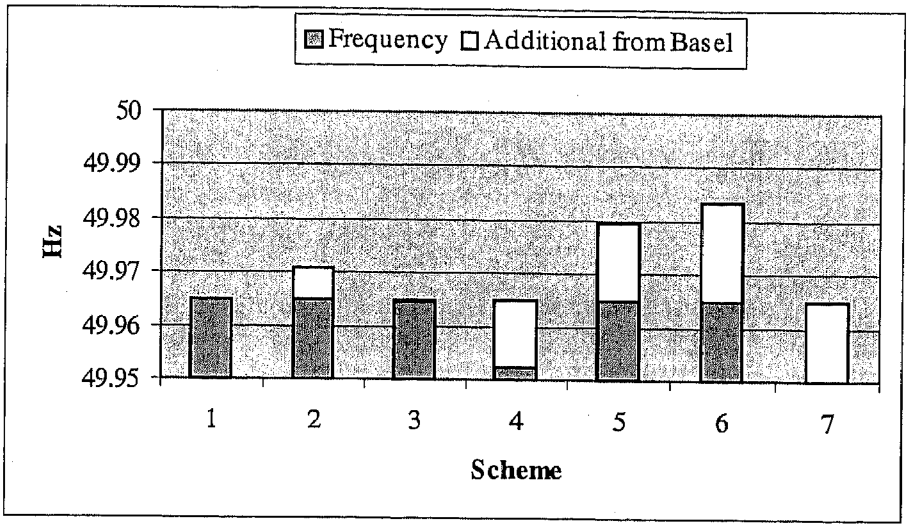


Figure 6-13. Comparison of Residual Frequency

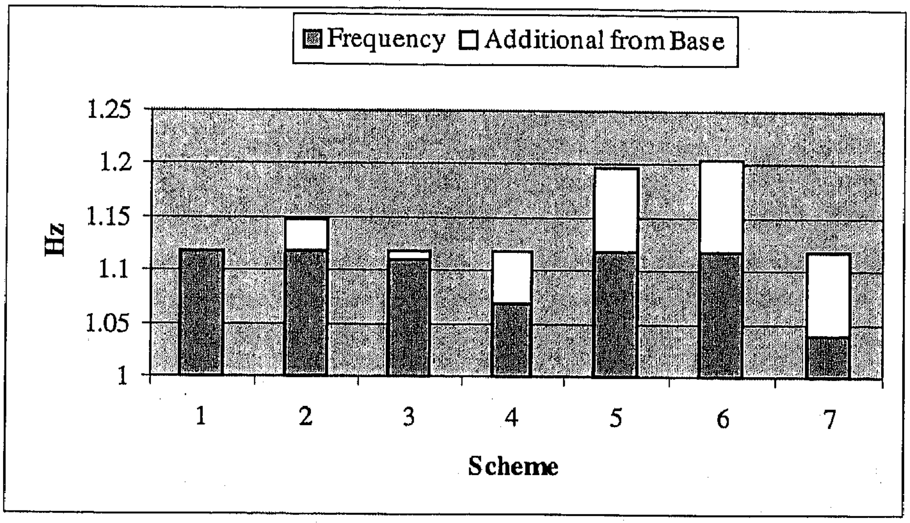


Figure 6-14. Comparison of Maximum Positive Deviation

Table 6-11. Numerical Load Type Comparison

Frequency Variable	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6	Scheme 7
Max. Pos. Deviation (Hz)	1.118615	1.148499	1.110736	1.068821	1.197019	1.20451	1.040087
Max. Neg. Deviation (Hz)	2.045526	2.043668	2.090024	2.048651	2.093116	2.04524	2.048563
df/dt (Hz/s)	1.944864	1.929815	2.025787	1.939525	1.994656	1.93176	1.95181
Residual Frequency (Hz)	49.96496	49.97077	49.96476	49.9525	49.9797	49.9835	49.94678

It should be mentioned that due to the dependency df/dt has on the maximum negative deviation it was not compared graphically, but instead shown only numerically.

Observing the figures it can be seen that each shedding scheme has an impact on the resulting frequency response. Identifying which load types have the best overall influence on the resulting frequency variables is the scope of this analysis. Therefore each of the 6 shedding schemes will be addressed separately, followed by a general conclusion about the overall influences, in regards to how it differs from the base scheme (scheme 1).

With respect to the base scheme, and the underlying objective function, a better scheme would portray the following traits:

- Decrease in the maximum negative deviation (MND);
- Decrease in the maximum positive deviation (MPD);
- Increase in the residual frequency.

Again due to the dependency df/dt has on the MND, any change in its value can be considered a result of a parallel change in the MND.

In regards to scheme 2, it presents a slight decrease in the maximum negative swing and an increase in the residual frequency value. However, this increase in residual frequency does bring on a parallel increase in MPD. With respect to scheme 3, it shows a large increase in MND and only slight decreases in the residual frequency. The only benefit is the decrease in MPD. Considering scheme 4, it provides an increase in MND and a decrease in the residual frequency. Again like scheme 3 it too has a decrease in MPD. Addressing scheme 5, it has an increase in the MND although it also has an increase in the resulting residual frequency, along with an increase in the MPD. In scheme 6, it appears that only a very small decrease in the MND occurs. However, a large increase in the RF occurs, along with an increase in the MPD. Lastly, scheme 7 again shows only a slight decrease in the MND. In terms of the RF a large decrease occurs, and a similar decrease in MPD as well.

From all of these evaluations a couple of conclusion can be drawn. Again as mentioned prior all comparisons will be made in terms of changes in the base scheme (scheme 1). Considering first the MPD. From figure 6-12 and table 6-11, four schemes provide the greatest changes in MPD. Schemes 4 and 7 provide a decrease, while schemes 5 and 7 show an increase in the value respectively. From these schemes three conclusions can be made.

1. First ZIP type loads seem to have little to no influence on the MPD, due to its contradictor influence in each scheme.
2. Exponential type 1 loads have a negative effect, meaning an increase in shedding these types of loads has a consequential increase in the MPD.
3. Exponential type 2 loads have a positive effect, meaning an increase in shedding these types of loads has a corresponding decrease in the MPD.

From these three conclusions, 2 and 3 have a heavier impact on the MPD. The question is which one has the greatest. Making this decision, based on deviation magnitude alone, it can be seen that conclusion 3 has a greater resulting effect than conclusion 2.

With respect to the RF, again three conclusions can be made.

1. First ZIP type loads seem to have little to no influence on the RF, due to its contradictor influence in each scheme.
2. Exponential type 1 loads have a positive effect, meaning an increase in shedding these types of loads has a corresponding decrease in the RF.
3. Exponential type 2 loads have a negative effect, meaning an increase in shedding these types of loads has a consequential increase in the RF.

Again from these three conclusions, 2 and 3 have more influence on the RF., but which one has the greater. Making this decision, based on deviation magnitude alone, it can be seen that conclusion 3 has a greater resulting effect than conclusion 2.

Finally, with respect to the MND, again three more conclusions can be made.

1. First an increase in the ZIP type load seems to have the greatest negative influence on the MND.
2. Exponential type 1 loads have little effect on the MND, meaning a decrease in shedding these types of loads has only a corresponding slight decrease in the MND.
3. Exponential type 2 loads have little effect on the MND, meaning an increase in shedding these types of loads has only a corresponding slight increase in the MND.

From these three conclusions, conclusion 1 has the greatest influence on the MND. Taking into consideration all of the nine previous conclusions a general perspective can be made in regards to what types of load should be shed to address the objective stated prior with respect to the overall frequency response of the network.

With respect to the first objective, decreasing the MPD, only exponential type 2 loads have a positive influence on this value. Although this outcome is desired, it is the least of the three to be concerned with when developing load shedding schemes. Therefore, since exponential type 2 loads have a negative influence on other frequency characteristics their benefit toward this characteristic is easily overlooked. In regards to the second objective of a load shedding scheme is to reduce the MND, loads that have an influence on this value should be considered. Since it seems that no one type of load has a great influence on reducing the MND, efforts in reducing the other frequency characteristics should be made. However, from the conclusions, it seems appropriate to limit the amount of ZIP type loads that are to be shed, since increasing them has a comparatively drastic outcome on the MND. Finally, with respect to the third objective, increasing the residual frequency, (decreasing the distance from nominal in general), exponential type 1 and 2 loads has the greatest influence on this. From the conclusion made earlier shedding more of exponential type 1 and less of exponential type 2 have the greatest positive influence on this characteristic.

So in conclusion, when developing load shedding schemes increasing the amount of exponential type 1 loads and decreasing the amount of exponential type 2 loads has the best overall influence on the resulting system frequency response. However, the amount of ZIP type load should also be considered due to its negative influence on the MND.

6-3.3 Load Shedding Scheme Evaluation

Making an evaluation of the schemes selected by the GA can be done by observing if the results produced are logical with respect to what the goal of the shedding scheme is. A recap of the load shedding scheme objectives can be seen below;

- Minimize MND
- Return RF to the threshold (nominal)
- Minimize Amount of Load to be Shed
- Minimize the Load Penalty Associated with the Shed Loads

Considering these objectives, two types of operating scenarios are of interest and will have the greatest effect on the selected load shedding schemes. First, due to the event selection being modeled, loss of the wind park generation, the value of wind generation has an effect on the amount of load being selected for shedding and the resulting dynamic response. The second is in terms of system loading level, high, medium and low. Since the load value has an influence and the number of loads being selected and hence potentials for higher fitness function values.

In regards to the first operating scenario, the top five selections for three different scenarios, a loss of 7.6 MW, 5.4 MW, and 2.9 MW respectively, will be evaluated in comparison to doing nothing, as shown in table 6-12. Each of these operating scenarios also has a total system load of around 15 MW, in order to eliminate the influence system load level has on the selected schemes and the overall fitness value.

Looking at the top five selections for the wind generation scenarios, two issues can be addressed. First and most obviously there is dramatic improvement in the system frequency response for all five selections in each scenario in comparison to do nothing. Second, and most importantly, all the schemes maximize the GA's objective function, by returning the RF to near nominal, minimizing the MND, minimizing load penalties, and lastly minimizing the amount of load to be shed, as can be seen in figure 6-15 to 6-17.

With respect to the second operating scenario, again the top five selections for three different shedding scenarios, 22.75 MW, 18.75 MW, 15.64 MW total system load respectively will be evaluated in comparison to doing nothing, as shown in table 6-13. Again like the previous system scenario in order to avoid wind generation influence, system generation was kept to around 4.4 MW.

Again looking at the top five selections for the load level scenarios a couple of issues can be addressed. Like the wind generation scenarios, the selected load shedding schemes improve the system frequency response in comparison with doing nothing. Likewise they also optimize the objective function, by minimizing the RF distant from nominal, minimizing the MND, minimizing the associated load penalty, and minimizing the amount of load to be shed, as can be seen in figure 6-18 to 6-20. A second issue to notice is with respect to the GA score. With an increase in system loading comes an increase of individual loads selected for shedding. These increased loads make the overall GA score higher with changes in the potential schemes.

Table 6-12. Load Shedding Scheme Evaluations, for Wind Generation Scenario

Scheme	Load Shedding Scheme	GA Score	GA Main Objectives			
			Amount Shed (MW)	MND (Hz)	RF (Hz)	Penalty
OP1	Do nothing	-	0	-2.558496	49.1712	-
1.BEST	10001000011000001101	8.05571	6.9395	-2.01512	49.9264	1
1.1	10001000011000011001	8.0955	6.9285	-2.017634	49.927	1
1.2	10101000011000001101	8.10758	7.4655	-2.056935	49.9838	2
1.3	10001000011000011101	8.12486	7.0945	-2.043981	49.947	1
1.4	10101000011000011001	8.15602	7.4545	-2.057072	49.982	2
OP2	Do nothing	-	0	-1.767302	49.4999	-
2.BEST	10000000011000010101	5.97904	5.456	-1.680773	49.9949	1
2.1	00001000011000010100	5.98968	5.429	-1.689068	49.9974	1
2.2	00001000011000000101	6.02665	5.244	-1.686422	49.983	1
2.3	00001000011000010000	6.02933	5.323	-1.688157	49.987	1
2.4	10000000011000010100	6.04084	5.3235	-1.679213	49.9801	1
OP3	Do nothing	-	0	-1.668711	49.5769	-
3.BEST	10001000000000011101	4.94723	3.1905	-1.550062	49.9957	0
3.1	10101000000000010101	5.13959	3.06	-1.543431	49.9849	1
3.2	10001000000000011001	5.16842	2.9445	-1.570725	49.9636	0
3.3	00000000001000010101	5.17861	3.187	-1.544654	49.9983	1
3.4	00000000010000010101	5.18552	2.915	-1.569898	49.9612	0

Table 6-13. Load Shedding Scheme Evaluations, for Load Level Scenario

Scheme	Load Shedding Scheme	GA_Score	GA Main Objectives			
			Amount Shed (MW)	MND (Hz)	RF (Hz)	Penalty
OP1	Do Nothing	-	0	-1.686352	49.4647	-
1.BEST	10001000000000000000	5.18194	4.4395	-1.539596	49.9775	0
1.1	10001000000000010100	5.20344	4.2935	-1.535105	49.9664	0
1.2	10000000000000011101	5.25612	4.2485	-1.541169	49.96	0
1.3	00001000000000011110	5.34206	4.612	-1.537546	49.9949	1
1.4	10001000000000011000	5.35811	4.7315	-1.526728	50.012	0
OP2	Do Nothing	-	0	-1.67648	49.495	-
2.BEST	10001000000000010101	5.05186	4.424	-1.530181	49.9966	0
2.1	10000000010000010101	5.06215	4.2605	-1.521142	49.9863	0
2.2	00000000010000011101	5.10855	4.063	-1.522746	49.972	0
2.3	10001000010000000000	5.12985	4.232	-1.530707	49.9797	0
2.4	10001000000000001100	5.14233	4.1815	-1.525722	49.9718	0
OP3	Do Nothing	-	0	-1.495398	49.5551	-
3.BEST	10100000010000001101	5.01321	4.4315	-1.446931	50.0041	1
3.1	10100000010000011001	5.0791	4.2705	-1.446211	49.9867	1
3.2	00000000010000011111	5.10918	4.0695	-1.444744	49.975	1
3.3	10000000010000011011	5.1176	4.4385	-1.451928	50.0052	1
3.4	10000000010000010101	5.18121	3.518	-1.4353	49.9121	0

Upon close examination of the schemes presented in the two scenarios, they reveal that the aforementioned phenomena in regards to load type influence on scheme selection holds true. For example looking at scheme 2.2 vs. 2.3 in the load level scenario, it can be seen that even though the amount of load shed in 2.2 is less than that of 2.3 the MND for 2.2 is smaller than that of 2.3.

Another issue to consider, with respect to any operating condition, is the "favoritism" of certain loads in the system. This means some system loads are ideal for shedding selection due to their low penalty factor, appearance in most all of the top ten schemes for any scenario, as is the same for loads that are never selected. This would imply that these loads provide the best results with respect to the shedding objective. Utilizing these loads for shedding can decrease the need to continually change the system relays and therefore avoid any unpleasantness inbetween schemes, should a perturbation occur resulting in ineffective shedding and the potential for system collapse.

Approximately 150 operating scenarios were used to evaluate load favoritism, as can be seen in figure 6-21. From this figure it can be seen that feeders 1, 5, 10, 16, 17, 18, and 20, are each selected over 50% of the time. With respect to feeders that are never selected, it can be seen that 2, 4, 7, 12, 14, and 15 fall into this category, along with feeders 6, 9, and 13 being selected less that 3% of the time. From this figure only one solid observation can be made as to why these loads have or haven't been selected. In the case of the feeders that are never selected it can be observed that each of them have penalty factors with values of 3 or higher associated to them. This would imply that high priority loads, i.e. loads with high penalty factors, need not be shed and the system could still be restored to close to nominal frequency. Therefore a reliability of "near" 100% could be guaranteed to these consumers. The same point can be made with respect to the loads with the highest rate of selection, they all had penalties of 0 or 1.

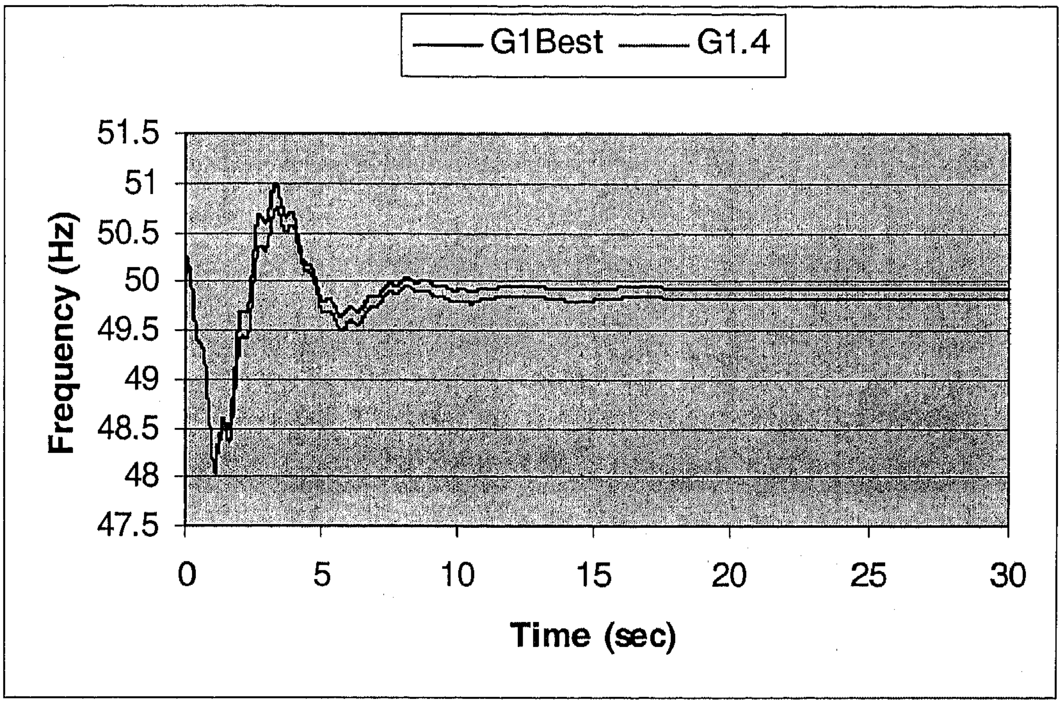


Figure 6-15. System Frequency Response to Scenario G1

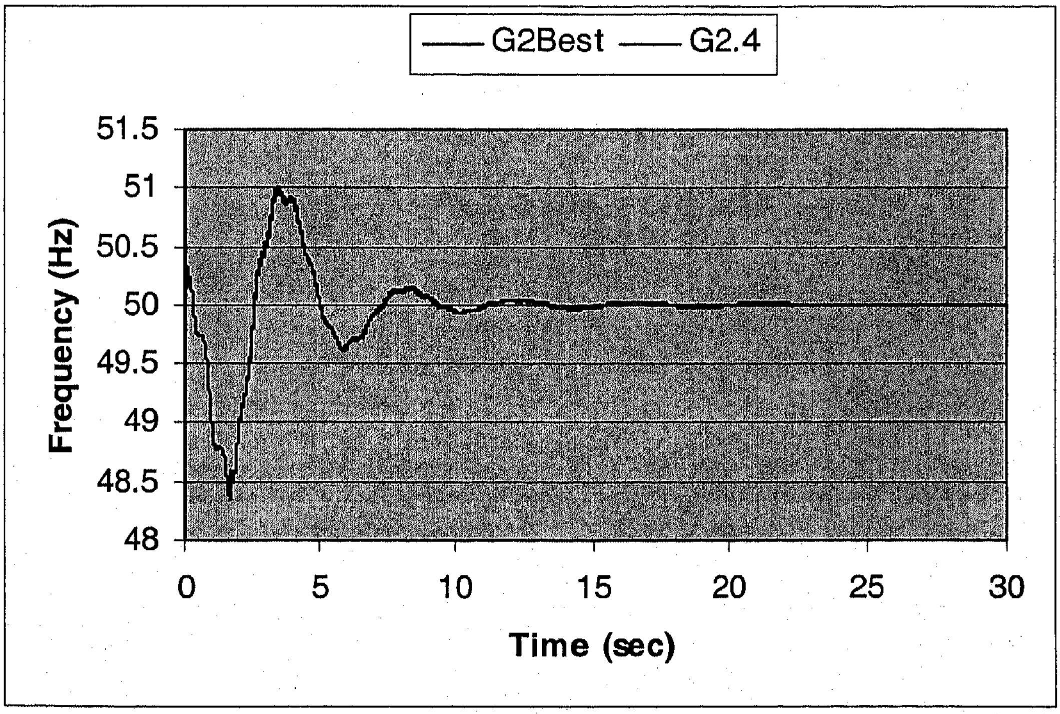


Figure 6-16. System Frequency Response to Scenario G2

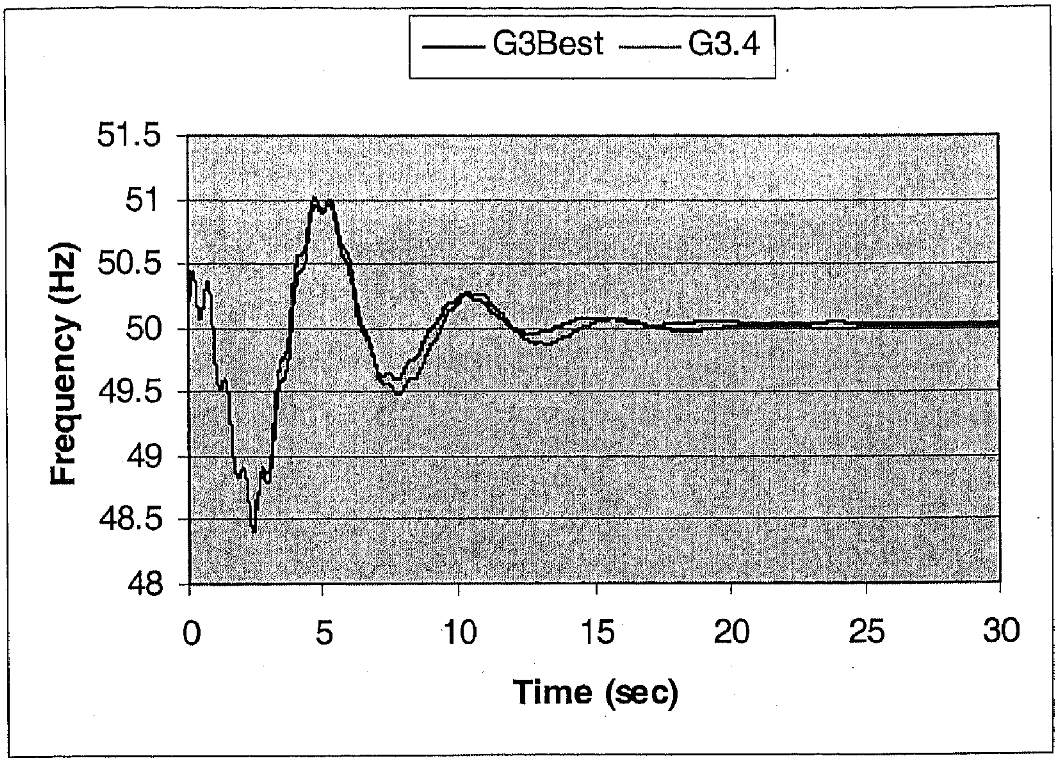


Figure 6-17. System Frequency Response to Scenario G3

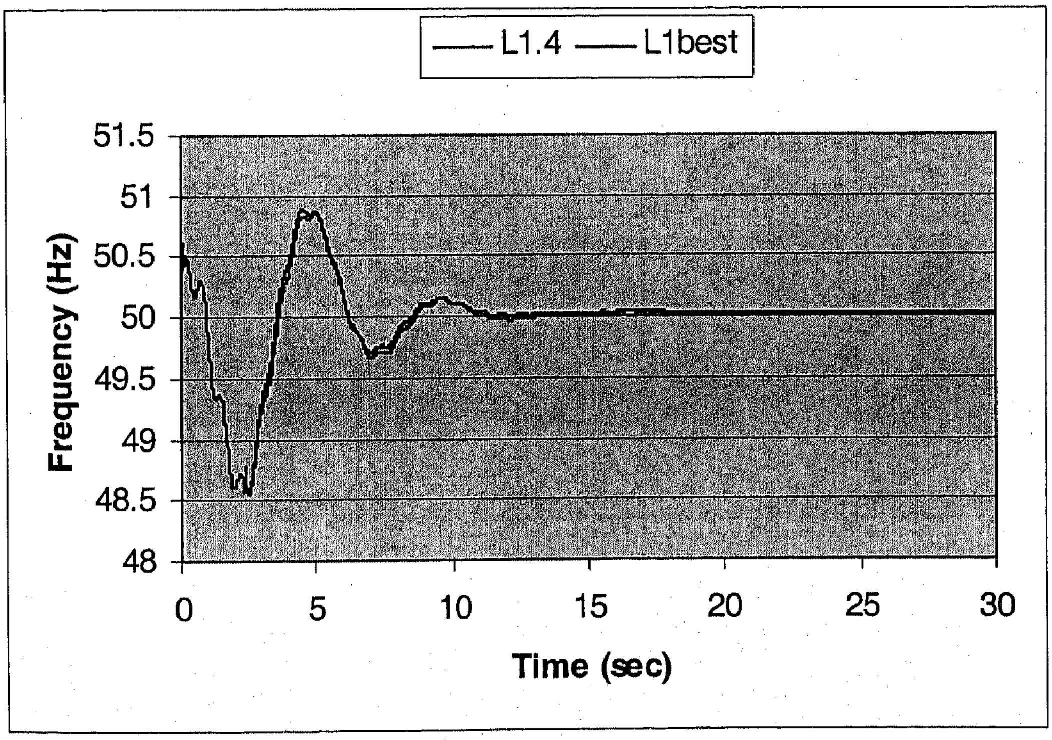


Figure 6-18. System Frequency Response to Scenario L1

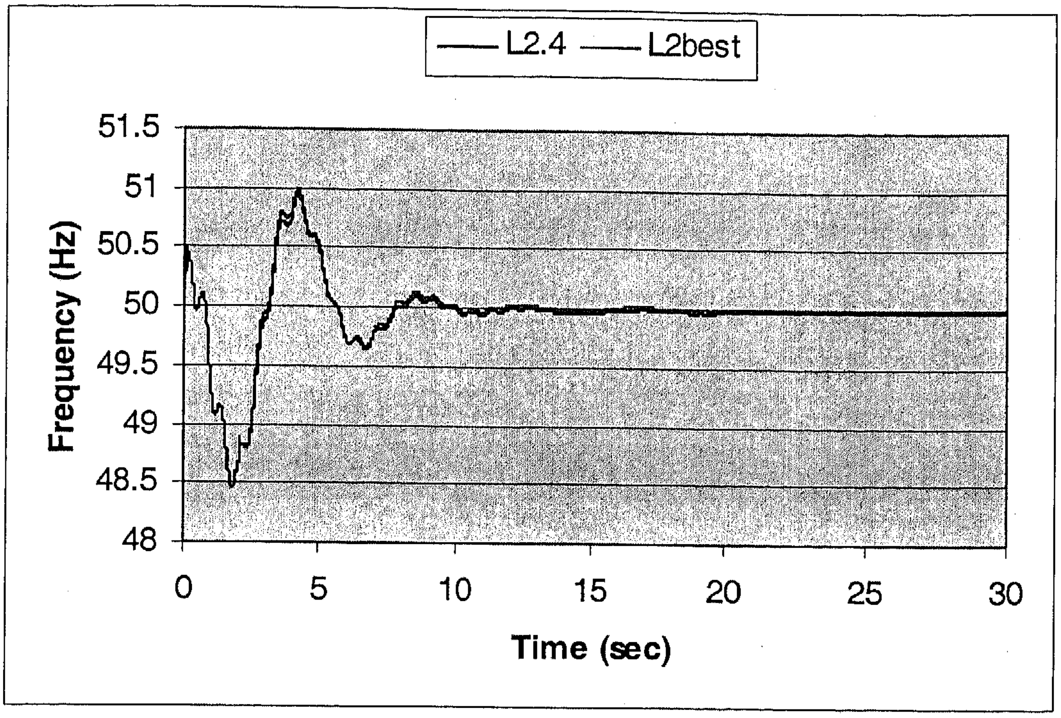


Figure 6-19. System Frequency Response to Scenario L2

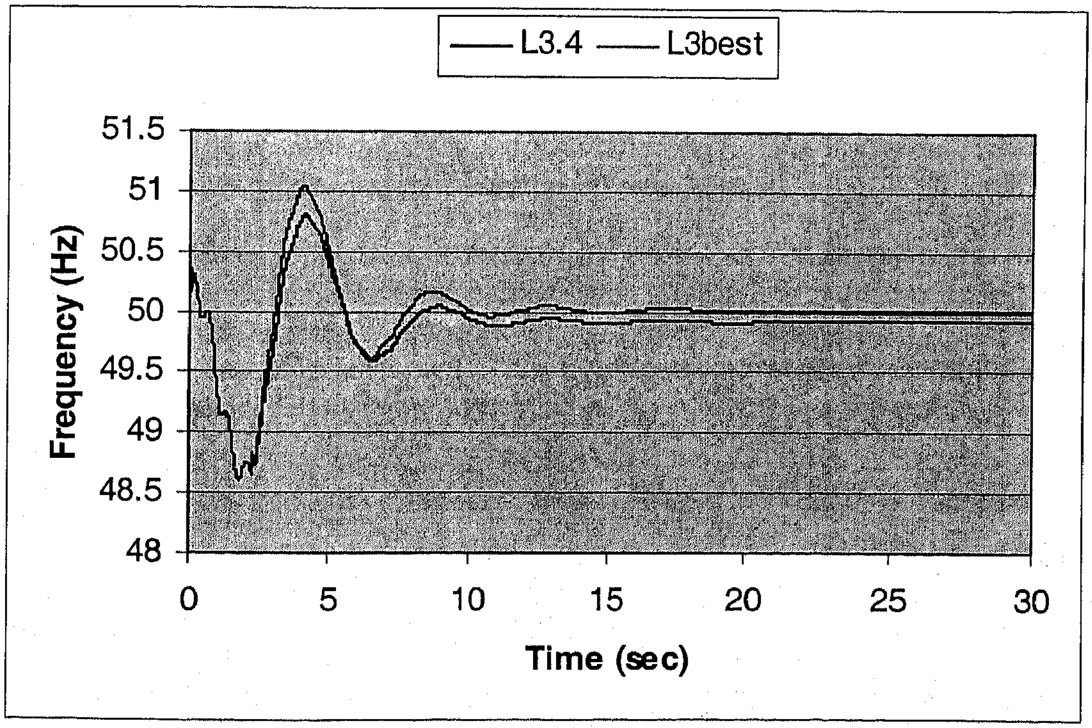


Figure 6-20. System Frequency Response to Scenario L3

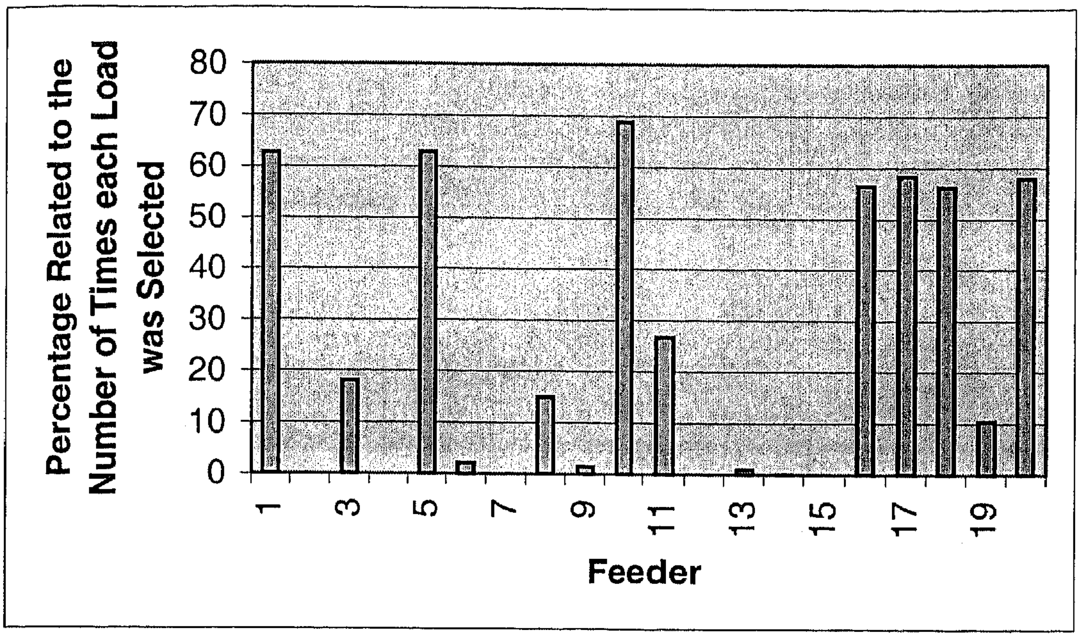


Figure 6-21. Percentage of Time Feeder was selected for Shedding

6-4 Conclusions

This chapter has provided the needed numerically analysis to show the approach developed within this thesis is indeed applicable and worthwhile for use in a power system. The Terceira network model provided has many typical facets that could be encountered in any power system, and has utilized the proper system models to assure complete and accurate behavior of the system in all simulations.

The NN results addressed two critical issues with respect to NN applicability. First, the results have shown that the NN used within this thesis has been sufficiently trained to provide good testing results, with respect to the data set developed and used within this work. Second, and most importantly, the NN has shown its ability to accurately predict and generalize the dynamic system behavior during under-frequency load shedding scenarios, as was compared with a dynamic simulation.

The numerical results provided, with respect to the GA used within this work, are excellent. The results have shown that the GA has the ability to converge to a global optima solution and avoid getting stuck in local optima, via convergence tests. Second, the load modeling influence on potential schemes has been provided to show further complexity in producing optimal load shedding strategies. Lastly, the numerical results have shown that the GA can select optimal load shedding strategies that satisfy the objective function adopted within this work.

Chapter 7 Conclusions

This last chapter provides general conclusions and results obtained from the work performed within this thesis, as well as potential areas for further research in relation to this work. As was done previously this chapter is broken into two sections, NN conclusions and GA conclusions.

7-1. Conclusions

7-1.1 NN Conclusions

The NN performance within this research was extremely good. The training procedure adopted by this research created a viable NN, the aggregation of feeder loads into one comprehensive busload model was exceptional, and the NN predictions were outstanding, as will be addressed in the following sections.

The combination of the load curve model and the entire range model provided ample OPs to the NN for complete and accurate training. As was seen by the comparative analysis of the two procedures, the load curve procedure provided the NN with concentrated information about the OP most probably to be realized by the NN within this study. The inclusion of points covering the entire operating range provided the additional coverage needed by the NN in the case that non-load curve points were used for evaluation.

The successful aggregation of feeder loads into a busload was paramount to the feasibility of this work, due to the overwhelming number of operating conditions that would be experienced by a comprehensive representation of the power system for the purpose of data set generation. As was seen by the generalization analysis of the NN the aggregation technique applied to this work did in fact provide the needed accuracy.

Lastly, and most importantly, the NN showed its ability to accurately predict the dynamic frequency response of a power system in emergency load shedding situations, in comparison with a dynamic simulation for a number of OP. Therefore, using a NN to replace a full dynamic simulation for predicting the dynamic frequency response of a power system during an emergency load shedding scenario enabled fast and accurate presentation of numerical results. The ability of the NN to accurately predict the dynamic frequency response of the system allowed it to be linked to the GA for calculation of optimal load shedding schemes quickly.

7-1.2 GA Conclusions

The results obtained by the GA approach were also very good. The GA showed its ability to converge to a globally optimal solution, its ability to select logical, efficient, and effective load shedding schemes, and further evaluations of the influence load type has on the system frequency response were also fruitful. Each of these issues will be addressed in the sections that follow.

The parameter values associated with crossover and mutation used within this work allowed the GA to avoid getting trapped in local optima and instead successfully provided optimal global solutions as was desired from these techniques.

In regards to the overall objective of this thesis research, the ability of the GA to select optimal load shedding strategies was achieved and with excellent results. As was seen in the previous chapter, the GA selected logical load shedding schemes according to the objective function that was applied to this work. The speed of selection was almost instantaneous, for one OP, due to the use of a NN in the fitness evaluation. Good perspectives are therefore identified in terms of future use for large systems and for fast evaluation, perhaps with the help of parallel processing.

Lastly, although not directly related to the use of the GA, the evaluation of load types showed that load type does have an influence on the systems dynamic frequency response. Recognizing this is important to the understanding of load selection by the GA and in load modeling in general.

7-2. *Future Work and Other Comments*

It is important that future work in this area of research is identified in hopes of further advances toward optimal operation of power systems. Therefore some of the potential research that can be made to improve on this work will be addressed in the section that follows.

One point that needs to be addressed is the way in which this procedure is affects other states in system operation, namely, the restorative process. One concern that needs to be addressed is how lost load and generation are brought back into service might initiate another tripping sequence. Although not addressed in the current technology section, loads and generation that are lost are typically brought back into service in small steps, similar to the current technology load shedding procedure. This procedure could still be utilized for system using the new approach presented in this thesis as long as the re-initiation steps taken do not invoke large frequency excursions that might accidentally re-trip the optimal shedding procedure.

Should the steps taken be too large and unavoidable, another way in which to address the restorative state, is to add an additional time delay to the optimal load shedding scheme such that re-tripping would not occur due to restorative actions.

One such area for improvement on this work is in regards to the modifications that could be made to the data set for training the NN. Although the generation of this learning set did not taking into account any system security constraints the potential for security evaluation exists. Evaluation of thermal line flows, bus voltage levels, and even perform N-1 contingency analysis could be performed to assure secure system operation. These security constraints would provide greater accuracy with respect to cloning actual system operation.

The issue of security could also be addressed in regards to post-load shedding system operation. Again although not addressed in this work, the state of the system, in terms of security, after load shedding as been applied could be utilized as an optimal load shedding scenario objective.

Another area for application is the potential use of this philosophy on large interconnected system. Since load shedding schemes are typically developed within given control areas, and these areas are typically small enough that the load location is independent, thus enabling the use of the load aggregation technique, as described previous. However, as was mentioned in the literature, communication between adjacent areas is crucial such that load shedding overlaps are avoided. Optimistically, the optimal load shedding scheme implemented in one area would be effective enough such that the frequency decline in adjacent areas would be small enough that load shedding would not be needed. Pessimistically speaking, if load shedding were need in these adjacent areas, a df/dt type relay could be utilized to trigger a second optimal shedding scheme that would be prepared for situation of frequency decay in adjacent areas and therefore any load shedding overlap would be avoided. Thus two schemes would need to be utilized by control areas, both of which are optimal calculated using the aforementioned procedure, but one would be designed for inter-area perturbations and the second for adjacent area perturbations.

Further study can be performed in order to make the research performed in this thesis non-event related. Meaning, now the training of the NN and optimization of the shedding schemes through the GA are dependent on the given perturbation that is expected. The procedure could be modified to create optimal load shedding schemes for any operating condition and any perturbation, thus creating the overall optimal load shedding scheme that could be applied to a power system. The use of risk assessment could be used to give weight to selected schemes and through the evaluation of all potential disturbances an overall optimal scheme could be identified and thus applied to the power system. Once an overall system optimal scheme was developed the potential use of this technology online, within a forecasting module, could easily be achieved due to its speed.

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ANNEX I

It should be noted that constant that do not appear in the table are assumed to be 0.

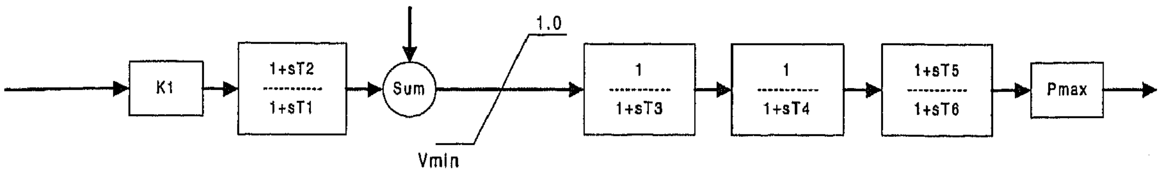

Figure AI-1. Governor Block Diagram

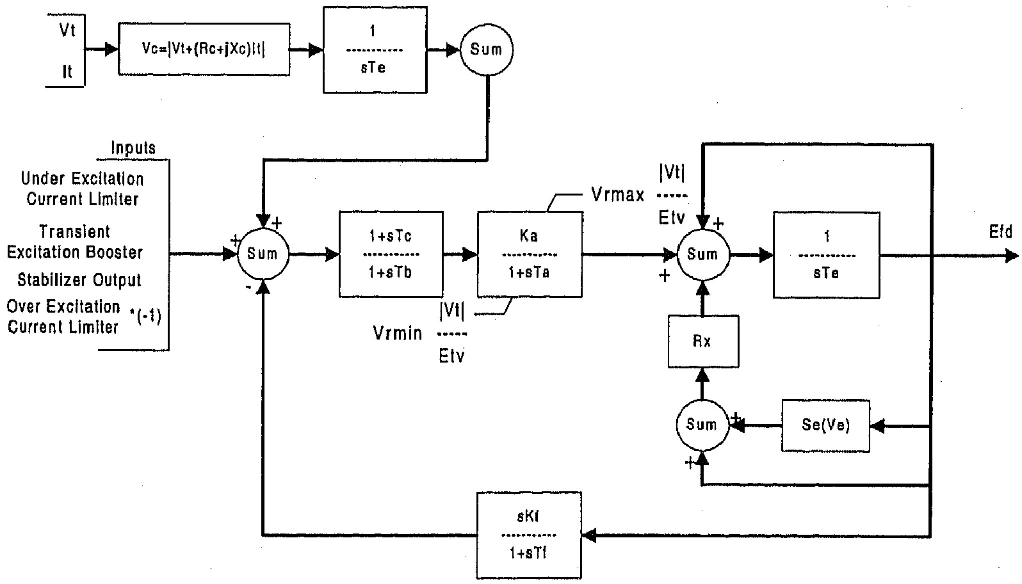

Figure AI-2. Exciter Block Diagram

Table AI-1. Generator Limits

CONSTRAINT UNIT (type)	Generator Limits Min. / Max. (MW)	Maintenance Percentage Out	Spinning Reserve Max. Available (MW)
Gen 1 (diesel uc)	1.84 / 2.8	100 to 95	2.8-1.84 = 0.96
Gen 2 (diesel uc)	1.84 / 2.8	95 to 90	2.8-1.84 = 0.96
Gen 3 (diesel uc)	1.84 / 2.8	90 to 85	2.8-1.84 = 0.96
Gen 4 (diesel uc)	0.78 / 1.96	85 to 80	1.96-0.78 = 1.18
Gen 5 (diesel)	2.5 / 6.1	Not applicable	6.1-2.5 = 3.6
Gen 6 (diesel)	2.5 / 6.1	Not applicable	6.1-2.5 = 3.6
Gen 7 (wind)	0.0 / 5.0	Not applicable	0.0
Gen 8 (hydro)	0.0 / 1.0	Not applicable	1.0-0.0 = 1.0

Table AI-2. Generator Impedance and Time Constants

Generator	Ra	Xd	Xq	Xl	X'd	X'q	X"d	X"q	T'do	T'qo	T"do	T"qo
1	0.0014	1.25	1.22	0.09	0.232	0.715	0.12	0.12	4.75	1.5	0.059	0.21
2	0.0014	1.25	1.22	0.09	0.232	0.715	0.12	0.12	4.75	1.5	0.059	0.21
3	0.0014	1.25	1.22	0.09	0.232	0.715	0.12	0.12	4.75	1.5	0.059	0.21
4	0.0014	1.25	1.22	0.09	0.232	0.715	0.12	0.12	4.75	1.5	0.059	0.21
5	0.0031	1.05	0.98	0.07	0.185	0.36	0.13	0.13	6.1	0.3	0.038	0.099
6	0.0031	1.05	0.98	0.07	0.185	0.36	0.13	0.13	6.1	0.3	0.038	0.099
7	0.0031	1.05	0.98	0.07	0.185	0.36	0.13	0.13	6.1	0.3	0.038	0.099
8	0.004	1	0.62	0.17	0.26	0.615	0.235	0.026	7.1	0	0	0

Note: All the values within table AI-2 are in per unit.

Table AI-3. Generator Inertia and Base Values

Generator	H (s)	Damp	BMVA	BVR	BFQR
1	1.5	1.5	3.8	1	50
2	1.5	1.5	3.8	1	50
3	1.5	1.5	3.8	1	50
4	1.5	1.5	3.6	1	50
5	1.696	1.5	7.8	1	50
6	1.696	1.5	7.8	1	50
7	2.4	1.5	10	1	50
8	4.856	1.5	1	1	50

Table AI-4. Governor Model Constants

Generator	K1	T1	T2	T3	Pmax p.u.	Vmin	T4	T5	T6
1	20	3	1	0.1	0.72	0	1	1	2
2	20	3	1	0.1	0.72	0	1	1	2
3	20	3	1	0.1	0.74	0	1	1	2
4	20	3	1	0.1	0.56	0	1	1	2
5	20	3	1	0.1	0.78	0	1	1	2
6	20	3	1	0.1	0.78	0	1	1	2
7	-	-	-	-	-	-	-	-	-
8	20	3	1	0.5	1	0	0	0.43	-0.86

Table AI-5. Exciter Model Constants

Generator	Ka	Ta	Te	Aex	Bex	Kf	Tf	Vrmax p.u.	Vrmin p.u.
1	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
2	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
3	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
4	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
5	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
6	25	0.2	0.65	0.0015	1.5833	0.105	0.35	1	-1
7	-	-	-	-	-	-	-	-	-
8	65.2	0.2	1.93	0.0042	0.9488	0.12	1	1	-1

ANNEX II

Table AII-1. Real and Reactive Power Busload Model Coefficients

Load	CI	CP	CZ	EXP. 1	EXP. 2
10	0	10	62	21	7
20	0	11	59	24	6
30	0	11	59	24	6
40	0	6	76	8	10
50	0	18	45	30	7

Table AII-2. Real and Reactive Power Load Model Exponents

a1	a2	kpf1	kpf2	b1	b2	kqf1	kqf2
1	1.5	0.2	-0.5	3.5	1.3	0	0

Table AII-3. Bus 10 Feeder Model Coefficients

Load Type	Bus 10 Real and Reactive Power				
	Total	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Priority Penalty	9	0	3	1	5
% of Total Load	100	25	15	10	50
C. Current	0	0	0	0	0
C. MVA	10	15	10	22.5	5
C. Impedance	62	62	52	27	72
Exponential 1	21	11	31	31	21
Exponential 2	7	12	7	19.5	2
Total	100	100	100	100	100

Table AII-4. Bus 20 Feeder Model Coefficients

Load Type	Bus 20 Real and Reactive Power				
	Total	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Priority Penalty	7	0	2	4	1
% of Total Load	100	30	30	20	20
C. Current	0	0	0	0	0
C. MVA	11	11	9	20	5
C. Impedance	59	69	57	35	71
Exponential 1	24	16	30	30	21
Exponential 2	6	4	4	15	3
Total	100	100	100	100	100

Table AII-5. Bus 30 Feeder Model Coefficients

Load Type	Bus 30 Real and Reactive Power				
	Total	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Priority Penalty	9	2	0	1	6
% of Total Load	100	15	35	40	10
C. Current	0	0	0	0	0
C. MVA	11	8	4	20	4
C. Impedance	59	77	61	47	73
Exponential 1	24	10	30	25	20
Exponential 2	6	5	5	8	3
Total	100	100	100	100	100

Table AII-6. Bus 40 Feeder Model Coefficients

	Bus 40 Real and Reactive Power				
	Total	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Priority Penalty	8	2	3	3	0
% of Total Load	100	25	25	25	25
C. Current	0	0	0	0	0
C. MVA	6	9	5	4	6
C. Impedance	76	83	77	68	76
Exponential 1	8	3	13	8	8
Exponential 2	10	5	5	20	10
Total	100	100	100	100	100

Table AII-7. Bus 50 Feeder Model Coefficients

Load Type	Bus 50 Real and Reactive Power				
	Total	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Priority Penalty	1	0	0	1	0
% of Total Load	100	35	20	20	25
C. Current	0	0	0	0	0
C. MVA	18	20	23	22	8
C. Impedance	45	52	40	44	40
Exponential 1	30	23	25	26	47
Exponential 2	7	5	12	8	5
Total	100	100	100	100	100

Table AII-8. Load Data Max. and Min.

Load	Min (MW)	Max (MW)
10	3	6
20	2.5	6
30	3	7
40	0.5	2.5
50	0.5	3

ANNEX III

Table AIII-1. Power System Impedance Data

Line / Transformer	Impedance p.u.
100 to 200	0.003,0.014
100 to 300	0.002,0.017
200 to 300	0.002,0.017
30 to 40	0.003,0.014
100 to 10 (A)	0.002,0.078
100 to 10 (B)	0.002,0.078
1 to 10	0.002,0.01
2 to 10	0.002,0.01
3 to 10	0.002,0.01
4 to 10	0.002,0.01
5 to 100	0.002,0.0599
6 to 100	0.002,0.0599
40 to 50 (A)	0.002,0.055
40 to 50 (B)	0.002,0.055
400 to 8	0.002,0.06
300 to 20	0.002,0.07159
300 to 30	0.002,0.0748
200 to 7	0.002,0.01