Q. In determining best industry practice for electrical networks, please explain what consideration Hydro gave to the reliability standards of other islanded systems (geographically and electrically) around the world. Did Hydro consider how these islanded systems standards differed from nearby interconnected systems under the same jurisdictions?

A. Isolated systems are unique and depending on the transmission configuration and generation mix of the particular system, the reliability standards chosen could be quite different from one isolated system to another.

Accordingly, Hydro plans its power system applying criteria that have been modeled after industry best practice used by neighbouring Canadian utilities. Hydro's criteria have been modified, for both technical and economic reasons, to compensate for unique features of the isolated Newfoundland system. In particular, under-frequency load shedding is one area where Hydro's practices differ from the North American standard and Hydro has spent considerable time and effort developing and refining a load shedding scheme to manage under-frequency. The May 2001 report "Review of Under-Frequency Load Shedding Scheme" (CA-NLH-033 Attachment 1) provides the results and recommendations of a study by Powertech Labs Inc. that validated Hydro's approach to managing under-frequency, suggested minor modifications to improve performance and confirmed that while under-frequency is a concern on most isolated systems, the impacts and management techniques vary from system to system.

Powertech

Powertech Labs Inc.
12388 - 88th Avenue
Surrey, British Columbia
Canada V3W 7R7

Powertech
12388 – 88th Avenue
Surrey, British Columbia
Canada V3W 7R7
Tel. (604) 590-7500
Fax (604) 599-8269
www.powertechlabs.com

Final Report

Review of Under-Frequency Load Shedding Scheme

For

Newfoundland and Labrador

HYDRO
THE POWER OF COMMITMENT

Powertech Project Number: 12501-21-00

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Powertech Labs Inc.
12388 – 88th Ave
Surrey, BC
Canada V3W 7R7

Prepared by:

Ali Moshref, Ph.D., Project Leader
Specialist Engineer, Powertech Labs. Inc.

Approved By:

Kip Morison, P.Eng.
Director, Power System Studies

PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
G. K. MORISON

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1. Introduction and Objectives

Power system steady-state operation requires a balance between generation and load. A sudden loss of generation due to abnormal conditions, such as a generator fault or line tripping, disturbs this balance and the system frequency begins to deviate from nominal. The system operation at low frequencies is harmful to the turbines and it can even lead to tripping of more generators further aggravating the situation. To arrest frequency decline, the governor actions of the generators with spinning reserve try to make-up for the lost generation. If the frequency decline is too fast and the governor cannot react fast enough or spinning reserve is not adequate, under frequency relays are used for initiating automatic load shedding.

The under-frequency load shedding (UFLS) scheme must be properly designed to:

- Prevent excessive load shedding resulting in over-frequency conditions, or unnecessary loss of service continuity and revenue
- Avoid insufficient load shedding which in turn may lead to system blackout
- Provide sufficient load shedding to maintain the frequency in the acceptable operating range

Static analysis of power systems is widely used to design UFLS schemes. In such analysis, the equivalent inertia of the power system is obtained, the effects of voltage variations are ignored, and the whole system is assumed to be a single mass with parameters, such as load damping, being approximated lumped values. Governor response of connected generation is also ignored for the sake of simplicity. The simplicity of static analysis makes it useful for rapid evaluation of numerous UFLS schemes to select a few designs that result in good performance over a wide range of conditions.

Software tools are now available wherein the various system components can be individually modeled to accurately simulate the systems' dynamic electrical and electromechanical behavior and to view the extended time frame where the effect of governor action can be observed. The more detailed revelation of system response makes dynamic analysis useful for in depth analysis of a short list of alternative UFLS schemes that have been identified by static analysis.

The Newfoundland and Labrador Hydro (NLH) power system is an isolated power system with maximum peak load of about 1500 MW (year 2000). The load in the light load condition can reach as low as 300 MW. The wide variations in the generation dispatch and load condition make the design of UFLS a very unique and challenging task. The objectives of this project are:

1. Review literature and guidelines on UFLS schemes with emphasis on the isolated power systems

2. Assess the adequacy of the existing Newfoundland and Labrador Hydro UFLS scheme, review the existing models used for the evaluation of UFLS, and provide recommendations for improving the load shedding scheme

3. Identify and evaluate the revised UFLS scheme through modification of settings, application of new relays, etc.
4. Identify and assess different operating strategies that improve load shedding

2. Background and Literature Survey

In this section an overview of the need for, and application of, UFLS schemes is discussed. Next, a variety of UFLS schemes and philosophies are presented. This includes NERC and other power pool councils' guidelines as well as technical papers.

2.1 Automatic Load Shedding and Under-Frequency Load Shedding

Power system frequency will decline when systems experience generation deficiency due to loss of generators or tie lines from neighboring systems. To arrest the frequency decline and avoid damage to equipment, and depending on the amount of deficiency, automatic load shedding schemes are designed to trip loads to bring the system frequency back to normal operating range. In the design and setting of the load shedding relays the following objectives are of importance:

- There must be enough load shedding relays installed for the designed frequency excursion and generation loss. Special attention should be given to load availability under different system conditions (peak load, light load, others)
- The load shedding relays must be properly coordinated with generating unit under-frequency protection relays. Enough loads should be shed to prevent tripping of generating units with due regard to thermal units
- Over/under shedding should be avoided as much as possible. If there is any discretion allowed, the preferred design option is to have over shedding
- There must be coordination between interconnected areas (utilities)

In the past, load shedding schemes were designed using static analysis which were mainly based on simple hand calculations. Nowadays, with technically sound power system analysis software, rigorous and accurate schemes can be designed and verified. However, sometimes simple rules and manual computation can be bring confidence and give comfort to power system engineers.

For example, for a single machine having inertia of H MW-sec/MVA, the rate of frequency decline for the first few seconds (assuming no governor action has taken place yet) can be obtained from the following:

$$df/dt = -\frac{dp}{2*H} f_b$$

The steady state frequency can be given by:

$$f_{ss} = f_b(1 - dp * R)$$

In the above equations,

dp is generation loss in p.u.

f_b is system base frequency (Hz)

R is droop in p.u.

The very first task in the UFLS scheme design is to establish a minimum acceptable frequency. This minimum frequency is normally a trade-off between minimum acceptable operation frequencies for different power system equipment.

2.2 Frequency Limits During Normal and Emergency Operation: The Minimum Frequency Operating Guideline

Constancy of power system frequency is essential to:

1. Avoid equipment damage (mainly generating units)
2. Avoid loss of life to equipment
3. Avoid mal-operation of control systems and protections

The thermal units are more susceptible to damage caused by off-nominal frequency operation than are hydraulic units due to the thermal units complex and multi-shaft assembly, and turbine blade structure. The operation of thermal units under low frequency conditions is time bounded and dependent on the specific design and manufacturer.

Thermal units employ under-frequency relaying to prevent significant damage to turbine blades due to metal fatigue when operating in the low frequency range. Fatigue results from the time accumulation of mechanical stresses that are generated due to unit operation at off-nominal frequency range which may excite the natural resonance frequencies of the blades.

For generating units the frequency limit is normally between 57 Hz and 63 Hz (hydro units can withstand higher frequency deviation). The frequency-time characteristics of the generating unit under-frequency protection relays are used with a wide range of setting including instantaneous. For example, unit trip in 1.4 seconds if frequency falls below 57 Hz and instantaneously for over frequency of 61.6 Hz. The ANSI/IEEE C37.106 1987 " IEEE guide for Abnormal Frequency Protection for Power Generating Plants", specifies the following limits:

Continuous Operation	59.4<f<60.0
11 min.	f=59.4
1.5 min.	f=58.5
10 sec.	f=57.5
2 sec.	f=57.0
0.35 sec.	f=56.5
Instantaneously	F<=55.5
Continuous Operation	60.0<f<60.6
11 min.	f=60.6
1.5 min.	f=61.5
2 sec.	f=63.0 (61.5 for thermal plant)
Instantaneously	f=63.5 (61.7 for thermal plants)

The above frequency limits have been compiled by sampling a large number of units. The aforementioned frequency limits are useful when the requirements for protection relays are being studied. The effect of operation in any of the above frequency bands is cumulative but independent from time operation in other frequency bands.

Naturally, the under-frequency load shedding relay settings are chosen to force load shedding before machine tripping. The load shedding is designed based on arresting frequency decline before thermal units are tripped off. The UFLS settings are normally in the 57-59 Hz range.

Since UFLS is the first line of defense for unit protection against low frequency operation, it is important that in load shedding settings, there is sufficient load tripping to avoid further loss of generation and to properly coordinate the relay settings with the unit under-frequency trip setting.

2.3 Load Shedding On An Isolated/Small Power Systems

The guidelines and policies of NERC and WSCC are presented in the Appendix. These guidelines generally deal with the subject of UFLS schemes and design in the context of large interconnected power systems. Smaller and isolated systems are much more susceptible to severe disturbances requires somewhat different guidelines due to their lower inertia, limited spinning reserve, and lack of outside assistance.

The UFLS scheme for isolated/small system should accommodate a much wider band of normal frequency deviations and at the same time more aggressive load shedding to avoid unacceptable frequency excursions (there is smaller margin of error). Therefore, fewer and larger load shedding steps is required as compared to interconnected systems. Time delays either intentional (or inherently slow relays such as electromechanical) should be minimized and greater percentage of load allocated for UFLS program.

Normally the amount of spinning reserve requirement should be approximately the same as the size of largest online unit. However, this requirement is normally hard to meet in smaller power systems. It is important that in small power systems spinning reserve allocation is uniformly distributed among as many units as possible, rather than assigned to a few larger or cheaper smaller units. The allocation of spinning reserve on generating units for the NLH power system will be discussed in details later in this report. In an isolated power system the amount of loads available for UFLS, in principle, should be all of the system loads. Normally for these power systems close to 80% of system load are under load shedding, some with much longer time delay (see reference 2). As stated before, frequency threshold, the 1st stage should not be close to nominal frequency to avoid un-necessary tripping on normal frequency swing. The stages should of course be coordinated with machine under-frequency protection relays.

Rate of change of frequency is an earlier indicator of an instantaneous change in load/generation imbalance than the absolute frequency, but it can be more prone to local disturbances than the latter. However, with the use of recent digital relays the detection of true rate of change of frequency is much more reliably achieved. Careful setting of rate of change of frequency UFLS relays can minimize the over shedding.

The literature survey on under frequency load shedding design and guidelines applicable to isolated/small power systems is very sparse. This is due to the fact that each UFLS design for small power system can be drastically different from others. Also the generation (thermal, hydro, gas, diesel) and load (industrial, commercial, residential with high percentage of air conditioning) compositions in isolated power systems differ from each other. It is often found that some UFLS design aspects in small power systems are economically/technically not justifiable but they are made due to political constraints. Majority of the isolated power systems are entirely thermal generation therefore economical/technical constraints exist on the maximum allowable loading of the units. Therefore, the majority of the recommendations of this report are drawn from the simulations results obtained.

When a power system experiences a mismatch between generation and loads, aggressive under-frequency load-shedding action is required in order to ensure that system security can be maintained and that further loss of generation and/or total system collapse can be avoided. Aggressive action implies that the UFLS must act with sufficient speed and with a sufficient amount of load. For this reason, when designing UFLS schemes, it is generally not practical to consider the differences in the various types of loads that should be used in the scheme. The exception is when large blocks of loads of specific characteristics can be identified which may be beneficial or detrimental to include in the scheme (such as large groups of synchronous motors which when shed, represent a large loss of inertia which may make the frequency response worse).

Because the time frame required for UFLS action is short, it does not provide sufficient opportunity to be selective as to which loads are to be shed; this is especially true in small isolated power systems. Also, the design should not rely on the specific loads to be shed because it is impossible to know a-priori which loads will be available at the time they are called upon. The most important requirement is that enough loads be put under UFLS relays and that they are distributed as uniformly as possible around the power system. Then, one needs to find the amount and frequency set points for each stage of load shedding in order to minimize the total load shed under different scenarios.

Since a survey of loads was not part of the scope of this project, our knowledge of the NLH system is limited to the data provided. From the data we can distinguish only two different types of loads in NLH power system: rotating loads and static loads. For us, all of the static loads have the same priority and same behavior. The same is true for all of the rotating loads. Therefore, our study findings concentrate on (a) recommendations regarding the frequency set-points and amount of load armed for each stage of load shedding and (b) recommendation on the choice between rotating loads and static loads. Even if more information was available on the composition of the static loads, for the reasons stated above, it is unlikely the UFLS scheme could take advantage of it due to the amount of load required for the scheme.

In the following sections we will evaluate the performance of the existing UFLS scheme of the NLH power system and design changes suggested to improve its performance.

3. Design Of Load Shedding Scheme

A well-designed UFLS scheme requires that power system be analyzed under different system operating conditions. To accomplish this, several system conditions (load levels and generation dispatches) were selected by the Newfoundland and Labrador Hydro System Operations amd Transmission Planning groups. Initially 16 such base cases (see Table 1) were prepared and submitted to PLI. This table shows that there are significant differences in each of the system conditions that makes the design and optimization of UFLS a nontrivial task. Some designs may yield better performance for a number of the base cases but not others, while other designs may be vice versa. Another important factor is in selecting "the best" design is that there is no single index against which the performance can be judged. For example, we cannot by simply finding a design that yields minimum load shedding judge the design to be "the best" since the frequency quality (minimum and final setting frequencies) is also of importance. If the frequency falls close to the generator under-frequency protection set point, then, there is a good possibility of losing generators. Yet another important consideration is that even though we are dealing with a number of base cases (system condition scenarios) we should associate some probability to the system being in that state. For example, if we shed more load, say for "cool_early_spring_day_dry" condition, and if probability of system being in similar condition (or even duration that the system may be in similar condition) is low, then, over-shedding may be acceptable in this situation.

Case	Total Generation	Total load	Total System Inertia (MW-Sec)
peak_load_wet	1431	1382	7612
peak_load_dry	1428	1382	7612
cool_early_spring_day_wet	1308	1256	7383
cool_early_spring_day_dry	1294	1256	6727
cool_late_spring_day_wet	1052	1005	7110
cool_late_spring_day_dry	1030	1005	5682
summer_day_wet	858	819	5693
summer_day_dry	838	819	5453
warm_winter_day_dry	730	704	4019
warm_winter_day_wet	719	704	4682
warm_early_spring_night_dry	669	643	4019
warm_early_spring_night_wet	659	643	5337
warm_late_spring_night_dry	557	538	4019
warm_late_spring_night_wet	552	538	4394
summer_night_wet	514	498	4928
summer_night_dry	509	498	4702

Table 1: Considered Scenarios for UFLS Scheme Evaluation

3.1 Simulation Of November 2000 Incident

During the course of this study a number of UFLS design scenarios (sixteen base cases listed in Table 1) were analyzed and documented in a progress report. The result of the simulations revealed that the frequency decline seemed more optimistic than the declines experienced by Newfoundland and Labrador Hydro had in the past under similar conditions. To gain confidence in the computer model and in order to adjust/calibrate the system dynamic data an attempt was made to replicate one of actual system load shedding incidents. Details of the incident are given below:

On Thursday, November 16th, 2000, the generator at Upper Salmon tripped while generating 88 MW. The total system load at the time was 996 MW. The frequency chart recorded a minimum frequency of 58.5 Hz at the Energy Control Centre (ECC). The ECC reported total load shed at 56 MW. The load shedding is summarized as follows:

59.0 Hz	CBP&P did not shed any load
58.8 Hz	14 MW of NP load at Massey Drive - Bus 115
	5 MW ACI - GFL rejects refiner - M/C 1 Bus 22 - motor tripped
	15 MW ACI - GFL refiner line 1 - M/C 1 Bus 21 and M/C 1 bus 30 – Load reduction over 6 seconds[1]
	CBP&P did not shed the scheduled 15 MW
58.6 Hz	15 MW ACI SVL refiner line 1 - M/C 1 Bus 273 - motor tripped
	7 MW of NLH load TL220 - Buses 244, 245, 246, 247 load tripped

The generation dispatch at the time of the trip was:

Bay D'Espoir	420 MW all units on
Holyrood	140 MW Only Unit 1 & 2 on - load limited at the time
Cat Arm	100 MW
Hinds Lake	off
Upper Salmon	88 MW
Paradise R	8 MW
Star Lake	17.6 MW
Rattle Brook	3.9 MW
NP	45 MW - this is generation behind the load
Abitibi	57 MW - includes Grand Falls Frequency Converter
DLP 60HZ	71 MW
DLP 50HZ	46 MW - includes Corner Brook Frequency Converter

Attempts to replicate the above scenario did not result in similar frequency excursion as the one recorded. After reviewing the dynamic data carefully the following modifications/adjustments were made:

1) The damping factors used in the dynamic data file (most of the damping factors were placed on the governor data and some on the generator) were removed. The damping factors were high as compared to what normally encountered in practice.

[1] Synchronous motors that are shed with time delay of 360 cycles (6 seconds) are actually offloaded within 6 seconds by ramping the mechanical load on them to zero within 6 seconds but keeping them spinning without load

2) The maximum output of Holyrood was changed to reflect what the generating output was in the Nov. 16 incident. The maximum generation at Holyrood units were adjusted based on the information provided by Newfoundland and Labrador Hydro
3) A constant impedance load model was adopted
4) Relays which did not pick up during the incident and which should have, were disabled.

After above changes were implemented the minimum frequency was close to the recorded value as shown in Figure 1. The total load shed was 61 MW as compared to 56 MW in the November incident. This difference in amount of load shedding explains why the minimum frequency obtained in the time domain simulation (58.69) was higher than the recorded minimum of 58.5 Hz.

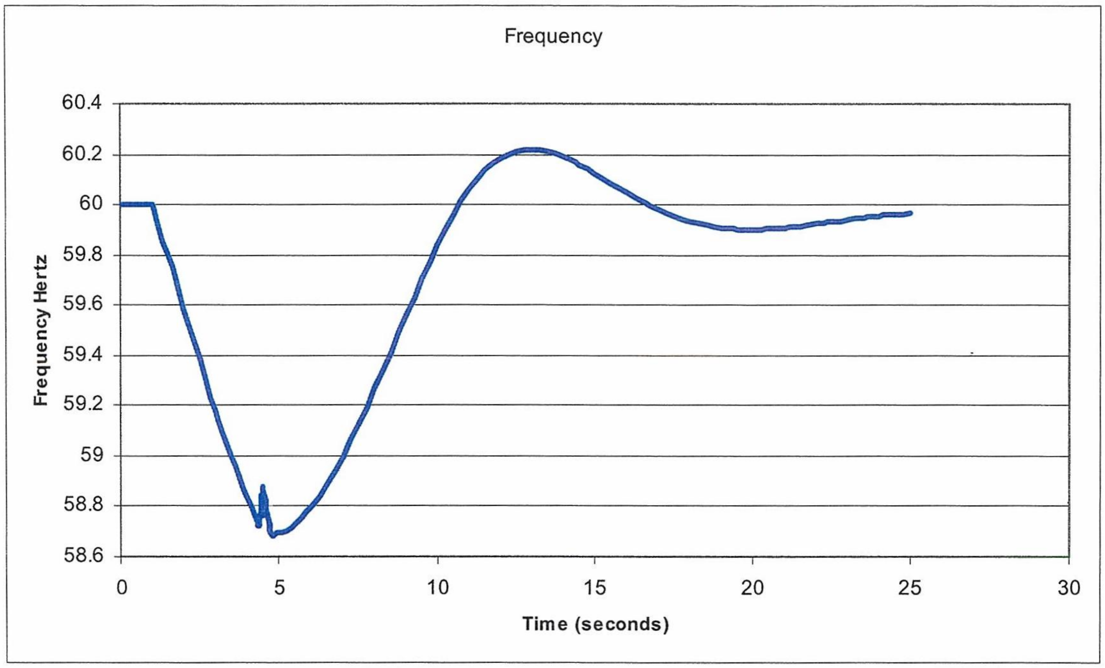

Figure 1: Simulated Frequency Response During November 16, 2000 Incident

Since considerable time was spent in the earlier analysis (with old dynamic data and sixteen base cases) it was decided that the study should continue with the revised data but with a reduced number of base cases. Therefore, the necessary data files for the NLH power system for the selected eight scenarios were updated. These scenarios are listed in Table 2 below:

Scenario (Base Case)	Total Gen MW	Total loads MW	Generating unit Lost
summer_night_wet	514	498	Upper Salmon , 406
peak_load_dry	1428	1382	Holyrood , 434
warm_early_spring_night_wet	659	643	Cat Arm,137

Scenario (Base Case)	Total Gen MW	Total loads MW	Generating unit Lost
warm_winter_day_wet	719	704	Cat Arm,137
warm_winter_day_dry	730	704	Holyrood , 434
cool_late_spring_day_wet	1052	1005	Hinds Lake, 250
cool_early_spring_day_wet	1308	1256	D'Espoir unit 7 , 2207
Extreme Light Load	280	269	Hinds Lake, 250

Table 2: Revised List of Considered Scenarios for UFLS Scheme Evaluation

3.2 Performance Evaluation Of Existing Load Shedding Scheme

The existing under-frequency load shedding sites and their corresponding settings are summarized in Table 3. The loads shown in this table correspond to the peak load condition of year 2000.

Bus #	Freq. Setting	Relay Delay	Breaker	SM	Shed MW	Shed %	Type	SM ID	Total MW	Shed MW
60	59.000	18	6		2.6	49.05	Static	0	5.3	2.6
63	59.000	18	6	5.4		100.00	SM	1	0	5.4
334	59.000	905	6		13.2	6.02	Static	0	216.5	13.0
335	59.000	905	6		4.4	2.20	Static	0	194.6	4.3
364	59.000	905	6		11.7	100.00	Static	0	11.6	11.6
244	58.800	18	6			100.00	Static	0	1.6	1.6
245	58.800	18	6			100.00	Static	0	2.5	2.5
246	58.800	18	6			100.00	Static	0	8.1	8.1
247	58.800	18	6			100.00	Static	0	5.9	5.9
115	58.800	18	6		14.0	21.80	Static	0	64.3	14.0
22	58.800	18	6	5.0		100.00	SM	1	0	5.0
21	58.800	360	6	8.0		100.00	SM	1	0	8.0
30	58.800	360	6	6.0		100.00	SM	1	0	6.0
66	58.800	18	6		1.3	13.82	Static	0	9.4	1.3
67	58.800	18	6	8.3		100.00	SM	1	0	8.3
67	58.800	18	6	5.4		100.00	SM	2	0	5.4
273	58.800	18	6	14.0		100.00	SM	1	0	14.0
21	58.600	360	6	8.0		100.00	SM	2	0	8.0
30	58.600	360	6	6.0		100.00	SM	2	0	6.0
102	58.600	18	6			100.00	Static	0	3.6	3.6
144	58.600	18	6			100.00	Static	0	0.1	0.1
147	58.600	18	6			100.00	Static	0	2.1	2.1
273	58.600	18	6	14.0		100.00	SM	2	0	14.0
326	58.600	18	6		27.3	100.00	Static	0	27	27.0
274	58.400	18	6	14.0		100.00	SM	1	0	14.0
31	58.400	18	6	5.0		100.00	SM	1	0	5.0
23	58.400	360	6	8.0		100.00	SM	1	0	8.0
32	58.400	360	6	6.0		100.00	SM	1	0	6.0
315	58.400	18	6		5.8	19.58	Static	0	29.3	5.7
334	58.400	18	6		15.1	6.88	Static	0	216.5	14.9
609	58.400	18	6			100.00	Static	0	3.5	3.5

Bus #	Freq. Setting	Relay Delay	Breaker	SM	Shed MW	Shed %	Type	SM ID	Total MW	Shed MW
327	58.400	18	6		6.2	100.00	Static	0	6.1	6.1
335	58.200	18	6		42.4	21.55	Static	0	194.6	41.9
273	58.200	18	6	5.0		100.00	SM	3	0	5.0
274	58.200	18	6	5.0		100.00	SM	3	0	5.0
334	58.100	18	6		21.7	9.90	Static	0	216.5	21.4
115	58.100	18	6		24.3	37.80	Static	0	64.3	24.3
335	58.100	18	6		33.0	16.76	Static	0	194.6	32.6
304	58.100	18	6		14.3	78.46	Static	0	17.4	13.7
334	58.000	18	6		63.4	29.30	Static	0	216.5	63.4
335	58.000	18	6		75.3	38.33	Static	0	194.6	74.6
306	58.000	18	6		11.6	26.10	Static	0	44	11.5
357	58.000	18	6		17.5	100.00	Static	0	17.3	17.3

Table 3: Existing UFLS Sites and Settings

The relay times in Table 3 represents time required by the relays to confidently sense the frequency plus any other intentional delay. The 18 cycles time delay is an average value obtained from the relay tests provided by the NLH System Performance and Protection Department. Some relays have longer time delay while others have smaller time delays with the following exceptions:

- 6% of the load at Oxen Pond (bus 334) is shed with time delay of 900 cycles (15 seconds). The loads that are shed with time delay of 15 seconds are used as a safety net in the event the frequency remains below 59 Hz for a long time
- Synchronous motors that are shed with time delay of 360 cycles (6 seconds) are modeled differently. These motors are actually offloaded within 6 seconds by ramping the mechanical load on them to zero within 6 seconds but keeping them spinning without load

Based on the information in Table 3, the existing load shedding stages (frequency and per cent of available load to be shed) are summarized in Table 4. Note that the time delay loads been included with the 18 cycle loads.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Load Shed, %	7	15	10	11	10	17	30
Relay time, cycles	18	18	18	18	18	18	18
Frequency setting, Hz	59.0	58.8	58.6	58.4	58.20	58.10	58.0

Table 4: Existing UFLS Stages

In the existing load shedding scheme, approximately 40% (552MW/1382MW) of the total load (based on the peak loading condition) in the system is made available for load shedding. This represents a sufficient amount of load since the load shedding scheme has been designed for the loss of the largest online unit. Should the design criteria include larger amount of generation loss, then, more loads should be made available for under-frequency load shedding. Normally, in isolated power systems, a larger amount of load is under UFLS (e.g. 80%) in order to cover for much larger generation loss (see reference 2). There are even suggestions that all the loads should be put under UFLS. This is not surprising because if the power system is supposed to handle large of amount of generation loss, it is better to shed a lot of loads to avoid total system collapse and damaging thermal units.

Before any suggestion for the improvement of the performance of the existing UFLS scheme is made we need to evaluate its performance and effectiveness.

To evaluate the performance of the existing load shedding scheme it is necessary to subject each of the given scenarios outlined in Table 2 to the loss of generation. NLH provided a list of possible generation loss for each of the scenarios as seen in last column of the Table 2.

The result of simulation runs for each of the scenarios is summarized in Table 5. The frequency plot for each of the scenarios is also shown in Figure 2. As was expected, it can be seen from Table 5 that due to variation in the load levels and system inertia the system response varies considerably from one scenario to the other. This table includes two important quantities namely, minimum frequency and amount of load shedding. These quantities are normally used to assess the effectiveness of the load shedding schemes.

The column marked as "Gen Pick up" in Table 5 is computed as follows:

Gen Pick Up = Total generation at 20 seconds - Total generation at 0 seconds

The generation at 20 seconds (as an indicator only and need not necessary be 20 seconds) is used to calculate generation pick up as in most cases the governors would have had time to respond and the frequency would be settling to a steady state value. Generation pick up is used to assess governor response and spinning reserve.

Since there are many scenarios to be considered, some form of global quantity is required to measure the effectiveness. For this reason, several quantities such as minimum of minimum of frequencies in all of the cases and average of minimum of frequencies are also reported in this table. The minimum frequency is 57.92 Hz for the scenario "***warm_winter_day_dry***" with highest amount of load shedding of 252 MW. The generation loss in this scenario is the loss of largest online unit. This is to be expected because system inertia is also the lowest for this scenario. It should also be noted that in this scenario excessive load shedding has taken place with the result of negative generation pick up after 20 seconds. The only other scenario in which the load shedding is substantially greater than the amount of generation lost (more than 20 MW) is the "***warm_winter_day_wet***" scenario.

Total load shed in all of the scenarios is 907 MW. The column "% load shed" in Table 5 is simply the ratio of total load shed to the total load in the corresponding scenario. In a perfect situation (no over- or under-shedding) and with good governor response the following relationship should hold:

$$\text{Generation Loss} - (\text{Spinning Reserve} + \text{Load Shed}) = 0$$

The frequency plot corresponding to Table 5 is shown in Figure 2. It can be seen that frequency in a few scenarios overshoots before settling down to nominal. This is an indication of slow and over-shedding action. The discontinuities seen on the frequency plot are attributed to two factors, first, the plot shows instantaneous frequency and second at the time of disturbances (generation loss, load shed) the frequency computation cannot be computed accurately.

The rate-of-change of frequency is directly proportional to the amount of generation lost and inversely proportional to the system inertia. The rate-of-change of frequency decline for the considered scenarios is shown in Figure 3. It can be seen from this figure that in most of the cases the rate-of-change is approximately –0.5 Hz/sec with the exception of "***warm_winter_day_dry***" which is around –1.0 Hz/sec. The selection of relay setting based on the rate-of-change of frequency should be such that it does not trigger load shedding for disturbances other than generation loss. Also, it should not be triggered frequently on loss of small amounts of generation. This information will be later used for the design of rate-of-change of frequency load shedding scheme.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	75	66	9	-3	58.58	15	Upper Salmon
peak_load_dry	1428	1382	161	149	80	69	-10	58.51	11	Holyrood
warm_early_spring_night_wet	659	643	50	66	52	14	-16	58.74	10	Cat Arm
warm_winter_day_wet	719	704	90	121	94	27	-27	58.38	17	Cat Arm
warm_winter_day_dry	730	704	161	252	123	129	-79	57.92	36	Holyrood
cool_late_spring_day_wet	1052	1005	75	76	52	25	-1	58.75	8	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	141	80	61	12	58.44	11	Bay D'Espoir#7
Extreme Light Load	280	269	58	27	0	27	36	58.18	10	Hinds Lake
Total	6690	6461	815	907	547	360	-88	467.51	118	
Min	280	269	50	27	0	9	-79	57.92	8	
Max	1428	1382	161	252	123	129	36	58.75	36	

Table 5: Load Shedding Summary For Existing UFLS Scheme Design #0 (18 Cycles Relay)

Based on NLH request, the scenario "warm_early_spring_night_wet" was re-simulated but assuming loss of both units of Cat Arm (137 and 138). The result of this case is summarized below. This scenario will not be repeated in other designs and only reported here for sake of comparison with the case where only one unit of Cat Arm is lost.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
warm_early_spring_night_wet	659	643	100	145	113	32	-41	58.37	23	Cat Arm both Units

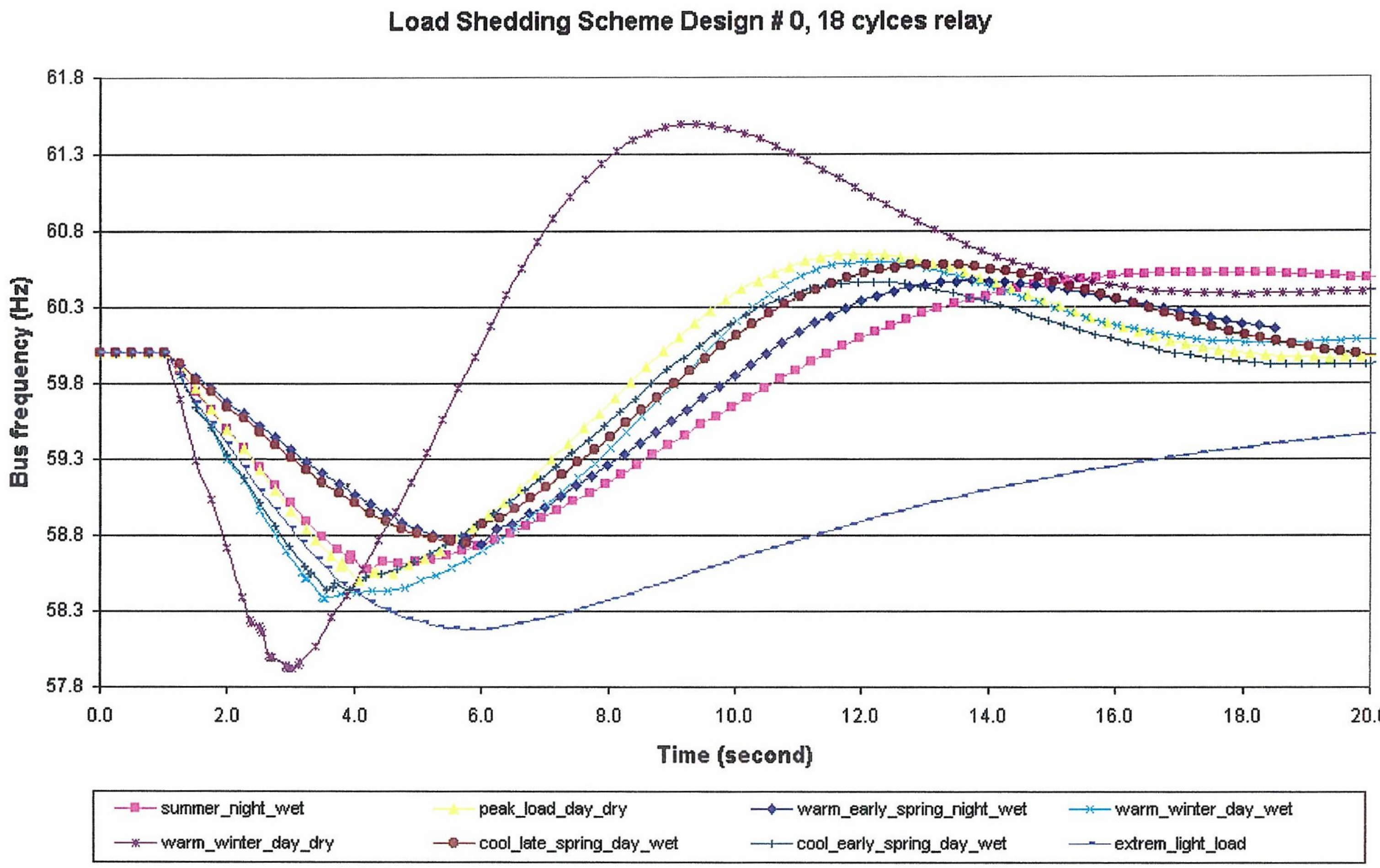

Figure 2: Frequency Response For Existing UFLS Scheme Design #0 (18 Cycles Relay)

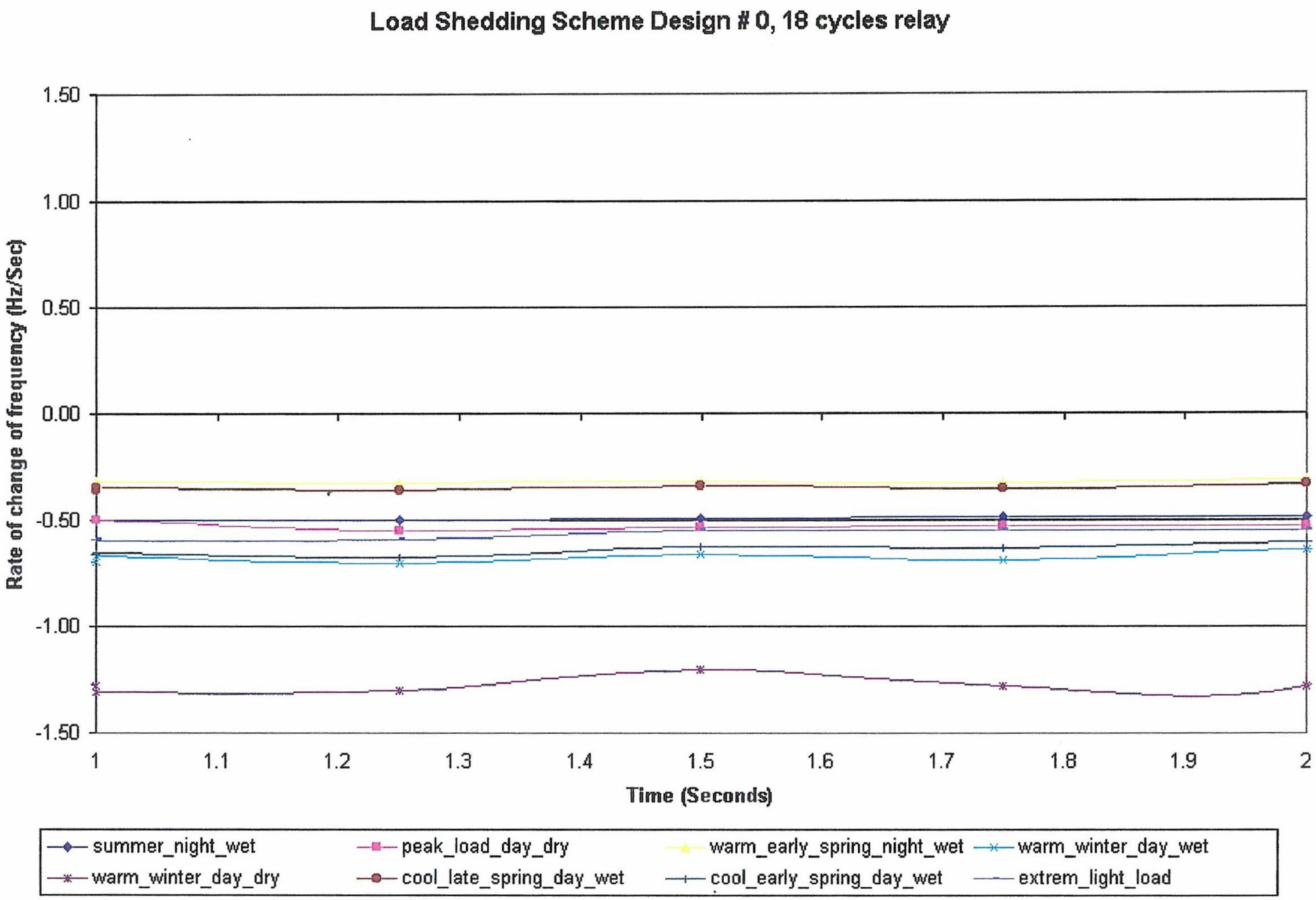

Figure 3: Rate of Change of Frequency For Existing UFLS Scheme Design #0 (18 Cycles Relay)

3.3 Load Shedding Scheme Design #0

An obvious improvement to the existing load shedding is utilization of much faster response time UFLS relays. Relay response time of 6 cycles or shorter is commonly offered by solid-state relays. Therefore, the very first attempt to improve the UFLS performance is application of 6 cycle relays. The result for this scheme, referred to as design 0 (6 cycles), is outlined in Table 6. It can be seen that faster relays have indeed offered improvement over the existing slower relays. The minimum frequency is now 58.09 Hz and total load shedding in all of the scenarios has been reduced to 831 MW from 907 MW. The frequency plots for this case is shown in Figure 4. It is also noticed from these plots that the number of cases and amount of overshooting have been reduced with faster relays application. The load shedding amount for every scenario is reduced as compared with the existing scheme. However, over shedding still exist for the scenarios "warm_winter_day_wet", "warm_early_spring_night_wet", and "warm_winter_day_dry.

The shedding of industrial synchronous motors has two drawbacks; first, shedding them will result in loss of inertia, and second, some of the motors are offloaded within 6 seconds which is certainly less effective than immediate load tripping. It may be a better idea to use these loads as a safety net similar to the loads that are tripped with 15 seconds time delay.

The minimum frequency of 58.09 Hz is still too close to the generator under-frequency protection setting. In this design, since faster relays are used, the total generation pick up (at 20 seconds) is greater (-16.07 MW) than the existing relay case that was –88 MW after 20 seconds. Faster relays (and better UFLS design) and faster governors response mainly influence the amount of generation pick up.

The next variation on the design for the UFLS should be directed to resolve two issues, first, yield a better frequency profile (at least higher minimum frequency) and second, avoid over shedding as much as possible. It important to note that in this analysis and search for better UFLS design the probability aspect of system being in any of the considered scenarios is ignored. As stated earlier, NLH may decide that one design is more acceptable than others because it has shown improvement in the most probable scenarios.

In all of the UFLS design schemes to follow, it is assumed that the relay speed is 6 cycles since this has offered significant improvement.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	61.2	52.0	9.2	11.2	58.65	12.28	Upper Salmon
peak_load_dry	1428	1382	161	148.8	80.0	68.8	-10.1	58.58	10.77	Holyrood
warm_early_spring_night_wet	659	643	50	65.6	52.0	13.6	-16.5	58.76	10.20	Cat Arm
warm_winter_day_wet	719	704	90	107.3	80.0	27.3	-12.7	58.48	15.24	Cat Arm
warm_winter_day_dry	730	704	161	204.6	123.0	81.6	-35.1	58.09	29.06	Holyrood
cool_late_spring_day_wet	1052	1005	75	76.5	52.0	24.5	-0.8	58.78	7.61	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	141.1	80.0	61.1	11.8	58.53	11.23	Bay D'Espoir#7
Extreme Light Load	280	269	58	26.6	0.0	26.6	36.2	58.19	9.90	Hinds Lake
Total	6690.00	6461.00	814.74	831.59	518.86	312.73	-16.07	468.06	106.29	
Min	280.00	269.00	50.00	26.63	0.00	9.20	-35.11	58.09	7.61	
Max	1428.00	1382.00	161.50	204.58	122.98	81.60	36.21	58.78	29.06	

Table 6: Load Shedding Summary For Design Scheme #0 (6 Cycles Relay)

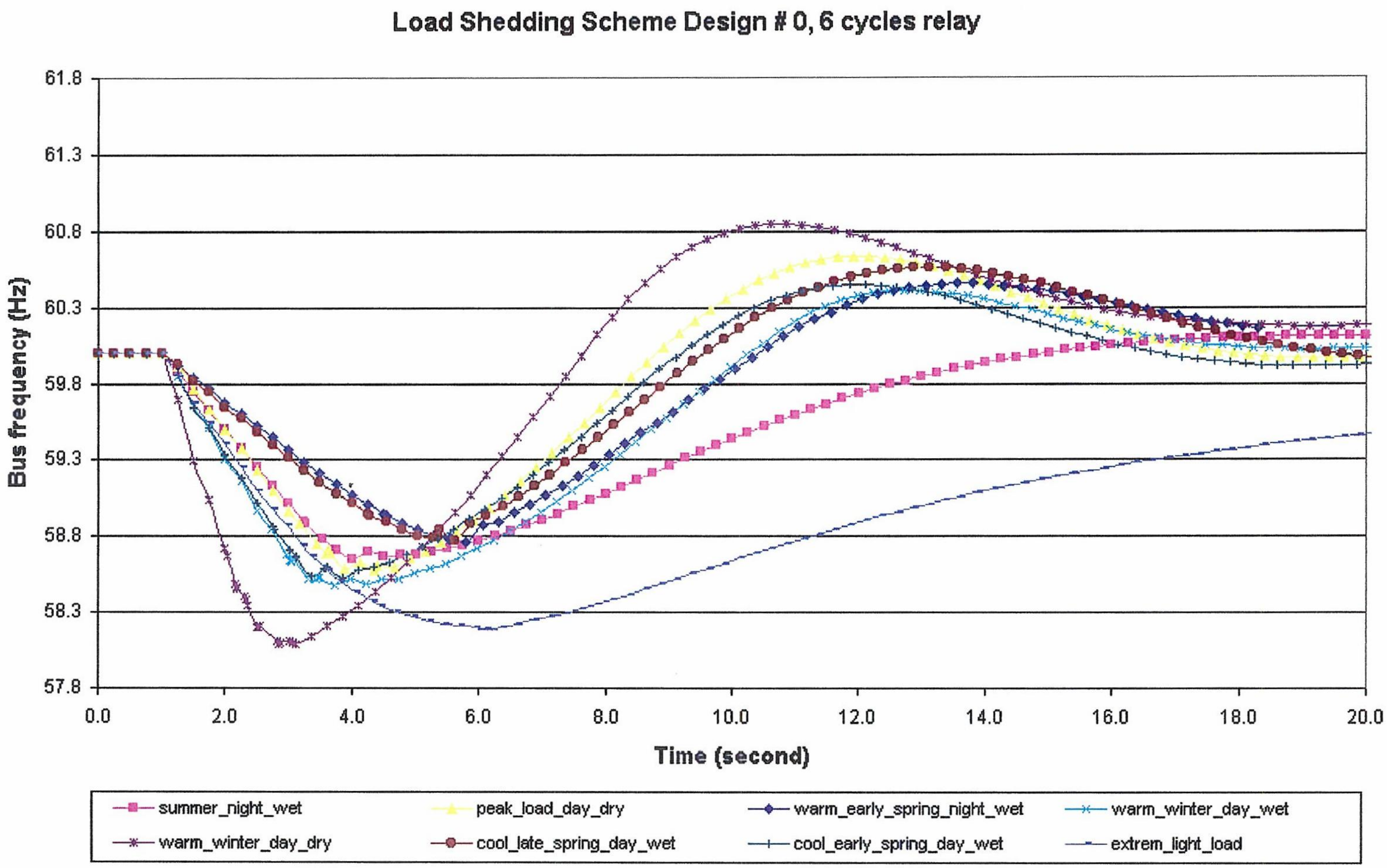

Figure 4: Frequency Response For Load Shedding Scheme Design #0 (6 Cycles Relay)

3.4 Load Shedding Scheme Design #1

Based on the Design #0 results it was decided to increase the amount of load shedding in the first stage of load shedding and try to have more uniform distribution over the frequency stages. The settings for the next UFLS design scheme is shown in the Table 7 below:

Load Shed, %	10	15	15	15	20	25
Relay time, cycles	6	6	6	6	6	6
Frequency setting, Hz	59.0	58.8	58.6	58.4	58.2	58.0

Table 7: The UFLS settings for design scheme #1

Also, in the above scheme we have eliminated the 58.1 Hz stage since it may not be accurately measured with existing relays even though this is possible with newer relays. But in islanded/small power systems the use of closely spaced frequency steps is not recommended. Note that in the above scheme the setting of the synchronous motor which are offloaded over 6 seconds and loads that are shed with intentional delay of 15 seconds have not been altered.

The results of dynamic simulation for all of the scenarios using design 1 are summarized in Table 8. The first noticeable improvement is a significant reduction in the total load shedding. Here total load shed for all of the scenarios is 727 MW versus 832 MW and 907 MW for design 0 and existing UFLS schemes respectively. The second improvement is the minimum frequency which is now at 58.22 Hz, which is much higher than the previous cases. As well, total generation pickup has increased to 90.8 MW.

Over shedding exists for the scenarios "warm_winter_day_wet" (47 MW), and "warm_winter_day_dry" (20 MW). For "warm_winter_day_dry" the over shedding has been reduced by 23.6 MW when compared to design 0 (6 cycles).

The frequency plot for all of the scenarios for this load shedding scheme is shown in Figure 5. It is apparent from this figure that much better profile has been obtained for this design.

The next section alternative load shedding schemes will be attempted to eliminate the over-shedding.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	72.4	57.7	14.7	-0.5	58.73	14.54	Upper Salmon
peak_load_dry	1428	1382	161	126.5	57.7	68.8	11.8	58.69	9.16	Holyrood
warm_early_spring_night_wet	659	643	50	24.0	10.4	13.6	28.5	58.85	3.73	Cat Arm
warm_winter_day_wet	719	704	90	136.7	90.7	46.0	-40.6	58.57	19.42	Cat Arm
warm_winter_day_dry	730	704	161	180.8	114.7	66.1	-13.4	58.22	25.68	Holyrood
cool_late_spring_day_wet	1052	1005	75	34.9	10.4	24.5	40.7	58.87	3.47	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	118.8	57.7	61.1	34.0	58.61	9.46	Bay D'Espoir#7
Extreme Light Load	280	269	58	33.3	0.0	33.3	30.3	58.37	12.38	Hinds Lake
Total	6690.00	6461.00	814.74	727.42	399.32	328.10	90.82	468.91	97.84	
Min	280.00	269.00	50.00	23.96	0.00	13.60	-40.58	58.22	3.47	
Max	1428.00	1382.00	161.50	180.82	114.72	68.80	40.68	58.87	25.68	

Table 8: Load Shedding Summary For Design Scheme #1

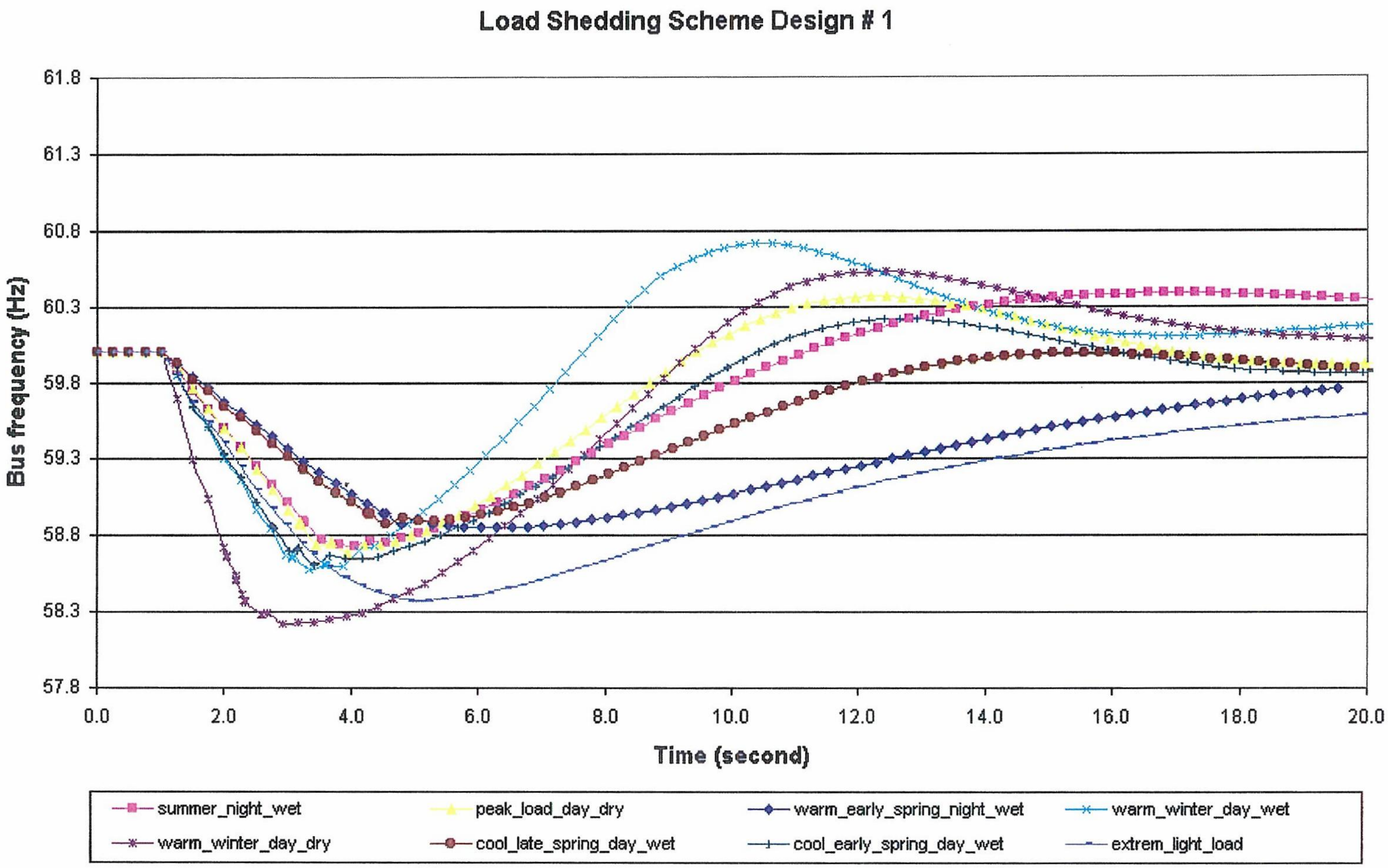

Figure 5: Frequency Response for load shedding scheme design 1

3.5 Load Shedding Scheme Design #2

Normally a uniform distribution of load shedding over the UFLS frequency range can result in reduction of over shedding. In this design scheme we analyze the case for equal distribution of load shed in each stage as shown below in Table 9:

Load Shed, %	17	17	17	17	17	17
Relay time, cycles	6	6	6	6	6	6
Frequency setting, Hz	59.0	58.8	58.6	58.4	58.2	58.0

Table 9: The UFLS settings for design scheme #2

The results of simulation for this design are summarized in Table 10. The total load shed in all of the scenarios is 859 MW which is higher than both design #1 and design 0 (6 cycles), but lower than the original settings. However, here the best frequency profile is obtained with minimum frequency being 58.36 Hz. There is over-shedding in this design as well with 22 MW over-shed in "warm_winter_day_wet", 42 MW in "warm_winter_day_dry" and 19 MW in "cool_early_spring_day_wet". The total generation pick up (-25.8 MW) is less than both design #1 and design #0 (6 cycles). The frequency response for the considered scenarios is shown in Figure 6.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	53.5	43.7	9.8	19.0	58.82	10.75	Upper Salmon
peak_load_dry	1428	1382	161	163.0	57.7	105.3	-22.0	58.75	11.80	Holyrood
warm_early_spring_night_wet	659	643	50	58.4	43.7	14.7	-7.9	58.91	9.09	Cat Arm
warm_winter_day_wet	719	704	90	112.2	71.7	40.5	-16.5	58.69	15.94	Cat Arm
warm_winter_day_dry	730	704	161	203.1	114.7	88.4	-33.8	58.36	28.85	Holyrood
cool_late_spring_day_wet	1052	1005	75	70.5	43.7	26.8	5.6	58.90	7.02	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	165.0	71.7	93.3	-0.6	58.69	13.14	Bay D'Espoir#7
Extreme Light Load	280	269	58	33.3	0.0	33.3	30.3	58.49	12.38	Hinds Lake
Total	6690.00	6461.00	814.74	859.14	447.04	412.10	-25.82	469.61	108.96	
Min	280.00	269.00	50.00	33.30	0.00	9.80	-33.80	58.36	7.02	
Max	1428.00	1382.00	161.50	203.12	114.72	105.30	30.34	58.91	28.85	

Table 10: Load Shedding Summary for design scheme #2

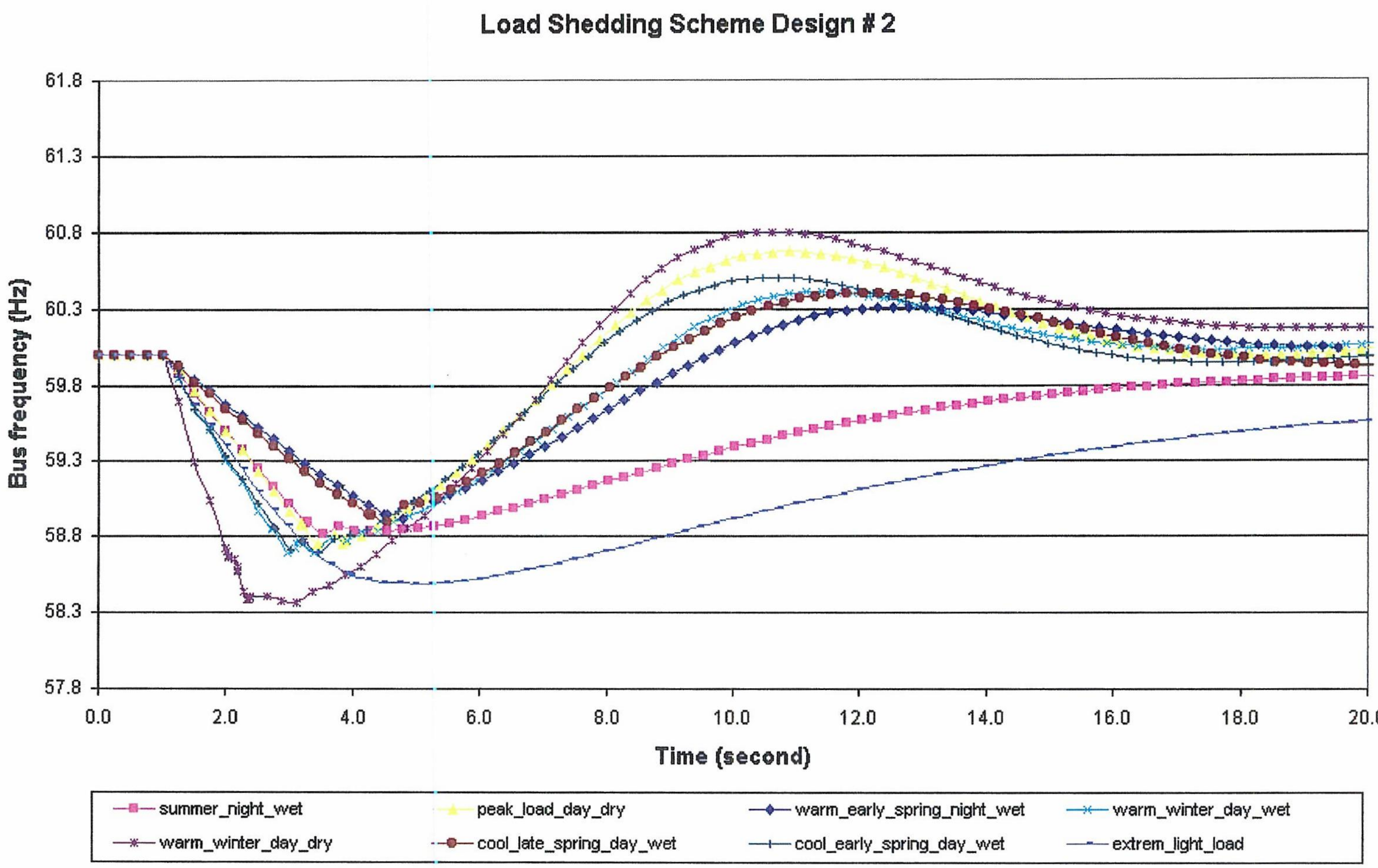

Figure 6: Frequency Response for load shedding scheme design 2

3.6 Load Shedding Scheme Design #3

Since over-shedding remains a problem in the designs investigated so far, the performance of a design with an increased number of stages is investigated next. This method, in theory, should yield less load shedding and a better frequency profile.

The frequency settings for a 10-stage load shedding scheme is shows in Table 11 below:

Load Shed, %	10	10	10	10	10	10	10	10	10	10
Relay time, cycles	6	6	6	6	6	6	6	6	6	6
Frequency setting, Hz	59.0	58.9	58.8	58.7	58.6	58.5	58.4	58.3	58.2	58.0

Table 11: The UFLS settings for design scheme #3

The results for this design scheme are summarized in Table 12. As expected, the minimum frequency of 58.38 Hz in this design is higher than any other schemes analyzed so far. The total load shed for this design is 826 MW, which is an improvement over design # 0 (6cycles), design #2 and the existing settings. The total generation pickup is 11.74 MW for design #3. Over shedding is still a concern for "warm_winter_day_wet" (22 MW), "warm_winter_day_dry" (42 MW) and "cool_early_spring_day_wet" (19 MW).

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	71.4	57.7	13.7	0.6	58.78	14.34	Upper Salmon
peak_load_dry	1428	1382	161	161.2	57.7	103.5	-20.9	58.76	11.67	Holyrood
warm_early_spring_night_wet	659	643	50	30.5	10.4	20.1	23.2	58.90	4.74	Cat Arm
warm_winter_day_wet	719	704	90	111.5	71.7	39.8	-15.8	58.75	15.84	Cat Arm
warm_winter_day_dry	730	704	161	206.6	114.7	91.9	-37.1	58.38	29.35	Holyrood
cool_late_spring_day_wet	1052	1005	75	48.7	10.4	38.3	30.7	58.92	4.84	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	163.4	71.7	91.7	0.5	58.76	13.01	Bay D'Espoir#7
Extreme Light Load	280	269	58	32.9	0.0	32.9	30.6	58.51	12.23	Hinds Lake
Total	6690.00	6461.00	814.74	826.22	394.32	431.90	11.74	469.76	106.02	
Min	280.00	269.00	50.00	30.46	0.00	13.70	-37.14	58.38	4.74	
Max	1428.00	1382.00	161.50	206.62	114.72	103.50	30.71	58.92	29.35	

Table 12: Load Shedding Summary for design scheme #3

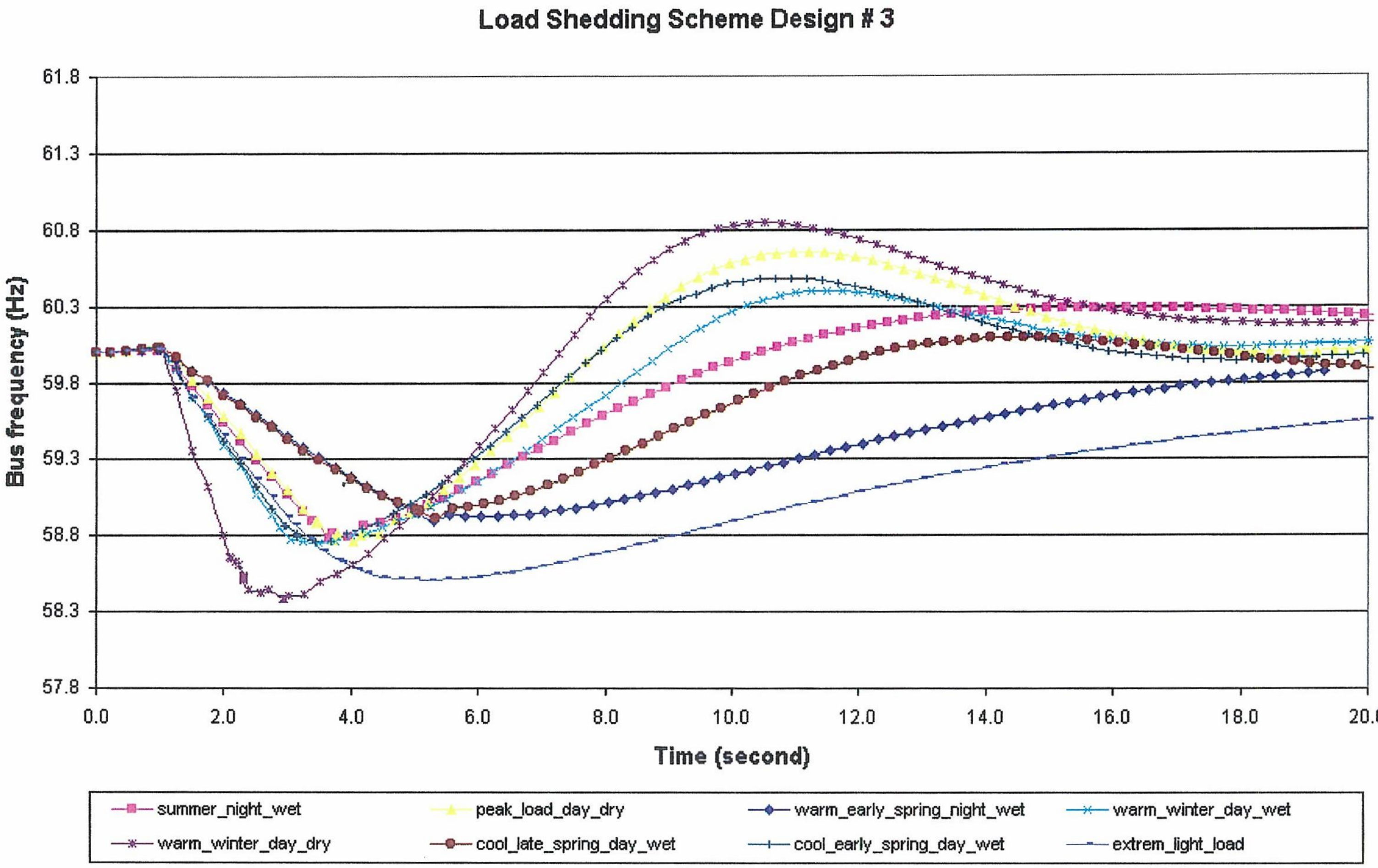

Figure 7: Frequency Response for load shedding scheme design 3

3.7 Load Shedding Scheme Design #4

In this design we try to shift more load shedding to the first stage and last stages. The scheme stages and amount of load shedding are summarized in Table 13.

Load Shed, %	13	9	11	11	9	17	30
Relay time, cycles	6	6	6	6	6	6	6
Frequency setting, Hz	59.0	58.8	58.6	58.4	58.20	58.10	58.0

Table 13: The UFLS settings for design scheme #4

The results of this design for all of the scenarios are shown in Table 14. The total load shed, 783 MW, is less than designs #0, #2 and #3. Also, in each of the scenarios listed in Table 14, there is less load shedding as compared to original settings. In design #4 over-shedding equals 17.3 MW in "warm_winter_day_wet" and 43.6 MW in "warm_winter_day_dry". The minimum frequency of 58.09 Hz is lower than designs #1, #2 and #3. The total generation pick up has improved over design #3 and equals 31.76 MW in design #4.

The frequency response plot for this case is shown in Figure 8.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	61.2	52.0	9.2	11.3	58.66	12.29	Upper Salmon
peak_load_dry	1428	1382	161	148.8	80.0	68.8	-10.2	58.61	10.77	Holyrood
warm_early_spring_night_wet	659	643	50	65.6	52.0	13.6	-16.4	58.80	10.20	Cat Arm
warm_winter_day_wet	719	704	90	107.3	80.0	27.3	-12.7	58.49	15.24	Cat Arm
warm_winter_day_dry	730	704	161	204.6	123.0	81.6	-35.1	58.09	29.06	Holyrood
cool_late_spring_day_wet	1052	1005	75	28.6	5.4	23.2	46.8	58.86	2.84	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	141.1	80.0	61.1	11.8	58.55	11.23	Bay D'Espoir#7
Extreme Light Load	280	269	58	26.6	0.0	26.6	36.3	58.20	9.89	Hinds Lake
Total	6690.00	6461.00	814.74	783.69	472.24	311.45	31.76	468.26	101.52	
Min	280.00	269.00	50.00	26.60	0.00	9.24	-35.12	58.09	2.84	
Max	1428.00	1382.00	161.50	204.58	122.98	81.60	46.80	58.86	29.06	

Table 14: Load Shedding Summary for design scheme #4

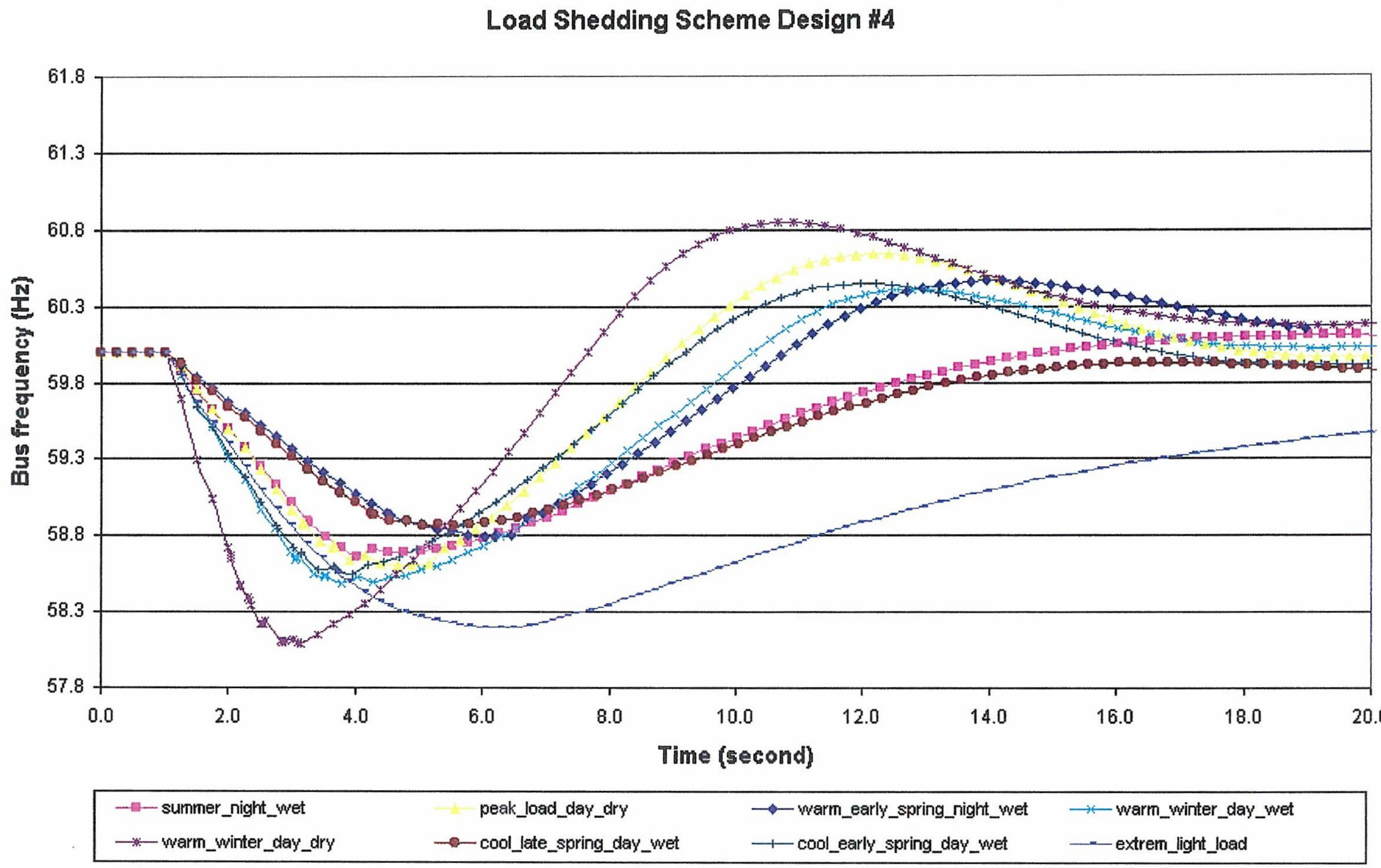

Figure 8: Frequency Response for load shedding scheme design 4

3.8 *Load Shedding Scheme Design #5*

Based on the rate of change-of-frequency (dF/dt) shown in Figure 3, it was decided that selecting UFLS relaying with 0.8 Hz/sec at 59.0 Hz would be appropriate for the NLH power system. This value is selected such that rate of change of frequency relay only picks up for severe frequency drops which can result from significant generation loss when compared to the total inertia system (0.8 Hz/sec is approximately the average rate of change of frequencies for different scenarios). This situation normally occurs in the medium to light loads depending on the units on line.

The setting and amount of load shedding in this design scheme is summarized in Table 15. In this design scheme we try adding more load shedding to the first stage and assess the performance of rate-of-change of frequency UFLS relays. Approximately 75 MW of static load is allocated for the rate-of-change of frequency relay.

Load Shed, %	13	13	9	11	11	9	17	17
Relay time, cycles	6	6	6	6	6	6	6	6
Frequency setting, Hz	59.0	59.0	58.8	58.6	58.4	58.2	58.1	58.0
dF/dt setting, Hz/sec		0.8						

Table 15: The UFLS settings for design scheme #5

It should be noted that, in this scheme, the allocated load for the dF/dt relays is static load. In the next design scheme, the effect of selecting rotating load (synchronous motors) will be investigated.

The results of the study for this scheme are outlined in Table 16. The following observations can be made from this table as compared with the result of other schemes presented in the previous sections. First, in every load scenario there is less, or equal, load shed in design #5 than in design #0 (6 cycles) and the existing scheme. Second, the minimum frequency of 58.2 Hz is higher than the minimum obtained for design #0 (6 cycles) and the existing scheme. The total load shed, 757 MW, is significantly lower than the existing scheme. Also, the total load shed is less than previous design scheme (recall 783 MW), which means that application of rate-of-change of frequency indeed has improved performance of the UFLS. The total generation pick up has improved to 54.58 MW. The frequency response for this design scheme is shown in Figure 9. The application of the rate of change of frequency relay for NLH helps to improve load shedding because it provides a fast and early means of load shedding when severe generation loss occurs.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	61.2	52.0	9.2	11.3	58.66	12.29	Upper Salmon
peak_load_dry	1428	1382	161	148.8	80.0	68.8	-10.2	58.61	10.77	Holyrood
warm_early_spring_night_wet	659	643	50	65.6	52.0	13.6	-16.4	58.80	10.20	Cat Arm
warm_winter_day_wet	719	704	90	107.3	80.0	27.3	-12.7	58.49	15.24	Cat Arm
warm_winter_day_dry	730	704	161	178.1	113.0	65.1	-12.3	58.23	25.30	Holyrood
cool_late_spring_day_wet	1052	1005	75	28.6	5.4	23.2	46.8	58.86	2.84	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	141.1	80.0	61.1	11.8	58.55	11.23	Bay D'Espoir#7
Extreme Light Load	280	269	58	26.6	0.0	26.6	36.3	58.20	9.89	Hinds Lake
Total	6690.00	6461.00	814.74	757.19	462.24	294.95	54.58	468.40	97.76	
Min	280.00	269.00	50.00	26.60	0.00	9.24	-16.38	58.20	2.84	
Max	1428.00	1382.00	161.50	178.08	112.98	68.80	46.80	58.86	25.30	

Table 16: Load Shedding Summary For Design Scheme #5

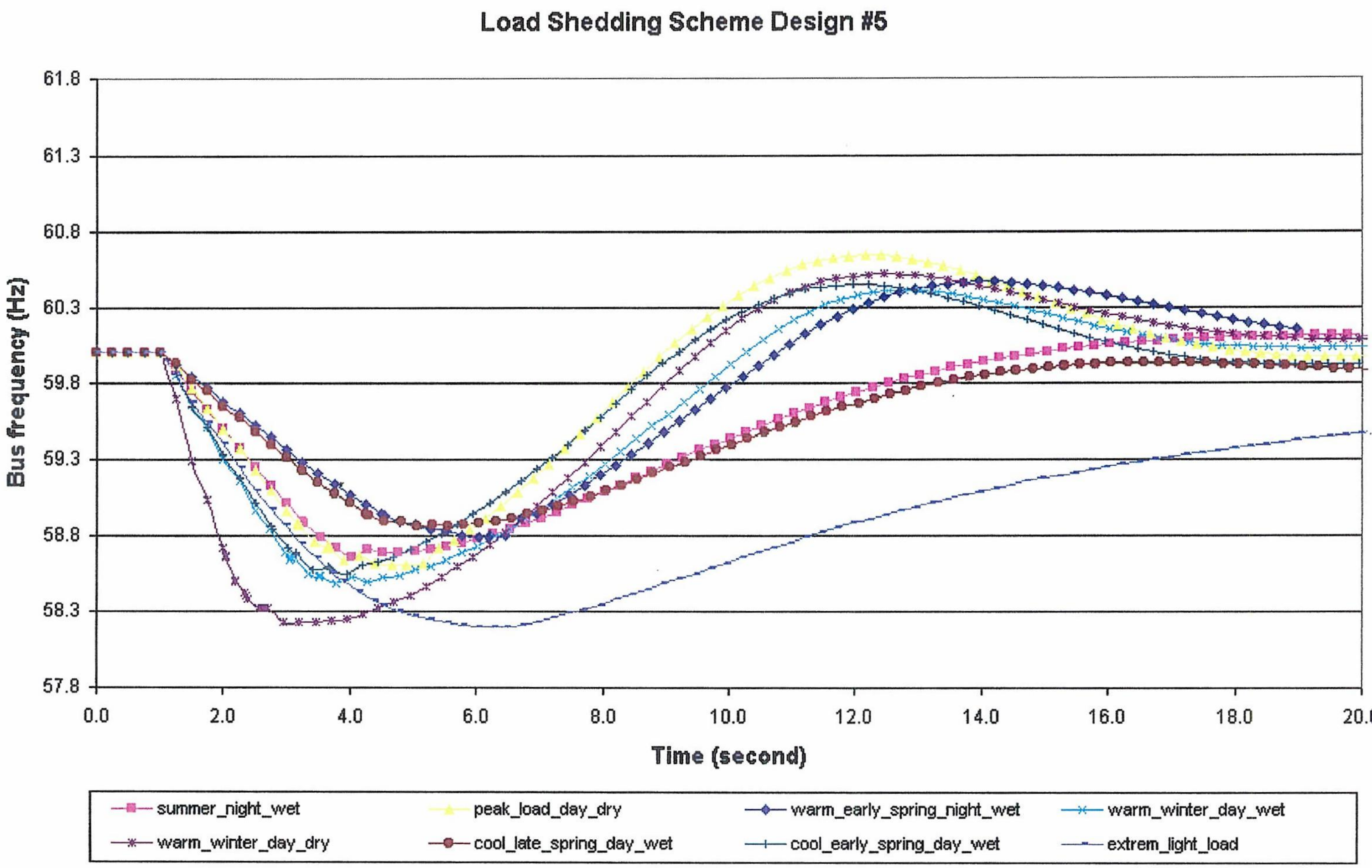

Figure 9: Frequency Response for load shedding scheme design 5

3.9 Load Shedding Scheme Design #6

This design scheme is similar to the previous one with exception of the type load that is being allocated for the rate-of-change of frequency UFLS relays. The setting of 0.8 Hz/sec at 59.0 Hz is still maintained for UFLS relay in stage 1. The setting and amount of load shedding of this design scheme is summarized in Table 17.

Load Shed, %	13	13	9	8	8	8	17	24
Relay time, cycles	6	6	6	6	6	6	6	6
Frequency setting, Hz	59.0	59.0	58.8	58.6	58.4	58.2	58.1	58.0
dF/dt setting, Hz/sec		0.8						

Table 17: The UFLS settings for design scheme #6

Of the 75 MW of load allocated to the rate-of-change of frequency about half is from synchronous motor load and the other half from static loads. It should be noted that this allocation means there are now less synchronous motors available in other stages for load shedding.

The results for design scheme #6 are summarized in Table 18. Noticeably, the total load shed in this design (710 MW) is less than any other design scheme studied so far. The result of this case may seem unexpected but it should be noted that the significant reduction in the amount load shed is a result of two factors: first is application of rate of change of frequency relays and second is the allocation of less synchronous motor load for load shedding. The minimum frequency of 58.20 Hz is similar to design #5 but higher than the result for the existing load shedding scheme. The amount over-shedding is this scheme is also smallest among all of the designs analyzed. As well, the total generation pick up is at its highest among schemes, equaling 101.59 MW in this design. The frequency response for this design is shown in Figure 10.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Generation Pick up	Minimum Freq	% Load Shed	Lost generator
summer_night_wet	514	498	73	61.2	52.0	9.2	11.3	58.66	12.29	Upper Salmon
peak_load_dry	1428	1382	161	134.8	66.0	68.8	3.4	58.61	9.75	Holyrood
warm_early_spring_night_wet	659	643	50	65.6	52.0	13.6	-16.4	58.80	10.20	Cat Arm
warm_winter_day_wet	719	704	90	93.3	66.0	27.3	1.0	58.41	13.25	Cat Arm
warm_winter_day_dry	730	704	161	172.6	123.0	49.6	-6.3	58.26	24.51	Holyrood
cool_late_spring_day_wet	1052	1005	75	28.6	5.4	23.2	46.8	58.86	2.84	Hinds Lake
cool_early_spring_day_wet	1308	1256	146	127.1	66.0	61.1	25.5	58.54	10.12	Bay D'Espoir#7
Extreme Light Load	280	269	58	26.6	0.0	26.6	36.3	58.20	9.89	Hinds Lake
Total	6690.00	6461.00	814.74	709.69	430.24	279.45	101.59	468.35	92.86	
Min	280.00	269.00	50.00	26.60	0.00	9.24	-16.38	58.20	2.84	
Max	1428.00	1382.00	161.50	172.58	122.98	68.80	46.80	58.86	24.51	

Table 18: Load Shedding Summary For Design Scheme #6

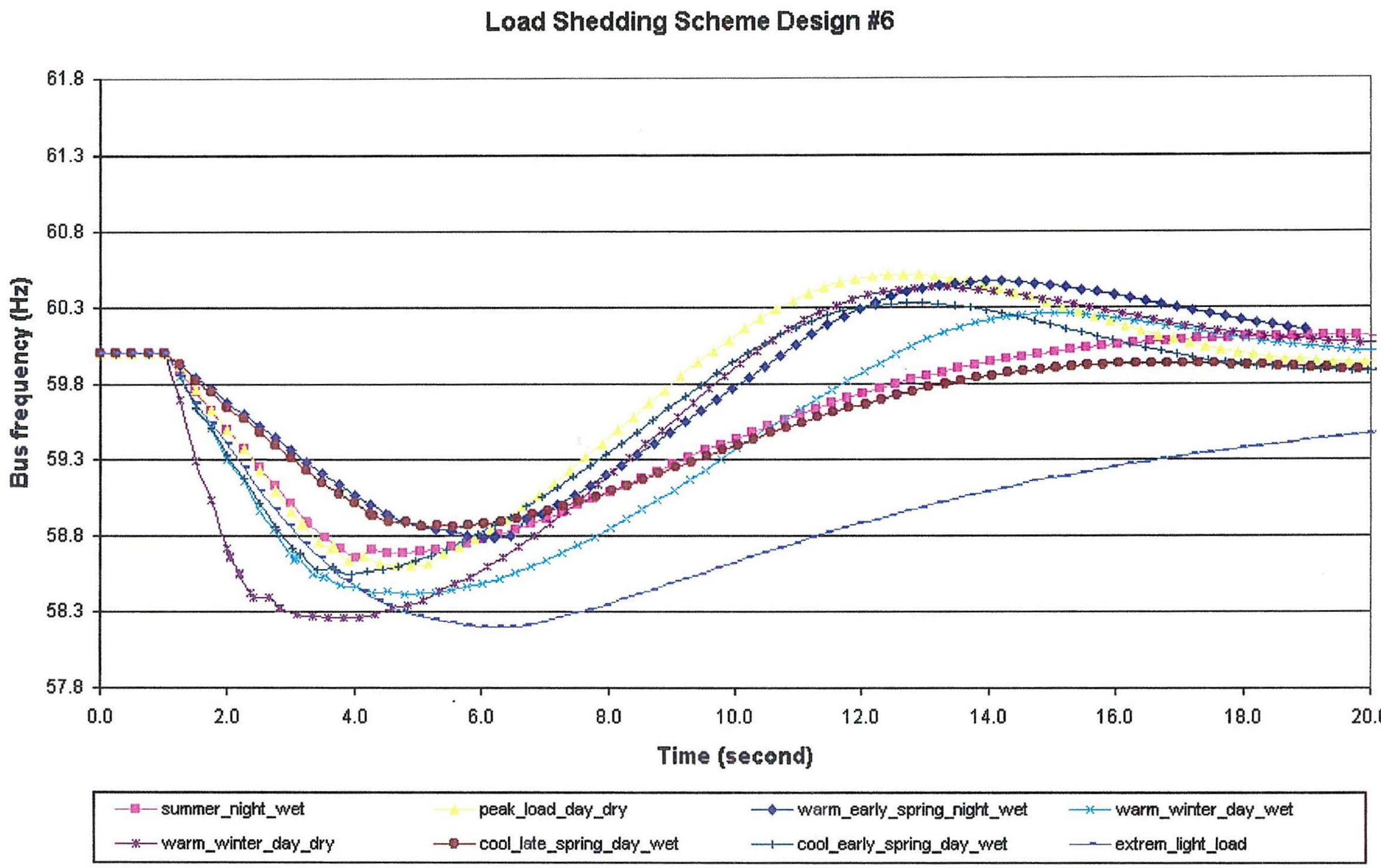

Figure 10: Frequency Response For Load Shedding Scheme Design #6

4. Coordination of Generator Under Frequency Protection and UFLS

In this section the setting of NLH generator under frequency protection relays are present. Most generators are incapable of operating below individually specified minimum frequency, typically less than 58.5 hertz. If, in spite of the automatic load shedding scheme, the frequency drops below the generator trip setting it is necessary to initiate steps to protect generating equipment, including separation from the system with or without load. It is recognized that, in special cases, unusual requirements may dictate higher settings for under frequency relays to protect equipment from damage. In such cases, additional automatic load shedding equivalent to the amount of generation to be tripped must be provided.

If a generator is tripped because of low frequency conditions, isolation onto its own auxiliaries is desirable to facilitate rapid re-synchronization as soon as system conditions permit.

Unit under-frequency protection settings for Newfoundland and Labrador Hydro power system provided to us in Table 19.

Generating Unit	Relay type and setting
Bay D'Espoir	No under frequency relays
Cat Arm	Westinghouse Type CF-1 relay with a frequency setting of 59 Hz and a time dial of 7. The relay picks up a timer which has contacts in the governor control (i.e. Governor setpoint/Power setpoint raise and lower). According to the setting notes the relay initiates an increase in generator output via the timer. The timer setting will have to be verified (timer range 2-20 seconds).
Upper Salmon	Westinghouse Type CF-1 relay with a frequency setting of 59 Hz and a time dial of 2. The relay has two instantaneous contacts that are connected to the Power Set Motor. Setting notes indicate that on closing of the contacts the governor is pulsed to open the wicket gates to increase unit speed when severe under frequencies occur.
Hinds Lake	Westinghouse Type CF-1 relay with a frequency setting of 59 Hz and a time dial of 7. The relay picks up a timer which has contacts in the speed/load control motor, which in turn causes the governor to open the wicket gates. The timer setting will have to be verified (timer range 2-20 seconds).
Holyrood Units #1 & #2	Westinghouse KF relays which cause a unit trip for a frequency setting of 57.6 Hz. In addition there is also a relay (Type CFF15A2A) with a setting of 58.8 Hz and a time delay of 45 seconds which resets should the frequency recover above 58.8 Hz.
Holyrood Unit #3	Under frequency relay type CFF15A2A which cause a unit trip for a frequency setting of 57.6 Hz. In addition there is also a relay (Type CFF15A2A) with a setting of 58.8 Hz and a time delay of 45 seconds which resets should the frequency recover above 58.8 Hz.
Hardwoods	Under frequency relay type IJF is set to trip the unit for a frequency of 57 Hz.

Generating Unit	Relay type and setting
Stephenville	Under frequency relay type CF-1 is set to trip the unit for a frequency of 57 Hz with a time dial of 1/2.
Star Lake	Under frequency relay set to trip the unit at 58 Hz.
Rattle Brook	Under frequency relay set to trip the unit at 58 Hz.

Table 19: Under-Frequency Generator Protection Setting For NLH Units

In comparison, for example, frequency-time characteristics used within NWPP (North West Power Pool) for unit under-frequency protection relays are as shown in Table 20 (the unit trip time does not include breaker time).

Sample 1

freq.	Sec.
59.5	180.0
59	108.
58.5	18.
58	6.
57.5	0.1

Sample 2

freq.	Sec.
58.5	30.
57	0.1

Sample 3

freq.	Sec.
58.	15.

Sample 4

freq.	Sec.
59.5	1.2 (Alarm only)
58.4	101
56	0.3

Table 20: Samples Of Under-Frequency Generator Protection Setting From NWPP

In all of the simulated conditions, the minimum frequency has been higher than 58.0 Hz. Even though result summaries shows that no generator should trip for the simulated cases, it is important specially for the thermal units (Holyrood) to consult with the manufacturer if short time operation below 58.8 causes damage/loss of life.

5. Spinning Reserve Guidelines

The reliable operation of power systems requires that adequate generating capacity be available at all times to maintain scheduled frequency, to avoid loss of firm load, and to be responsive to system separation. This generating capacity is necessary to provide the required supply for load variations and to replace generating capacity lost due to forced outages of generation or transmission equipment. North American Councils and many utilities around the world define the following categories of reserve:

5.1 Synchronized Reserve

The unused portion of generating capacity that is synchronized to the system and ready to pick up load to claimed capacity (the maximum allowable/declared capacity) and capacity which can be made available by curtailing pumping hydro units. Also interruptible loads can be considered in this category (for example, agreement with an industrial client that can be interrupted at high frequency set-point e.g. 59.7 Hz)

5.2 Ten-Minute Reserve Requirement

The Ten-Minute Reserve shall at least be equal to the largest capacity outage including any assigned Ten-Minute Reserve that would result from the loss of a single element. This requirement shall be maintained at all times. It is also required that this Ten-minute reserve be provided by Synchronized Reserve.

5.3 Thirty-Minute Reserve Requirement

The Thirty-Minute Reserve shall equal one-half its Second Contingency Loss which is defined as the largest capacity outage which would result from the loss of a single element after allowing for the First Contingency Loss. This requirement shall be maintained at all times except During Shortages of Operating Reserve. Fast start gas and hydro turbine units are normally considered in this category.

5.4 AGC Reserve Requirement

The Reserve on Automatic Generation Control in each Area shall be sufficient to meet the following frequency performance criteria:

1. Frequency should return to 60 Hz within ten minutes of previously reaching 60 Hz.
2. The average frequency deviation for each ten minute must be within ± of 0.02 Hz

The average frequency deviation for each ten-minute period is determined based on the variation of load (e.g. an arc furnace).

The above requirements, even though proposed by interconnected utilities, have been adopted by isolated and smaller power systems as well (e.g. Saudi Arabian, Malaysian, Israelis, etc) power System. Maintaining spinning reserve equal to the size of largest on-line unit is a good practice but often uneconomical especially for smaller power systems. Some isolated power systems have restricted the size of installed units since loss of largest unit could trigger load shedding. Some utilities have restricted the maximum output of largest unit to minimize the impact of loss of this unit. In smaller power systems, the loss of the largest unit normally leads to load shedding, however, the power system should be able to ride through such a disturbance while maintaining acceptable voltage and frequency quality without excessive over-shedding or further loss of generation.

5.5 Distribution of Spinning Reserve

The operating reserve shall be distributed so as to ensure that it can be utilized without exceeding individual element rating or transfer limitations. The first task in allocating spinning reserve is the determination of the required amount of spinning reserve. It is common practice to set the amount of spinning reserve equal to the size of the largest unit. Lower values can be considered, in which case the output of the largest unit is limited such that the system frequency does not fall below 59.5 Hz in the event of sudden tripping of a generating unit on the system. This is basically to avoid the operation of automatic load shedding relays for the largest unit outage. For efficient use of the governor response, the spinning reserve should be allocated such that no one unit reaches it's maximum output while another unit is left with a significant amount of reserve after governor response following a disturbance. This can be achieved if the distribution is according to the following relation:

$$SPR_i = \frac{\frac{HDL_i}{R_i}}{\sum \frac{HDL_i}{R_i}} \times SPRR$$

Where,

SPR_i = Spinning Reserve for unit i, MW
SPRR = Spinning Reserve Requirement, MW
HDL_i = The Highest Dispatch Limit for unit i, MW
R_i = Droop of unit i, p.u.

The above summation should be carried out for all of the on-line generating units participating in governor response. If all units are assumed to have similar percentage droops, then the spinning reserve can be allocated in proportion to the MW rating of the units.

5.5.1 Existing Spinning Reserve Allocation for NLH

As an example, Table 21 shows the spinning reserve allocation for NLH generating units based on the method described earlier. In this table unit droops are also tabulated. It is assumed that HDL of each unit is 85% of it's generator rating. It can be seen that the highest amount of spinning reserve is allocated to the Bay D'Espoir Unit #7 since the unit is large with rather small droop setting while Bay D'Espoir units and Holyrood units are also sharing large portion of spinning reserve (assuming that the droop settings provided are correct). It is important that the proportion of allocation of spinning reserve be maintained no matter what the final spinning reserve requirements is.

Bus #	Bus Name	Turbine type	MVA	H Sec	H*MVA MW*Sec	R Droop	HDL MW	HDL/R	SPR %
435	HRD GEN216.0	Thermal	194.5	2.58	502	0.050	165.3	3305.7	6.3
434	HRD GEN116.0	Thermal	194.5	2.58	502	0.050	165.3	3305.7	6.3
436	HRD GEN316.0	Thermal	177.2	1.29	229	0.045	150.6	3347.7	6.4
2207	BDE7 13.8	Hydro	172.0	4.01	690	0.020	146.2	7310.0	14.0
109	DLP DLK 6.00	Hydro	92.9	4.32	401	0.060	79.0	1316.2	2.5
406	U.SALMON13.8	Hydro	88.4	3.67	324	0.020	75.1	3757.0	7.2
2201	BDE1 13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
220	BAYDESPR13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
220	BAYDESPR13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
220	BAYDESPR13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
220	BAYDESPR13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
220	BAYDESPR13.8	Hydro	85.0	5.20	442	0.020	72.3	3612.5	6.9
250	HINDS LK13.8	Hydro	83.3	6.70	558	0.050	70.8	1416.1	2.7
138	CAT ARM213.8	Hydro	75.5	4.48	338	0.040	64.2	1604.4	3.1
137	CAT ARM113.8	Hydro	75.5	4.48	338	0.040	64.2	1604.4	3.1
209	STPHNVIL13.8	Gas	63.5	2.06	131	0.070	54.0	771.1	1.5
237	HRDWOODS13.8	Gas	63.3	2.06	130	0.069	53.8	780.3	1.5
370	GREENHIL13.8	Gas	31.1	1.09	34	0.070	26.4	377.6	0.7
33	ACI G4 6.90	Hydro	27.5	2.96	81	0.050	23.4	467.5	0.9
303	RATTLING6.9	Hydro	15.0	2.50	38	0.050	12.8	255.0	0.5
25	ACI G5G66.90	Hydro	10.0	5.50	55	0.050	8.5	170.0	0.3
24	ACI G7G86.90	Hydro	10.0	5.50	55	0.050	8.5	170.0	0.3
284	PRDSERIV4.20	Hydro	8.9	3.50	31	0.050	7.6	151.3	0.3
287	RBLANCHE6.90	Hydro	7.6	3.28	25	0.035	6.5	185.1	0.4
325	SANDY BR6.9	Hydro	7.0	3.00	21	0.050	6.0	119.0	0.2
871	STARLAKE13.8	Hydro	18.8	6.25	118	N/A	16.0		

Table 21: Example of Spinning Reserve Allocation for the NLH Generating Units

The performance of unit load pickup for peak_load_day_dry and warm_winter_day_dry scenarios is shown in Figures 11 and 12 respectively. It is clear from these plots that the generator pick up performance is in agreement with the conclusion drawn from Table 21.

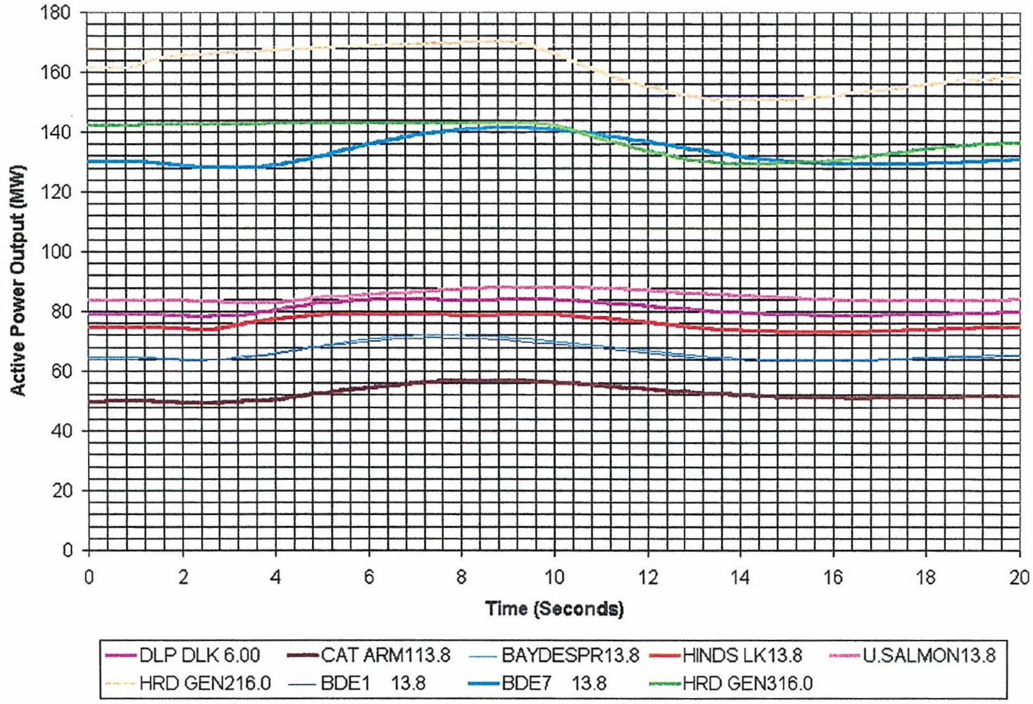

Figure 11: Generation Pick up for the Case: peak_load_day_dry

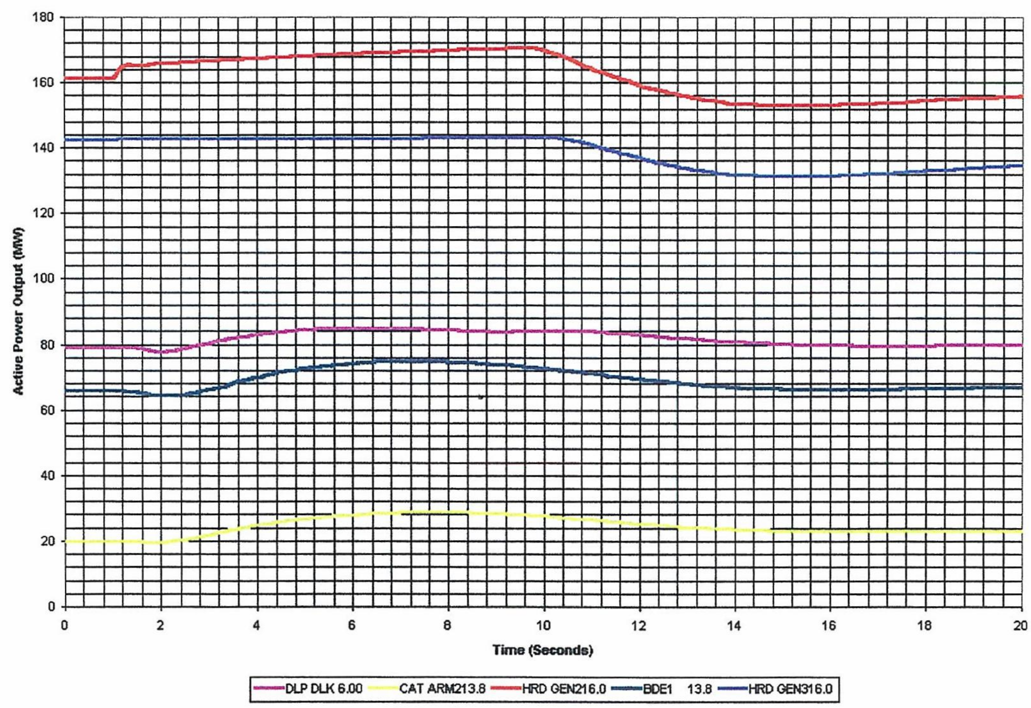

Figure 12: Generation Pick up for the Case: warm_winter_day_dry

5.5.2 Improved Spinning Reserve Allocation for NLH

To improve the spinning reserve allocation for the NLH system, the distribution method described above is used. It must be noted that prior to a change in the allocation of spinning reserve, NLH must consider water management issues and complete an economic evaluation. The peak load condition for the UFLS design scheme # 6 was simulated and Table 22 shows the spinning reserve of each unit "as found" in the provided base case power flow. The proposed spinning reserve allocation on each unit is also reported in the same table. The proposed allocation is computed based on the SPR factors listed in the Table 21.

Bus #	Bus Name	Original Unit Reserve MW	Original Generation Schedule MW	Proposed Generation Schedule MW
109	DLP DLK 6.00	10.21	79.1	81.7
137	CAT ARM113.8	28.41	50.0	69.1
138	CAT ARM213.8	28.41	50.0	69.1
220	BAYDESPR13.8	18.77	64.4	62.2
220	BAYDESPR13.8	18.77	64.4	62.2
220	BAYDESPR13.8	18.77	64.4	62.2
220	BAYDESPR13.8	18.77	64.4	62.2
220	BAYDESPR13.8	18.77	64.4	62.2
250	HINDS LK13.8	11.50	75.0	78.3
287	RBLANCHE6.90	0.71	6.1	5.7
406	U.SALMON13.8	11.61	84.0	73.8
435	HRD GEN216.0	13.46	161.5	155.8
436	HRD GEN316.0	1.03	142.5	124.1
2201	BDE1 13.8	19.22	63.9	62.2
2207	BDE7 13.8	45.48	130.0	133.1

Table 22: Original and Proposed Unit Spinning Reserve Allocation for the "peak_load_day_dry"

The result of the simulation run using the proposed spinning reserve allocation is compared with the original spinning reverse distribution in Table 23. With the proposed allocation of spinning reserve the total load shed has been reduced and minimum frequency is higher than the case with original distribution of spinning reserve.

Case	Total Gen	Total loads	Gen lost	Total Load Shed	Synch. motor Load Shed	Other loads shed	Gen Pick up	Minimum Freq	% Load Shed	Generation Lost at Bus #
Original	1428	1382	161	134.8	66.0	68.8	3.4	58.61[2]	9.75	434
Proposed	1428	1382	161	88.0	52.0	36.0	44.1	58.69	6.36	434

Table 23: Comparison of Original and Proposed Spinning Reserve Allocation for the "peak_load_day_dry" Case

[2] Actual frequency was lower than 58.6. Time domain program solves system equations with 0.01 seconds interval but reports frequency at 0.25 seconds interval.

The load shedding details for the original and proposed allocation of spinning reserve are summarized in Tables 24 and 25 respectively. It should be noted that the synchronous motors that are off-loaded (the mechanical load on them is ramped down to zero in 6 seconds) are not effective in frequency recovery due to slow load relief. It is also important to note that despite of higher load shedding in the original allocation of spinning reserve the minimum frequency is still lower than the case with proposed allocation of spinning reserve.

Time of load shedding (sec)	Bus Name	Bus #	Synchronous Motor ID	Load shed (MW)
3.180	BANK 60 4.60	60		2.60
3.180	BANK 63 6.60	63	1	5.36
3.185	MDR B2B366.0	115		14.02
3.200	BARACHOX25.0	246		8.10
3.200	BAYDESPR24.0	247		5.90
3.200	CONRIVER12.5	244		1.60
3.200	ENGHRTAP25.0	245		2.50
3.645	ACI 1RR 6.90	22	1	5.00
3.655	BANK 67 6.60	67	1	8.26
3.655	BANK 67 6.60	67	2	5.36
3.660	ACISVLB16.90	273	1	14.00
3.660	BANK 66 4.60	66		1.31
4.880	GLENBURN12.5	147		2.10
4.880	ROCKY HR12.5	102		3.60
4.880	WILTONDL12.5	144		0.10
4.900	GRANDFAL138.	326		27.00
Load removed in 6 seconds	ACI 1P2P6.90	21	1	8.00
Load removed in 6 seconds	ACI 1P2P6.90	21	2	8.00
Load removed in 6 seconds	ACI 1S2S6.90	30	1	6.00
Load removed in 6 seconds	ACI 1S2S6.90	30	2	6.00

Table 24: Load Shedding Details for the Original Spinning Reserve Allocation for "peak_load_day_dry" Case

Time of load shedding (sec)	Bus Name	Bus #	Synchronous Motor ID	Load shed (MW)
3.380	BARACHOX25.0	246		8.10
3.380	BAYDESPR24.0	247		5.90
3.380	CONRIVER12.5	244		1.60
3.380	ENGHRTAP25.0	245		2.50
3.385	BANK 60 4.60	60		2.60
3.385	BANK 63 6.60	63	1	5.36
3.385	MDR B2B366.0	115		14.02
3.900	BANK 67 6.60	67	1	8.26
3.900	BANK 67 6.60	67	2	5.36
3.905	BANK 66 4.60	66		1.31
3.930	ACI 1RR 6.90	22	1	5.00
3.930	ACISVLB16.90	273	1	14.00
Load removed in 6 seconds	ACI 1P2P6.90	21	1	8.00
Load removed in 6 seconds	ACI 1S2S6.90	30	1	6.00

Table 25: Load Shedding Details for the Proposed Spinning Reserve Allocation for "peak_load_day_dry" Case

5.6 Generator Droop Setting

The droop setting for NLH units are summarized in Table 21. The interconnected North American utilities have adopted WSCC or NERC standards for the governor droop setting which states: "**All turbine generators equipped with governors should be capable of providing immediate and sustained response to abnormal frequency excursions. Governors should provide a 5% droop characteristic. Governors should, as a minimum, be fully responsive to frequency deviations exceeding ± 0.036 Hz**". The regulation plot for 5% droop setting is shown in Figure 13. For example, a 5 % droop setting for loss of 50% output will result in frequency drop by 1.5 Hz on the unit ($\Delta f = -\Delta p * R * f_b$). All of the NLH units fulfill the NERC governor droop setting requirements. It is obvious that smaller droop setting should yield less load shedding.

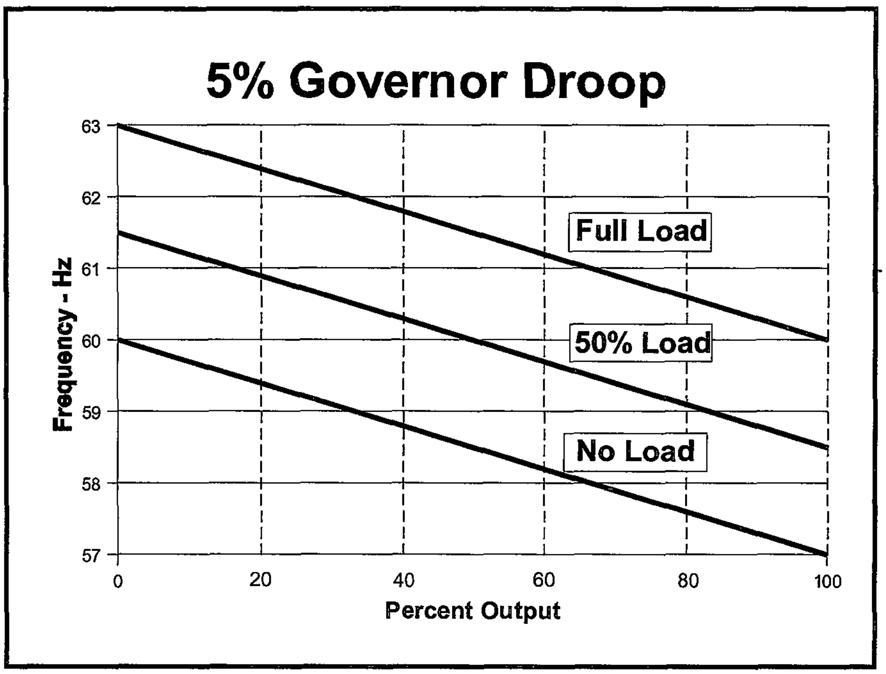

Figure 13: Regulation For 5 % Droop Setting

However, having smaller droop setting than the present NLH Hydraulic units is not recommended since load sharing and frequency follow up of different unit types i.e. thermal, gas and hydraulic becomes very sensitive. The droop setting on the NLH's thermal units, especially Holyrood units, seems to be very good based on our experience of thermal unit governor testing.

6. Conclusions and Recommendations

The existing scheme and several alternatives of load shedding schemes were analyzed in this work. The comparisons of the results from different UFLS schemes are summarized in Table 18.

Scenario	Total Gen Lost MW	Total load shed MW	Min. Frequency Hz
Design 0, 18 cycles relay	814	906	57.92
Design 0, 6 cycles relay	814	831	58.09
Design 1	814	727	58.22
Design 2	814	859	58.36
Design 3	814	826	58.38
Design 4	814	783	58.09
Design 5	814	757	58.20
Design 6	814	709	58.20

Table 26: Comparisons of the Results from Different UFLS Design Schemes

It can be seen that different load shedding schemes have resulted in significant differences in the total amount load shed and frequency response. However, this summary (Table 26) may be misleading if one has to exclude some of the considered scenarios. The result of each load shedding scheme was summarized in tables presented in the previous sections and, as discussed earlier, if the probability of the NLH power system being in some of the considered scenarios is low, then the total load shed for those scenarios should not be considered. Again, simple inspection of Table 26 for judging the "optimal" scheme may not be appropriate because there is no single index available to determine the "best" scheme. If we assume that probability of NLH power system to be in each of the studied scenario is the same, then, "total load shed" (as compared with the existing scheme) can be used to judge performance and scheme # 6 is the best. In this scheme the minimum frequency criteria is also achieved.

The following comments and recommendations can be made from the result:

- Application of recent solid state relays (fast response relays) yields better performance, less load shedding, and higher minimum frequency
- The result for the existing scheme (even with fast relays) suggests that under some scenarios (see Table 19) the minimum frequency can be very close to the generator under frequency trip set point. NLH should decide what a comfortable and acceptable minimum frequency should be (see also chapter 4)
- Allocating more loads to UFLS relays in 59.0 Hz band, i.e. early shedding, result in less load shedding in all of the load scenarios as compared with the original scheme,
- Application of rate-of-change of frequency relays in 59.0 Hz results in less load shedding in all of the base cases as compared with the original scheme. Selecting a rate of change

of frequency equal to 0.8 Hz/s proved to be safe (did not operate for cases where the generation loss is not severe as compared to total system inertia) and effective (resulted in less load shedding). It is important to note that no attempt was made to try to determine optimum setting of rate of change of frequency. It is therefore recommended that NLH further pursue this aspect if optimization of rate of change of frequency is desired.

- Shedding synchronous motor (including the motor with 6 seconds off-loading delay period) is not as effective as shedding static loads
- Based on the practices of other isolated power systems and to prevent system collapse following severe generation loss it is recommended to place higher percentage of loads under UFLS relays (normally 80%)
- Allocation of spinning reserve based on the governor droop settings can reduce amount of load shedding

6.1 Discussion on UFLS, load types, and generating unit size

In the past many utilities have avoided application of rate-of-change of frequency relaying due to: a) means of reliably detecting the rate-of-change of frequency was not available, b) selecting appropriate set points for rate-of-change of frequency could not be determined without resorting to advanced time domain programs. The digital relays (micro-processor based) can now reliably sense accurate rate-of-change of frequency and relay logic can be made to detect complex criteria. Also, time domain programs have reached a very mature state of development and can be used to determine optimum rate-of-change of frequency set points.

The selection of load to be put under UFLS is determined by a number of factors,

- Interruptability – can the load be disconnected when required. This is determined by several issues including,
    - health and safety
    - politics
    - economics
- Availability – will the load be available when shedding is required.
- Restoration requirements – how readily can the load be reconnected following the disturbance and correction of system frequency problems.
- Effectiveness – when the load is shed, how much does it contribute to the control of frequency, and conversely, if it is not shed, does it help or hinder frequency recovery? This is determined by factors including the size of the load and the characteristics of the load. Issues associated with load characteristics include,
    - whether or not the load has rotating inertia, which if shed, could reduce the overall system inertia and therefore lead to further frequency decline,

- the dP/dV, dQ/dV, dP/df, and dQ/df characteristics. Depending on these characteristics, if the load is not shed, it could have a beneficial or detrimental influence on system frequency.

It is important to note that for small isolated power systems most utilities do not have much freedom in selection of loads[3] that should be put under UFLS control because to maintain system security almost all loads are required to be allocated for load shedding. The result of this study shows that it is more effective to shed static loads before shedding synchronous motors. This is obvious since loss of synchronous motors reduces total system inertia that in turn causes further depression of frequency. Another important rotating load that was not considered in this study is induction motor. Induction motors exhibit different behavior under low frequency operation than synchronous motors. Shedding induction motors are more effective than synchronous motors since they demand higher power under low voltage and frequency. Also, with the exception of very large industrial processes, induction motors loads generally tend to have lower inertias than synchronous motor loads; the resulting loss of inertia when shed is therefore less impactive. The load voltage and frequency dependency for several loads are summarized in Table 27. These are obtained from the Canadian Electricity Association report 113 T 1040, "Laboratory Measurement of Modern Loads Subjected to Large Voltage Changes for Use in Voltage Stability Studies", prepared by Ontario Hydro Technologies, May 1996.

Load	pf	Vmin	∂P/∂V	∂Q/∂V	∂P/∂f	∂Q/∂f
Industrial Heater/Blower	0.99	0.5	1.98	1.63		
Baseboard Heater	1.00	0	2.00	0.00		
Electronic Compact Fluorescent 1	-0.99	0.5	1.05	-0.46	0.393	0
Electronic Compact Fluorescent 2	-0.97	0.5	1.12	-0.47	0.254	-3.35
Conventional Magnetic Compact Fluorescent	0.49	0.83	1.99	3.17	-1.60	-1.26
Battery Charger	0.76	0.61	3.08	4.34		
Microwave Oven	1.00	0.83	0.50	0.00		
Microwave (Low V)	0.99	0	5.89	4.18		
Adjustable Freq Drive + Compressor	0.79	0.75	1.48	1.05		
Adjustable Freq Drive + Pump/Fan	0.79	0.75	2.54	2.00		
Dryer Heater	1.00	0.5	1.96	0.00		
Dryer Motor	0.45	0.5	1.58	2.68		
Office 1	1.00	0.67	0.36	0.00	-0.017	0.309
Office 2	1.00	0.67	0.24	0.00		
Office 2 (Low V)	1.00	0	0.59	0.00		
Washer	0.61	0.5	0.42	1.09		
Refrigerator/Freezer	0.84	0.76	2.12	1.84		
Electronically Ballasted Fluorescent 1	1.00	0.65	0.49	0.00	0.218	0
Fluorescent 1 (Low V)	1.00	0	3.97	0.00		
Electronically Ballasted Fluorescent 2	0.98	0.54	0.38	1.43	0.115	4.26
Electronic Dimming Ballast	1.00	0.63	1.46	0.00	0.2	0
External Fluorescent Dimmer	0.94	0.78	0.93	6.05	0.924	-6.25
High Pressure Sodium Lamps	-0.99	0.73	1.92	14.43	-1.31	0
Heat Pump (Split Design)	0.93	0.75	0.47	5.85		
Heat Pump Blower	0.74	0.87	-3.28	1.90		
Heat Pump Compressor	0.90	0.87	0.29	5.45		

[3] However there is some freedom in assignment loads to different stages of load shedding

Table 27: Voltage and Frequency Dependency of Loads

Note in the above table power factor (pf) shown negative for loads with capacitive reactive power and Vmin represents the minimum voltage (in p.u.) for which the load model is valid.

6.2 Discussion on Maximum Generating Unit Size in the NLH System

The issue of selecting maximum generating unit size that NLH should allow to be put on-line depends on several factors including:

1. Application of the unit for base load or peak load
2. Location of the unit and voltage issues
3. Type of the unit
4. Economical factors
5. Running at reduced output
6. Existing UFLS scheme
7. System spinning reserve

For example, if we assume that the operating policy is that on the loss of largest unit frequency should not fall below a certain frequency without resorting to load shedding, then, one can estimate the unit size and system conditions that this can be achieved. However, if it is allowed to shed load, then, the unit size will be different and still can be estimated. It should be noted that the maximum size also depends on how much load is under UFLS control. The maximum unit size cannot be simply determined for any system unless the objectives and operating policies are known.

7. Appendix A: NERC/WSCC General Policies and Guidelines

Most of the policies and guidelines available in the literature are for UFLS programs designed for large interconnected power systems. Therefore, these guidelines cannot be directly applied to the NLH power system. In this section the issues that are relevant to NLH are presented.

NERC (North American Reliability Council), WSCC (Western System Coordinating Council) and other utility councils present guidelines for proper design of an off-nominal frequency program. For example, Policy 4, Subsection D, Criteria of the NERC Operating Guides states that:

"Systems and control areas shall coordinate the application, operation, and maintenance of protective relays on the bulk electric system, including the coordination of under frequency load shedding relays. They shall develop criteria which will enhance their system reliability with the minimum adverse effect on the Interconnection".

NERC Policy 5 in the Operating Manual entitled Emergency Operations, addresses the issues of generator protection, load restoration, frequency restoration, and regional coordination. The following statement from Policy 5 summarizes the overall objectives of the off-nominal frequency program:

"Each system, control area, and region shall establish a program of manual and automatic load shedding which is designed to arrest frequency or voltage decays that could result in an uncontrolled failure of components of that interconnection. The program shall be coordinated throughout the interconnection to prevent unbalanced load shedding which may cause high transmission loading and extreme voltage deviations."

WSCC Minimum Operating Reliability Criteria (MORC), further clarifies the objectives and requirements of an off-nominal frequency program:

- Minimize the risk of total system collapse in the event of separation
- Protect generating equipment and transmission facilities against damage
- Provide for equitable load shedding among entities serving load
- Improve overall system reliability
- Leave the system in a condition to permit rapid load restoration and re-establishment of interconnections
- Should be matched to meet island area needs and coordinated within the island area
- Should coordinate with under frequency protection of generating units
- Should coordinate with any manual or automatic action that can be expected to occur under conditions of frequency decline
- **Should be based on studies of system dynamic performance, using latest state-of-the-art computer analytical techniques**
- Should minimize the risk of further separation, loss of generation, or excessive load shedding accompanied by excessive over frequency conditions

- Should incorporate automatic generator tripping or other remedial measures to prevent excessive high frequency and resultant uncontrolled generator tripping and/or equipment damage

7.1 WSCC Uniform UFLS Plan

Assumptions regarding specific design parameters need to be identified and used to provide a quantifiable assessment of a uniform UFLS plan. It is recognized that actual parameters may deviate somewhat from the assumptions listed below without compromising the program (the important conclusion from each Assumption is typed in bold):

Assumption 1: The uniform **UFLS plan should coordinate with the 5% loss of life of turbine blades recommendations** as determined by generator manufacturers. Turbine blade loss of life is the most limiting of the off-nominal frequency restrictions imposed by the generating units. A 0% loss of life criteria implies that the generators are not exposed to any off-normal frequency operation outside of the continuous band. Some generators within WSCC have robust operating limits that permit operation within a relatively large bandwidth. Other regions like the Rocky Mountain area have determined that an off-nominal frequency program could be developed using the relatively conservative 5% loss of life criteria. Designing an off-nominal frequency program to meet the 5% loss of life criteria is an aggressive goal, but nevertheless a realistic goal. Owners/operators of generating units are more likely to accept the potential for loss of life to their units if this risk is minimized to the greatest extent possible. Determining the loss of life for frequency excursions is not an exact science. Nevertheless, the manufacturers have developed recommendations. These requirements are described in ANSI/IEEE Standard C37.106-1987, Guide for Abnormal Frequency Protection for Power Generating Plants. A composite requirement was made using the most restrictive limitations imposed by any manufacturer. One advantage of trying to meet the 5% loss of life criteria is that it allows all generation owners to protect their units per manufacturer recommendations. This is an additional reason why generation owners/operators should support this off-nominal frequency program.

Assumption 2: Sufficient load should be shed in uniform UFLS plan to leave the system frequency within the continuous operating range of the generating units. **The generating units can operate continuously between 59.5 Hz and 60.5 Hz**. It would be desirable to have the frequency following a disturbance (that results in under-frequency load shedding) to be restored within this range to minimize the potential for loss of life. This will allow the dispatcher time to analyze the situation and make appropriate adjustments to restore ties and the frequency to 60 Hz. If the frequency were left in the "time to damage" range of the generating units, immediate response is required of the dispatcher to be totally effective within minutes otherwise some generators may automatically trip to prevent further damage. This is both impractical and unnecessary.

Assumption 3: The uniform **UFLS plan should provide coverage during a substantial loss of generation or resources (e.g. 25-33%)**. A UFLS plan can be designed for a 50% range of generation overload. For example, a 33% loss of generation represents a 50% overload on remaining generation. A 50% loss of generation represents a 100% overload on remaining generation. A good off-nominal under-frequency program can be designed for a 0%-50% generation overload, a 25%-75% overload, or a 50%-100% overload. A program designed for a 50%-100% overload will not work at all for a contingency that involves only a 0%-50% overload. The loss of 33% of total generation is, by any standard, a severe contingency. As a practical matter, a well behaved UFLS program cannot be designed for loss of generation beyond 33% unless load is massively over-shed at high frequencies to prevent the dynamic frequency from falling below the point at which units trip instantaneously (56.5 Hz). This massive over-shedding of load must then be accompanied by massive automatic and high speed load restoration to prevent the units from tripping due to over frequency. The program designed for loss of generation beyond 33% will not work at all for loss of generation less than 33%. In view of these problems, **the uniform off-nominal program should be designed up to a maximum generation and load imbalance of 33%.**

Assumption 4: The minimum permissible frequency during a disturbance is 57.9 Hz. The maximum permissible dynamic frequency during a disturbance is 61.0 Hz. Discussion: **This minimum limit of 57.9 Hz was chosen because the allowable time of operation below 57.9 Hz to coordinate with the 5% loss of life criteria**, is only 7.5 seconds. Intentional operation below 57.9 Hz was judged to be imprudent. The maximum limit of 61 Hz was chosen because above this frequency some governors may go into an "emergency over speed mode" and close the main steam control valves. This causes the boiler to go into an "upset condition" and the unit will trip in the short term if the frequency is not reduced or may trip in the longer term because of the unstable boiler condition. A maximum frequency limit of greater than 61 Hz could have been chosen and still coordinate with the emergency controls of the governor, but as a practical matter the 61 Hz limit is easily achieved.

Assumption 5: Current UFLS plans utilize 5-6 steps, but a new and uniform UFLS plan for WSCC need not be restricted to this number. **The minimum separation between steps should be 0.1 Hz**. As a practical matter, it is just as easy to administer a 10-step UFLS plan as a 6 step. If we can get better performance with a 10-step UFLS plan than a 6-step program, then it ought to be considered. Absent any technical considerations, the preference would be to have fewer steps rather than more. The under frequency relay manufacturers provide set points in increments of 0.01 Hz. However, practical considerations suggest that the minimum separation between steps should be 0.1 Hz.

Assumption 6: Under frequency **relays have a maximum operating time of 6 cycles**. Relay manufacturers state that the minimum operating time of their equipment is 3.4 cycles. This is a hardware consideration. There are no advantages to having operating times longer than 6 cycles that incorporate some additional intentional detection time, and **longer detection times or intentional time delay will destroy the integrity of the off-nominal program**. It is the intent that additional time delay not be introduced beyond that inherent in the equipment itself.

Assumption 7[4]: As a system average, a **6 cycle operating time of breakers is used to trip load**. Many systems will use distribution breakers to trip load. These distribution breakers are

[4] The recommendation is to use system average total tripping (relay & breaker) time no more than 14 cycles at the indicated frequency set points.

typically slower than transmission breakers. Although some systems will use transmission breakers to trip load, a system wide and conservative figure of 6 cycles will be used. This is not to imply that only breakers that operate in 6 cycles or less can be used in the UFLS plan. However, Assumptions 6 and 7 taken together imply that load will tripped 12 cycles after the frequency reaches the threshold level and that this 12 cycle operating time to trip the load is a system average. Moreover, there should be no intentional time delay introduced.

Assumption 8: If there is any discretion allowed, the **preferred option is to have the post-disturbance frequency settle out above 60 Hz, as opposed to below 60 Hz**. If the frequency settles out above 60 Hz (but less than 60.5 Hz), then in short order the governors will automatically act to restore the system to 60 Hz. This will facilitate the restoration of ties (in the case of islanding) and in any event it is the preferred operating mode of the generators (to prevent spurious trips within the generating plant). If the frequency levels out below 60 Hz (but above 59.5 Hz), then governors will act to raise generation, however longer time delays are potentially possible because additional fuel must be added to boilers before the increased generation can be supported. There is also the possibility that increased generation may not be available, and load must be manually shed to achieve 60 Hz. A post-disturbance frequency of 60 Hz or slightly above is judged to maximize the dispatcher's ability to initiate system restoration activities.

WSCC should adopt the 59.1 Hz Plan as a minimum standard (local differences are permitted as long as it can be demonstrated that the WSCC Coordinated Plan is not adversely affected):

Stage	Load Shedding (%)	Frequency Setting (Hz)
1	5.3	59.1
2	5.9	58.9
3	6.5	58.7
4	6.7	58.5
5	6.7	58.3
Total	**62.2**	

Additional automatic load shedding to correct under frequency stalling:

Load Shedding (%)	Frequency Setting (Hz)	Time
2.3	59.3	15 sec
1.7	59.5	30 sec
2.0	59.5	1 min

Load automatically restored from 59.1 Hz block to correct frequency overshoot:

Load Shedding (%)	Frequency Setting (Hz)	Time
1.1	60.5	30 sec
1.7	60.7	5 sec
2.3	60.9	0.25 sec

The system average total tripping (relay & breaker) time should be no more than 14 cycles at the indicated frequency set points.

Intermittent load shall not be used unless monitoring is in place to allow changes in real time to accommodate the availability of the intermittent load and ensure the load shedding requirements of the Coordinated Plan are met.

Additional load can be tripped at frequencies higher than 59.1 Hz provided it does not violate the MORC or adversely impact neighboring systems. Frequency overshoot must be adequately addressed.

It is not permissible to start shedding load at frequencies lower than 59.1 Hz or to trip less load than called for by the Coordinated Plan. Additional frequency set points can be used provided the cumulative total load shedding amounts meet the requirements of the Coordinated Plan for each of the Plan's frequency set points.

Intentional tripping of tie lines due to under frequency is permitted at the discretion of the individual system, providing that the separation frequency is no higher than 57.9 Hz with a one-second-time delay. While acknowledging the right to trip tie lines at 57.9 Hz, the preference is that intentional tripping not be implemented.

Generators connected to the grid that protect for off-nominal frequency operation should have relaying protection that accommodates, as a minimum, under frequency and over frequency operation for the specified time frames:

Under frequency	Over frequency	Time
60.0-59.5 Hz	60.0-60.5 Hz	N/A (continuous operating range)
59.4-58.5 Hz	60.6-61.5 Hz	3 minutes
58.4-57.9 Hz	61.6-61.7 Hz	30 seconds
57.8-57.4 Hz		7.5 seconds
57.3-56.9 Hz		45 cycles
56.8-56.5 Hz		7.2 cycles
less than 56.4 Hz	greater than 61.7 Hz	instantaneous trip

Systems that have generators that do not meet the requirements above must automatically trip load (in addition to that required in for load shedding) to match the anticipated generation loss and at comparable frequency levels.

Only solid state and/or microprocessor under frequency relays shall be used as part of the Coordinated Plan. Only load tripped by solid state and/or microprocessor under frequency relays will be considered when determining compliance with the Coordinated Plan.

Only solid state and/or microprocessor frequency relays should be used on generators to provide off-nominal frequency protection in the range of 57.9-61.0 Hz. All frequency relays shall use the definite time characteristic and should not be disabled for voltages 80% of nominal or higher but can be disabled for voltages below 80% of nominal at the discretion of the setting entity. **Electro-mechanical frequency relays can be used only for settings outside the 57.9-61.0 Hz range.**

To protect against over voltages following an under frequency load shedding event, systems shall implement automatic measures to maintain voltages within acceptable limits. Direct load tripping is allowed if it complements the Coordinated Plan.

7.2 Manual Load Shedding

Each Area must be capable of manually shedding at least fifty percent of its load in ten minutes or less. Insofar as practical, the first half of the manually shed load should not include that load which is part of any automatic load shedding plan.

Care should be taken that manual load shedding plans do not interrupt transmission paths. The plan should include the capability of shedding load proportionately over the whole system, but it must also recognize that operating requirements may limit shedding to one area. An Area may require manual load shedding capability in excess of the minimum 50 percent.

Manual load shedding procedures should be reviewed at least annually to ensure that the proper amount of load can be shed within the time limits prescribed. Studies should be performed to ensure that satisfactory voltage and loading conditions prevail after manual load shedding.

8. References

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