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FREQUENCY RESPONSE OF PRIME MOVERS DURING RESTORATION

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Abstract: In the initial phase of restoration, operators are often concerned with the size of load which can safely be picked-up, and the effectiveness of the generation reserve. There has been a need for a methodology to readily address these concerns by providing simple guidelines to facilitate an orderly power system restoration.

In this paper, a simple approach is developed based on an approximate frequency response rate of prime movers for determining: (a) the maximum load pickup within the allowable system frequency dip, and (b) the amount and distribution of reserve for maintaining firm generation.

Keywords: Frequency Response Rate, Generator Reserve Rate, Reserve Distribution, Load Pickup, Prime Movers,

1. INTRODUCTION

Restoration procedure following a major power system disturbance may span over three periods, depending on the types and availability of prime movers: (a) the initially available prime movers which typically consist of; blackstart combustion turbines (CT), low-head short-conduit hydro-electric (HE), and gas or oil-fired drum-type boiler-turbine steam-electric (SE), (b) the subsequently available prime movers consisting of; large CTs, high-head long-conduit HEs, and combined cycle units, and (c) the finally available prime movers consisting of; large drum-type coal-fired SEs, super-critical once-through units and nuclear plants [1].

During the above three periods and in particular during the initial period, operators are concerned with: the rate at which generators are loaded, the mismatch between load pickup and prime movers' frequency response, the adequacy and distribution of generator reserve, to cope with the loss of the largest unit [2].

In this paper, a simple guideline is developed for: (a) evaluating frequency response rates of prime movers to sudden increase in loads, and (b) determining the amount and distribution of reserve to meet the loss of the largest generator. The frequency responses of a typical CT, HE and SE units are determined for different increments of load pickups. These responses are used to develop guidelines to assist the operators in keeping the frequency above the allowable limits and to maintain adequate reserve. The approach is applied to several case studies and results are verified by simulation. Although these guidelines provide approximate solutions, they do expedite the restoration process.

2. PROCEDURE

2.1. Prime Movers' Block Diagram

Figure 1 shows a simple block diagram for the prime movers under consideration. The $G_1(s)$, $G_2(s)$, and $G_3(s)$ represent the transfer functions for the speed-governor systems, prime movers, and the power system, respectively. The change in system frequency ΔF, is related to the change in load ΔL, by [3]:

$$\Delta F = -F(s)\Delta L/s,$$

where,

$$F(s) = N(s)/D(s),$$
$$N(s) = G_3(s),$$
$$D(s) = 1+G_1(s)G_2(s)G_3(s)/R, \text{ and}$$

R is the governor speed regulation.

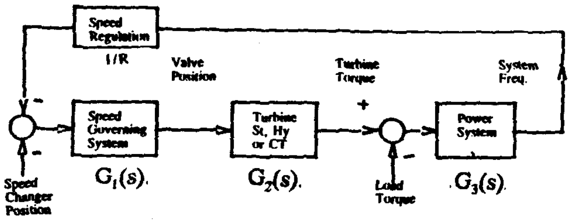

Figure 1 - Prime Movers Block Diagram

2.2 Combustion Turbine Units Frequency Response

The transfer functions and data for a typical blackstart CT are as follows:

$$\Delta F = -F(s)\Delta L/s,$$
$$F(s) = N_1(s)/D_1(s),$$
$$N_1(s) = G_3(s),$$
$$D_1(s) = 1+G_1(s)G_2(s)G_3(s)/R,$$
$$G_1(s) = 1/(1+sT_G),$$
$$G_2(s) = 1/(1+sT_T), \text{ and}$$
$$G_3(s) = (1/D)/(1+sT_P).$$

where,

R , governor speed regulation = 5.00, %
T_G, governor time constant = 0.15, sec.
T_T, turbine time constant = 0.50, sec.
T_P, inertia constant = 10.00, sec.
D , damping torque coefficient = 0.75, %.

Figure 2 shows frequency response of a typical CT to sudden increase in loads. The upper curve shows about 0.25 Hz frequency decline in response to a 5% sudden

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increase in load when the CT is under 20% of load. The lower curve shows about 0.5 Hz frequency decline for a 10% sudden load increase under no load condition.

The CT frequency responses for different load pickups have been used to determine the "frequency response rates" of the CT, as shown in **Figure 3**. Accordingly, the frequency response rates for the CT are:

Curves	Load %	$\Delta F/\Delta L$ Hz/p.u.
CT-1	5.0	-4.81
CT-2	40.0	-4.61
CT-3	75.0	-4.41

From **Figure 3**, it can be seen that: (a) the frequency decline, ΔF is proportional to the load increment, ΔL, and (b) the prime mover load has an insignificant effect on the frequency response rate.

2.3 Steam Electric Units Frequency Response

The transfer functions and data for a typical tandem compound, single reheat SE unit are as follows:

$\Delta F = - F(s)\Delta L/s,$
$F(s) = N_3(s)/D_3(s),$
$N_3(s) = G_3(s),$
$D_3(s) = 1+G_1(s)G_2(s)G_3(s)/R,$
$G_1(s) = 1/(1+sT_G),$
$G_3(s) = (1/D)/(1+sT_P)$, and
$G_2(s) = N_2(s)/D_2(s)$
$N_2(s) = (1+sT_C)(1+sK_1T_R)+(K_3)$
$D_2(s) = (1+sT_S)(1+sT_R)(1+sT_C)$

where,
T_G, Governor time constant = 0.20, sec.
T_R, Dashpot time constant = 5.00, sec.
R , Governor speed regulation = 3.00, Hz/p.u.
D , Damping torque coefficient = 3.00, p.u.
T_P, Inertia time constant = 5.56, sec.
T_S, HP steam box time constant = 0.50, sec.
T_R, Reheater time constant = 10.00, sec.
T_C, Crossover (IP-LP) time constant = 0.50, sec.
K_1, HP turbine Power Fraction = 0.30, p.u.
K_2, IP turbine power fraction = 0.40, p.u.
K_3, LP turbine power fraction = 0.30, p.u.

Figure 4 shows frequency response of a typical drum-type tandem compound, single reheat SE unit to sudden increase in loads. The upper curve shows about 0.4 Hz frequency decline in response to a 5% sudden load increase when the SE unit is under 20% load. The lower curve shows about 0.9 Hz frequency decline for a 10% sudden load increase under no load condition.

The SE frequency responses for different load pickups have been used to determine the "frequency response rates" of the SE, as shown in **Figure 5**. Accordingly, the frequency response rates for the SE unit are:

The frequency response rates for the SE unit are:

Curves	Load %	$\Delta F/\Delta L$ Hz/p.u.
SE-1	5.0	-8.56
SE-2	40.0	-7.94
SE-3	75.0	-7.33

From **Figure 5**, it can be seen that: (a) the frequency decline, ΔF is proportional to the load increment, ΔL, and (b) the prime mover load has a relatively small damping effect on the frequency response rates (as long as the unit is not loaded near a valve point).

2.4 Hydro Electric Units Frequency Response

The transfer functions and data for a typical run-of-the-river Kaplan turbine are as follows:

$\Delta F = - F(s)\Delta L/s,$
$F(s) = N_4(s)/D_4(s),$
$N_4(s) = G_3(s),$
$D_4(s) = 1+G_1(s)G_2(s)G_3(s)/R,$
$G_1(s) = 1/(1+sT_G)(1+sT_R)/(1+(sT_R)(r/R))$
$G_2(s) = (1-sT_W)/(1+sT_W/2)$, and
$G_3(s) = (1/D)/(1+sT_P).$

where,
R , Permanent speed droop coefficient = 0.050, p.u.
r , Transient speed droop coefficient = 0.600, p.u.
T_G, Gate servomotor time constant = 0.200, sec.
T_R, Dashpot time constant = 5.000, sec.
T_P, Inertia time constant = 10.000, sec.
T_W, Water starting time penstock = 1.000, sec.
D , Damping torque coefficient = 0.025, p.u.

Figure 6 shows frequency response of a typical Kaplan HE unit to sudden increase in loads. The upper curve shows about 0.4 Hz frequency decline in response to a 5% sudden load increase when the HE unit is under 20% load. The lower curve shows about 0.5 Hz frequency decline for a 10% sudden load increase under no load condition.

Figure 7, is a plot of frequency declines for the HE to sudden load increases. The frequency response rates for the HE unit are:

Curves	Load %	$\Delta F/\Delta L$ Hz/p.u.
HE-1	5.0	-5.35
HE-2	40.0	-4.61
HE-3	75.0	-1.46

From **Figure 7**, it can be seen that: (a) the frequency decline, ΔF is proportional to the load increment, ΔL, and (b) the HE unit load does affect the frequency response rate.

Figures 3 and 5, show that whereas one can approximate the frequency response rates, $\Delta F/\Delta L$, for the CT and the SE units to a constant value over their entire generation outputs, such an assumption does not fully hold for the HE unit as shown in **Figure 7**. However, as the following case study results verify, the above approximation may also be extended to the HE unit.

Accordingly, the frequency response rates for the three

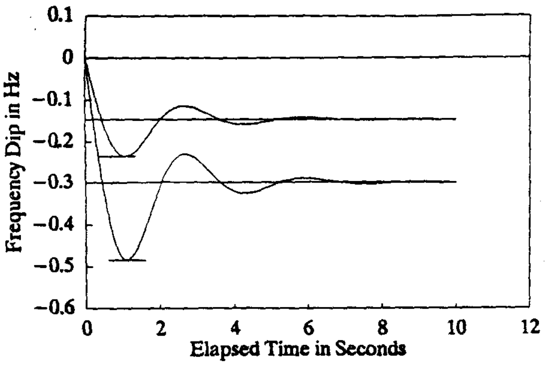

Figure 2. Frequency Response of the CT Unit

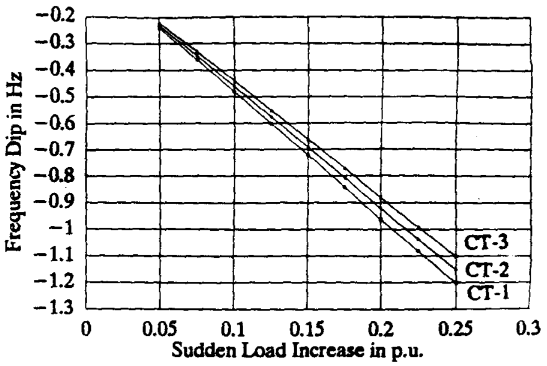

Figure 3. Frequency Response Rates of the CT Unit

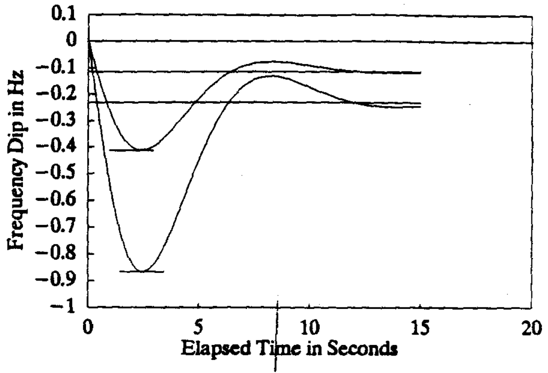

Figure 4. Frequency Response of the SE Unit

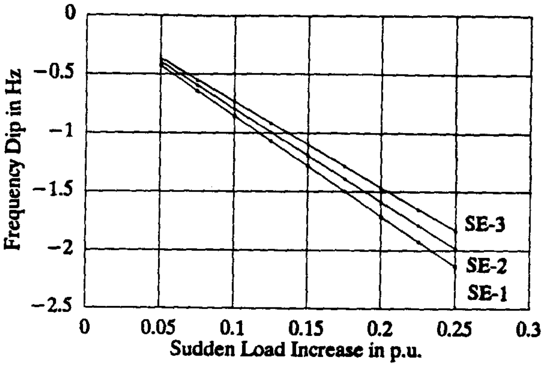

Figure 5. Frequency Response Rates of the SE Unit

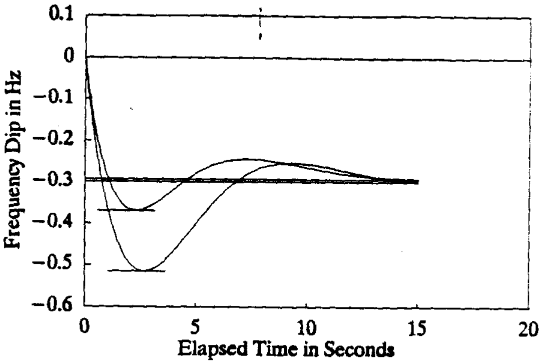

Figure 6. Frequency Response of the HE Unit

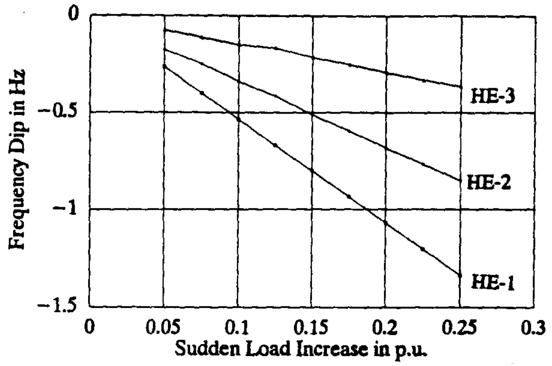

Figure 7. Frequency Response Rates of the HE Unit

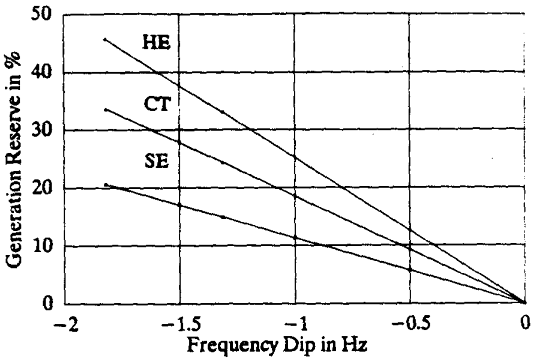

Figure 8. "Optimal" Generation Reserve Distribution

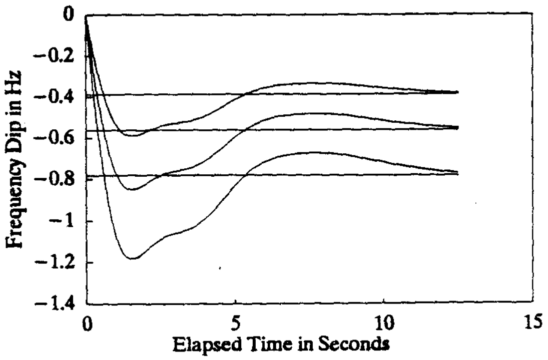

Figure 9. Frequency Response of the Power System

types of prime movers over their entire generation outputs can be approximated as:

Curves	Load %	$\Delta F/\Delta L$ Hz/p.u.
HE-2	40	-3.40
CT-2	40	-4.61
SE-2	40	-7.94

It follows that, in the initial restoration phase, by using the above frequency response rates ($\Delta F/\Delta L$), one can readily determine: (a) the maximum amount of load which can be picked up for a given frequency dip (or vice versa), and (b) the amount and distribution of generator reserve for coping with the loss of the largest generator. These guidelines are illustrated in the following case studies.

3. CASE STUDIES

3.1 Determination ΔL for a Given $\Delta F'$

Table 1. lists the prime movers which may be in operation in the initial phase of a power system restoration. Assuming that the maximum frequency decline allowed is $\Delta F' = -0.75$ Hz, the objective is to find the maximum amount of load which can be picked up. This would guide the operator to, e.g., pickup a low voltage AC (LVAC) network load of an estimated size.

Accordingly, the size of LVAC Network load which can be picked up for $\Delta F' = -0.75$ Hz, is 57 MW or about 13% of the total on-line generation capacity. This assumes that prior to the load pickup: (a) the generation reserve is distributed on the basis of 45, 37 and 18% for the SE, HE and CT units, respectively, and (b) the generation reserve is greater than 57 MW.

3.2 Determination of ΔF for an Estimated $\Delta L'$

In **Table 2.** the size of an LVAC Network load is estimated at about $\Delta L' = 50$ MW, the objective is to find the maximum frequency dip [4].

Accordingly, the maximum frequency dip for a $\Delta L' = 50$ Mw sudden increase in load is $\Delta F = -0.66$ Hz. This again assumes that prior to the load pickup: (a) the generation reserve is distributed on the basis of 45, 37 and 18% for the SE, HE and CT units, respectively, and (b) the generation reserve is greater than 50 MW.

The above two case studies show that: (a) distribution of generation reserve should be based on the frequency response rates of prime movers, and (b) reserve distribution is constant for a given prime mover configuration.

3.3 Amount and Distribution of Generation Reserve

Tables 3, 4 & 5 list prime movers which may be in operation during the initial or subsequent phases of a power system restoration. The objective is to determine the effect of reserve distribution on the frequency dip due to the loss of the largest unit, i.e. 300 MW. Three cases are listed: the uniformly distributed reserve in **Table 3**, the "optimally" distributed reserve for the same frequency dip of -1.32 Hz, in **Table 4**, and the "optimally" distributed reserve for an allowable frequency dip of -0.95 Hz, in **Table 5** [5].

In **Table 3**, the total load of 782 MW is divided between SE-A, SE-B, HE and CT plants proportional to their capacities, i.e., "uniformly" distributing the generation reserve. After the loss of the largest unit, i.e., SE-A, its load of 270 MW is carried by the remaining three plants, resulting in the overloads of the HE and CT units and their possible trip outs. The frequency dip in case of survival of these two plants would be 1.32 Hz.

In **Table 4**, considering the same frequency dip of 1.32 Hz, the total load of 782 MW is divided between SE-A, SE-B, HE and CT plants proportional to their frequency response rates, i.e., "optimally" distributing the generation reserve. After the loss of the largest unit, i.e., SE-A, its load of 217 MW will be carried by the remaining three plants, resulting in no overloads. It should be noted that after the contingency, all the plants are loaded well below their capacities.

The case studies listed in **Tables 4 and 5** are similar, except that in the latter case, a frequency dip of 0.95 Hz has been allowed. The comparison of the two reserve distributions shows constant reserve rates for a given prime mover configuration, as shown in the following table:

Table 6 - Comparison of the Two Reserve Distributions

Type	Reserve %	Frequency Dip Hz	Reserve Rate %/Hz
From Table 4			
SE-B	14.9	-1.32	-11.3
CT	24.3	-1.32	-18.5
HE	33.0	-1.32	-25.1
From Table 5			
SE-B	10.8	-0.95	-11.3
CT	17.6	-0.95	-18.5
HE	23.8	-0.95	-25.1

Clearly, with no-load on SE-A, there will be no frequency dip after its outage. It can be shown that with the above reserve rates, when SE-A plant carries the full capacity of 300 MW, upon its outage, there will be a frequency dip of 1.82 Hz. Therefore, for a given frequency dip between 0.0 and 1.82 Hz, as long as the generation reserve is distributed on the basis of the above reserve rates, there will be no risk of plant overloads. **Figure 8.** shows the reserve distributions to be used for the CT, HE and SE-B plants to meet the generation contingency for any frequency dip between 0.0 and 1.82 Hz. The reserve distributions are based on reserve rates of the plants.

3.4 Verification

Figure 9. shows the frequency response curves for three of

Table 1. Determination of Load Pickup

GIVEN $\Delta F = -0.75$ Hz, FIND ΔL:

Type	No of Units	Cap. MW	Pi MW	dfi Hz/pu	Pi/dfi MW/Hz	ΔLi MW	Load Li	Reserve %
SE	2	135	270	-7.94	-34.0	25.5	244.5	44.67
HE	3	32	96	-3.40	-28.2	21.2	74.8	37.09
CT	4	16	64	-4.61	-13.9	10.4	53.6	18.24
Total			**430**		**-76.1**	**57.1**	**372.0**	**100.0**

$\Delta L = \Sigma \Delta Li = \Delta F * \Sigma(Pi/dfi) = 57.1$ MW or 13.3 %.

Table 2. Determination of Frequency Dip

GIVEN $\Delta L = 50$ MW, FIND ΔF:

Type	No of Units	Cap. MW	Pi MW	dfi Hz/pu	Pi/dfi MW/Hz	ΔLi MW	Load Li	Reserve %
SE	2	135	270	-7.94	-34.0	22.3	247.7	44.67
HE	3	32	96	-3.40	-28.2	18.5	77.5	37.09
CT	4	16	64	-4.61	-13.9	9.1	54.9	18.24
Total			**430**		**-76.1**	**49.9**	**380.0**	**100.0**

Load Increase $= \Sigma(Pi/dfi) = -76.1$ MW/Hz, and Frequency Dip $\Delta F = 50/\Sigma(Pi/dfi) = -0.66$ Hz.
Accordingly, the frequency dip for picking up a LVAC Network load $\Delta L' = 50$ MW is about $\Delta F'' = -66$ Hz.

Table 3. "Uniformly" Distributed Reserve

"Uniform" Reserve Distribution:

Type	No of Units	Pi MW	Li' MW	dfi Hz/pu	Pi/dfi MW/Hz	ΔL MW	Li" MW	Reserve %
SE-A	1	300	217	-7.94	out			27.7
SE-B	2	270	195	-7.94	-34.0	44.7	240	25.0
HE	8	256	185	-3.40	-75.3	99.0	284*	23.7
CT	16	256	185	-4.61	-55.5	73.0	258	23.7
Total		**1082**	**782**		**-164.8**	**217.0**	**782**	**100.0**

$\Sigma Pi = 1082$ MW, $\Sigma Pi - 300 = 782$ MW, $\Sigma(Pi/dfi) = -164.8$ MW/Hz, The Initial Load, $Li' \propto Pi = 72.3\%$,
The Final Load, $Li'' = Li' + \Delta L$, and $\Delta F = 217/-164.8 = -1.32$ Hz.
The HE and CT Units Are Overloaded

Table 4. "Optimally" Distributed Reserve

"Optimal" Reserve Distribution Assuming $\Delta F = -1.32$ Hz:

Type	No of Units	Pi MW	dfi Hz/pu	Pi/dfi MW/Hz	ΔL MW	Li MW	Reserve %
SE-A	1	300	-7.94	out		217	27.7
SE-B	2	270	-7.94	-34.0	44.7	225	14.9
HE	8	256	-3.40	-75.3	99.0	157	33.0
CT	16	256	-4.61	-55.5	73.0	183	24.3
Total		**1082**		**-164.8**	**217.0**	**782**	**100.0**

$\Sigma Pi = 1082$ MW, $\Sigma Pi - 300 = 782$ MW, $\Sigma(Pi/dfi) = -164.8$ MW/Hz, $\Delta L = \Delta F * (Pi/dfi)$, and $Li = Pi - \Delta L$.
There are no overloads.

Table 5. "Optimally" Distributed Reserve

"Optimal" Reserve Distribution Assuming $\Delta F = -0.95$ Hz:

Type	No of Units	Pi MW	dfi Hz/pu	Pi/dfi MW/Hz	ΔL MW	Li MW	Reserve %
SE-A	1	300	-7.94	out		157	47.8
SE-B	2	270	-7.94	-34.0	32.3	238	10.8
HE	8	256	-3.40	-75.3	71.5	185	23.8
CT	16	256	-4.61	-55.5	52.8	203	17.6
Total		**1082**		-164.8	**156.6**	**782**	**100.0**

$\Sigma Pi = 1082$ MW, $\Sigma Pi - 300 = 782$ MW, $\Sigma(Pi/dfi) = -164.8$ MW/Hz, $\Delta L = \Delta F * (Pi/dfi)$, and $Li = Pi - \Delta L$.
There are no overloads.

the above case studies. The upper, middle and lower curves show the frequency dips due to: the 50 MW load pickup, the optimal reserve distribution for 0.95 frequency dip, and the "uniform" reserve distribution.

The following table provides a comparison between the simulation results and the results of using the "frequency response rates," $\Delta F/\Delta L$, as a guide:

Table 7 - Simulation & Guideline comparison

ΣPi MW	ΔL MW	ΔF,Hz Sim.	ΔF, Hz Guide	Difference Hz
430	50	-0.59	-0.66	-0.07
782	157	-0.85	-0.95	-0.10
782	217	-1.18	-1.32	-0.14

The differences between the simulation results and the results obtained from the use of "frequency response rates," justify the use of the above approximations in developing the guidelines.

4. CONCLUSION

In this paper, "frequency response rates," and "reserve rates" have been developed for typical CT, SE and HE units. The response and reserve rates have then been used to develop several operator guides for determining:

- the maximum load pickup for a given frequency decline,
- the maximum frequency dip for an estimated Low Voltage AC Network load, and
- the amount and distribution of reserve required for generation contingency.

It has been shown that:

- the distribution of generation reserve should be based on the frequency response rates of prime movers,
- the reserve distribution is constant for a given prime mover configuration, and
- as long as the generation reserve is distributed on the basis of reserve rates, there will be no risk of plant overloads.

The prime mover models described in this paper can readily be used to determine the frequency response rates and reserve rates of the prime movers for developing similar guidelines. It should be emphasized that although these guidelines provide approximate solutions, they do expedite the restoration process.

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BIOGRAPHIES

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