Frequency Stability Considerations of Reciprocating Gas Engine Generators in Microgrids

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***Abstract*—This paper considers the suitability of the standard DEGOV diesel generator governor model for use with reciprocating gas engine generators acting as primary frequency control units, within microgrids, due to the reduced capability of gas engines to accept step loads. The paper found that use of the standard DEGOV model would significantly overestimate the gas engines capability to accept step load, and an alternate model was developed using a gain scheduling controller, based on the generators existing loading. This model was found to be effective, but it was identified that the varying values of gain could lead to controller instability and tuning problems, and further investigation work in this area is necessary.**

Keywords—Microgrid, Governor, DEGOV, Gas Engine, Diesel Engine, Generator, ISO 8528-5.

I. INTRODUCTION

Power System Stability is a key area of interest for system designers and the system operators of microgrids, where reciprocating diesel engines and gas engines are commonly used to provide primary frequency control. Traditional microgrid design would often favor diesel engines to provide the primary frequency control, due to their robust operating performance; however, due to increasing environmental pressures and awareness many microgrid operators have started moving away from this approach.

Many sectors are adopting the use of grid-forming inverter based renewable technologies [1] to resolve these problems; but for many existing sites and industrial applications, grid forming inverters are not always practical or economic, and the use of reciprocating gas engines is preferred, due to their simplicity, dispatchability, availability, high efficiencies, inertia, and greater availability of fuel types.

A common problem faced by reciprocating as engines when operating in an isochronous / speed control mode, is that they gas engines have a much lower ability to accept and reject step load changes due to their mechanical engine limits [2], [3], and consequently have a much reduced wider frequency deviation limits given in ISO 8528-5 [4].

Work by the IEEE PES and CIGRE have resulted in a number of guidance reports on governing modelling for stability simulations [5] & [6], however these reports tend to favor large interconnected power systems, and historically less attention has been given to Microgrids. Recent work by the IEEE has shown that microgrid system stability considerations remain a very active research topic [7].

Within this paper the suitability of reciprocating gas engine generators as the primary means of providing frequency stability, will be examined in contrast to traditional reciprocating diesel engine generators. This will be carried out by considering the suitability of the standard IEEE DEGOV / DEGOV1 governor model used in most power system simulation studies against a new customized gas engine governor model, referred to as GEGOV.

The analysis is carried out using a simplified model of a power system frequency response, through implementation in Matlab/Simulink of the swing equation in a feedback loop with the governor output.

II. MICROGRID STABILITY

A. Stability Classification

Power system stability problems have been conventionally split into three main areas known as frequency stability, voltage stability and rotor angle stability, which are then further sub-divided into different areas for analysis [8]. Recent developments in renewable technologies have led to wider definition of stability classifications to include systems with high penetration of renewable technologies [9] and for the specific requirements of microgrids. A summary of the key classifications of microgrids can be seen below in Figure 1.

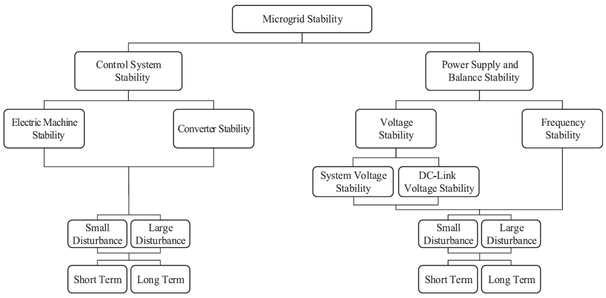

Figure 1 Microgrid Stability Definitions

Conventional microgrids have been usually based around either diesel generators, or small gas turbines that provide main power and primary frequency control, however, in recent years this has changed due to the increasing penetration of inverter-based generation and prevalence of reciprocating gas engines. Microgrid stability remains an active area of interest and research, as they face additional concerns when compared to traditional stability analysis [10] & [11].

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B. *Frequency Stability*

Within Microgrids the problem of frequency stability remains acute, and system collapse due to mismatches between available generation and load is a key concern due to the low inertia available in the system and the potential rapid frequency collapse. Even relatively modest changes in loads can lead to large frequency and voltage deviations in the electrical system, and conventional control systems may not be sufficient to manage the rapid fluctuations. A typical system response can be seen below in Figure 2.

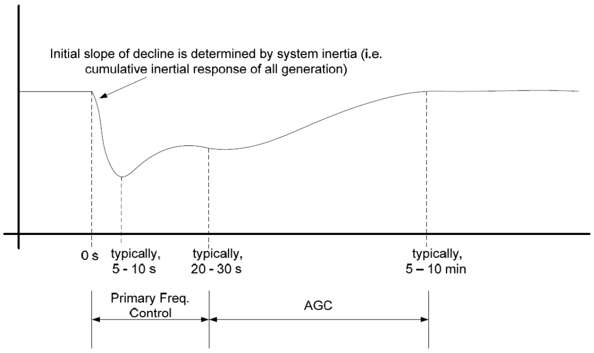

Figure 2 Typical Frequency Response

Considering the typical response curve shown in Figure 2, a number of key values can be observed. The initial slope of the frequency decline is the Rate of Change of Frequency (RoCoF) and is determined by the system inertia. The lowest value of the frequency is known as the nadir and is determined by the size of the load step and the generators governor response. The steady final frequency represents the new steady state equilibrium point once the system has stabilized.

In classical power system stability, the system frequency response and rate of change of frequency can be determined through solving of the swing equation as shown below in Equation 1, and in alternative format in Equation 2.

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \qquad (1)$$

$$\frac{df}{dt} = \frac{P_{in} - P_{out}}{2SH} f \qquad (2)$$

Most modern computer simulation packages use repeated iterations of the swing equation to solve frequency stability problems. When this is coupled with the generator governor control the system the instantaneous power mismatch and the relationship between system inertia and frequency and generator power output can be resolved to find the new operating point for generators in the system.

III. DIESEL ENGINE & GAS ENGINE COMPARISON

A. *Combustion Technologies*

Reciprocating gas engines and diesel engines are similar in principle, but there are a number of important differences between the technologies; conventional diesel engines are fed with a constant pressure of diesel that is pumped to the injectors, whilst gas engines are fed with a gas that can vary in pressure and in methane/oxygen content. This leads to a more complex set of parameters for consideration in a gas engine and different response characteristic [12] & [13]. Typical parameters that need to be considered in the performance of reciprocating generator set are:

- Fuel Type – Liquid Diesel vs Gas Type
- Calibration & Sizing of Throttle Body.
- Air & Fuel Ratio Requirements.
- Throttle Control Geometry.
- Gas Pressure.
- Available Gas Volume.
- Methane / Oxygen Content.

B. *Load Step Capability*

The electrical performance of reciprocating diesel and gas engine sets are defined within the ISO 3046-4 [14] and ISO 8528-5 standards. ISO 8528-5 defines the ability of a reciprocating engine generator sets load acceptance capability, where the performance is given in terms of an individual machines frequency drop for a given load step.

A generators load step capability is defined in ISO 8528-5 by the engine's Break Mean Effective Pressure (BMEP), and the load step percentage compared to the overall machine rating. The generator is then defined in the number of steps (between 1 and 6), that are needed to take a specific percentage load. This can be seen below in Figure 3, where the percentage load step is show on the x-axis, the engine BMEP is shown on the y-axis and the number of steps required to meet a specific load step are shown by the area above the curves. If the product of the machine BMEP and the load step is below the first curve, a single load step is required; if the load is above the first curve, but below the second curve, it will require two load steps; if the load step is above the first two curves, but below the third, then it will take three load steps and so on.

The load step figure shown in Figure 3, is not always clear to follow, and can be best illustrated through an example. A generator with a 20bar BMEP, could take up to a 40% load step in a single step, while a 50% load step would need to be split into two smaller steps, and a 100% load step would require 4 steps. Similarly, a machine with a 30bar BMEP, would require 2 steps to take 40% load, 3 steps to take 50% loads and exactly 5 steps to take 100% load.

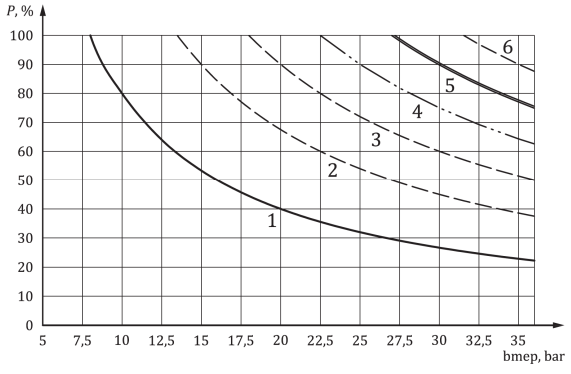

Figure 3 ISO 8528- Load Step Diagram

The load step limitations given in Figure 3 are based on the expected frequency and voltage deviation that the machine is permitted according to its performance class of G1, G2, G3 or G4. These limits are detailed in Table 1, of ISO 8528-5, and are presented in a simplified format below.

Table 1 ISO 8528-5 Performance Limits

Parameter		Operating limit values			
		Performance class			
		G1	G2	G3	G4
Steady-state frequency band		2.50%	1.50%	0.50%	AMC
Transient frequency difference from initial frequency	100 % sudden power decrease	≤18%	≤12%	≤10%	AMC
	Sudden power increase (Diesel)	≤15%	≤10%	≤7%	
	Sudden power increase (Gas)	≤25%	≤20%	≤15%	
Frequency recovery time		10s	5s	3s	AMC

Typically, G1 performance class machines are intended for light use and parallel operation with a grid, whilst G2 and G3 performance class are heavier duty and have an improved capability to manage step loads and are more suitable for microgrid operation. Generator sets classified as type G4 are subject to specific performance requirements and are referred to as an Agreement between the Manufacturer and Customer (AMC), based on the machine design, ambient conditions, and available fuel gas.

From Figure 3 and Table 1 above it can be observed that a diesel generator, rated 1000 kW, with a BMEP of 20bar, taking a load step of 40% would be allowed a frequency deviation of 7% and a 3s recovery time if it was rated for G3 performance class. The equivalent gas engine would be allowed a 15% frequency deviation and 3s recovery time.

C. *Load Step Capability Diagrams*

Due to the differing performance characteristics of gas engines, based on their specific installation conditions and fuel supplies, most manufacturers define the load step capability of their machines through the use of a load step capability diagram. An example of this comparing a diesel engine to a typical gas engine is shown below taken from a position paper produced by the International Council on Combustion Engines (CIMAC), on the transient response of gas engines, reproduced below in Figure 4.

The graph for the diesel engine shows a fixed load acceptance value of 33% up to a base load of 67%, at which point the load acceptance drops off linearly with the base load, such that the total load does not exceed 100%. It can be seen that for the Gas Engine, the situation is more complex and the load acceptance capability is non-linear, and consists of a number of different Load Acceptance *(LA)* capability values, depending on the Base Load (*BL)*.

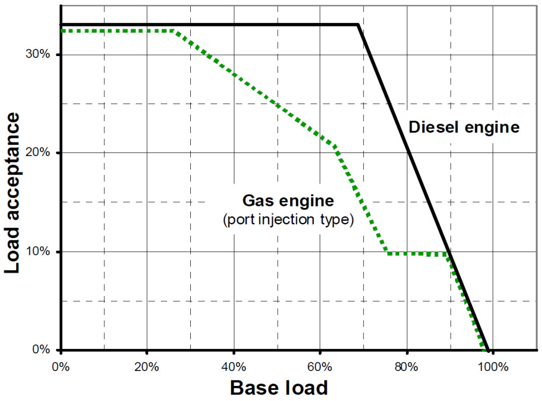

Figure 4 Generator Load Step Capability Comparison

The gas engine response show in Figure 4, can be represented by a set of discrete piecewise defined linear functions, as indicated below in equation (3), based on a simple analysis of the graph gradients Where a flat response is present on the Gas Engine capability diagram the slope is represented as a constant value.

$$LA = \begin{cases} 0.333 & (0 < BL < 0.28) \\ 0.415 - 0.332BL & (0.28 \le BL < 0.63) \\ 0.725 - 0.833BL & (0.63 \le BL < 0.75) \\ 0.1 & (0.75 \le BL < 0.9) \\ 1 - BL & (0.9 \le BL < 1.0) \end{cases} \tag{3}$$

IV. DEGOV / DEGOV1 GOVERNOR MODEL

A. *History*

The DEGOV and DEGOV1 governor models have been used as a standard modelling approach for diesel engine governors for a number of years. These are based on an original model developed by PTI/Siemens for PSS/E with input from Woodward and are referenced in a number of the IEEE and NERC guidelines [15]. It is noted that the DEGOV and DEGOV1 models are virtually identical, with the DEGOV1 model including an extra feedback loop to allow droop control.

A literature review carried out by the authors indicated, that while a significant amount of research work has been carried out into developing accurate governor models for gas, steam and hydro turbines; only limited development work has been carried out on expanding the DEGOV / DEGOV1 governor models for reciprocating gas engines.

B. *Governor Model*

The DEGOV model used in most power system studies, is a generic model that allows operation of the engine in both isochronous and a droop control model, and is based on a PID type configuration, containing 8 differential equations and 2 algebraic states, with an addition a transport delay to allow for the engine time [16] & [17]. A standard implementation of the DEGOV governor model can be seen in Figure 5.

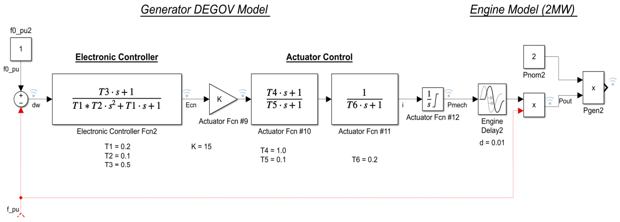

Figure 5 DEGOV Model

C. Governor Parameters

The various gain and time constants typically associated with the DEGOV model shown in Figure 5, are shown in Table 2. These are commonly given in various software packages such as DIgSILENT Powerfactory [18]. Considering the various values, gain K, and the time constants T4, T5, T6 and Td are specific to the engine performance, whilst constants T1, T2 and T3 are tuned based on the desired performance.

The typical factors that affect the load response of the DEGOV model is the gain K, and the fuel gate opening time constants T4 and T5, as these are responsible for delivering more fuel into the system. This means that modifying the gain K or the two time constant T4 or T5 will alter the load step response of the generator [19] & [20] and be used as the starting point for tuning. Based on the information from Table 1, the basic tuning process of a classical DEGOV model is carried out to adjust the parameters of K, T4 & T5 based on the engine parameters and its classification as G1/G2/G3.

Table 2 Typical DEGOV Values

Name	**Typical DEGOV Parameters**		
	Description	***Value***	***Unit***
K	Actuator Gain	15	[pu/pu]
T4	Actuator derivative time constant	1	[s]
T5	Actuator first time constant	0.1	[s]
T6	Actuator second time constant	0.2	[s]
Td	Combustion Delay	0.01	[s]
T1	Electric control box first time constant	0.2	[s]
T2	Electric control box second time constant	0.1	[s]
T3	Electric control box derivative time constant	0.5	[s]
Tmin	Min. Throttle	0	[pu]
Tmax	Max. Throttle	1.1	[pu]

V. MATLAB / SIMULINK MODEL

A. Base Model and Validation

Initially a model of the DEGOV governor was created in Matlab/Simulink, which was then coupled with a mathematical equivalent model of the swing equation shown in equation (2). As the generator load response in isochronous / speed control mode is of key interest, the DEGOV version of the governor was used, as the DEGOV1 model includes a droop control loop that was not of interest for this analysis.

It was decided to model the governor and swing equation directly in Matlab/Simulink, rather than in Simscape Electrical, or a simulation package such as DIgSILENT Powerfactory, to allow a more detailed analysis and modification of the governor model, in isolation from other system variables, such as reactive power flows and synchronous generator parameters. The combined model of the DEGOV governor and system representation with the swing equation can be seen below in Figure 6.

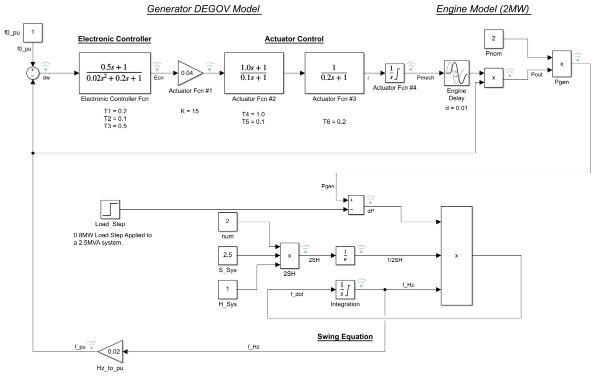

Figure 6 Simulink Model of Governor & Swing Equation

Several initial simulations were carried out to validate the test network shown in Figure 6 against an equivalent model in DIgSILENT PowerFactory. This was initially carried out using the standard governor parameters in Table 2, and some typical machine characteristics defined below.

- Machine Rating 2MW
- System Inertia 2.5MVA
- System Inertia Constant of 1.0
- BMEP of 20 bar
- Load Step of 0.8MW (40% of machine rating)

After the initial validation, the test network was used to identify the DEGOV gain factor K relationship with the frequency nadir during the specified load step, whilst keeping the other parameters constant. For each of the different machine types of G1/G2/G3, as detailed in Table 1. The results obtained, during the initial validation are summarized in Table 3.

Table 3 Benchmark Results

Base Load	**Expected Frequency Nadir**	**Inertia Constant (H)**	**Gain Value (K)**	**Frequency Nadir (DEGOV)**
G1 Diesel	42.5Hz	1	2.5	42.6 Hz
G1 Gas	37.5Hz	1	1.2	37.6 Hz
G2 Diesel	45Hz	1	5	45.1 Hz
G2 Gas	40Hz	1	1.6	40 Hz
G3 Diesel	46.5Hz	1	10.1	46.5 Hz
G3 Gas	42.5Hz	1	2.4	42.5 Hz

B. *DEGOV Gain Factor Preliminary Results*

From the validation several general conclusions were drawn. The key relationship observed, was that for a fixed inertia, the controller gain factor K was the main parameter that could be adjusted to define the governor response, and that a lower gain resulted in a lower frequency nadir. As a preliminary conclusion it was identified that G3 class diesel engines would typically have a high gain factor of 10 or above, and a class G1 gas engine, would have a low gain factor just above 1. It was further identified that the engine delay T_d difference between gas engine and diesel engine creates only a minimal difference in the frequency nadir.

It can therefore be concluded that simple adoption of the standard values given in the DEGOV model is unlikely to be suitable and will give misleading results in power system stability studies for gas engines. As a minimum, the designers must consider the machine classification, BMEP and inertia and then carry out a tuning exercise to obtain a typical response characteristic before beginning any stability studies.

VI. PROPOSED GAS ENGINE GOVERNOR

A. *Outline*

The previous sections have shown that a gas engine has a very different response characteristic to a diesel engine, and therefore some modifications of the standard DEGOV model are needed. It is therefore proposed to extend the DEGOV model, to a new model known as GEGOV, where an additional feedback control will be included, to modify the gain factor K, based on the gas engine existing loading, through a gain scheduling system.

B. *Gain Scheduling*

The problem identified with the basic DEGOV model application to gas engines, is that the gas engine load step characteristic is non-linear, and therefore the governor gain K will vary depending on the base load of the generator. This can be managed through adjusting the governor gain for a non-linear system, with an approach that is known as gain scheduling. The concept of gain scheduling is a well-established concept for nonlinear systems and is discussed further in [21].

Implementing a gain scheduling system within Simulink can be done in a variety of different ways, but the most straightforward is to use a 1D-Lookup table, with the input based on the machine loading and the output is the required gain value K. An additional engine loading model is also included to determine the engine base load, calculated from the system output and a pre-set loading value, is also included as shown below in Figure 7.

In order to define the values in the 1D-lookup table, it is necessary to refer to the linear equations (3) shown earlier. This is achieved through a simple calculation to convert the known values of Base Load (*BL*) and Load Acceptance value *(LA)*, to a specific gain factor K. The individual gain values can be determined, based on the assumption that gain is proportional to the load acceptance value (K α *LA)*, and thus the individual values of constant c, can be determine for the various base load conditions:

$$K = c\,LA \tag{4}$$

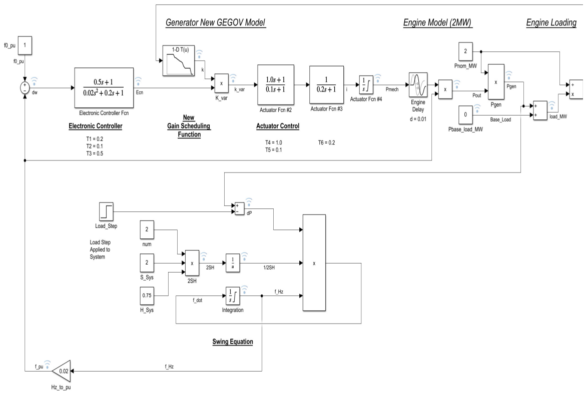

Figure 7 Modified DEGOV Model & Swing Equation

To determine the necessary constant *c* for each of the stages in the equations given in (3) and (4) a tuning exercise is then carried out in a similar manner to that used in Section II. This is achieved by selecting known *LA* and *BL* values, which corresponds to a limit point of the step loading curve and then tuning the value of K to get the expected response. Once these values are obtained, the value of *c* can be derived and used to determine the other required gains to populate the lookup table.

Base Load (BL)	**Load Acceptance (LA)**	**Constant 'c'**	**Gain**	**Test Load (MW)**
0%	33.00%	3.788	1.25004	0.66
50%	24.85%	3.38	0.83993	0.497
70%	14.19%	2.676	0.3797244	0.2838
80%	10.00%	3.788	0.3788	0.2
95%	5.00%	0.8	0.04	0.05

Table 4 Tests Loads for Lookup Table

C. *Testing*

To demonstrate the system behavior several simulation studies were carried using the new GEGOV model shown in Figure 7, with different base loads set within the model, and a constant 33% load step applied. Case 1 represents the base condition and shows the ideal response of the gas engine at zero load, and if a gain scheduling system was not used. The subsequent cases use different base loads to configure the gain scheduling controller value of gain K.

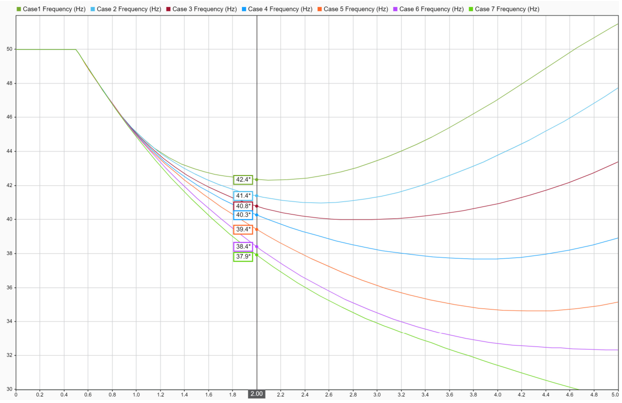

Figure 8 GEGOV Gain Scheduling Results

For each test case the frequency output at 2s is recorded, as can be seen in Figure 8 where an output plot of the frequency response and the results summarized in Table 5.

Table 5 GEGOV Model Tests

Case	**Base Load % on 2MW**	**Calculated Load Step Limit**	**Load Step Limit Type**	**Load Applied (MW)**	**Frequency Value at 2s.**
1	0% (0MW)	33.3%	Constant	0.667	42.4
2	20% (0.4MW)	33.3%	Constant	0.667	41.4
3	30% (0.6MW)	31.5%	Linear	0.667	40.8
4	40% (0.8MW)	28.2%	Linear	0.667	40.3
5	50% (1.0MW)	24.8%	Linear	0.667	39.4
6	60% (1.2MW)	21.5%	Linear	0.667	38.4
7	70% (1.4MW)	14.2%	Linear	0.667	37.9

Overall, the results are generally in line with what was expected and demonstrate that the GEGOV model produces greater frequency deviations, and slower recovery time depending on the initial loading. An unexpected result identified was the constant varying of the gain during the load step event, and it was considered that this may lead to some instability on the control and overly pessimistic results.

VII. CONCLUSIONS & FURTHER WORK

It has been demonstrated in this paper that the existing DEGOV model is suitable for diesel engines, provided that the the gain value K is tuned accordingly to match the machine classifications and the engine BMEP. It was shown however, that the use of the DEGOV model for gas engine generators, was unsuitable, as the gas engine load-step acceptance capability is non-linear and depends on the existing loading. Such differences in performance would be critical for a microgrid, where a reciprocating gas engine is used as primary frequency control, and use of a simple DEGOV model, may therefore not accurately predict system performance in response to load steps.

The DEGOV model, was revised to a new model called GEGOV, which implemented a gain scheduling controller, to adjust the governor gain K, based on the generator base load. It was then demonstrated that the new GEGOV model provided a more realistic response, and significantly larger frequency deviations and recovery times were identified. This allows more accurate simulation studies and modelling of load steps, to improve the system performance under transient load changes. It was further noted from the results that use of a sample and hold element on the output of the lookup table, would prevent the gain varying during the load response and may be a more realistic approach, than a continual gain scheduling approach.

The simulation technique used in Matlab/Simulink to connect a governor model to an implementation of the swing equation, could be used in modelling any other similar governor type, or adapted for use in testing grid forming inverters.

Further work in this area would involve some liaison and field testing with gas engine generator set manufacturers to benchmark the governor parameters against a number of actual generating set data and to carry out some Hardware in the Loop field testing of the proposed GEGOV governor model and parameters.

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