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Synchronous Generator Load Sharing Models for Diesel-Based Remote Systems

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SUMMARY

Remote power systems in the Canadian territories implement load sharing control between diesel generators. Load sharing controls are required for situations where more than one diesel generator is supplying the system demand or for load transfer between generators for dispatching. Standardized power system models for synchronous machines, turbine-governors/speed-governors, and excitation systems do not represent all forms of load sharing that are commonly implemented in remote power systems. This paper describes and models load sharing controls commonly used with diesel generators in the Canadian territories that are not represented in standardized models found in literature. The implemented load sharing models address active and reactive power load sharing, focusing on the specific implementations in the field.

An overarching generation plant and generator model structure is presented for representing load sharing between generator models. To allow for all possible forms of active and reactive load sharing, the load sharing model structure allows outputting a biasing signal, adjusting the reference signal, or compensating the measured signal. In addition, the active power load sharing model outputs an active power reference in order to allow the use of the LCFB1 as an active power load sharing model with the GGOV1 governor model. The overarching model structure was then used to simulate load sharing between generators for a step-loading scenario. The synchronous generators were modeled with an IEEE Model 2.1 (salient-pole) synchronous machine model, an AC5A excitation system model, a modified version of the DEGOV1 model, a simplified isochronous load sharing model based on the Woodward 2301A load sharing bridge, and a simplified model for reactive differential compensation based on IEEE 421.5-2016. The use of different speed governor and voltage regulator gains ensured each generator had a different response during the step-loading to show the action of the load sharing controls. The generators showed close agreement in steady-state, which is the desired result of the load sharing controls.

A consistent approach for modelling load sharing was developed in the MATLAB/Simulink environment that interacts with existing speed-governor, turbine-governor and excitation system models. Preliminary tests of the models show effective load sharing between different generators, both in steady-state and during transients. Future work requires the experimental validation of the models, and development of further models.

KEYWORDS

Remote Power Systems; Isolated Microgrid; Rural Electrification; Power Generation Control; Generation Controls; Load Sharing Controls; Power System Modeling

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INTRODUCTION

Remote power systems in the Canadian territories implement load sharing control between diesel generators; such is the case in Old Crow, Yukon, and Cape Dorset, Nunavut, for examples. Load sharing controls are required for situations where more than one diesel generator is supplying the system demand, which can occur at times of high demands or during load transfer between generators for dispatching. Standardized power system models for synchronous machines, turbine-governors/speed-governors, and excitation systems do not represent all forms of load sharing that are commonly implemented in remote power systems. This paper explicitly describes and models load sharing methods that are employed in diesel generator controls in the Canadian territories and are not properly represented in standardized models found in literature [1-3].

Load sharing controls can be described in terms of active power load sharing and reactive power load sharing. Active power load sharing may be performed using either isochronous load sharing or droop. Isochronous load sharing is commonly used in remote power systems and relies on the principle of isochronous control. Isochronous control is a strategy wherein the power output is allowed to swing in order to maintain frequency at reference value. In isochronous load sharing, biasing signals are supplied to each governor which are determined from the error between the average demand on the interacting machines and the machine's specific demand. Isochronous load sharing can be represented by the principle of both analog isochronous load sharing controls, such as the method implemented by the Woodward 2301A load sharing and speed control, and digital network based active power load sharing [4-6].

In droop control, each machine adjusts its power output for changes in load and therefore frequency according to a linear curve describing a relationship between frequency and active power. An outer control loop is required to set the load reference about which the droop curve is centred. Droop is not typically used in diesel-based remote systems in the territories.

Reactive power load sharing may be performed using reactive droop, reactive differential (cross-current) compensation, or network based reactive power load sharing [3,7]. Reactive droop uses the same principle as in droop for active power; however, an outer control loop is not necessarily required as the control curve can be centred about zero reactive power. Reactive droop is sometimes used in remote systems with a relatively small reactive demand, as the changes in reactive load will cause relatively small changes in the terminal voltage which can remain within system requirements. Reactive differential compensation uses a similar compensation method as in reactive droop; however, it also sends and receives a compensation signal to and from another generator, thereby allowing sharing of reactive load. Reactive droop and reactive differential compensation can be modelled as described in IEEE 421.5-2016 [3]. Network based reactive load sharing can be modelled using the similar methods to network based active load sharing as the principle is the same.

MODEL OVERVIEW

The overarching generation plant and generator model structures used to represent load sharing between generator models is represented in Figure 1 and Figure 2. The nomenclature with regards to the inputs and outputs of the models are described in Table 1.

In Figure 1, the apparent power load sharing output (S_{LSO}), active power load sharing output (P_{LSO}), and reactive power load sharing output (Q_{LSO}) signals from each generator model are combined into a signal bus, and then they are passed into each of the generator models as the as the respective load sharing inputs (S_{LSI}, P_{LSI}, and Q_{LSI}). In Simulink, a signal bus is used, such that the signals in the signal bus (i.e. multiple S_{LSO}, P_{LSO}, or Q_{LSO} signals) can then be summed to obtain the total apparent capacity, total active load, or total reactive load of the machines. The reactive differential compensation voltage output (V_{RDCO}) signals from each generator model are passed to the next respective generator model as the respective input (V_{RDCI}). When a generator is disconnected, S_{LSO}, P_{LSO}, and Q_{LSO} are grounded (i.e. set to zero) while V_{RDCI} is passed through as V_{RDCO}.

To represent all possible forms of active and reactive load sharing, the load sharing models must be capable of i) outputting a biasing signal (W_{BIAS} or V_{BIAS}), ii) adjusting the reference signal (W_{REF} or V_{REF}), or iii) compensating the measured signal (W_C or V_C).

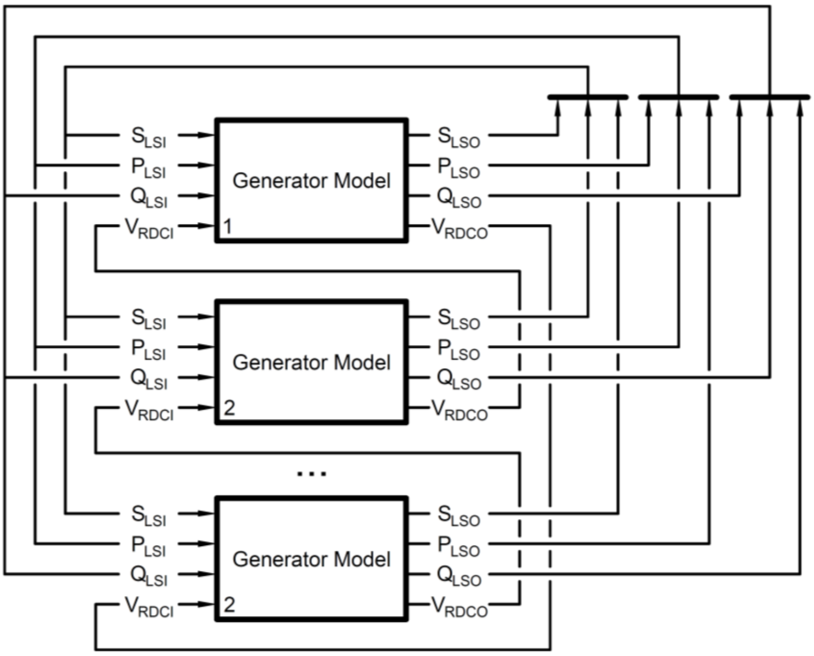

Figure 1: Load sharing input and output signals for an arbitrary number of generator models.

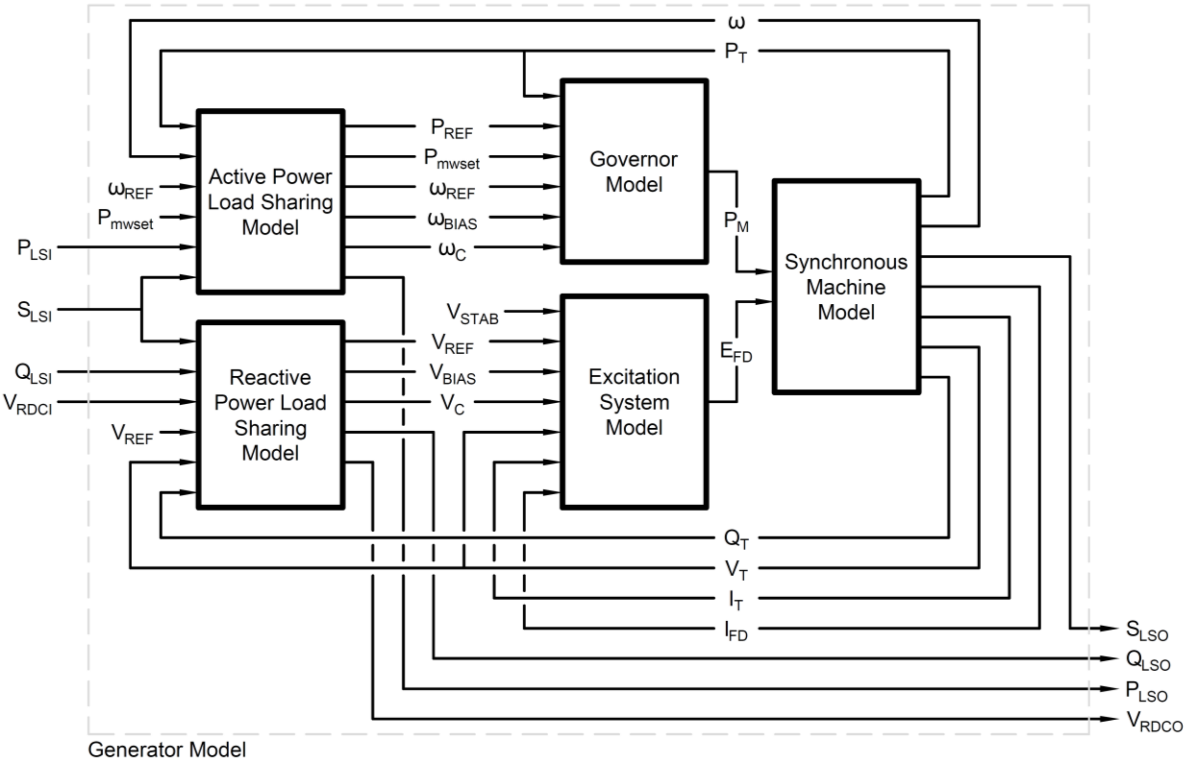

Figure 2: Active and reactive power load sharing models and their inputs and outputs in the generator model. Note: changes of base are not shown in this figure.

Any unused signals can simply be grounded or terminated where appropriate or may be passed through a load sharing model. In addition, the active power load sharing model outputs an active power reference (P_{REF}) in order to allow the use of the load controller model (LCFB1) as an active power load sharing model. The LCFB1 model is used with the GGOV1 model, which is one of two standard models that has any reference to use for diesel engine governors [1,2,8]. Furthermore, the active power load sharing model should allow the load reference of the supervisory load control loop to be passed through in order to allow the supervisory load controller within the GGOV1 model to be used alternatively to using the GGOV1 and LCFB1 models together. The reactive differential compensation signals (V_{RDC}) are used within the IEEE Std. 421.5-2016 voltage transducer and current compensator model [3].

Table 1: Active and reactive power load sharing model input and output parameter descriptions

Parameter	Description
P_T	Terminal Active Power (pu)
I_T	Terminal Current (pu)
V_T	Terminal Voltage (pu)
Q_T	Terminal Reactive Power (pu)
S_{LS}	Apparent Power Load Sharing (VA).
P_{LS}	Active Power Load Sharing (W).
Q_{LS}	Reactive Power Load Sharing (VAr).
V_{RDC}	Reactive Differential Compensation Voltage (pu)
ω	Speed (pu)
ω_C	Compensated Speed (pu)
ω_{REF}	Speed Reference (pu)
ω_{BIAS}	Speed Bias (pu)
P_{REF}	Power Reference (pu)
P_{mwset}	Load reference of this supervisory load control loop (pu) [8]
P_M	Mechanical Power (pu)
V_{REF}	Voltage Reference (pu)
V_{STAB}	Power System Stabilizer Voltage (pu)
V_{BIAS}	Voltage Bias (pu)
V_C	Compensated Voltage (pu)
E_{FD}	Field Voltage (pu)
I_{FD}	Field Current (pu)

Note: the subscripts $_I$ and $_O$ in Figure 1 and Figure 2 denote inputs and outputs, respectively

SIMULATION METHODOLOGY

The overarching model structure is then used to simulate combinations of 2 and 3 generators when subjected to a step loading at the generator terminals. For the simulations, the models and parameters as defined in Table 2, Table 3, and Figure 3Figure 3: Modified DEGOV model to Figure 5 are used. Figure 3 shows the modified version of the governor model used with the active load sharing model. Figure 4 and Figure 5 show the active and reactive load sharing models, respectively.

Table 2: Salient-pole synchronous machine model data.

Parameter	Symbol	Value (assumed)
Rated Apparent Power	S	1000 kVA (G1), 1000kVA (G2), 500kVA (G3)
Rated Frequency	f	60 Hz
Rated Voltage	V	4.160 kV
Pole Pairs	P	3
Stator Resistance	Rs	0.0153 pu
d-Axis Synchronous Reactance	Xd	1.5000 pu
d-Axis Transient Reactance	Xd’	0.1891 pu
d-Axis Subtransient Reactance	Xd”	0.1337 pu
q-Axis Synchronous Reactance	Xq	0.8424 pu
q-Axis Subtransient Reactance	Xq”	0.1181 pu
Leakage Reactance	Xl	0.0835 pu
d-Axis Transient Open-Circuit Time Constant	Tdo’	2.378 s
d-Axis Subtransient Open-Circuit Time Constant	Tdo”	0.020s
q-Axis Subtransient Open-Circuit Time Constant	Tqo”	0.011s
Inertia Constant	H	0.7986 kW·s/kVA

The synchronous machine model data is based on data obtained for 21 different internal combustion engine generators throughout the Canadian territories. 2 of the 21 generators are natural gas engines, while the remainder are diesel engines. 3 of the 19 diesel engines are 2-stroke compression ignition engines, while the remainder are 4-stroke compression ignition engines. In many cases, there are partial or atypical data (based on the collected data) for many of the generators. Consequently, atypical data is not used in estimating parameters in order to provide representative values.

Table 3: AC5A model data.

Parameter	Symbol	Value
Low-Pass Filter Time Constant	Tr	1e-5 s
Voltage Regulator Gain	Ka	400 (G1), 360 (G2), 440 (G3)
Voltage Regulator Time Constant	Ta	0.02 s
Voltage Regulator Output Limits	VRmin	-7.3 pu
	VRmax	7.3 pu
Damping Filter Gain	Kf	0.03
Damping Filter Time Constants	Tf1	1.0 s
	Tf2	0 s
	Tf3	0 s
Exciter Gain	Ke	1
Exciter Time Constant	Te	0.25 s
Field Voltage Values	Efd1	5.6 pu
	Efd2	4.2 pu
Exciter Saturation Function Values	Se[Efd1]	0.86 pu
	Se[Efd2]	0.5 pu

The excitation system model data is based on the sample data from IEEE Std. 421.5-2005 [9]. Note that different values of the voltage regulator gain, Ka, are used for each of the generators to ensure different responses.

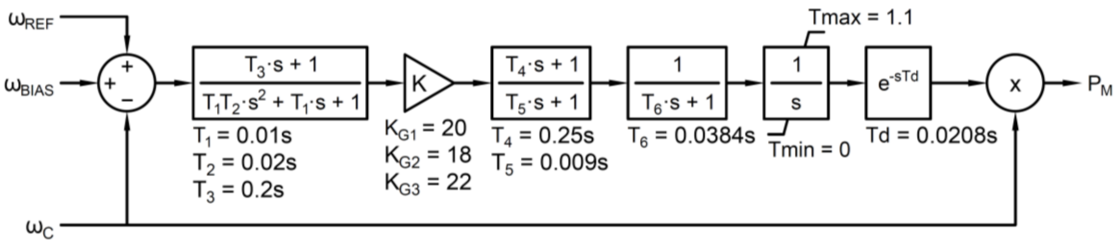

Figure 3: Modified DEGOV model

The diesel governor model (DEGOV) is modified for this analysis to include a biasing signal, as shown in Figure 3 [10,11]. DEGOV/DEGOV1 is the second of the two standard models for use with diesel engine governors [1]. The model parameters are as shown in the figure. Note that different values of the governor gain, K, are used for each of the generators to ensure different responses. The engine time delay (Td) is calculated based on (1), for an engine speed of 1200 rpm and one half of 12 cylinders firing per revolution (i.e. a 12-cylinder four-stroke engine) [2,12].

$$T_d = \frac{15}{N} + \frac{60}{Nn} = \frac{15}{speed} + \frac{60}{speed \times no.cylinders\,firing\,per\,revolution} \quad \textbf{(1)}$$

The isochronous load sharing model (ILS1) shown in Figure 4 is based on the load sharing bridge described by Woodward, which is an example of analog isochronous load sharing as used in the Woodward 2301A load sharing and speed control [4]. The parameters used within the model are as shown in the Figure 4. The gain allows the proportion of the loading on each generator to be set. The lag filter is used to delay the response and emulates the action of the capacitor in the load sharing bridge, which prevents instantaneous changes in the load sharing control. This is necessary as the load sharing controls act as an outer control loop and must act more slowly than the governor and excitation systems.

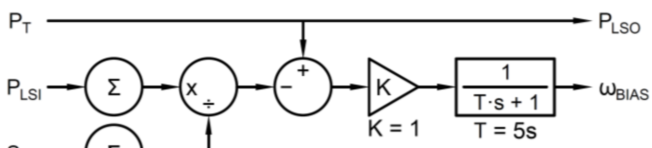

Figure 4: Isochronous Load Sharing Model – ILS1

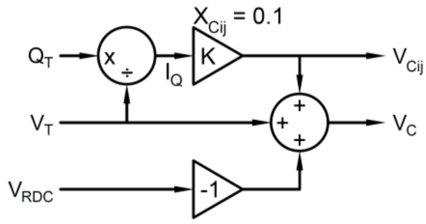

Figure 5: Reactive Differential Compensation Model – RDC2

The reactive differential compensation model (RDC2) shown in Figure 5 is based on reactive differential compensation, as shown in (2) and described by the voltage transducer and current compensator in IEEE Std. 421.5-2016 [3]. The parameters used within the model are as shown in Figure 5.

$$\begin{gathered} V_{Ci} = |\bar{V}_T| + X_{Cii} I_{Qi} + X_{Cij} I_{Qj} = V_{Ti} + X_{Cij} I_{Qi} - X_{Cij} I_{Qj} \\ V_{Ci} = V_{Ti} + X_{Cij} \frac{Q_{Ti}}{V_{Ti}} - X_{Cij} \frac{Q_{Tj}}{V_{Tj}} = V_{Ti} + X_{Cij} \frac{Q_{Ti}}{V_{Ti}} - V_{RDCj} \end{gathered} \quad \textbf{(2)}$$

The component $X_{Cij}I_{Qi}$ can be passed to the next generator (which is thus $X_{Cij}I_{Qj}$) as the V_{RDCj} signal (i.e. V_{RDCO} in Figure 1 and Figure 2). This signal can then have a gain of -1 applied to satisfy the requirement that X_{Cii} = -X_{Cij} as described by IEEE Std. 421.5-2016 [3].

Results and Discussion

The use of different speed governor and voltage regulator gains ensured each generator had a different response during the step-loading, thereby showing the action of the load sharing controls. In all cases each generator was subjected to a step load increase of 0.1pu active and 0.0329pu reactive (i.e. 0.1 pu active with a power factor of 0.95). Figure 6 shows the response of G1 and G2 with load sharing as compared to G1 only. Figure 7 shows the response of G1, G2, and G3 with load sharing as compared to G1 only.

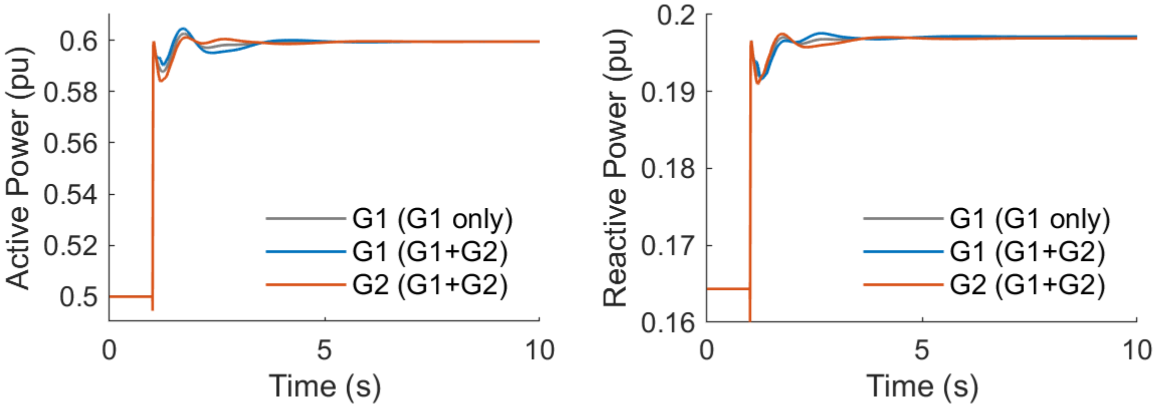

Figure 6: Active and reactive power response of G1 and G2 for a step load as compared to G1 only.

The generators show close agreement in steady-state, which is the desired result of the load sharing models.

Conclusion

Synchronous generator models require additional load sharing models for remote power systems. A consistent approach for modelling load sharing is developed in the MATLAB/Simulink environment that interacts with existing speed-governor, turbine-governor and excitation system models. Preliminary tests of the models show effective load sharing between different generators, both in steady-state and during transients. Future work requires the experimental validation of the models, and development of further models.

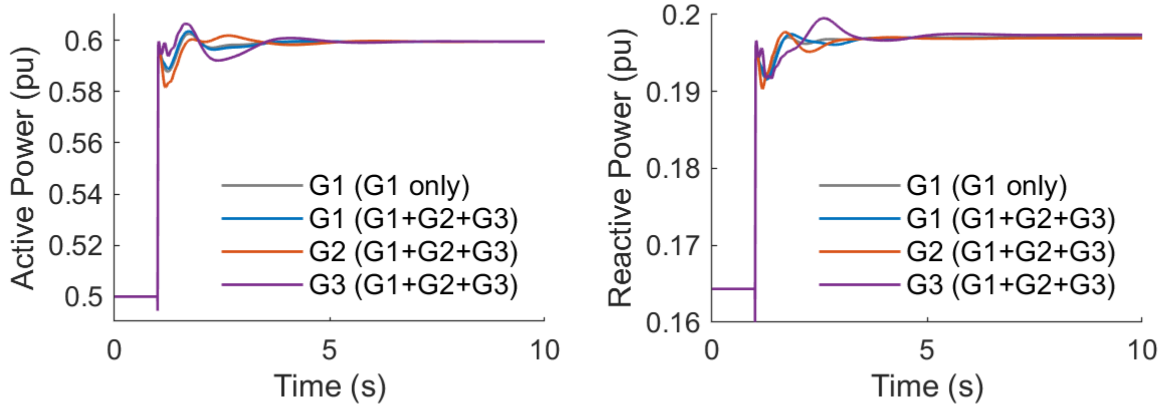

Figure 7: Active and reactive power response G1, G2, and G3 for a step load as compared to G1 only.

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