Multiple Input Governor Control for a Diesel Generating Set

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***Abstract*—The paper presents a multiple-input single-output fuzzy logic governor algorithm that can be used to improve the transient response of a diesel generating set, when supplying an islanded load. The proposed governor uses the traditional speed input in addition to voltage and power factor to modify the fueling requirements during various load disturbances. The use of fuzzy logic control allows the use of proportional–integral–derivative (PID) type structures that can provide variable gain strategies to account for nonlinearities in the system. Fuzzy logic also provides a means of processing other input information by linguistic reasoning and a logical control output to aid the governor action during transient disturbance. The test results were obtained using a 50 kVA naturally aspirated diesel generator testing facility. Both real and reactive load tests were conducted. The complex load test results demonstrate that, by using additional inputs to the governor algorithm, enhanced generator transient speed recovery response can be obtained.**

***Index Terms*—Diesel engine, digital governors, distributed generation, fuzzy control, real-time control.**

NOMENCLATURE

K	Controller gain.
K_{epd}	Proportional–derivative (PD) type fuzzy controller—input speed error scaling.
$K_{\Delta\mathrm{epd}}$	PD-type fuzzy controller—input change in speed error scaling.
K_{epi}	Proportional–integral (PI) type fuzzy controller—input speed error scaling.
$K_{\Delta\mathrm{epi}}$	PI-type fuzzy controller—input change in speed error scaling.
K_{ev}	Fuzzy voltage monitor—input voltage error scaling.
G	Proportional output gain.
K_{pd}	PD-type fuzzy controller—output gain.
K_{pi}	PI-type fuzzy controller—output gain.
K_{es}	Voltage error scaling.
K_{pfv}	Fuzzy voltage monitor—output gain.
t_i	Integral time constant.
t_d	Derivative time constant.
Z	Zero.
PVVS	Positive very very small.
PV	Positive very small.
PS	Positive small.
PM	Positive medium.
PL	Positive large.
PVL	Positive very large.
PVVL	Positive very very large.
NL	Negative large.
NM	Negative medium.
NS	Negative small.
e	Error.
e_v	Voltage error.
$\Delta e_{\mathrm{speed}}$	Change in speed error.
u	Controller output.
$\mu_{()}$	Output membership function.
X_d	*d*-axis synchronous reactance.
X_q	*q*-axis synchronous reactance.
δ	Rotor angle.
I_d	*d*-axis current.
I_q	*q*-axis current.
E	Generated electromotive force (EMF).
V	Alternator terminal voltage.
$f_{d\_\min}$	Maximum speed deviation—load application.
$f_{d\_\max}$	Maximum speed deviation—load rejection.
t_f	Disturbance settling time.
PF	Power factor.
AVR	Automatic voltage regulator.
SISO	Single-input single-output.
MISO	Multiple-input single-output.

I. INTRODUCTION

DIESEL generating sets have traditionally used mechanical droop or analogue proportional–integral–derivative (PID) type governors for engine speed control. However, the relentless necessity for improved emissions and the desire for enhanced engine and generator performance has led engine and generator control manufacturers to implement sophisticated digital engine/generator control algorithms [1], [2], [3]. The use of modern microprocessors, or microcontrollers, gives the manufacturer the ability to provide improved engineer and end–user interfaces for fault diagnosis and historical engine information.

This paper acknowledges the need for diesel generating sets to further utilize the capabilities of the modern microprocessor by the use of control techniques such as fuzzy logic. It has been shown in other work that, when a fixed-gain PID control strategy is employed in industrial applications such as diesel engine control, the selection of controller gains must provide a compromise of engine performance during both steady-state and transient load disturbances [4], [5]. The authors and others have previously shown that a fuzzy-logic-based algorithm can provide a variable gain strategy that enhances engine transient

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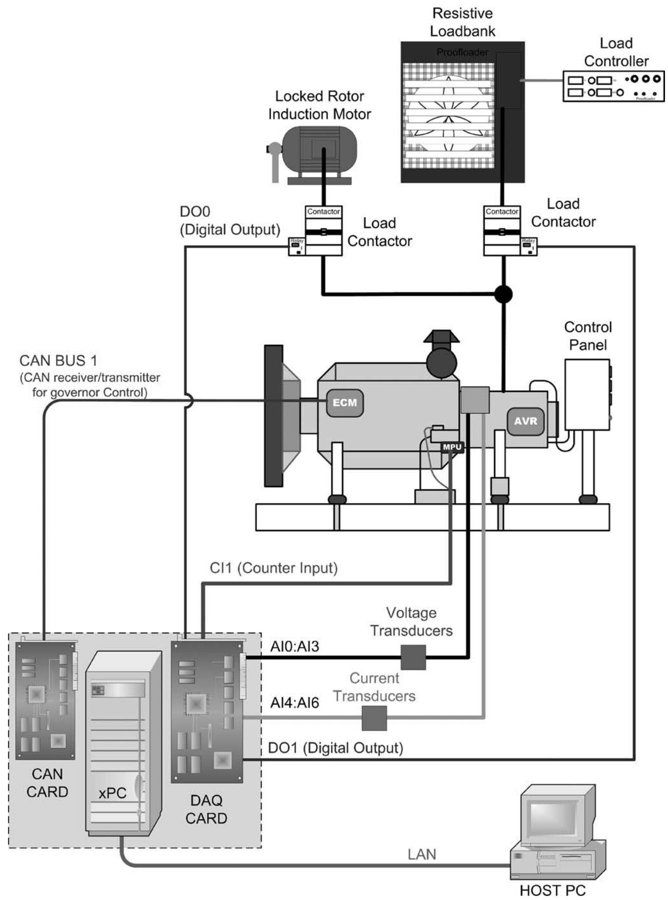

Fig. 1. Illustration of the actual test bed layout.

response to load disturbances while maintaining good steady-state stability [6]–[8]. The ultimate object of this work is, however, that full communication between the engine governor and the alternator's automatic voltage regulator (AVR) be achieved to provide improved power quality for the end-user.

Fig. 1 illustrates the actual test bed hardware layout. The governor input signals are speed sensed from a magnetic pickup and counter input [1] (CT1), three-phase voltage (AI0:AI3), and three-phase current (AI4:AI6) supplied by the alternator. The governor output to the engine control module (ECM) is via controller area network (CAN BUS 1). Digital outputs DO0 and DO1 provide load contactor control and a local area network (LAN) enables communication between the xPC Target PC and the xPC Host PC.

The experimental testing of the governor algorithm considered the load scenario of island operation, i.e., the generating set is connected to an island load, and is not part of a multiple generating set system or synchronized with the mains utility grid. The governor algorithms were implemented in real-time using the generic real-time control environment xPC Target from Mathworks [9]. Further details of the real-time implementation in the Mathworks xPC Target have been detailed elsewhere by the authors [6].

This paper will demonstrate that the engine speed regulation can be improved by using inputs traditionally only processed by the AVR, such as the voltage amplitude or the power factor of the load. The results presented show that load-type determination is achieved. This information is then used to influence the fueling commands from the governor to allow the supplemental control inputs act proportionally during transient load disturbances. Enhanced governing performance of the diesel generating set is achieved, which provides the end-user with a better quality of supply.

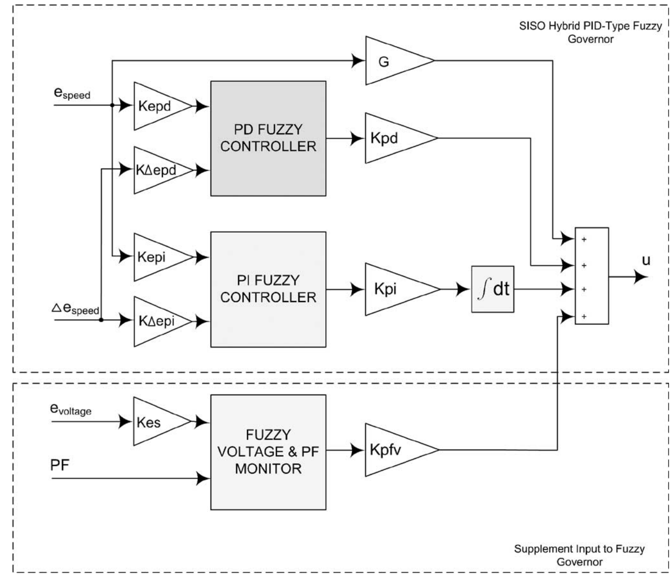

Fig. 2. Hybrid PID-type fuzzy governor with voltage and power factor feed forward control.

II. xPC Target Fuzzy Logic Governor

The control theory chosen for the implementation of the xPC Target-based governor was fuzzy logic. This decision was based on the experience that a digital AVR could be successfully implemented using fuzzy logic control [10], [11]. It must also be noted that as the ultimate objective is a fully integrated generating set controller, consistency of control technique was desirable.

Fig. 2 illustrates the parallel hybrid fuzzy PID-type control structure, it is made up of a fuzzy proportional–intergral (PI) controller and a fuzzy proportional–derivative (PD) controller. Both the PI and PD fuzzy controllers use inputs of engine speed error and change in engine speed error for continuous control of engine speed. A further fuzzy-logic-based voltage and power factor monitor uses the voltage error and power factor of the measured load to preemptively introduce supplemental proportional control into the governor control loop during transient load disturbances. The hybrid parallel fuzzy control structure was chosen because it reduces the complexity of the controller design by reducing the size of the rule base that can result from using more than two inputs to an individual controller [10]–[12].

As was alluded to in the Introduction, previous work was conducted to investigate the suitability of "preemptive" fueling commands [6]. This work concluded that the use of voltage as a feed-forward command could be effective in the minimization of transient speed excursions during real-power load applications. However, the work also highlighted the problem of overfueling due to the voltage error caused by a voltage of low power factor, such as a locked-rotor induction motor. This could cause undesirable overspeed excursions, suggesting the need for load-type determination.

This paper investigates how variables such as voltage and power factor that are closely allied to the desired power output of the engine can be assimilated to provide suitable preemptive fueling inputs to the engine speed governor.

The use of voltage and power factor in an engine speed regulator is unheard of in the current market place. Most engine speed governors employ only speed as an input detected from a flywheel magnetic pickup or proximity sensor [1], [13]– [15]. Traditional speed governing techniques depend on the speed error of the engine for determining the fueling requirement for nominal speed operation at a desired power level. Voltage and power factor may be considered as "alien" inputs to traditional governor control. The use of fuzzy logic is one solution that readily facilitates multiple supplemental inputs that could provide enhanced "fueling influence" to the engine governor, as shown in Fig. 2. This would otherwise be difficult if implemented using conventional PID techniques.

A. *Hybrid PID-Type Fuzzy Logic Controller Tuning*

Hybrid PID-type fuzzy logic controllers can be tuned using a two-tier approach at high and low level.

Low level tuning can be considered as application specific design of the controller. There are a number of factors which influence this:

1) the nature of the system being controlled;
2) number, shape, and distribution of input/output membership sets;
3) rational of the rule base; and
4) type of defuzzification process.

These factors determine the shape of the fuzzy control surface produced. For example, the speed governing of a diesel generating set requires the PD fuzzy controller design to provide proportional and derivative control with the following characteristics.

1) Low gain while regulating close to the nominal speed ensures that there is good steady-state performance.
2) High gain during transient disturbances to minimize the speed deviation and settling time.

Section II-B details the design and low level tuning of the supplementary input fuzzy-logic-based voltage and power factor monitor.

High level tuning involves the selection of the controller gain term values in Fig. 2. For this controller, there are two distinct groups.

1) Input scaling gains (K_{epd}, $K_{\Delta\mathrm{epd}}$, K_{epi}, $K_{\Delta\mathrm{epi}}$, and K_{es}). These gains scale the input values (e_{speed}, $\Delta e_{\mathrm{speed}}$, e_{voltage}, and PF) to the appropriate universes of discourse used in the fuzzy logic inference mechanisms (*Section III-A*).
2) Output gains (K_{pd}, K_{pi}, and K_{pfv}) are used to tune the governor algorithm output value to the correct fuel requirement for the engine.

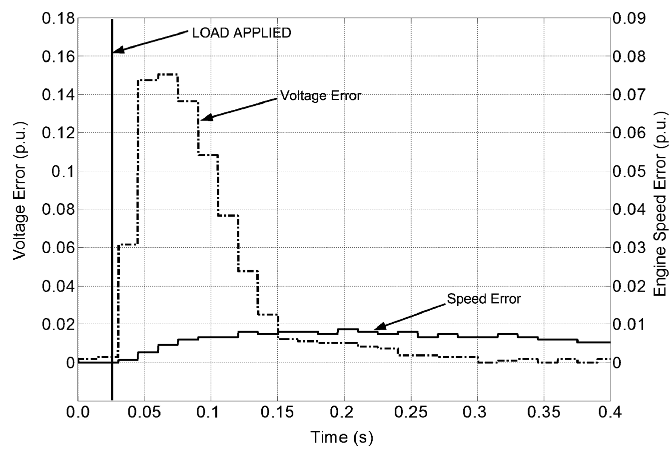

Fig. 3. Comparison of voltage and speed error—30 kVA zero power factor load application.

Other work has shown that for the SISO hybrid PID-type fuzzy structure, the seven gain value can be reduced to three. This is achieved through fixing of input values and the insertion of a nonfuzzy parallel gain term in the control structure [11].

The supplemental input to the fuzzy governor uses the input scaling K_{es} to scale the voltage error to the fuzzy voltage and power factor monitor universe of discourse. No scaling is applied to the power factor input, as it is already rationalized to values between 0 and 1. The K_{pfv} term is used to scale the output to an appropriate value for proportional control input to the SISO hybrid PID-type fuzzy governor control loop.

B. *Fuzzy Voltage and Power Factor Monitor*

Why use voltage and power factor? Initial load tests were conducted to determine the gen-set response to different islanded load scenarios. The tests were conducted on the P50E gen-set using an analogue AVR and the standard variable gain PID governor.

Figs. 3 and 4 show the results from a 30 kVA zero power factor load step and a 33 kW unity power factor load step. The results show the under voltage and under speed as positive error traces. It is apparent from the comparison of Fig. 3 with Fig. 4 that low power factor load applications produce a larger voltage deviation as compared to speed excursion, whereas a unity power factor load application produces a large speed deviation as compared to a relatively low voltage deviation.

It can also be observed from Figs. 3 and 4 that the maximum voltage error is evident before the maximum speed error. Figs. 3 and 4 clearly demonstrate that initial voltage error response is faster than speed error irrespective of the power factor of the load.

The deceleration of the engine/alternator combination, and hence, the speed error is determined by the overall inertia of the rotating mass within the gen-set and also the applied load. The initial response of the voltage deviation depends on the

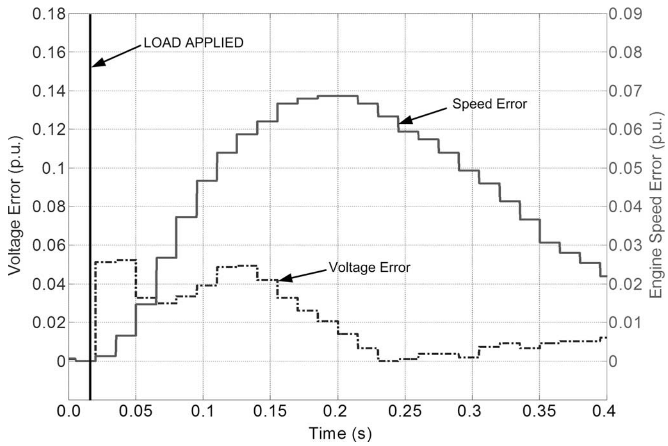

Fig. 4. Comparison of voltage and speed error—33 kW unity power factor load application.

alternator's internal sub-transient and transient impedances and their associated time constants. The time constants associated with the test alternator are 5 ms for the sub-transient time constant and 50 ms for the transient time constant [16]. It is the initial change in voltage that is used to trigger the supplemental control to the governor.

Steady-state phasor representations of a resistive and inductive load are presented in Fig. 5. It can be seen that with unity power factor load, there is very little difference in the magnitudes of the generated EMF (E) and the terminal voltage (V). Fig. 5 also illustrates that for a zero power factor load, there is a relatively large difference between E and V. Thus, the voltage variation for a given current demand is more pronounced for a low power factor than for a high power factor.

Therefore, low power factor loads demand more excitation to maintain nominal alternator terminal voltage, whereas unity power factor load has less of an effect on excitation. Unlike zero factor loads real power loads do, however, require the engine governor to increase fuel in order to maintain the nominal engine speed.

C. Voltage and Power Factor Monitor Controller Design

The implementation of a modern control technique such as fuzzy logic enables the use of linguistic algorithms. This allows the engineer to design the control based on reasoning aligned with human thinking, so that voltage and power factor can be used as additional inputs to the governor algorithm. The control function of the fuzzy voltage and power factor monitor subsystem should provide high gain transient proportional action with minimal proportional gain during steady state or low power factor loads.

The merit of voltage as an early indication of complex load application to the gen-set has been demonstrated in Figs. 3 and 4. The results from complex load testing highlight the need for a further term in the control loop to determine the real power component of the applied load. Load power factor was chosen as an input to quantify the real power.

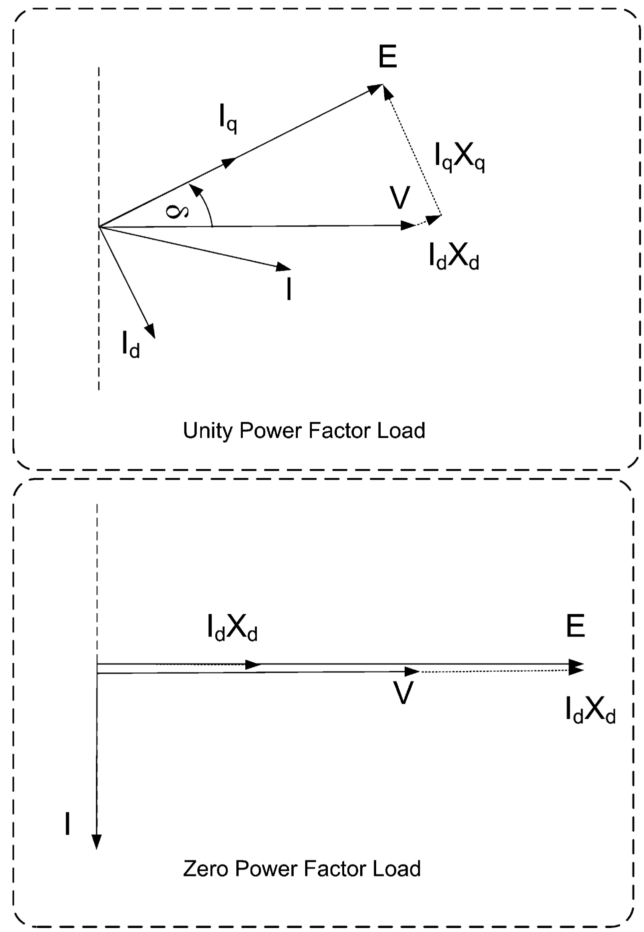

Fig. 5. Phasor comparison of unity and zero power factor load applications.

The fuzzy voltage and power factor monitor was designed using fuzzy control techniques. The control loop is a three-stage process, namely, input fuzzification, inference mechanism, and output defuzzification. This process is called fuzzy inference.

D. Input Fuzzification

Input fuzzification is the method by which the input is assigned membership of different membership sets. These membership sets are described by membership functions such as triangular, trapezoid, Gaussian, or bell shaped. In the interests of simplicity, triangular and trapezoid shaped membership sets were used for the voltage error and power factor inputs, as illustrated in Fig. 2. Another influencing factor was that the PD and PI fuzzy controllers (see Fig. 2) were designed using the same membership sets [6].

The membership sets are assigned linguistic variable names that allow the designer to easily identify the membership set. For example, negative very small (NVS), zero (Z), and positive large (PL). The number of membership sets gives the engineer the desired resolution for the application. In this case, seven sets were chosen. The overlapping of membership sets ensures smooth transition between sets and infers that generally an input will be assigned membership of two sets.

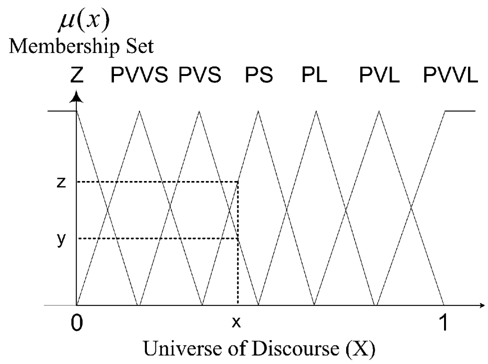

Fig. 6. Graphical representation of input fuzzification for power factor.

For example, a low power factor load with an initial discrete power factor of x_i is applied to the alternator. The power factor input fuzzification process uses a zero membership set and six positive membership sets. The sets are evenly dispersed across the universe of discourse (*X*) $0 \in 1$, which represents the power factor values zero to unity. This is graphically represented in Fig. 6.

For a discrete time period, the input x_i is related to the membership set (function) $\mu_{()}$ as follows

$$\mu_Z(x_i) = 0$$
$$\mu_{\text{PVVS}}(x_i) = 0$$
$$\mu_{\text{PVS}}(x_i) = y$$
$$\mu_{\text{PS}}(x_i) = z$$
$$\mu_{\text{PL}}(x_i) = 0$$
$$\mu_{\text{PVL}}(x_i) = 0$$
$$\mu_{\text{PVVL}}(x_i) = 0$$

This infers that the input x_i is no membership of the input membership sets where its value is zero and a proportionate relationship with the membership sets where its value is nonzero.

The power factor is used to provide a modulus/relative measure of real power. Thus, the inductive/capacitive nature of the load is not determined. This information is used to calculate the required level of proportional control by which the voltage error should preempt the engine fueling quantity

The voltage error input fuzzification process used the following membership sets: one zero membership set, three positive membership sets, and three negative membership sets. This gives the controller the ability to determine whether a load disturbance is load application or load removal and the relative magnitude of load applied.

E. Inference Mechanism

This function in fuzzy logic control is referred to as the rule base. It provides the engineer with a linguistic method by which to describe the control process with heuristic knowledge. The rule base uses a system of *IF* ... *THEN* ... statements. The number of rules is equal to the number of memberships sets to the power of the number of inputs. Consequently, additional inputs give rise to an exponential increase in the number of rules, and thus, an excessively large rule base [12], [17]. A controller with two inputs each with seven membership functions will contain 49 rules.

	Load Rejected			Steady State	Load Applied		
pf \ e_v	NL	NM	NS	Z	PS	PM	PL
Z (Zero PF)	Z	Z	Z	Z	Z	Z	Z
PVVS	NVVS	NVVS	NVVS	Z	PVVS	PVVS	PVVS
PVS	NVS	NVVS	NVVS	Z	PVVS	PVVS	PVS
PS	NS	NVS	NVVS	Z	PVVS	PVS	PS
PL	NL	NS	NVS	Z	PVS	PS	PL
PVL	NVL	NL	NS	Z	PS	PL	PVL
PVVL (Unity PF)	NVVL	NVL	NL	Z	PL	PVL	PVVL

Fig. 7. Voltage and power factor rule table.

For the fuzzy voltage and power factor monitor two inputs were used: voltage error (e_v) and power factor (pf). The design of the rule base was such that the power factor was used to provide deterministic evaluation of the real power component of the voltage deviation during complex load disturbances.

Following on from the example in Section D, the power factor input x_i was assigned membership of two sets PVS and PS. Assume that the voltage error has been fuzzified to be represented by two membership sets NS and Z. From this information, it can be determined that 4 out of the 49 rules will be "fired."

This can be represented in a lookup table, as illustrated in Fig. 7.

The rule base can also be described linguistically as follows.

IF e_v is NS and *pf* is PVS *THEN u* is NVVS
IF e_v is NS and *pf* is *PS THEN u* is NVVS
IF e_v is *Z* and *pf* is PVS *THEN u* is *Z*
IF e_v is *Z* and *pf* is *PS THEN u* is *Z.*

Heuristic assessment of the rule-based lookup table allows the engineer to determine that the control action has been appropriate. A small voltage error and low power factor input should yield a relatively small controller action. Section II-F will discuss how these rules are arithmetically interpreted.

The use of a rule table demonstrates how expert knowledge of the system is required to design the voltage and power factor controller. The rule base is designed so that the influence of voltage deviation takes into account both load application and rejection. The measured power factor determines the extent to which the voltage input should influence the fuel output of the governor.

Fig. 7 highlights the four rules that have been executed or "fired." The next stage in the inference mechanism is calculation of the firing strength of each of the rules. Two common methods by which to determine the firing strength are the algebraic product and the intersection method [18]. For the voltage and power factor monitor, the algebraic product method was chosen:

for all $e_v \in [-, 1], pf \in [0, 1]$
algebraic product $e_v pf = u_{i()}$.

This uses algebraic multiplication of the voltage error and power factor membership sets to determine rule firing strength. The rule firing strength is used by the defuzzification process to "fire" the relevant output membership sets.

F. Output Defuzzification

There are two main methods of fuzzy logic defuzzification [19].

1) *Mandani method:* output membership set functions similar to the input fuzzification process. Computationally intensive [20].
2) *Takagi–Sugeno method:* uses output singleton values. The use of singleton outputs yields crisp control values, simplifying the defuzzification process [21].

The Takagi–Sugeno method was implemented in the voltage and power factor monitor controller. The weighted mean method of defuzzification was used to sum the "fired" control rules are to give a "crisp" output signal. Work by Butkiewicz concluded that the behaviors of fuzzy logic depends on the rule base and plant parameters rather than the defuzzification methods employed [22].

G. Online or Offline Fuzzy Inference Mechanisms?

The fuzzy logic inference mechanism can be implemented as an "online" or "offline" control algorithm.

The "online" implementation is selected used during testing as the xPC Target PC's processing power and memory was not a limiting factor. The "online" implementation permits for the tuning of all the individual parameters during the development process. The algorithm receives actual input data and processes the data step by step through the inference mechanism to generate the controller output.

For field trialing of the fuzzy logic control techniques an embedded hardware platform would be more suitable. An "offline" implementation would be more appropriate when the execution of the algorithm is on a microprocessor, where processor resources and memory are a premium, and hence, become limiting factors. The fuzzy control algorithm requires execution in simulation with dummy input data to generate a control surface. The real-time control is performed using the control surface lookup table with interpolation between input data to determine the required output value, see Fig. 8.

The choice of online or offline implementation of the fuzzy control algorithm depends on processor power. During testing, the online implementation of the algorithm was used. This provided the online tuning of all algorithm parameters, whereas an offline implementation requires a new surface each time a variation to the control surface is required. As stated by Braae and Rutherford, the use of offline or online is not significant, rather it is a matter of computational time for the controller to obtain an output for a given input [23].

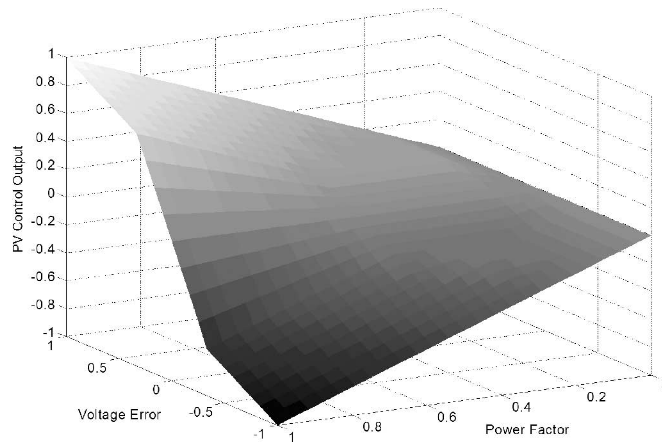

Fig. 8. Voltage and power fuzzy control monitor offline control surface.

III. Complex Load Testing

Previous work using a hybrid PID-type fuzzy governor with voltage only influence provided preemptive fuel control [6]. The complex load testing was conducted to investigate whether the use of fuzzy-logic-based control could be used to determine the real power load component of a voltage dip. The influence of the control should be proportional, hence improving transient performance without degradation of the steady-state frequency band.

The experimental test procedure conducted and results presented are in accordance with the G3 performance classification outlined in ISO8528 Part 5 [24].

A. Unity Power Factor Performance

The unity power factor load application test results are shown in Table I. This compares the transient performance of the SISO and MISO governing approaches. It is evident that the use of supplemental inputs reduces the maximum speed deviation during transient conditions. A 2.1% improvement for load application is obtained when using supplemental inputs to the governor and 2.2% improvement for load removal.

This table demonstrates that the use of a voltage and power factor influenced governor provides the same enhanced governor performance as compared with a MISO fuzzy governor with voltage only influence. This is achieved by assessing that the load applied is of unity power factor, therefore, all voltage deviation is due to real power load applied (*neglecting the effect of internal machine losses*).

B. Zero PF Load Application

The zero power factor load testing should respond with minimal speed deviation, as the change in real power is due only to

TABLE I
COMPARISON OF SISO GOVERNOR WITH MISO GOVERNORS—33 kW UNITY POWER FACTOR LOAD APPLICATION

		Variable gain PID (SISO)	Hybrid PID type fuzzy with voltage influence (MISO)	Hybrid PID type fuzzy with voltage & PF influence (MISO)
33 kW load applied	$f_{d,min}$	-6.9%	-4.8%	-4.8%
	t_f	1.67 s	1.24 s	1.25 s
33 kW load removed	$f_{d,max}$	+7.2%	+5.5%	+5.5%
	t_f	1.35 s	1.56 s	1.34 s

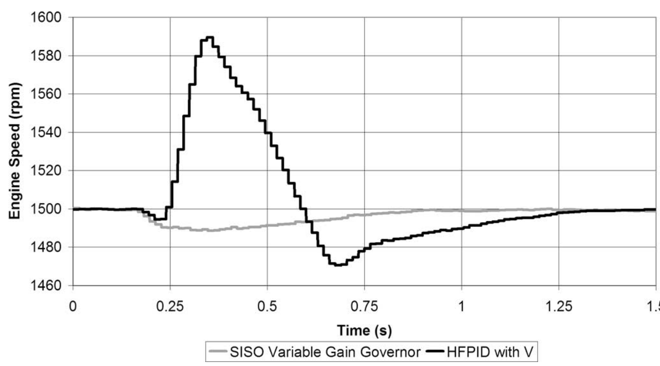

Fig. 9. Comparison of an SISO variable-gain governor with a hybrid PID-type fuzzy governor with voltage influence for a 30 kVA zero power factor load application.

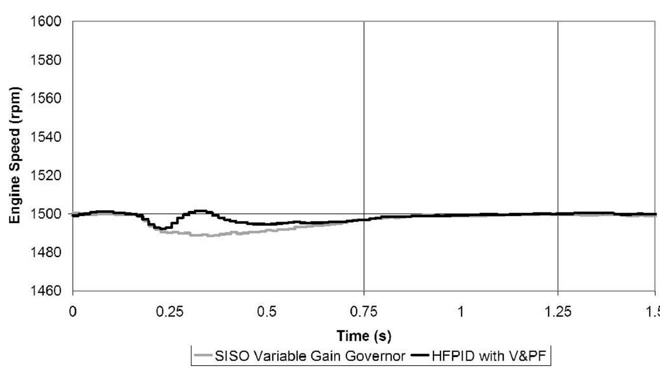

Fig. 10. Comparison of a SISO variable-gain governor with a hybrid PID-type fuzzy governor with voltage and PF influence for a 30 kVA zero power factor load application.

I^2R losses within the machine. Previous work highlighted the problem that with a zero power factor load, and voltage only influenced governor control, undesirable control action occurred. It was this problem that prompted a move to a voltage and power factor influenced governor, so that a quantification of the real power demand from the load could be ascertained. Results for zero power factor load application are presented in Figs. 9, 10, and Table II.

It is apparent from comparison of Figs. 9 and 10 that the use of a load discerning term such as power factor enables the governor algorithm with voltage and power factor influence to prevent the unnecessary overshoot that occurs with the voltage only influenced governor algorithm.

TABLE II
COMPARISON OF SISO AND MISO GOVERNOR ENGINE SPEED RESPONSES—30 kVA ZERO POWER FACTOR LOAD APPLICATION

	Variable gain PID (SISO)	Hybrid PID type fuzzy with voltage influence (MISO)	Hybrid PID type fuzzy with voltage & PF influence (MISO)
$f_{d,min}$	-0.76%	-2.0%	-0.51%
$f_{d,max}$	+0.02%	+5.97%	+0.11%
t_f	0.63s	1.06s	0.59 s

The small improvement in speed regulation of Fig. 10 can be attributed to the real power (I^2R) losses of the "zero power factor" inductive load bank. This power is detected by the voltage and power factor controller, which increases the fueling proportionally. This enhances the speed regulation of the MISO fuzzy voltage and power factor governor in comparison to the SISO variable-gain PID governor.

From Table II, it can be observed that the use of the power factor term within the control loop prevents the $+5.97\%$ overshoot experienced with the voltage only influenced term.

The use of the voltage and power factor algorithm also improved the governor response as compared to the SISO governor in that it was still able to discern the speed deviation due to machine losses, and apply a small preemptive fueling adjustment with proportional voltage input.

C. Motor Load Application

The motor load application was conducted to verify the engine speed regulation performance due to a complex load application. The motor details were as follows.

1) three-phase 11 kW induction motor;
2) 400 V delta connected; and
3) locked rotor test—power factor 0.5.

The results for the motor load application tests are presented on a dual *y*-axis graph with the axis labels engine speed in revolutions per minute (rpm) and fuel quantity per injection in milligram.

Fig. 11 illustrates a conventional PID engine-speed recovery response. The fuel quantity trace that is observed is wholly dependent relationship between speed error and the gain selection of the variable gain scheduled PID controller. The maximum fueling quantity is achieved when the speed error is at the maximum value.

From Fig. 12, it can be observed that the use of a fuzzy-logic-based proportional voltage error controller can add preemptive fueling demand to the final fuel quantity. The initial step in fuel quantity demand is principally due to the voltage error caused by the motor load application. As the locked rotor motor load has a low power factor, voltage error will be significantly larger that that of an 11 kW unity power factor load. Hence, without a load discriminating term such as power factor, there is

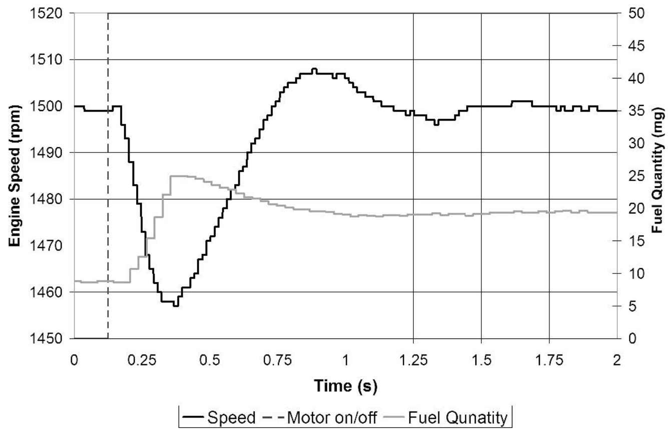

Fig. 11. Engine speed and fuel load acceptance response for a three-phase, 11 kW locked rotor induction motor application—Governor algorithm SISO variable-gain PID.

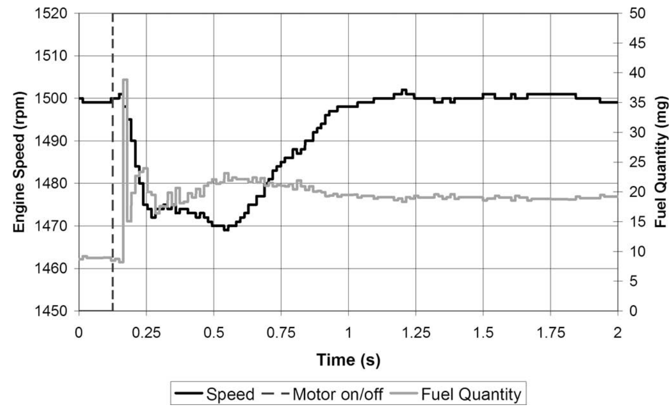

Fig. 13. Engine speed and fuel load acceptance response for a three-phase, 11 kW locked rotor induction motor application—Governor algorithm MISO hybrid PID-type fuzzy control with supplementary voltage and power factor influence.

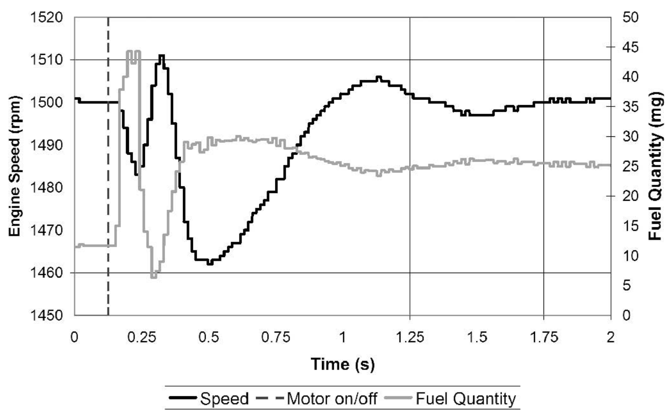

Fig. 12. Engine speed and fuel load acceptance response for a three-phase, 11 kW locked rotor induction motor application—Governor algorithm MISO hybrid PID-type fuzzy control with supplementary voltage influence.

TABLE III
COMPARISON OF SISO AND MISO GOVERNOR ENGINE SPEED RESPONSES—THREE-PHASE111 kW LOCKED ROTOR INDUCTION MOTOR LOAD APPLICATION

	Variable gain PID (SISO)	Hybrid PID type fuzzy with voltage influence (MISO)	Hybrid PID type fuzzy with voltage & PF influence (MISO)
$f_{d,min}$	-2.9%	-2.5%	-2.1%
t_f	1.24 s	1.40 s	0.80 s

sustained over fueling of the engine. This results in an undesirable speed excursion and an increased settling time of the control response as compared to that of the variable gain PID governor, as observed from Table III.

Fig. 13 indicates that when both voltage and power factor are utilized for preemptive control, that there is an initial stepped response in fueling. When power factor is used to determine the real power component of the load, a compensated proportional gain term based on voltage error is used to prevent over fueling.

It is clear from Figs. 12 and 13 that the effect of earlier fueling response aids in the reduction of the maximum speed deviation experienced during transient load disturbances. From Table III, it can be determined that a 27% improvement in maximum speed deviation can be obtained using the hybrid PID-type fuzzy controller with voltage and power factor when compared with the variable gain PID controller.

The classical control response characteristic, as represented by Fig. 11, is not apparent when using nonlinear control techniques such as hybrid PID-type fuzzy control. The introduction of the proportional voltage and power factor monitor adds a further degree of nonlinearity into the control loop.

IV. CONCLUSION

The use of voltage and power factor influence with an engine speed governor can be utilized to provide enhanced transient complex load acceptance performance.

The paper demonstrates successful implementation of a supplementary input to an engine speed governor algorithm. Engine recovery during transient conditions is improved without affecting steady-state stability.

Use of power factor provides discrimination between real and reactive elements of complex load. Testing with voltage only influence caused unnecessary overfueling on the application of zero and low power factor motor loads. When power factor load discrimination was implemented, this unnecessary fueling was eliminated.

This control method provides proportional control, which preemptively provides more fuel before speed error increases.

This technique could be used to give preemptive control during load application to aid the engine in achieving the tolerance level demanded by the International Standards Organization (ISO) standards body [24]. This will provide a clear advantage to the manufacturers of the gen-set when they are close to or exceeding the ISO8528 Part 5 performance classification for a specific engine size.

The authors are currently evaluating multiple input governor control for application on turbocharged diesel gen-sets, and will hope to describe the results in a sequel to the present paper.

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