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Simulation & Performance Analysis of Stand-by Distributed Generation System

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The engineering fraternity faces the formidable challenge to cope with the exponential rise of energy demand simultaneously with the depleting reserves of fuel and environmental issues. With the development in technology and the rising demand for supply of electricity, diesel-based power generation is being used as a standby or emergency to feed this demand and at the time of unavailability of other sources. In case of emergency or as a backup system diesel-based power generation is considered in this thesis. A simulation model of diesel engine along with governor and exciter unit is developed in MATLAB/SIMULINK. The simulation performance is analyzed for different operating conditions with various resistive, inductive and capacitive loads. The exhaustive simulation results show the good dynamic and transient performance with voltage and frequency. The parameters of the machine are selected to achieve the desired electrical supply with a controlled voltage and frequency for 10%-80% loading conditions. The controller parameters (such as time constants, gains and coefficients) of the governor and automatic voltage regulator (AVR) are selected and tuned for a good transient and steady-state performance. The simulation results show a satisfactory performance in terms of efficiency, generated voltage, generator speed and frequency.

Keywords — *Automatic Voltage Regulator, Diesel Machine, Exciter Unit, Generator, Governor*

1 Introduction

The wind and PV generation systems are major source of renewable power generation. Wind and PV are good energy sources to provide reliable power at steady state, and also respond to electrical load transients as fast as desired.

Due to lack continuity and unavailability of wind & solar power, stand-alone wind/PV based energy systems generally require storage system or some available generation resources (diesel generator considered) to develop a hybrid system[1].

The power system industry is going through a revolutionary stage in technology as well as business structure. Today's technologies, such as smart appliances are growing the capability of utility. But none of these can revolutionize the planning & operation of distribution generation[1]. The concept of distributed generation has some different meaning with some confusion. Distributed generation means any modular power generation at or near the load[2] such as fuel cells and micro turbines and diesel based power generation. With the recent development in technology and increasing demand of electrical energy, diesel-based power generation is found as a feasible alternative to fulfill this growing demand and during unavailability of other sources.

The original structure of distribution networks is radial and it is not considering penetration of any significant power in it. In a radial feeder, the power is unidirectional from a source to the load. The interconnection of diesel generator to the feeder may lead a reverse power flow. This reversal flow violates the criteria of "radial design" and will have wrong impact on the performance of the feeder.

In view of the above discussion it can be seen that a lot of works have been carried out in the area of hybrid distributed generation based on RES, also the number of control methodologies is carried out in the past to eliminate distributed generation control problem. The uncertainty of the RES due to external reasons may be environmental or geological; it creates irregularity in supply demanded by load. So to fulfill the load demand continuously a diesel based back-up system will solve the problem of irregularity in supply.

Now the diesel generator can also be connected to feed load when an emergency saturation or can be said if solar & wind supply is not available. One

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cannot legally connect an AC generator to the grid unless voltage, frequency is in phase with in coming supply. No home generator can do that without a phase synchronizer. It can be possible with proper control at point of integration, using a stand-alone diesel generator based system is an alternate option for the small and medium load with a simple control structure.

Figure 1 shows the schematic diagram for the component models based diesel power generation. A simulation based system for the alternative energy source is developed in Simulink. Figure 2 is the diagram of overall simulation model in Simulink. The overall control strategy for power management of the diesel based generation system is presented in this paper. The performance is investigated in various operating conditions.

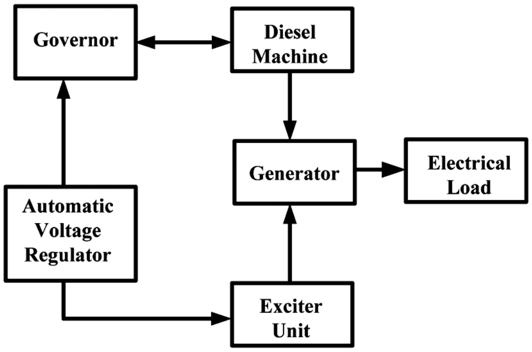

Fig. 1 — Schematic diagram of diesel generator.

2 Mathematical Model of the Diesel Generator

Diesel generator based power supply is used as secondary source in case of unavailability of grid supply. Therefore their reliability matters a lot. For reliability test of control system governing the diesel-generator is simulated by using an alternator having its mechanical energy from diesel engine.

The mathematical model of the diesel based power generator is developed in MATLAB[3], is shown in Fig. 2. The alternator gets its field voltage from the excitation system. The main components of diesel generator are synchronous generator, excitation system, diesel engine and its speed controller that has been modeled.

2.1 Mathematical Modeling of Synchronous Generator

The performance analysis depends on the analysis of the salient rotor generator's mathematical model. The electromechanical and transient model of machine is sufficient enough to characterize the generator performance[4]; thus a fifth-order practical generator has been modeled Eqs 1-7[5].

$$u_d = E_x'' + X_q'' i_q - R_s i_d \quad \dots (1)$$

$$u_q = E_q'' + X_d'' i_d - R_s i_q \quad \dots (2)$$

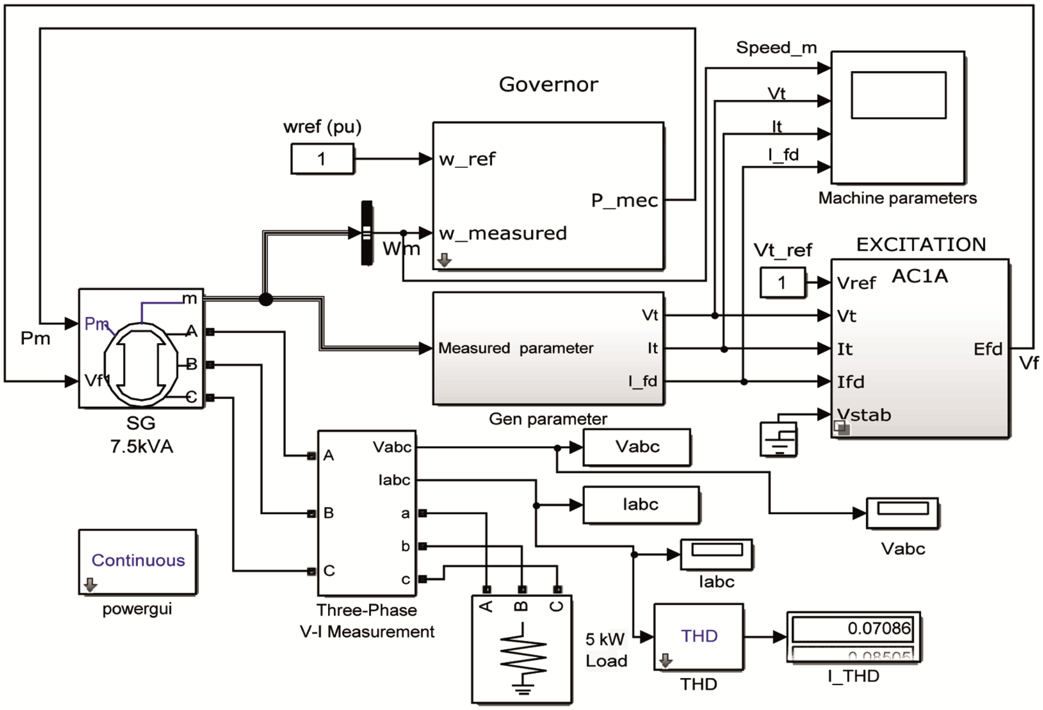

Fig. 2 — Simulink diagram of stand-alone diesel generator with load.

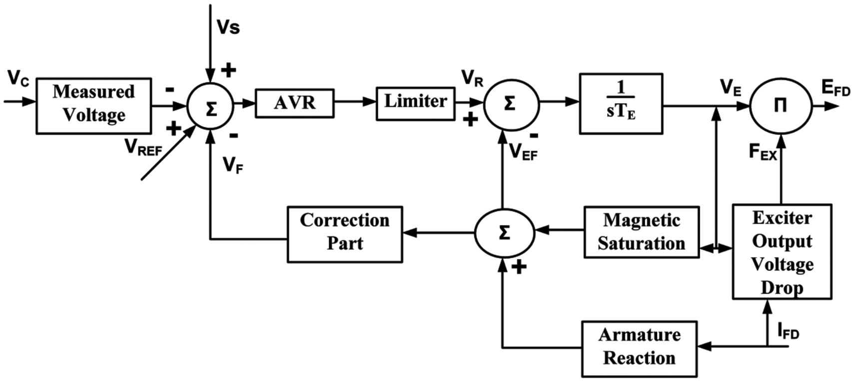

Fig. 3 — Block diagram of an AC exciter with AVR.

$$T_{d0}^{'}pE_q^{'} = E_f - (E_q^{'} - X_{d\tau} + X_{d\tau}E_q^{''}) \quad \text{... (3)}$$

$$T_{d0}^{''}pE_q^{''} = -E_q^{''} + E_q^{'} - (X_d^{'} + X_d^{''})i_d \quad \text{... (4)}$$

$$T_{q0}^{''}pE_d^{''} = -E_d^{''} + (X_q - X_q^{''})i_q \quad \text{... (5)}$$

$$T_J p\omega = T_m - \left[E_q^{''}i_q + E_d^{''}i_d + \left(X_d^{''} - X_q^{''}\right)i_d i_q\right] - D\omega \text{... (6)}$$

$$P\delta = \omega \text{ -}1 \quad \text{... (7)}$$

Where:

P is	differential operator
E_d is	d-axis sub-transient force
D is	generator damping
T_m is	drag torque of the generator
E_f is	stator excitation force
E_q is	q-axis transient force
E_d is	q-axis sub-transient force

2.2 Mathematical Modeling of Excitation System

The AC exciter is used in diesel generator excitation system. AC exciter used here is with a rotary rectifier, so that carbon brushes and slip rings are not required. That becomes more robust and reliable than the exciter using a static rectifier.

The block diagram of exciter with AVR (Automatic Voltage Regulator) is shown in Fig. 3

2.2.1 Saturation-Coefficient of an AC Exciter

Here the excitation characteristics of the AC exciter based on the equations given below is shown in Fig. 4. The structure of exciter is shown in Fig. 5.

$$\frac{E_{FD}}{V_R} = \frac{K/(R(1+R/r))}{\frac{1-K/r}{1+R/r}+\frac{M}{R}s} \quad \text{… (8)}$$

$$V_E = E_{FD} = KI_{FF}(B/A) \quad \text{… (9)}$$

Where in E_{FD} is output voltage of exciter, V_R is the excitation voltage of exciter, is shown in Fig. 4[6].

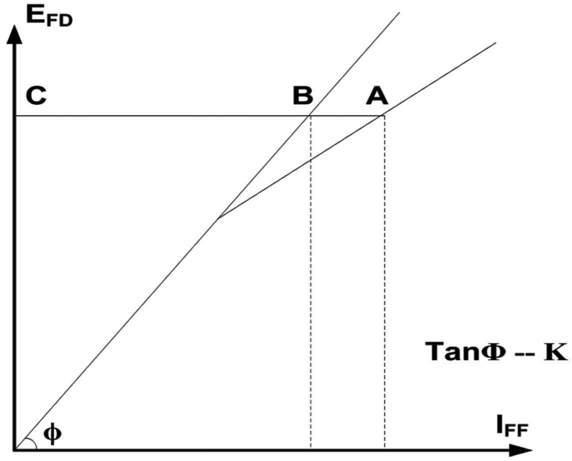

Fig. 4 — Exciter saturation characteristics.

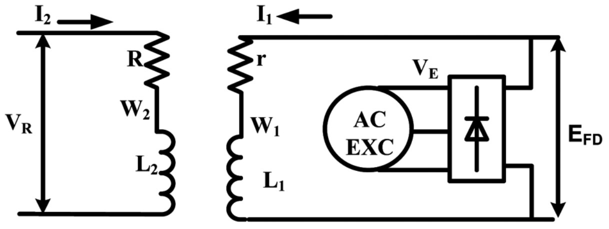

Fig. 5 — Exciter structure and AC alternating current.

Combining Eqs 8 and 9, it would be the following Eq 10, considering magnetic saturation.

$$\frac{E_{FD}}{V_R} = \frac{K/(R(1+R/r))}{K_E+((A-B)/B)/(1+R/r)+T_Es} = \frac{K/(R(1+R/r))}{K_E+S_E+T_Es} \quad \text{… (10)}$$

Where

Exciter saturation factor $S_E = (\frac{(A-B)}{B})/(1+R/r)$

K_E is self-excited coefficient of exciter

$r = \infty$; and $S_E = \frac{(A-B)}{B}$

2.2.2 AC Exciter - Armature Reaction

The main diversity between DC exciter and AC exciter reflects on the characteristics; armature reaction of AC exciter is stronger and it should be always considered. The current of AC exciter is assumed as vector value on the vertical axis and K_D is the armature reaction coefficient.

2.2.3 Voltage Drop Due to Changing Arc

The output of the generator is connected to the various loads, and then the voltage drop will be occurred. If the voltage drop is neglected in the rectifiers, the DC output voltage will be difference of no-load voltage and voltage drop due to load. As per the current characteristics of three-phase bridge rectifier, it can be derived by the following formula[7].

$$E_{FD} = V_E(1 - 0.577 I_N) \qquad \text{When } I_N \le 0.4333$$

$$E_{FD} = V_E\left(\sqrt{0.75 - I_N^2}\right) \qquad \text{When } 0.433 < I_N < 0.75$$

$$E_{FD} = V_E\left(\sqrt{3}(1 - I_N)\right) \qquad \text{When } 0.75 \le I_N \le 1$$

… (11)

2.2.4 Modeling of Automatic Voltage Regulator (AVR)

The voltage regulator generally has voltage sensing, comparing, and the correction part. The voltage sensing part commonly presented by first-order transfer function as

$$W_B(s) = \frac{K_T}{1+T_T s} \qquad \dots (12)$$

$$W_F(s) = \frac{K_F s}{1+T_F s} \qquad \dots (13)$$

Where

K_T coefficient of the RC filter
T_T time constant
K_F the ratio coefficient and time constant of
and T_F the feedback

The correction of excitation system is necessary to improve the static and dynamic performance of exciter.

2.3 Modeling of the Diesel Engine with Governor

The diesel engine itself and its governor are dynamic and non-linear in nature, whose structure diagram is shown in Fig. 6.

2.3.1 Controller Modeling

The controller is in diesel engine is used to set the speed, here PID controller is used. Here the controller uses critical ratio method to obtain at its factor control performance. The measurement of speed is presented by the first-order inertia link and its transfer function can be set to 1 if the dynamic effect on the governor is neglected.

2.3.2 Actuator Modeling

The actuator is used to translate the controller output into an axial displacement that is associated with the controller output. The transfer function of actuator can be expressed as

$$\frac{a(s)}{u_c(s)} = \frac{K_1}{T_1 s+1} \qquad \dots (14)$$

Where

$K_1 \mathit{is\ the\ actuatorgain}$
$T_1$is the time constant of the actuator

2.3.3 Mathematical Modeling of Torque Lag

The time delay generated due to actuator, combustion process of engine and thermodynamic process is presented by the given equation:

$$\frac{M_d(s)}{a(s)} = \frac{1}{t_d s+1} \qquad \dots (15)$$

Where t_d is the time constant, and calculated by

$$t_d = \frac{15}{n_n} \le t_d \le \frac{15}{n_n} + \frac{120}{n_n i}$$

Where n_n is the rated speed of engine and *i* is number of strokes of engine.

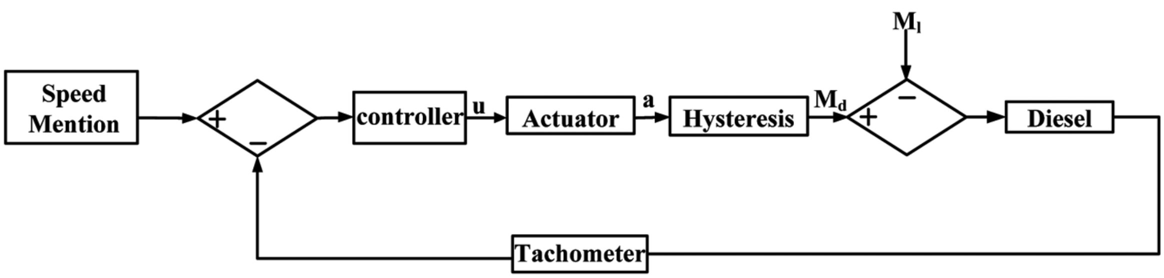

Fig. 6 — Structures of diesel and its governor.

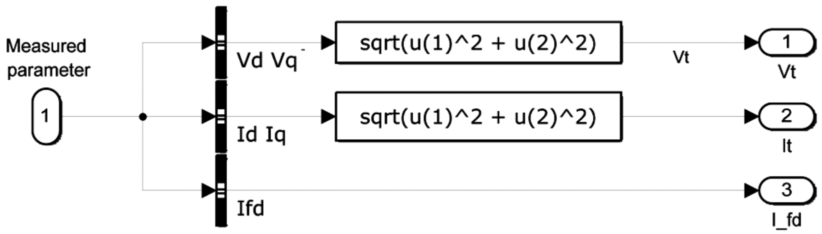

Fig. 7 — Measured parameters from generator.

2.3.4 Mathematical Modeling of Diesel Engine

The transfer function of diesel engine is presented by first-order expression

$$\frac{\omega(s)}{M_d(s)-M_1(s)} = \frac{1}{T_a s+C_d} \qquad \dots (16)$$

Where

C_d is coefficient of damping

T_a the diesel engine time constant

3 Simulation Results

The rated capacity of synchronous generator is 7.5 kVA with the rated line voltage of 415V and rated frequency of 50 Hz. Measured parameters from generator has been shown in Fig. 7.

There is provision for diesel generator to start manually/automatically, and produce voltage at the moment when grid supply is not available. If the entire load is connected at one time, then there will fluctuations in voltage and frequency, and the high capacity generator will be required; therefore, the diesel generator loads in step so that less chances of instability and it will maintain the capacity of the diesel generator, reduction in cost, and enabling the fast and efficient loading. The results of simulations are given in Figures below. The PID controller parameter is given in Table-1 and Main parameters of the diesel engine is given in Table-2

3.1 Output Voltage Curve at 3 kW Load

The generator parameters are given in above Table 2. A 3 kW load is connected to the synchronous generator. The output voltage wave form of the synchronous generator is shown in the Figure 8.The simulation is performed for 10 seconds. The output voltage waveform of the synchronous generator at any instant can be observed as line voltage. The performance of synchronous generator is found satisfactory in all conditions of load. The voltage across the output terminal is constant i.e. 415 volts as shown in Fig. 8. The voltage wave form shown here for a specific time (zoomed view).

Table-1 — The PID controller parameter

Parameter	Values
K_p	20
T_I	0.1
K_D	0.05

Table 2 — Parameters of Synchronous Machine

Nomenclature	Values
Nominal Power	$7.5\text{x}10^3$VA
Voltage	415 V
Frequency	50 Hz
Synchronous Reactance X_d (p.u.)	0.7
Transient Reactance X_d' (p.u.)	0.28
Sub-transient Reactance X_d'' (p.u.)	0.027
Synchronous Reactance X_q(p.u.)	0.2
Transient Reactance X_q' (Only in case of round rotor)	NA
Sub-transient Reactance X_q'' (p.u.)	0.08
Leakage Reactance X_l (p.u.)	0.02
Stator Resistance (p.u.)	0.0012
Inertia Coefficient H	0.4
Friction factor F (p.u.)	0.1
No of Poles	4

3.2 Output Current Curve at 3 KW Load

The output current waveform of the synchronous generator at 3 kW is approximately 4.8 amps, as shown in the simulated result at particular instant. The performance of synchronous generator is within the specified limit. The current waveform is shown in Fig. 9.

3.3 Output Voltage Curve at 4 kW Load

Now 4 kW load is connected to the synchronous generator. The output voltage waveform of the synchronous generator is shown in the Fig. 10. The simulation is performed for 10 seconds. The output voltage waveform of the synchronous generator at any instant can be observed as line voltage. The performance of synchronous generator is found satisfactory in all conditions of load. The voltage across the output terminal is constant i.e. 415 volts as shown in Fig. 10. The voltage waveform shown here for a specific time (zoomed view).

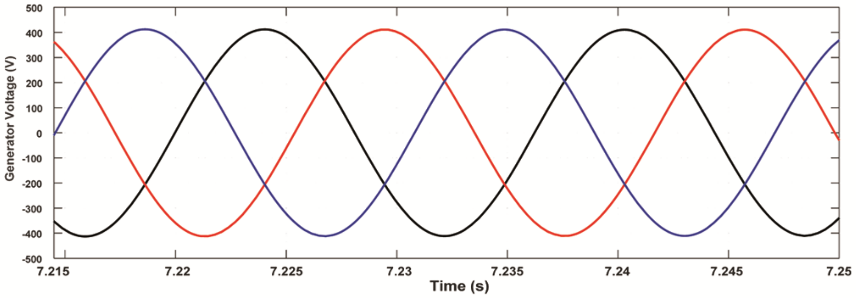

Fig. 8 — Generator output voltages at 3 kW.

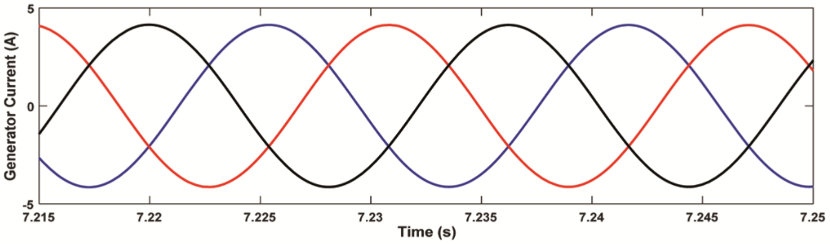

Fig. 9 — Generator current at 3 kW.

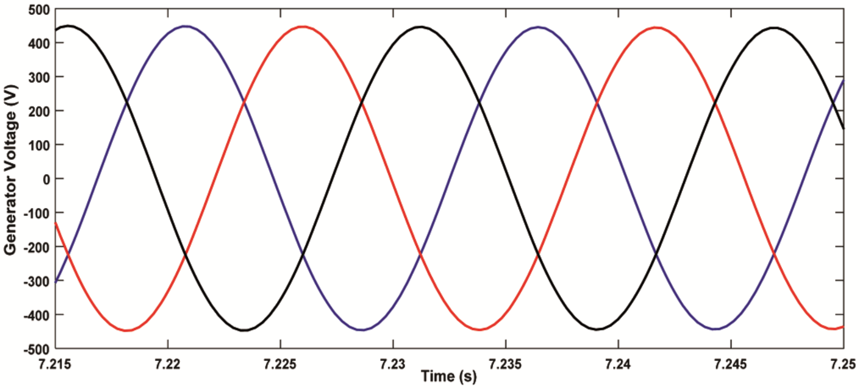

Fig. 10 — Generator Voltages at 4kW.

3.4 Output Current Curve at 4 kW Load

The output current waveform of the synchronous generator at 4kW is approximately 4.8 amps, as shown in the simulated result at particular instant. The performance of synchronous generator is within the specified limit. The current waveform is shown in Fig. 11.

3.5 Output Voltage Curve at 5 kW Load

The 5 kW load is connected to the synchronous generator. The output voltage waveform of the synchronous generator is shown in the Fig. 12. The simulation is performed for 10 seconds. The output voltage waveform of the synchronous generator at any instant can be observed as line voltage. The performance of synchronous generator is found satisfactory in all conditions of load.

3.6 Output Current Curve at 5 kW Load

The output wave form current of the synchronous generator at 5 kW is approximately 9 amp as shown in the simulated result at particular instant. The performance of synchronous generator is within the specified limit. The current wave form is shown in Fig. 13

3.7 Output Speed Curve

The speed of the generator is within the specified range around 1 p.u. There is a small variation in speed as shown in Fig 14. The variation in speed curve is shown in Fig. 14 and deviation is 0.2 p.u.

3.8 Generator Id & I_q curve

To control the rotor flux in the synchronous generator the I_d component reference is used and to

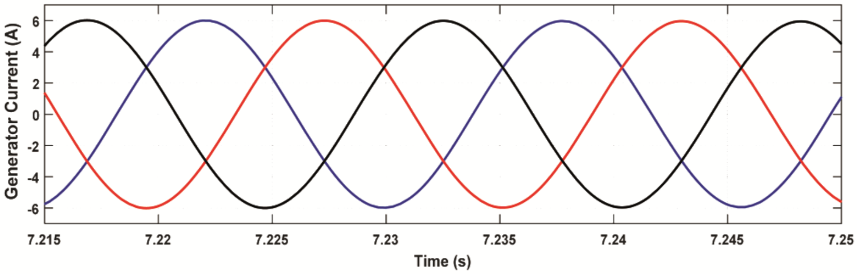

Fig. 11 — Current at 4kw.

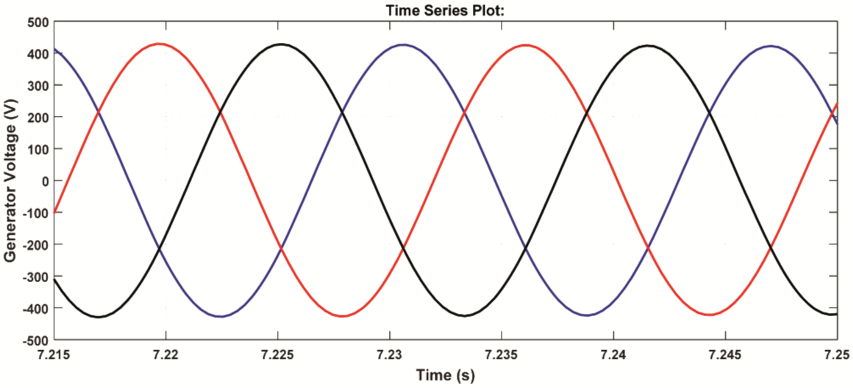

Fig. 12 — Generator Voltage at 5kW.

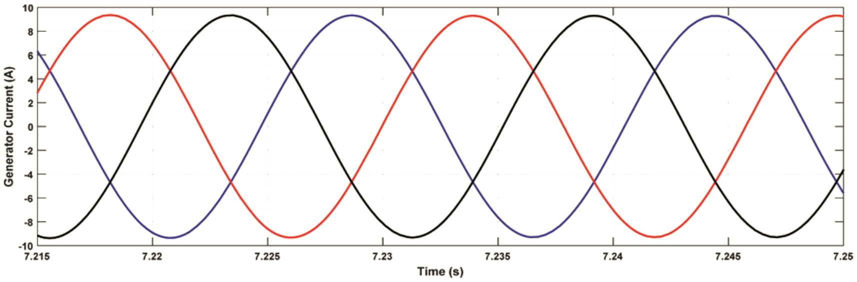

Fig. 13 — Generator current at 5 kW.

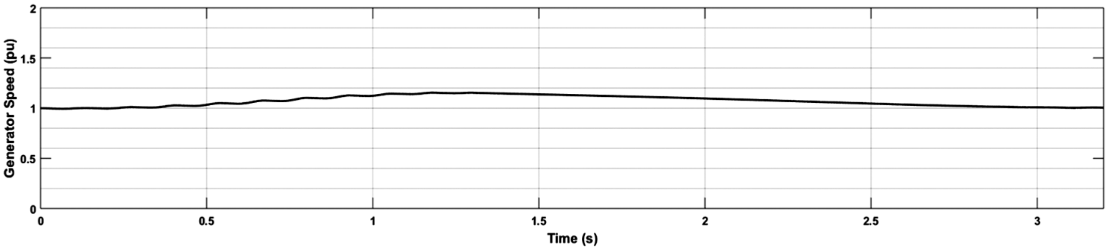

Fig. 14 — Generator speed curve at 4 kW load.

control the produced torque the I_q component reference is used. The value of I_d is near to zero i.e the produced torque is maintained. The stability of the system is satisfactory. The d-q components are used in the calculation of rotor flux and the slip speed and therefore the reference currents can be generated. The I_d-I_q reference currents are generated by the speed control loop and the position control loop. The generator d-axis and q-axis currents I_d and I_q at 4 kW load are shown in Fig. 15.

3.9 Generator V_d &V_q Curve

The two components and V_q are converted back into the stationary reference frame using the

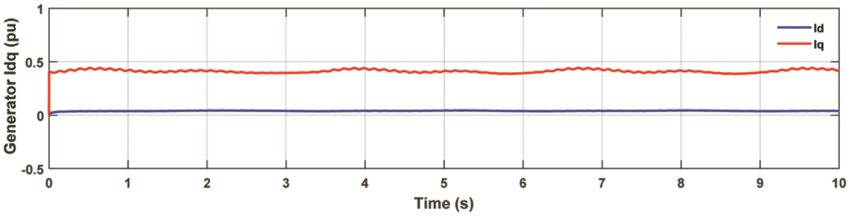

Fig. 15 — Generator Id and Iq currents.

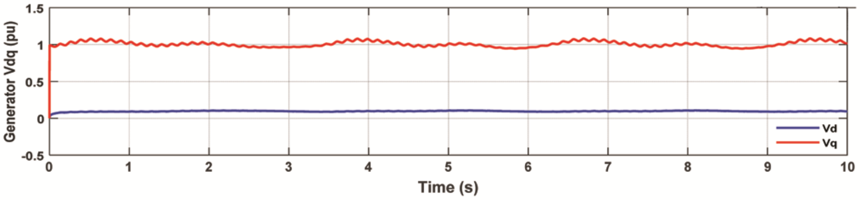

Fig. 16 — Generator voltage V_d and V_q (pu).

transformation angle to obtain quadrature voltage values. This maintains the speed of synchronous generator within the normal value. This is part of voltage equation of generator in rotating reference frame. The generator d-axis and q-axis voltage V_d and V_q at 4 kW load are shown in Fig. 16. From this it is clear that d-axis voltage is near to zero.

The diesel engine starts and catches the rated speed i.e 1500 rpm. The synchronous generator armature coupled with diesel engine. The rise time of synchronous generator terminal voltage is 0.93 sec, peak time is 1.11 sec, the overshoot is 9.0 %, and the adjusting time is 1.37 s (with deviation of 2 %).

From the simulation results it is observed that the amplitude of voltage is stable during the process of loading, the exciter adjustment is appropriate, and the deviation in speed comparatively less. The load rate is 80 % at the end of the loading process with the load rate of maximum 100 %; thus, the simulation model shows a three-fold margin to fulfill the demand.

4 Conclusion

The diesel generator is a vital alternative to make sure the availability of electrical supply in case of non-availability of commercial supply and other RES based supply to facilitate smooth life of living human as well as to feed critical loads etc. It is very important to simulate and analyze the diesel generator's parameter with respect to time. The simulation model of generator based on the MATLAB is developed and simulated the loading process with the satisfactory results validating the validity and efficacy of proposed system.

This paper does not promote use of diesel engine as power back-up but it is supposed to be used in emergency situation, when no other options are available, as it increases pollution and emission level that is not suitable for environment. The Government of Delhi has put a ban on use of diesel based electric generators for domestic and commercial purpose, that step is appreciable but with same time government has to ensure the 24x7 continuous grid supply so that daily life should not be affected.

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