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Dynamic operation of isolated self excited synchronous generator under static loads

In the present work, the dynamic model for the synchronous generator expressed by the rotor reference frame was studied and the modeling of the stand-alone synchronous generator was created by MATLAB /SIMULINK software package with varied mechanical input power (104.93 and 5010KW) and loads (100KW and 100KVA) with constant excitation (6.36 and 8.84V). The sudden decrease in the mechanical input power was estimated by 20% of the mentioned values. In addition also, the sudden change in the load at constant speed (1800 rpm). These parameters were manually entered and the terminal voltage, current, output power, electromagnetic torque, load angle, and speed were measured as functions of time.
The obtained results show changes in the terminal voltage, the current, the output power, the electromagnetic torque, the load angle, and speed were observed in case of resistive and inductive load except the current which was constant in case of inductive load at sudden decrease in the mechanical input power.

Keywords: Synchronous generator; Dynamic model; MATLAB /SIMULINK

1. INTRODUCTION

A three phase synchronous generators are an AC rotating machines which convert the mechanical energy into an electrical energy whose speed under steady state condition is proportional to the frequency of the current in its armature. Synchronous machines may be operated either as a generator, a motor or as a synchronous condenser. Synchronous motors are used mainly for power factor correction when operate at no load. There are two different types of synchronous generator according to rotor structures: round rotor and salient pole rotor. Generally, round rotor structure is used for high speed synchronous machines, such as steam turbine generators, while salient pole structure is used for low speed applications, such as hydroelectric generators. There are three modes to operate the synchronous generators; stand-alone, island, and parallel with the utility. Each mode requires a specific turbine fuel (steam, hydraulic, diesel engines) and a specific control of excitation. Stand- alone is the simplest operation mode of a synchronous generator and is not common as parallel mode. Stand alone operation may be applied in two cases: 1) emergency back-up when the power grid fails, and 2) remote generation such as the far north, logging or drilling camps, and portable diesel generator sets[1-3]. The dynamic operation of the synchronous generator is mainly influenced by three factors including the sudden decrease in the mechanical input power which obtained by steam or water turbine, change the excitation voltages, and the sudden increase in the load resulting in a transient

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response of the synchronous generator which leads to a new steady state conditions. The studies [4, 5] showed that a resistive, an inductive loads will significantly reduce the terminal voltage, and a capacitive load will increase the terminal voltage if the total reactance of the generator and load is capacitive. To alleviate this effect, an AVR can be used to control the excitation current of the generator which maintained the terminal voltage constant. The different loads of synchronous generators were studied in many works and there is no work available concerning the sudden changes in the mechanical input power. So, the objective of this study was to investigate the effect of the sudden decrease in the mechanical input power with different loads on the behaviour of the generator, including the terminal voltage, current, torque, output power, load angle, and speed as functions of time.

2. Materials and Methods

2.1. The Dynamic Model of synchronous generator

The synchronous generator which used in this study is a machine with three armature windings in symmetrical form and a sinusoidal distribution along air gap, and one field winding. Damper windings are located in the round rotor. One damper winding is located along direct-axis (D), and one along the quadrature-axis (Q) with 90 electrical degrees behind the d-axis. The field winding is placed on the d-axis, and the damper circuit can be modeled by short-circuited winding along direct and quadrature axis to represent the effects of induced currents in damper bars as well as in the rotor body [6]. The positive direction of rotation is counter-clockwise and the positive angle θ is measured from the axis of phase-A to the d-axis in the direction of rotation. Some assumptions were made for developing the dynamic model of the synchronous generator [7]:

- The flux linkage of the winding is a function of the rotor position,
- All the windings are magnetically coupled,
- Stator and rotor iron permeability is assumed to be infinite, and
- Copper losses and the slots in the machine are neglected.

The winding of phase A is schematically represented with the inductance La (self and mutual inductance). Similarly phases B and C are schematically represented with the inductors La Lb, and Lc. Since the magnetic coupling between the phase windings and the rotor circuit is a function of the rotor position, the flux linking of the windings is also a function of the rotor position. The electrical equations are obtained by writing Kirchhoff's voltage law for every winding, i.e. by equating the voltage at the winding's terminal to the sum of resistive and inductive voltage drops across the winding [7-11]. It is worth to mention here that the damper windings, if present, are always short-circuited and their terminal voltage is therefore equal to zero.

2.1.1. Voltage Equations

2.1.1.1. Stator Circuit

Equation (1) represents the voltage of the three phases as follows:

$$v_a = -r_a.i_a - \frac{d\psi_a}{dt} = -r_a.i_a - p\psi_a$$
$$v_b = -r_b.i_b - \frac{d\psi_b}{dt} = -r_b.i_b - p\psi_b \quad (1)$$
$$v_c = -r_c.i_c - \frac{d\psi_c}{dt} = -r_c.i_c - p\psi_c$$

Where: ψ_a, ψ_b, ψ_c: the magnetic flux linkage of phases a, b, and c.

2.1.1.2. Rotor Circuit

The rotor voltage is described according to the 'Equation (2)' as follows:

$$v_f = r_f.i_f + \frac{d\psi_f}{dt}$$
$$v_D = 0 = -r_D.i_D - \frac{d\psi_D}{dt} \quad (2)$$
$$v_Q = 0 = -r_Q.i_Q - \frac{d\psi_Q}{dt}$$

Where: ψ_f, ψ_D, ψ_Q: The magnetic flux linkages of the field, and the damper windings.

2.1.2. Flux Linkage Equations

It is worth to mention that in the previous equations, the magnetic flux linkages are complex functions of rotor position and electric currents flowing in the various winding of the machine. The general expressions are described [6, 8, and 10] according to the 'Equation (3)' as follows

$$\psi_a = L_{aa}i_a + L_{ab}i_b + L_{ac}i_c + L_{af}i_f + L_{aD}i_D + L_{aQ}i_Q$$
$$\psi_b = L_{ba}i_a + L_{bb}i_b + L_{bc}i_c + L_{bf}i_f + L_{bD}i_D + L_{bQ}i_Q \quad (3)$$
$$\psi_c = L_{ca}i_a + L_{cb}i_b + L_{cc}i_c + L_{cf}i_f + L_{cD}i_D + L_{cQ}i_Q$$
$$\psi_f = L_{fa}i_a + L_{fb}i_b + L_{fc}i_c + L_{ff}i_f + L_{fD}i_D + L_{fQ}i_Q$$
$$\psi_D = L_{Da}i_a + L_{Db}i_b + L_{Dc}i_c + L_{Df}i_f + L_{DD}i_D + L_{DQ}i_Q$$
$$\psi_Q = L_{Qa}i_a + L_{Qb}i_b + L_{Qc}i_c + L_{Qf}i_f + L_{QD}i_D + L_{QQ}i_Q$$

Many of the inductances in the previous equations are depending on the position of the rotor which is varying with time [6, 8, 10, and 11]. So, these inductances are time-dependent.

2.1.2.1. Stator - Stator Inductances

The variation of the permeance of magnetic flux path with the rotor position produces the second harmonic terms for both self and mutual inductances. The stator self and mutual inductances are expressed according to equations 4 and 5 as follows:

$$L_{ss}(\theta) = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} = \begin{bmatrix} L_{aa0} & L_{ab0} & L_{ac0} \\ L_{ba0} & L_{bb0} & L_{bc0} \\ L_{ca0} & L_{cb0} & L_{cc0} \end{bmatrix} +$$

$$\begin{bmatrix} L_{aa2}\cos 2\theta & L_{ab2}\cos\left(2\theta-\frac{2\pi}{3}\right) & L_{ab2}\cos\left(2\theta+\frac{2\pi}{3}\right) \\ L_{ab2}\cos\left(2\theta-\frac{2\pi}{3}\right) & L_{aa2}\cos\left(2\theta-\frac{2\pi}{3}\right) & L_{ab2}\cos 2\theta \\ L_{ab2}\cos\left(2\theta+\frac{2\pi}{3}\right) & L_{ab2}\cos 2\theta & L_{aa2}\cos\left(2\theta+\frac{2\pi}{3}\right) \end{bmatrix} \quad (4)$$

Where: L_{aa0} and L_{ab0}: the constant value of the self-inductance of each stator winding and mutual inductance between any two stator windings, respectively. Lab2 is the maximum value of the second harmonic term for both the self-inductance of each stator winding and the mutual inductance between any two - stator windings.

2.1.2.2. Stator - Rotor Inductances

The stator-rotor mutual inductances could be expressed as described in equation 5 and the variation of the mutual inductance may due to the relative motions of the windings.

$$L_{sr}(\theta)=\begin{bmatrix} L_{af} & L_{aD} & L_{aQ} \\ L_{bf} & L_{bD} & L_{bQ} \\ L_{cf} & L_{cD} & L_{cQ} \end{bmatrix}=\begin{bmatrix} L_{aF}\cos\theta & L_{aD}\cos\theta & L_{aQ}\sin\theta \\ L_{aF}\cos\left(\theta-\frac{2\pi}{3}\right) & L_{aD}\cos\left(\theta-\frac{2\pi}{3}\right) & L_{aQ}\sin\left(\theta-\frac{2\pi}{3}\right) \\ L_{aF}\cos\left(\theta+\frac{2\pi}{3}\right) & L_{aD}\cos\left(\theta+\frac{2\pi}{3}\right) & L_{aQ}\sin\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix} \quad (5)$$

2.1.2.3. Rotor - Stator Inductances

The rotor-stator mutual inductances could be described according to Eq. (6) as follows:

$$L_{rs}(\theta)=L_{sr}^{T}(\theta) \quad (6)$$

2.1.1.4. Rotor - Rotor Inductances

It is worth that the self-inductances of the rotor circuit and the mutual inductances between each other were not depending on the rotor position. The constant rotor-rotor inductance matrix can be written as follows:

$$L_{rr}=\begin{bmatrix} L_{FF} & L_{FD} & L_{FQ} \\ L_{FD} & L_{DD} & L_{DQ} \\ L_{QF} & L_{QD} & L_{QQ} \end{bmatrix}=\begin{bmatrix} L_{FF} & L_{FD} & 0 \\ L_{FD} & L_{DD} & 0 \\ 0 & 0 & L_{QQ} \end{bmatrix} \quad (7)$$

Where: LFF, LDD, and LQQ: the self inductances of the windings F, D and Q, respectively. LFD is the mutual inductance between F and D windings.

2.2. Park's Transformation

The previous equations are simplified by Park's transformation which is a technique where stator parameters are expressed as rotor parameters. In the circuit analysis, the parameters are given as stator quantities, and the inductance is observed as time-varying by the stator phase, due to the rotation of the field winding. Under power invariance, the transformation is defined according to 'Equation (8)'.When the stator parameters are transformed to rotor quantities, the variables rotate with the rotor. The electrical behaviour of the synchronous machine is described by 'Equations (3, 7, and 10)'. Nevertheless, these equations can be solved numerically and they are not suitable for analytical solution due to time-varying inductances. The time-invariant set of machine equations can be obtained through Park's Transform; cite directly as [6, 9, and 11]

$$P = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{8}$$

Where: θ: the rotor angle.
Using vector-matrix notation phase voltages, currents and flux linkages in the abc-frame could be expressed in the dqo-frame according to 'Equation (9)' as follows:

$$\begin{aligned} v_{dqo} &= P v_{abc}, \\ i_{dqo} &= P i_{abc}, \\ \psi_{dqo} &= P \psi_{abc} \end{aligned} \tag{9}$$

Once the machine performance is obtained in terms of Park's variables, the original phase quantities could be obtained by the inverse transformation [6, 9]

$$P^{-1} = P^{T} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \sin\theta & \frac{1}{\sqrt{2}} \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & \frac{1}{\sqrt{2}} \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{10}$$

From this we get:

$$\begin{aligned} v_{abc} &= P^{-1} v_{dqo} \\ i_{abc} &= P^{-1} i_{dqo} \\ \Psi_{abc} &= P^{-1} \Psi_{dqo} \end{aligned} \tag{11}$$

By expanding and re-arranging terms, the synchronous machine equations becomes as follows:

2.2.1. Armature Equations

$$v_d = -r_s i_d + \frac{d\psi_d}{dt} - \omega_r \Psi_q = -r_s i_d - (L_{ls} + L_{md})\frac{di_d}{dt} + L_{md}\frac{di_{fd}}{dt} + L_{md}\frac{di_{kd}}{dt} - \omega_r \Psi_q \tag{12}$$

$$v_q = -r_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d = -r_s i_q - (L_{ls} + L_{mq})\frac{di_q}{dt} + L_{mq}\frac{di_{kq}}{dt} + \omega_r \psi_d \tag{13}$$

$$v_0 = -r_s . i_0 + \frac{d\psi_0}{dt} \tag{14}$$

2.2.2. Field Equation

$$v_{fd} = r_{fd}\, i_{fd} + \frac{d\psi_{fd}}{dt} = r_{fd}\, i_{fd} - L_{md}\cdot\frac{di_d}{dt} + \left(L_{lfd} + L_{md}\right)\frac{di_{fd}}{dt} + L_{md}\frac{di_{kd}}{dt} \qquad (15)$$

2.1.3. Damper Winding Equations

$$v_{kd} = r_{kd}\, i_{kd} + \frac{d\psi_{kd}}{dt}$$

$$0 = r_{kd}\, i_{kd} - L_{md}\frac{di_d}{dt} + L_{md}\frac{di_{fd}}{dt} + \left(L_{lkd} + L_{md}\right)\frac{di_{kd}}{dt} \qquad (16)$$

$$v_{kq} = r_{kq}\, i_{kq} + \frac{d\psi_{kq}}{dt}$$

$$0 = r_{kq}\, i_{kq} - L_{mq}\frac{di_q}{dt} + \left(L_{lkq} + L_{mq}\right)\frac{di_{kq}}{dt} \qquad (17)$$

Equations (12–17) describe the synchronous generator's equivalent circuit in the rotor reference frame which shown in Fig. 1

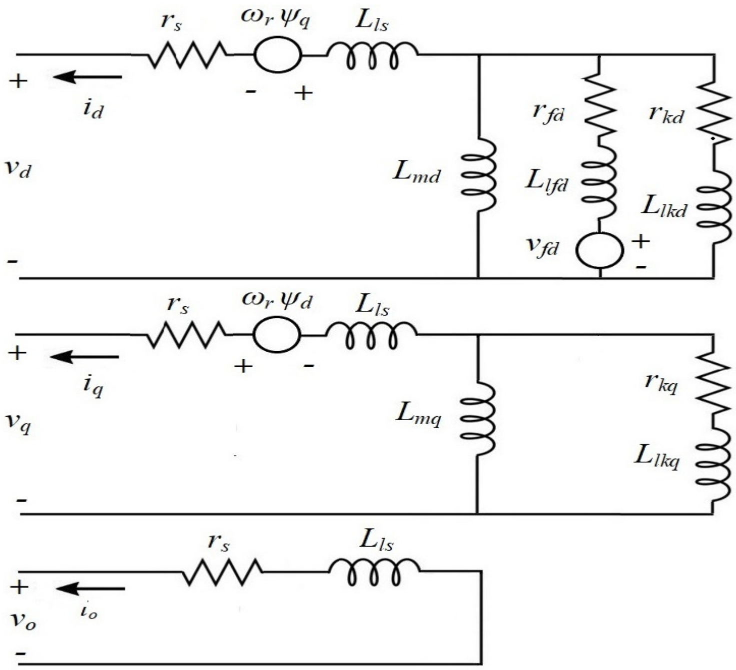


Fig. 1 Synchronous generators equivalent circuit in the rotor reference frame

Therefore, the transformation dq_o voltage equations could be re-arranged in the matrix form [6, 8, and 9]

$$\begin{bmatrix} v_d \\ v_q \\ v_o \\ v_{fd} \\ v_{kd}=0 \\ v_{kq}=0 \end{bmatrix} = \begin{bmatrix} -(r_s+pL_d) & -\omega_r L_q & 0 & pL_{md} & pL_{md} & -\omega_r L_{mq} \\ \omega_r L_d & -(r_s+pL_q) & 0 & 0 & 0 & pL_{mq} \\ 0 & 0 & -(r_s+pL_o) & 0 & 0 & 0 \\ -pL_{md} & 0 & 0 & (r_f+pL_f) & pL_{md} & 0 \\ -pL_{md} & 0 & 0 & pL_{md} & (r_{kd}+pL_{kd}) & 0 \\ 0 & -pL_{mq} & 0 & 0 & 0 & (r_{kq}+pL_{kq}) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_o \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} \quad (18)$$

3. Results and Discussion

3.1. MATLAB/SIMULINK Model

Figure (2) shows the basic modeling of a synchronous generator operating alone which created by MATLAB /SIMULINK. The synchronous generator was loaded by purely resistive and inductive loads and the machine parameters were manually entered. The simulated values (terminal voltage, current, output power, electromagnetic torque, load angle, and speed as functions of time) were subsequently measured.

In case of no load, the internal generated voltage at the stator winding appears as the terminal voltage. Whereas in the presence of a load, the load current flows through the armature coils producing a stator flux and making the terminal voltage depends on the nature of the load. The produced stator flux distorts the main flux since the internal generated and terminal voltages across the machine are not equal. Furthermore, the excitation remains equal to the amount required to keep the generator's terminal voltage equal to the rated value.

The performance of the synchronous generator at constant excitation is influenced by many factors such as the sudden change in the mechanical input power and in the load at constant speed.

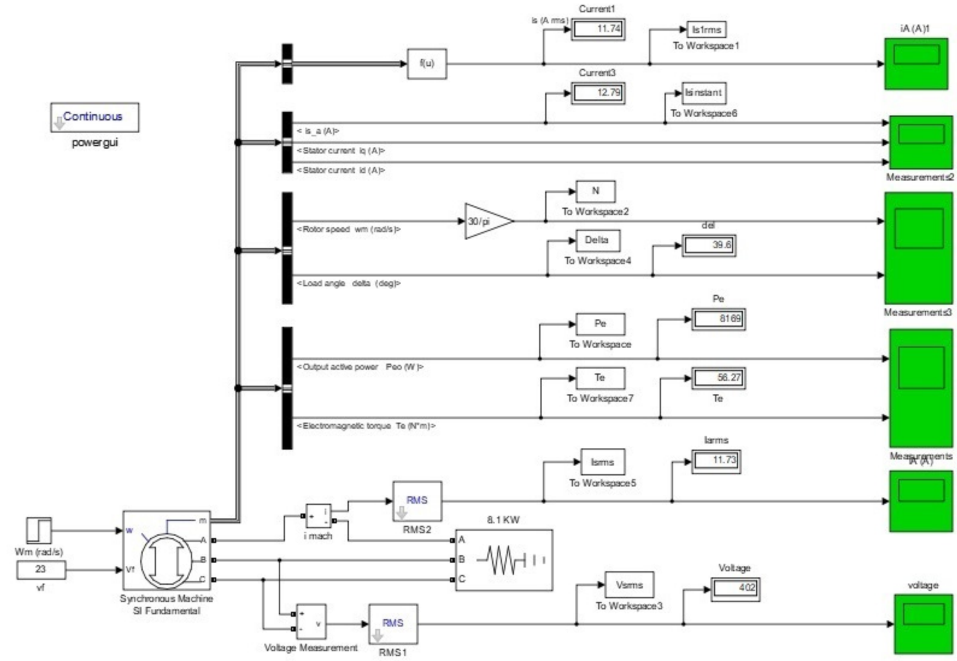


Fig. 2 MATLAB / SIMULINK model of a synchronous generator operation alone

3.1.1. Resistive Load

When the load is purely resistive load (unity power factor), the terminal voltage and current are sine waves in phase with each other. In manual mode, the excitation current was adjusted in order to obtain a rated terminal voltage of 460V and 100KW as a load which was connected in star form on each phase.

3.1.1.1. Effect of the sudden change in the mechanical input power

The sudden change in the mechanical input power which decreased from 104.93-KW to 83.944-KW in time of 3 to 4 second results in a decrease in the turbine torque leading to a decrease in the rotor speed according to the acceleration equation $J\frac{dw_m}{dt} = T_T - T_e$ (Fig. 3a). During this transient, the rotor speed is not equal to the synchronous speed (about 1122.7 rpm).

Moreover, both the load current (113A) and the terminal voltage (414V) were decreased by about 10% from the rated (125.3A and 460V respectively) as a result of decreasing the mechanical input power (figures 3(b) and 3(c)) which influenced the rotor speed. The internal generated voltage (E_A) was subsequently decreased wherein $E_A= K\phi\omega$ Therefore, the output power was decreased as a result of the decrease in both terminal (V_t) and the internal generated (E_A) voltages wherein $P_{out} = \frac{3*V_t*E_A}{z} * \sin\delta$ reaching a new steady state point at 81.06-KW after the change period (fig. 3(d)).

Along with that, the electrical torque was proportional with the output power and inverse proportional with the speed wherein $T_{em} = \frac{P_{out}}{\omega_s}$ until the sudden decrease in the mechanical input power reaching a new steady-state operating point at 707.38 Nm after the change period (Fig. 3(e)). On the other hand, the load angle (δ) was increased wherein $\frac{d\delta}{dt} = \omega_e - p\,\omega_m$ as a result of the rotor speed decreasing and reached a new steady-state operating point after change period (Fig. 3(f)).

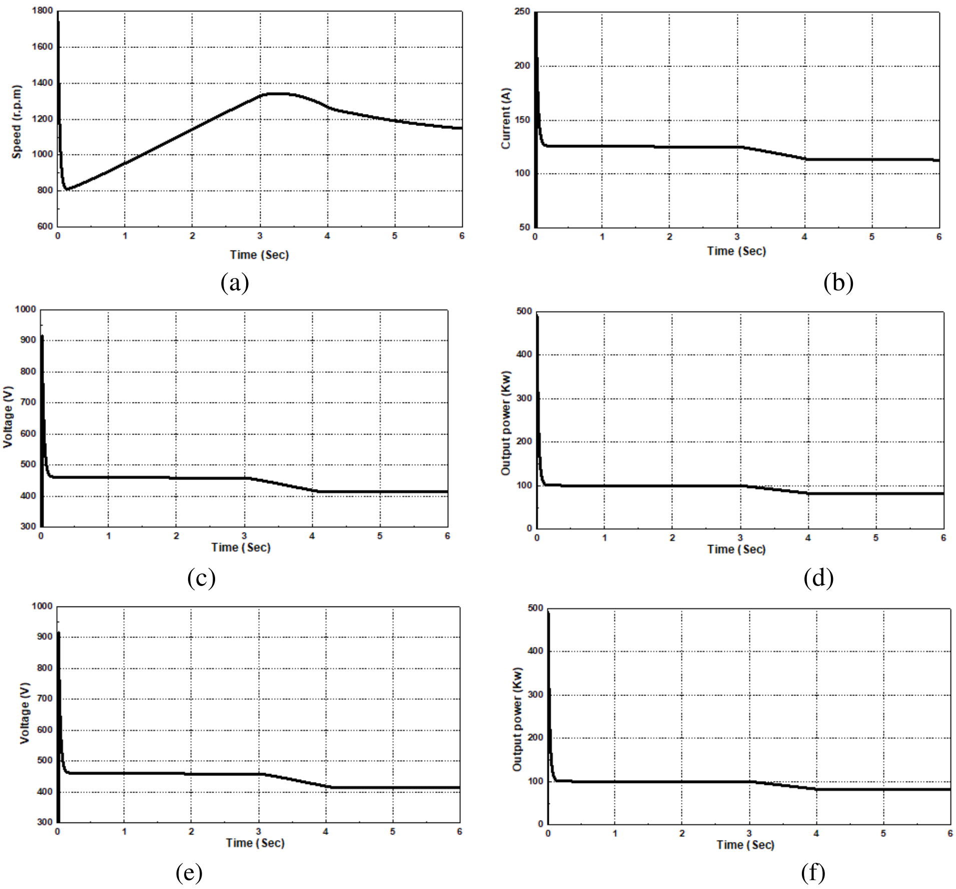
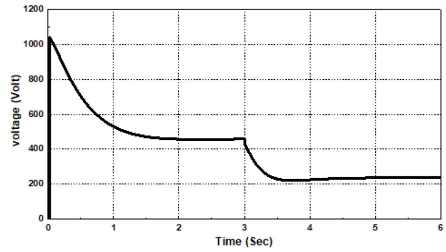


Fig. 3 Effect of sudden change in the mechanical input power in case of resistive load on (a) Speed, (b) Current,
(c) Voltage, (d) Output Power, (e) Torque and (f) Load Angle.

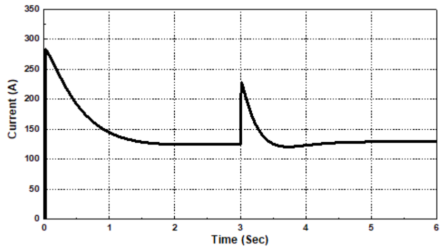
3.1.1.2. Effect of the sudden change in the load at constant speed

The armature current was increased from 125A to 129.3A as a result of adding in parallel an additional load of 100KW on each phase at the same power factor φ (UPF). But its angle (φ) with the terminal voltage (V_t) remained constant with the initial value (zero) wherein the value of the terminal voltage (V_t) was decreased to 237.1V (Figures 4(a) and 4(b)).

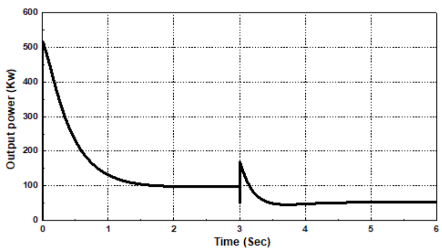
In the manual mode, the speed of the prime mover was constant at 1800 rpm and the excitation was adjusted to 6.36V in order to maintain field flux constant. The internal generated voltage E_A= Køw was therefore constant. As a result, the output power decreased to 53.11KW with decreasing the terminal voltage wherein $P_{out} = \frac{3*V_t*E_A}{Z} * \sin\delta$. On the other hand, decreasing the output power $(T_{em} = \frac{P_{out}}{\omega_s})$ caused decreasing the electrical torque to 296.4 Nm and reached a new steady-state point (Figures 4(c) and 4(d)). Moreover, the load angle was increased to 63.6° by maintaining the internal generated voltage EA constant (Fig. 4(e)).



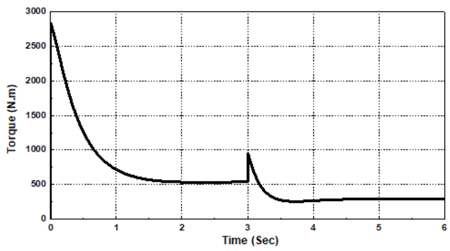
(a)



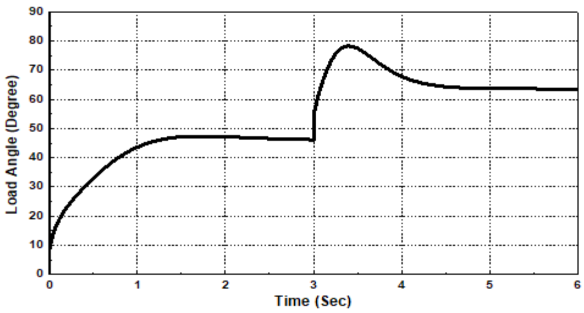
(b)



(c)



(d)



(e)

Fig. 4 Effect of sudden change in the generator load in case of the resistive load at constant speed on
(a) Current, (b) Voltage, (c) Output Power, (d) Torque, and (e) Load Angle

3.1.2. Inductive Load

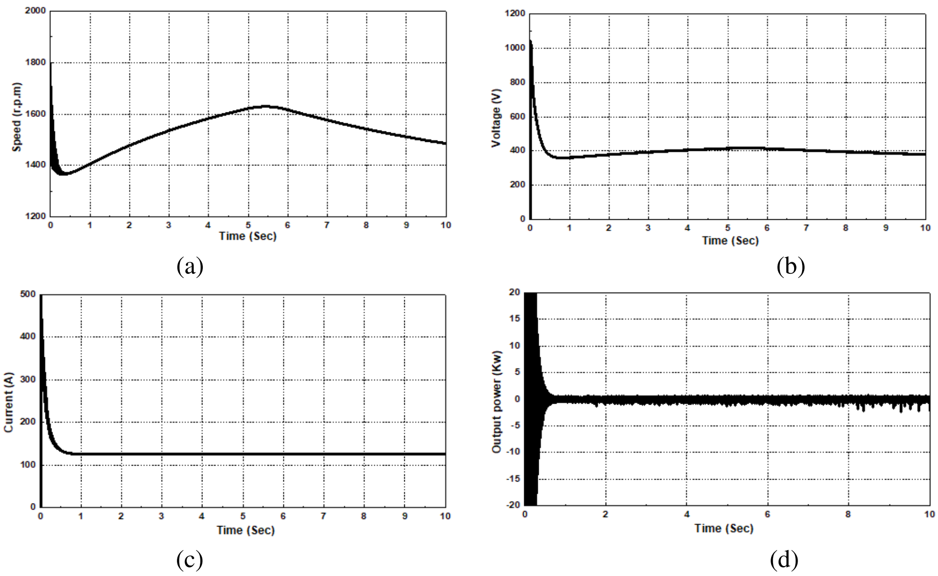
The current is lagging the terminal voltage by angle (89.85 lagging), when the load is inductive (lagging power factor). In manual mode, the excitation current was adjusted to maintain the rated terminal voltage at 460 V and 100 KVA as a load which was connected in star form on each phase. This load has an active load power of 0.25425 KW and reactive load power of 99.999 KVAR.

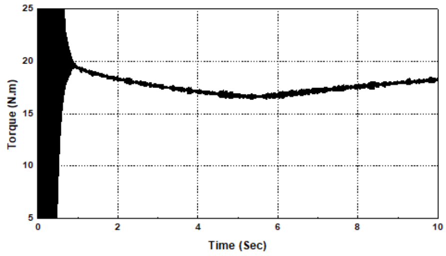
3.1.2.1. Effect of sudden change in the mechanical input power

The sudden change in the mechanical input power from 5.01-KW to 4.008-KW in a time of 5 to 6 second caused an decrease in the turbine torque, rotor speed, and terminal voltage by about of 20%, 17.4%, and 17.2% respectively (Figures 5(a), 5(b). While, the current was remained constant (not affected) (Fig. 5c)

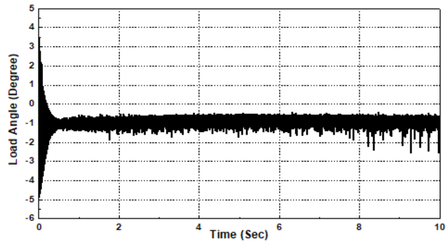
The internal generated voltage (E_A) decreased as a result of speed reduction wherein E_A= Køw. Therefore, the output power decreased as a result of the terminal (V_t) and the internal generated (E_A) voltages decreasing wherein $P_{out} = \frac{3*V_t*E_A}{z} * \sin\delta$. The output power reached afterward a new steady-state point at 252.4-KW (Figure 5d).

The electrical torque was proportional with the output power and inversely proportional with the rotor speed wherein $T_{em} = \frac{P_{out}}{\omega_s}$. So, the electrical torque decreased with the decrease in the output power and reached afterward a new steady-state point at 18.3 Nm (figure 5e). On the other hand, the load angle becomes negative (-0.79) meaning that the terminal voltage phasor (V_t) leads the generated voltage phasor (E_A) (Figure 5(f)).





(e)



(f)

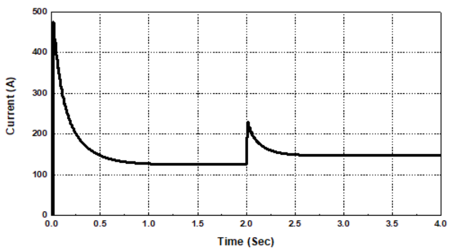
Fig. 5 Effect of a sudden change in the mechanical input power in case of the inductive load on (a) speed,
(b) Voltage, (c) currents, (d) Output Power, (e) Torque, and (f) Load Angle

3.1.2.2. Effect of sudden change in the load at constant speed

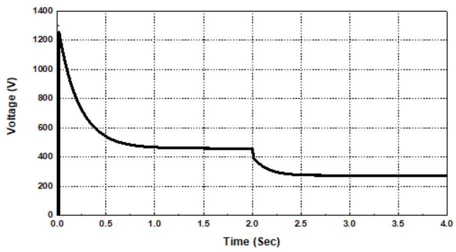
The armature current was increased from 125A to 147.7A as a result of adding in parallel an additional load of 100KVA on each phase at the same power factor φ (Lagging PF). But its angle (φ) with the terminal voltage (V_t) remained constant with an initial value of 89.85 lagging, wherein the value of the terminal voltage (V_t) was decreased from 460V to 273.9V (Figures 6(a) and 6(b)).

In the manual mode, the speed of the prime mover was constant at 1800 rpm and the excitation was adjusted to 8.84V as constant value in order to maintain the field flux constant. As a result, the internal generated voltage ($E_A = K\phi w$) remained constant. On the other hand, the output power decreased to 74.5KW with the decrease in the terminal voltage wherein $P_{out} = \frac{3*V_t*E_A}{Z} * \sin\delta$.

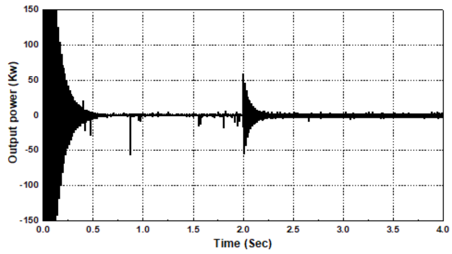
Along with that, the electrical torque decreased to 19.9 Nm reaching a new steady-state point with the decrease in the output power wherein $T_{em} = \frac{P_{out}}{\omega_s}$ (Figures 6(c) and 6(d)). On the other hand, the load angle becomes negative (-0.997) meaning that the phasor terminal voltage (V_t) leads the phasor of the internal generated voltage (E_A) (Fig. 6(e)).



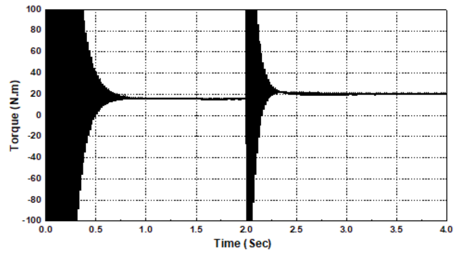
(a)



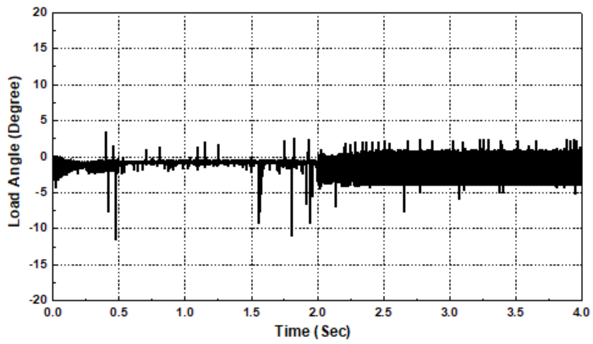
(b)



(c)



(d)



(e)

Fig. 6 Effect of a sudden change of the inductive load at constant the speed on (a) Current, (b) Voltage,
(c) Output Power, (d) Torque, and (e) Load Angle

Conclusion

In this work, the dynamic model for the synchronous generator expressed by the rotor reference frame was studied and the modeling of the stand-alone synchronous generator was created by MATLAB /SIMULINK software package with different mechanical input power (104.93 and 5010KW) and loads (100KW and 100KVA) with constant excitation (6.36 and 8.84V). The synchronous generator was loaded by purely resistive and inductive loads and the machine parameters were manually entered. The simulated values (terminal voltage, current, torque, output power, load angle, and speed as functions of time) were subsequently measured. The obtained results in case resistive load show that the terminal voltage, the current, the speed, the output power, the electromagnetic torque, and the load angle of synchronous generator decreased by decreasing the mechanical input power. The same behavior was observed for the terminal voltage, the output power, and the electromagnetic torque by increasing the load, while the current and load angle of synchronous generator increased. Moreover, the same tendency of was observed in case of inductive load; the terminal voltage, the speed, the output power, and the electromagnetic torque of synchronous generator decreased by decreasing the mechanical input power with no change of the current (constant) and the load angle become negative. The terminal voltage also decreased by increasing the load, and the current, the output power, and the electromagnetic torque however increased. The load angle was also negative with increasing the load.

References

[1] Tze-Fun Chan: Electrical Engineering-Vol. III-*Synchronous Machines*, Encyclopedia of Life Support Systems (EOLSS),
pp. 84-97, 2009, available at https://books.google.com.eg/books?id=RweeDAAAQBAJ&pg=PA84&lpg=PA84&dq=SYNCHRONOUS+MACHINES
[2] 'The view of Hans Stutvoet MSc power systems consultant', latest version available at http://www.svri.nl/en/generator-operation-modes, last accessed 20 December 2020
[3] 'The view of Andy Knight Professor in the Department of Electrical and Computer Engineering', latest version available at http://www.people.ucalgary.ca/~aknigh/electrical_machines/synchronous/stand_alone/sa_intro.html, last accessed 20 December 2020
[4] Gaber El Saady, El-NobiA.Ibrahim, HamdyZiedan, and mohammed M. Soliman: Analysis of wind turbine driven permanent magnet synchronous generator under different loading conditions, Innovative systems design and engineering, vol. 4, pp. 97-111, 2013.
[5] M.M.A. Rahman, Daniel Mutuku: Design, Implementation, and Dynamic Behaviour of a Power Plant Model', Proceeding of the ASEE North Central Section Conference, 2015.
[6] Abdelhay A. Sallam, Om P. Malik, Power System Stability Modeling, analysis and control, The Institution of Engineering and Technology , London, United Kingdom, pp. 13-25, 2015.
[7] Martin Kanálik, Anastázia Margitová, Michal Kolcun: Modeling of Synchronous Machines Including Voltage Regulation, Przegląd Elektrotechniczny, pp. 125-132, 2019, doi:10.15199/48.2019.07.26
[8] Onah, C.O., and Reuben, J: Dynamic Modelling and Simulation of Salient Pole Synchronous Motor Using Embedded Matlab, American Journal of Engineering Research, Vol. 5, pp. 318-325, 2016, http://www.ajer.org
[9] Miljenko Brezovec, Igor kuzle, and Matej Krpan: Detailed Mathematical and Simulation Model of a Synchronous Generator, Journal of Energy, Vol. 64, pp. 102-129, 2015, http://JournalofEnergy.com
[10] Ion Boldea, Synchronous Generators, 2nd edn. CRC Press by Taylor & Francis Group, LLC, 2016, PP. 187-200
[11] K. R. Padiyar, Anil M. Kulkarni: Dynamics and Controls of Electric Transmission and Micro grids, John Wiley & Sons, Inc., 2019

Appendix

The synchronous machine used in this study is 100 KVA, 460 V, 125.5 A, 60 Hz, 4 pole 3-phase non-salient pole synchronous generators, Y connected

Stator per phase resistance $R_s = 0.055\ \Omega$
Stator per phase reactance $X_s = 21.6317\ \Omega$
Field resistance $R_f = 0.03386\ \Omega$
Moment of inertia of the machine J = 0.7136 kg.m2
Friction factor of the generator B = 0.06 N-ms
Rated Rotor Speed =1800 r.p.m.