SINGLE-PHASE SEPARATELY EXCITED AC GENERATOR

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ABSTRACT

Generation of AC electrical energy plays a great role in modern century. Synchronous generators occupy the interest of most research work as they present the most common generators in the power stations. Self-excited induction generators are suitable for wind energy conversion where the wind speed continuously changes such that the variable voltage-variable frequency power is converted to constant voltage-constant frequency power using power electronics. Application of both separately excited and self-excited DC generators is limited because the development of the power electronics converter which converts from AC to variable and fixed DC voltage. In this paper, the conventional separately excited DC generator is fed by a sinusoidal field current and as a result the output armature voltage is sinusoidal whose frequency equals the frequency of the field current while the magnitude depends on the speed and magnitude of the field current. The basic idea is explained. The equivalent circuit of the machine is presented and the dynamic model is simulated using MATLAB-SIMULINK software. The steady state and transient performance of the machine is concluded. The experimental and theoretical results are compared and showed satisfactory matching.

1. INTRODUCTION

The role of the DC generator as a major contender in the power generation field has declined rapidly over the years. The rate of decline accelerated with the introduction of high power solid-state rectifiers and thyristor phase controlled converters, which now form the prime sources of fixed and variable DC voltages (Guru and Hiziorglu, 2001), (EL Sharkawi,

2000), (Slemon, 1992) and (Sen, 1997). Synchronous generator and induction generators are commonly used for the generation of AC power. Synchronous generators are the primary energy conversion devices of the electric power system as they are usually large machines generating electrical power rating several hundreds MVA (Hughes, 1960), (Ivanov-Smolensky, 1988), (Pearman, 1994), (Fitzgerald and Kingsley, 1980) and (Say, 1965). Self-excited induction generators are suitable choice in wind energy conversion because of the nature of wind speed fluctuations where induction generators can convert mechanical power into electrical power over a wide range of rotor speeds. The induction generator requires its magnetic current in the form of leading reactive power to be supplied at its terminal by an external source to operate in the self-excited mode (Bansal, 2005). In this paper, the conventional separately excited DC generator is operated to develop a single phase AC voltage where the machine is then running as a single phase separately excited AC generator where the field winding is fed by a sinusoidal field current and therefore the shape of the output voltage waveform would resemble that of the field current. The basic idea of feeding the DC generator from an AC current to obtain an AC voltage is mentioned in (Kostenko and Piotrousky, 1970). The basic principle and theory of operation is explained and the model of the machine is concluded from the basic dynamic equations. The steady state and transient performance are analyzed. The application of this machine is proposed and a comparison between the separately excited AC generator with the synchronous generator for large high power range and with the bipolar junction transistor for low power range is illustrated.

2. GENERATOR PRINCIPLE

It is well known that when the armature of a DC machine is revolving in a magnetic filed, an emf is generated by induction according to Faraday's law such that the direction of the generated emf in the conductors could be determined by applying Fleming's right hand rule (Hindmarch, 1997). As the coil rotates, the emf in the coil is sinusoidal. A DC generator

however has to give a voltage that remains constant in direction and magnitude. As for the direction, it is therefore necessary to use a commutator to enable a direct voltage to be obtained from the alternating emf generated in the rotating conductors and as for the magnitude, it is necessary to wind the armature as a ring wound or a fully pitched armature (Hubert, 1991). The average voltage, e produced by the complete armature winding is given by (Thaler, 1996):

$$e = \frac{P}{a} \frac{Z}{2f} \Psi \, \check{S}_r \qquad (1)$$

Where

'a' is the number of current paths in the armature circuit

'P' is the number of poles

'Z' is the total number of conductors

' ' is the average magnetic flux per pole

A field current, i_f is passed in the field coil wound around the magnetic poles to produce the necessary flux such that the resulting flux is increased proportionally with the field current. Accordingly and with reference to (1), it could be concluded that:

$$e = K \, i_f \, \check{S}_r \qquad (2)$$

Where K is the constant of the DC generator. Simply from (2), it could be concluded that if the separately excited DC machine is rotated in a certain direction and fed by a DC current from a separately DC supply, the generated induced emf is then constant in magnitude and direction as conventionally known. It could be also concluded from (2) that the shape of the waveform of the induced voltage is similar to that of the field current since the generated emf is proportional to the field current. When the field current was DC, the generated emf was also DC and the machine runs as a separately excited DC generator. Now, if the field current is sinusoidal given by:

$$i_f(t) = I_{FM} \, sin \, (\check{S}_e \, t) \qquad (3)$$

Where

'I_{FM}' is the maximum value of the field current.

and substituting (3) into (2) yields:

$$e(t) = K \, \check{S}_r \, I_{FM} \, sin \, (\check{S}_e \, t) \qquad (4)$$

It is concluded from (4) that the machine is now running as a single phase separately excited AC generator such that the magnitude of the output voltage is dependent on both rotor speed and maximum value of the field current while the frequency of the output voltage is only dependent on the frequency of the field current.

3. MODELING OF SINGLE-PHASE SEPRATLEY EXCITED AC GENERATOR

The connection diagram for the 1-phase separately excited AC generator is shown in Fig. (1). It is well known that:

$$e(t) = v_a(t) + R_a \, i_a(t) + L_a \, \frac{d \, i_a(t)}{dt} \qquad (5)$$

And

$$v_f(t) = R_f \, i_f(t) + L_f \, \frac{d \, i_f(t)}{dt} \qquad (6)$$

The effect of saturation on the performance can be represented by evaluating the relationship between the generated emf per unit speed and the field current from the conventional no load test, which still holds good in this mode of operation. The MATLAB-SIMULAINK software can be used to simulate this generator as shown in fig. (2) where the magnitude and frequency of the field voltage define those of the field current and accordingly the frequency of the generated emf is determined. The value of the rotor speed and magnitude of the field current define, from the no load test, the magnitude of the emf which is then represented as a controlled voltage source whose output represents the emf of the generator which has an internal inductive impedance, Z_a and is feeding an AC load. This equivalent circuit can be

used to evaluate the performance of the machine whose details is given in appendix (A) for both transient and steady analysis.

4. STEADY STATE ANALYISIS

Voltage and current waveform at steady state are sinusoidal and therefore the equations of the machine tend to:

$$V_a \angle 0 = E \angle u - I_a \angle \Phi \ (R_a + J\check{S}_e L_a) \qquad (7)$$

$$V_a \angle 0 = I_a \angle \Phi \ \left(R_L + J\check{S}_e L_L - J\frac{1}{\check{S}_e C_L}\right) \qquad (8)$$

Where   : load power angle of the machine

          : angle of load power factor

     J   : complex operator

The relationship between the induced emf and the field current can be represented to include the saturation by approximating the no load curve a third order polynomial as follows:

$$E = \check{S}_r \left(a_3 I_f^3 + a_2 I_f^2 + a_1 I_f + a_0\right) \qquad (9)$$

where coefficients $a_4 \ldots a_0$ are constants and defined in Appendix (A).

$$P_o = V_a I_a cos(\Phi) \qquad (10)$$

$$P_d = E I_a cos(\Phi - u) \qquad (11)$$

Equations (7) to (11) help determine the external characteristics and performance curves of the generator for a certain operating point defined by: 1) shaft speed, 2) load power factor, 3) frequency of the induced emf and 4) the magnitude of the field current. Fig. (3) to fig. (6) show the calculated and measured external characteristics of the machine for different operating conditions. Fig. (3) shows effect of load power factor which resembles that of the synchronous generator such that for leading power factor load, the load voltage is higher than no load voltage because the armature voltage drop is effectively added to no load voltage. Fig. (4) and fig. (5) show the effect of speed and amplitude of field current on the machine where

it could be seen that the voltage can be controlled either using speed or field current. Fig. (6) shows the operation of the machine as a separately excited AC and a separately excited DC generator where the armature voltage drop for AC generator is higher than the DC generator because of the armature reactance.

5. TRANSIENT RESPONSE

The model presented in fig. (2) can be used to analyze the transient response of the machine. Fig. (7) and fig. (8) show both the simulated and experimental load voltage waveform for different operating conditions. Fig (7) shows the effect of changing speed from 2500 rpm to 3000 rpm for a filed current of 0.6 A and frequency of 50 Hz for resistive load and fig. (8) shows the effect of changing field current from 0.25 A to 0.65 A for a speed of 3000 rpm and frequency of 50 Hz for a resistive load. This would also prove that the voltage can be controlled either using speed or field current

6. APPLICATION OF SINGLE PHASE SEPARATELY EXCITED AC GENERATOR

This machine can operate as an AC generator or as a mechanical amplifier. As an AC generator, the machine is converting the mechanical power into single phase AC power in existence of AC field current excitation. This generator can be compared with the synchronous generator from different point of views as follows:

i. Synchronous generator can be constructed to give single phase or poly phase machine while separately excited AC generator runs only as a single-phase machine.

ii. Synchronous generator needs DC excitation field current while separately excited generator needs AC excitation field current.

iii.Changing speed of the synchronous generator affects both frequency and magnitude of the output voltage while changing speed of separately excited generator affects only the magnitude of the output voltage.

iv. Frequency of synchronous generator is only dependent on speed while frequency of separately excited AC generator is only dependent on frequency of excitation field current.

v. No of poles defines the frequency and correspondingly the induced voltage in the synchronous generator while number of poles in the separately excited AC generator affects only the magnitude of the induced voltage, as seen from (1), and not the frequency.

vi. Construction maintains and cost of synchronous generator is less than separately excited generator.

Both machines have common points as follows:

i. No excitation capacitor is needed for both machines.

ii. Magnitude of the output voltage of both machines depends on the speed and the magnitude of the field current.

iii. Frequency of both machines does not depend on load.

As a mechanical amplifier, this machine amplifies a current signal applied to the field coil at a low power level to a voltage signal obtained on the armature at a high power level. This mode of operation can be compared with a bipolar junction transistor, BJT working as a power amplifier to amplify a current signal on the base at a low power to a voltage signal between collector and emitter at high power level from many point of views:

i. Construction, maintains and cost of BJT is much cheaper than separately excited AC generator, which needs an extra small motor to drive the generator.

ii. High power side and low power side are not electrically isolated in the BJT where the emitter is a common point between them while the high power side and low power side are completely isolated in the separately excited AC machine where the coupling is magnetic.

iii. Best performance operating range of the BJT is the medium frequency region while separately excited machine runs better at low frequency because at high frequency the armature reactance causes high voltage drop.

iv. Power rating of the BJT could be limited not like the separately excited AC generator.

7. **DISCUSSION**

- It should be noted that this machine runs as a separately excited single phase AC generator as has been explained and it can also run as a conventional separately excited DC generator when fed from a DC current. In other word, the output frequency of the voltage depends on the frequency of the field current starting from DC value and up to any value.

- The lower the operating frequency of the machine, the better the performance because at high frequency, the voltage drop in the armature and field impedance becomes considerable.

- If the field current is DC, the output voltage is also DC as conventionally known and when the field current is sinusoidal, the output voltage is also sinusoidal as has been explained. With reference to (2), it should be noted that whatever the shape of the field current, the output voltage of the machine would have the same shape. This could be useful in mechanical amplifier mode where some times the BJT transistor cannot reach high power rating.

- The model of the machine can be modified to produce better results by simulating the relationship between the field current and the induced emf of the machine using the actual B-H curve of the machine to include the hysteresis losses of the machine. This would give better-calculated results.

- The generated emf would have some spikes due to commutation. This would result in some harmonic in the voltage. However, the load current and hence voltage waveforms

would be near sinusoidal as the armature and load impedance would act as a low pass filter. On the other hand, the higher the number of the commutator segment, the smoother the sinusoidal waveform of the voltage (Hamdi, 1998).

- Similar to conventional DC generator, in the separately excited AC generator, the armature mmf reaction distorts the flux density distribution and produces a demagnetization flux causing poor commutation leading to sparking. A compensation coil can be connected in series with the armature to produce a flux in opposition to the flux produced the current flowing through the armature. This results in increasing both induced emf, hence speed and the power factor hence efficiency. Because the armature current is AC, alternatively, a shorted compensation coil can be installed such that the induced current in the coil can oppose the armature reaction.

- The output voltage of the separately excited AC generator can be controlled using the magnitude of the field current or the shaft speed independently without affecting the output frequency.

- For self-excitation, the field coil can be connected in series with the armature coil and load where an excitation capacitance is then needed. Voltage building up takes place due to residual magnetism and this process stops according to saturation.

8. CONCLUSION

The conventional DC separately excited machine is operated to develop a single phase AC voltage. The machine can then be called a single-phase separately excited AC generator. The theory of operation is explained from the basic principle of energy conversion concept. It is concluded that the shape of the armature voltage should look like that of the field current and therefore when the field current is sinusoidal, the armature voltage is also sinusoidal. The frequency of the output armature voltage equals that of the field current while the magnitude of the output armature voltage depends on both the speed and the maximum value of the field

current. The model of the machine is simulated using the MATLAB-SIMULINK software. The performance characteristics curves of the machine at steady state are concluded. The experimental results showed satisfactory matching with the simulation. The transient response of the machine due to a step change in the rotor speed and field current is analyzed. The application of this generator is proposed and a comparison between this machine and both synchronous generator and bipolar junction transistor is held.

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10. APPENDIX (A)

The parameters of the 80 W, 220V, 3000-rpm series universal AC machine is given by:

$R_a = 68$ $\qquad$ $R_f = 82$

$L_a = 0.21$ H $\qquad$ $L_f = 0.74$ H

The conventional no load characteristics between the emf normalized to speed and the maximum value of the field current is shown in fig. (9). This curve is approximated to a third order curve whose parameters a_0 to a_3 are given by:

$a_0 = 0.0058$ $\quad$ $a_1 = 0.1549$

$a_2 = -0.1696$ $\quad$ $a_3 = 0.0732$

11. LIST OF SYMBOLS

E, e $\quad$: $\quad$ RMS steady state and instantaneous induced emf, V

V_a, v_a $\quad$: $\quad$ RMS steady state and instantaneous armature voltage, V

V_f, v_f $\quad$: $\quad$ RMS steady state and instantaneous field voltage, V

I_a, i_a :   RMS steady state and instantaneous armature current, A

I_f, i_f :   RMS steady state and instantaneous field current, A

ω_r, ω_e :   Angular shaft speed and induced emf frequency, rad/sec

N_r, f_e :   rotor speed (rpm) and induced emf frequency, Hz

P_o, P_d :   Output and developed power, W

R_a, R_f :   Armature and field resistance,

L_a, L_f :   Armature and field inductance, H

R_L, L_L, C_L :   Load resistance, inductance and capacitance