

Study the Effects of “Starting a Salient Pole Synchronous Motor in Isolated Power Grid, Run by “Wind-Turbine Asynchronous Generator”

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Abstract - In this paper, the effect of starting a salient pole synchronous motor in an isolated power grid run by wind-turbine-asynchronous generator is studied. The isolated grid frequency is controlled by ‘Discrete frequency regulator’. The salient pole synchronous motor has inherent pulsating current and torque. This feature effects isolated grid and its connected load. In this study, system currents, frequency, torques are studied and shown by oscillograms. The simulation is done using ‘MATLAB’. The basic model used for study is available in MATLAB.

Key Words: Isolated power grid, Synchronous Motor, Simulation, MATLAB

1.INTRODUCTION

Microgrids are a growing segment of the energy industry. They provide efficient, low-cost clean energy and flexibility in parallel operation with conventional grid and can operate as isolated grid. They face challenges like power system stability and quality.

When they run as isolated grid, they are more sensitive to the type of load and its characteristics. The loads like salient-pole synchronous motor are different from resistive loads. The features of synchronous motors are

- i) They do not have inherent starting capability.
- ii) The damper windings are provided in rotor pole faces. They help in creating starting torque and bring the rotor to near synchronous speed.
- iii) When the rotor comes near synchronous speed, the rotor field winding is excited, and the motor is synchronized
- iv) When rotor comes near synchronous speed, rotor field winding is excited, and the motor is synchronized.
- v) The motor produces pulsating torque. the magnetic circuit varies from point to point around the rotor. The instantaneous torque, during starting is greater when the flux pass through the poles and less torque is developed when passing between poles. Thus, the torque pulsates during each rotation. At a given speed, the frequency of pulsation is at twice slip frequency. At stand still, the torque pulsation is 120 Hz (for 60 Hz supply) and at 95% speed, the slip is 5% and therefore, the pulsating component is 6Hz. This pulsating torque effects all the associated mechanical

components in the rotor including shaft, couplings, flywheel.

TABLE -1: NOMENCLATURE

Symbol	Description
F	Supply frequency
I	Phase current
L	Self-inductance
L_{sl} L_{rl}	Stator and rotor self-leakage inductances
L_m	Mutual Inductance
L_{1kd}	Direct axis damper winding leakage inductance
L_{1kq}	Quadrature axis damper winding leakage inductance
P	Pole pairs
P, Q	Active and reactive power
R	Winding resistance referred to stator
R_{cb}	Crow- bar resistance
R_{kd}	Damper winding direct axis resistance
R_{kq}	Damper winding quadrature axis resistance
X_{sl} , X_{rl}	Stator and rotor winding leakage reactance referred to stator
X_m	Magnetizing reactance
X_s'	Stator transient reactance
S	Rotor slip
a	armature subscript
s, r	Stator and rotor subscripts
d, q	D and Q axis subscripts
1, 2	Subscripts for stator and rotor
f	Subscript for field winding
T_{em}	Electro-magnetic torque
V	Volts per phase
Z	Impedance
ω	Synchronous angular frequencies

The contents of the paper are divided into three following sections:

- a) Salient-pole synchronous motor and its behavior when started on conventional grid

- b) Isolated grid-its main components and working, frequency control is described.
- c) The behavior of isolated grid when salient-pole synchronous motor is started.

2.1 SYNCHRONOUS MOTOR

To understand the complexity of salient pole synchronous motor, the equivalent circuit and the expressions for torque and currents may be referred. They are given in Annexure.

A low tension 60 cycles 4 pole damper connected salient-pole synchronous is considered for study.

Table - 2: Technical particulars of synchronous motor

Parameters	Value
Number of poles	4
Rotor Type	Salient
Nominal power (kVA)	52.5
Line to line voltage (Volts)	460
Frequency	60
Armature	
Stator winding resistance (pu)	0.04491
Stator winding leakage (L1) (pu)	0.09
L_{md} (pu)	2.51
L_{mq} (pu)	1.11
Field winding	
Field winding Resistance (pu)	0.02185
L_{fd} (pu)	0.2004
Direct axis dampers	
R_{kd} (pu)	0.1687
L_{lkd} (pu)	0.3763
Quadrature axis dampers	
R_{kq} (pu)	0.05044
L_{lkq} (pu)	0.03083
Inertia coefficient	0.1349

2.1.1 Synchronous motor starting procedure

When a synchronous motor is started, direct online currents are induced in the damper winding, producing torque in the air gap. Voltage is induced in the rotor field winding. The magnitude of the induced voltage is crucial for the life of field winding insulation. To limit the open circuit induced voltages in the field winding, a resistance known as starting resistance is connected in the field winding. When the field is closed, current starts flowing in the field circuit and its magnitude is decided by the value of field resistance. Therefore, while deciding the value of field winding external resistance, the above two points namely

the induced voltage and circulating currents are to be considered.

When the motor reaches near synchronous speed, dc voltage is applied to field winding and starting external resistance is disconnected from the circuit. Then rotor field gets locked with air gap rotating magnetic field and the motor runs at synchronous speed. The field resistance connected in field circuit, usually is 2 to 5 times the field winding resistance. Starting time depends upon the developed torque and load inertia and its torque speed characteristics. In the present simulation, ramped part of full load torque is applied.

The following figures 1,2 ,3,4 show rotor speed, motor starting current, motor field current when started on conventional grid.

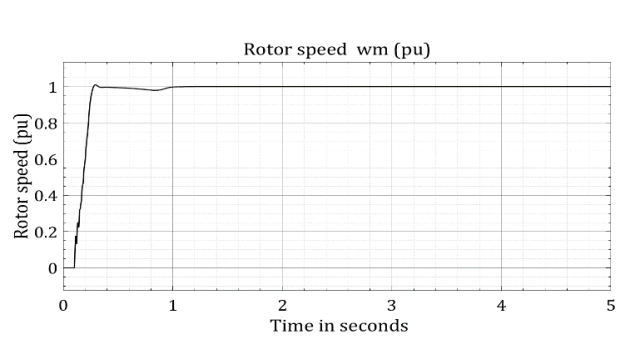


Fig 1. Synchronous motor speed when started from conventional grid

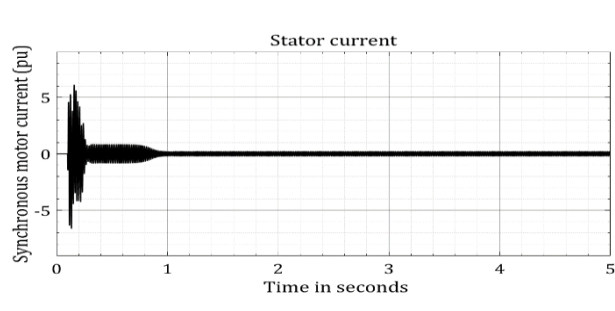


Fig 2. Starting current of synchronous motor current when started from conventional grid

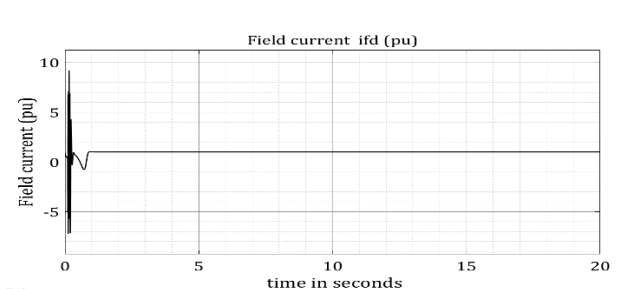


Fig 3. Synchronous motor field current when started from conventional grid (Motor load 0.2 PU)

Fig 5 below shows starting of a 52.5kVa, 460 volts, 60 cycles salient pole synchronous motor from a source of 460 volts 60 Hz supply. As explained above, starting resistance 'Restart' is connected in field. The rotor speed is sensed. When speed reaches 99%, voltage V_f is applied to field. The desired load torque is ramped. The stator current, rotor speed, electromagnetic torque, field current, applied field voltage wave forms are recorded. They are shown in fig 1,2,3, and 4.

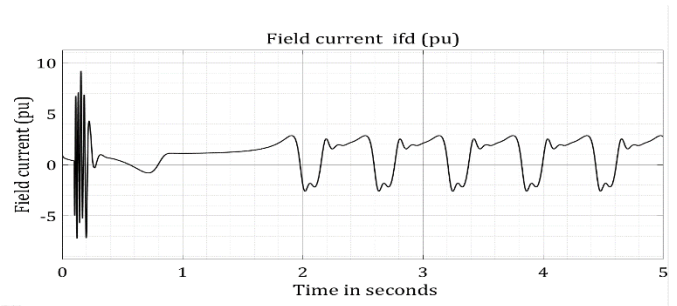


Fig 4. Synchronous motor field current when started from conventional grid (Motor load 0.8 PU)

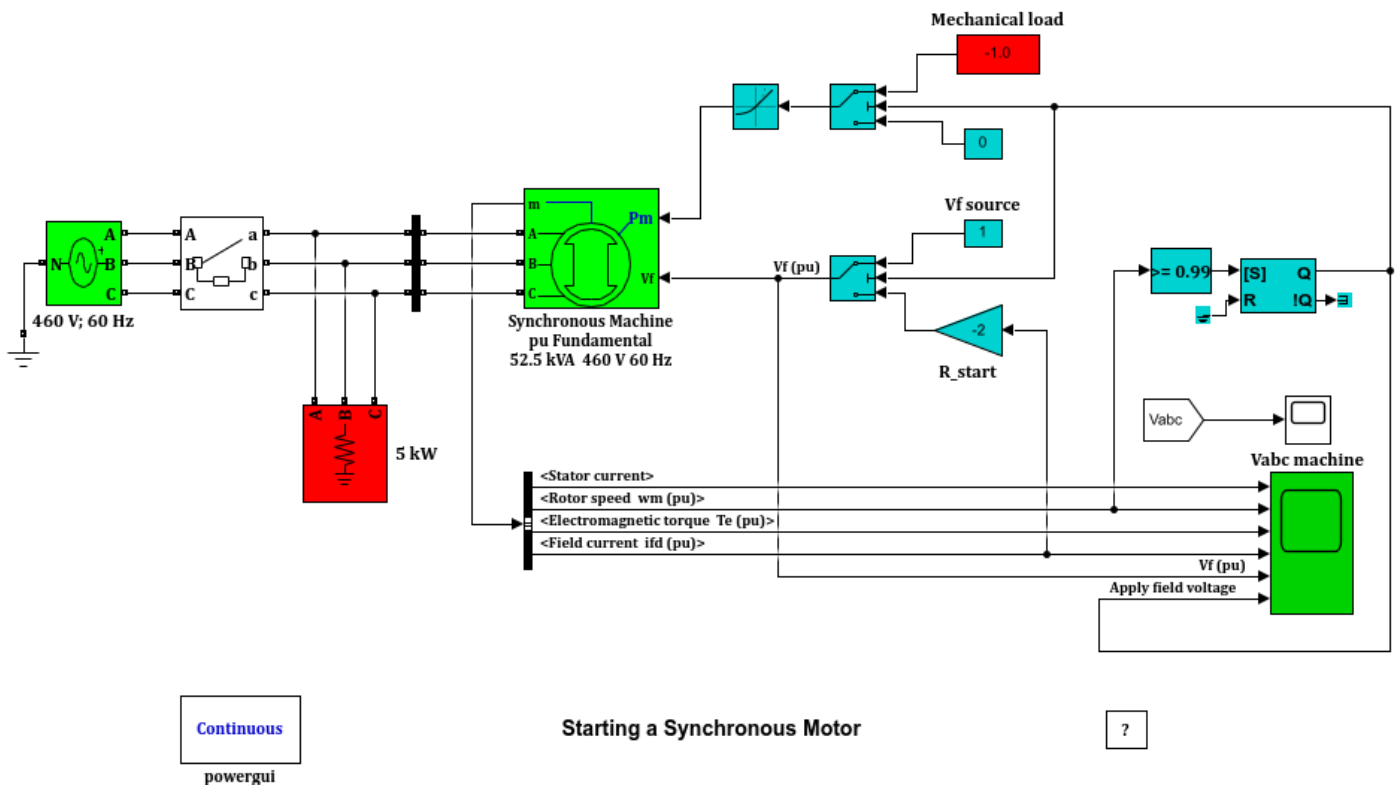


Fig 5. Starting a Synchronous Motor

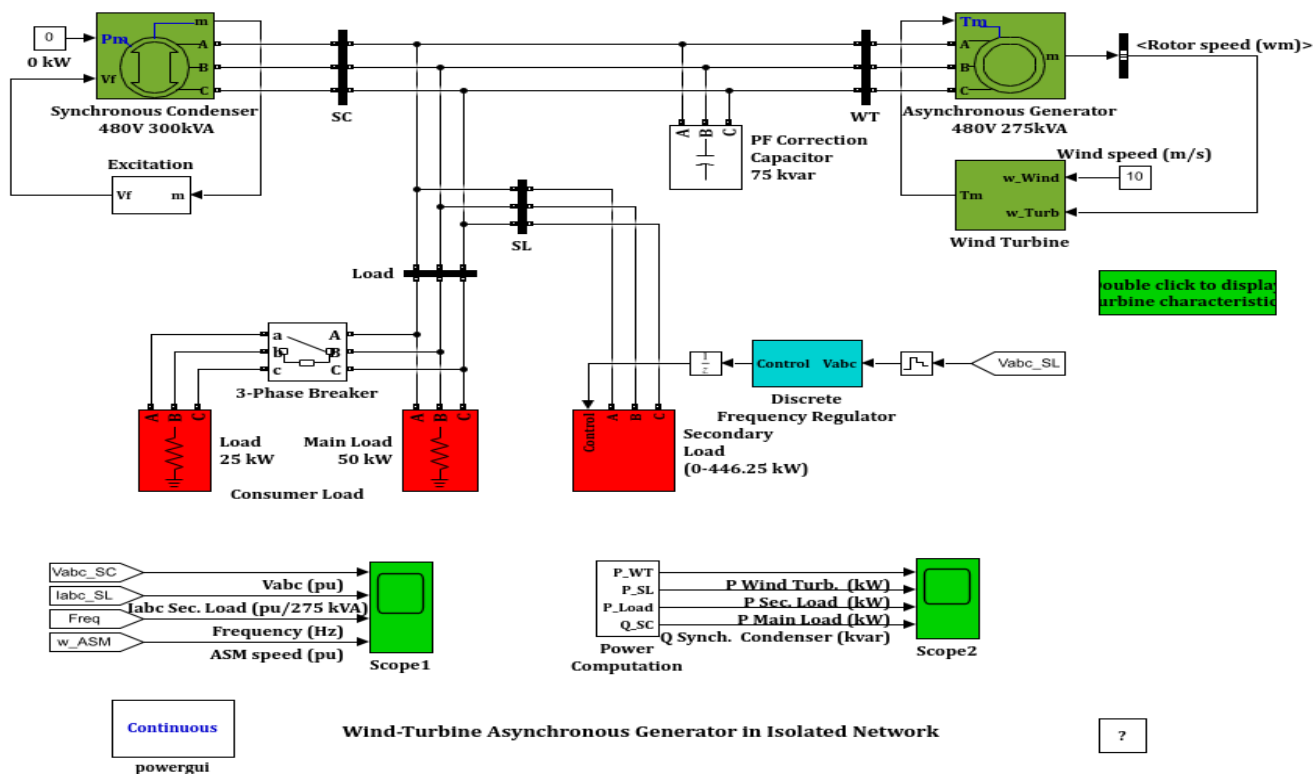
3. ISOLATED GRID (Salient-pole synchronous motor is not considered in the system):

The isolated grid system adopted is “High-Penetration No Storage Wind diesel” (HPNSWD). This system is taken from MATLAB (2). The system is shown in fig 6.

The main components are,

- i) Diesel driven synchronous generator (300kVA)
- ii) Wind turbine driving induction generator, (275kVA)

- iii) Customer load (50kW)
- iv) Variable secondary load (0 to 446.25kW)
- v) Discreet frequency regulator.



This example uses an initial state vector to start the simulation from steady-state. When you make changes to the model (add, delete, rename blocks, etc), the initial state vector needs to be regenerated or disabled, otherwise Simulink signals an error when the simulation is started. To disable the use of initial state vector for this model, go to the Data Import/Export section of the Model Configuration Parameters tool and uncheck the **Initial state** option under the 'Load from workspace' section. To regenerate the initial state vector after a change to the model, follow the instructions given in the initialization file for this model. Type `open('init_power_windgen')` at the matlab prompt to view this file.

Fig 6. Isolated grid with wind turbine Asynchronous generator

3.1 Working Principle

At low wind speeds, both induction generator and synchronous generator feed the load. When the wind power is more than load demand, synchronous generator is used as synchronous condenser, to maintain grid voltage. The secondary load is used to regulate system frequency.

In island mode, the objective is to control both its frequency and voltage, while supporting the energy demand.

Frequency is an important characteristic. This effects reliability and power quality of microgrid. In the present isolated power grid, the frequency is controlled by "Discrete Frequency Regulator". With the help of error frequency signal, Proportional – Differential (PD) controller, the secondary load is controlled. Thus, the frequency is controlled. For details of operation of 'Discrete frequency regulator', the reference (3) may be referred.

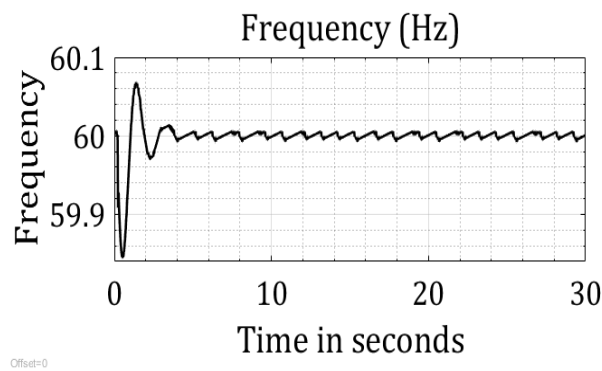


Fig 7. Isolated grid frequency when synchronous motor not connected to grid

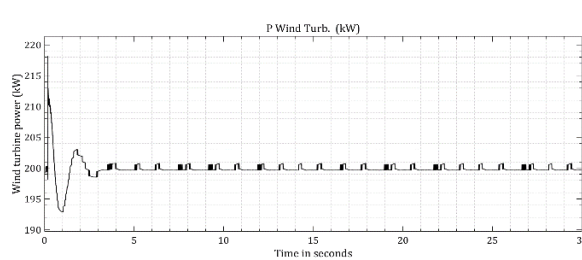


Fig 8. Power generated by wind turbine - synchronous motor not connected to grid

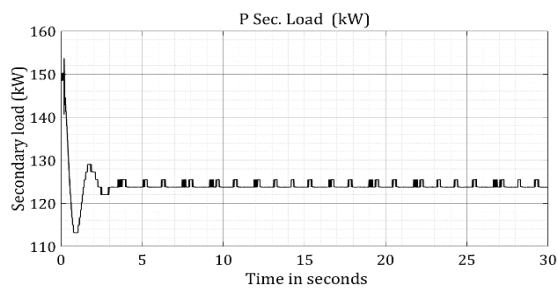


Fig 9. Secondary load current when synchronous motor is not in isolated grid system

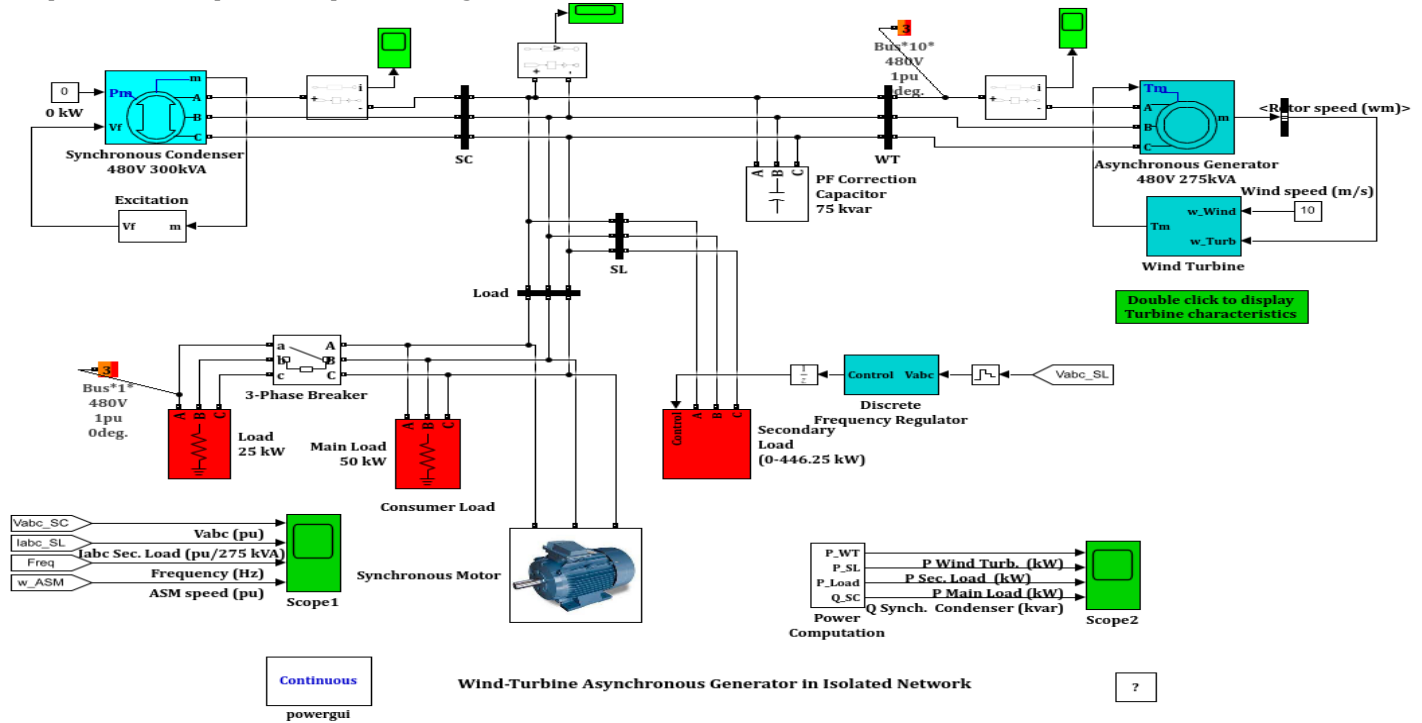
and its special features during starting and running. In the present paper, resistance loads are connected to the grid. In such an isolated grid, when salient pole synchronous motor is connected to the grid, the system frequency and voltage and wave shapes deviate from norms. The objective of this paper is to study the grid variations.

A subsystem is created for the salient pole synchronous motor. The motor details are given in Table 2. In the model “Wind-turbine Asynchronous Generator in Isolated Network”, a subsystem “synchronous motor” is included. The speed range for the selected wind turbine are 12 m/s and 5 m/s.

The simulation is done with wind speed of 10 m/s. The observations are given below.

4. ISOLATED GRID (Salient-pole synchronous motor connected to grid)

In isolated power grids, the grid performance parameters like grid frequency, voltage and the variation of these critical parameters depend on upon the magnitude of the load



This example uses an initial state vector to start the simulation from steady-state. When you make changes to the model (add, delete, rename blocks, etc), the initial state vector needs to be regenerated or disabled, otherwise Simulink signals an error when the simulation is started. To disable the use of initial state vector for this model, go to the Data Import/Export section of the Model Configuration Parameters tool and uncheck the **Initial state** option under the 'Load from workspace' section. To regenerate the initial state vector after a change to the model, follow the instructions given in the initialization file for this model. Type `open('init_power_windngen')` at the matlab prompt to view this file.

Fig 10. Wind Turbine Asynchronous generator in Isolated Network with synchronous motor in the circuit.

4.1 Initialization

Before starting the simulation of the model, it is necessary “to initialize” it. This model simulates, with “initial state vector”. It is necessary to initialize the vector to avoid “error signals” during simulation. The initialization procedure briefly is – Disconnect all loads and run the model for at least 20 seconds. Save the final state. Now connect all the loads and run the model from its previous final state. This is essential whenever changes are made in the model.

The detailed procedure for initialization can be found in MATLAB-SIMULINK documentation.

For both the models, with and without synchronous motor, are initialized and then simulation is carried out. The system frequency, voltage, power generated, synchronous motor current, field current, load currents are observed. The wave forms are shown below.

Case ‘a’: With resistive loads. (No synchronous

motor load in isolated grid)

Case 'b': With resistive loads (52.5kVA

synchronous motor in isolated grid.)

Frequency

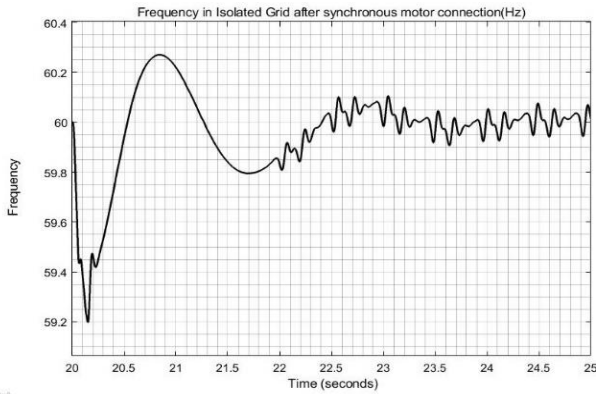


Fig 11. Isolated grid frequency - synchronous motor connected to grid (case 'b').

Table 3.: Frequency comparison for case 'a' and 'b'

System frequency	Case 'a'	Case 'b'
Maximum Frequency (Hz)	60.005	60.27
Minimum Frequency (Hz)	59.999	59.93
% variation	0.010	0.567
RMS value	60.000	59.98

Synchronous motor speed

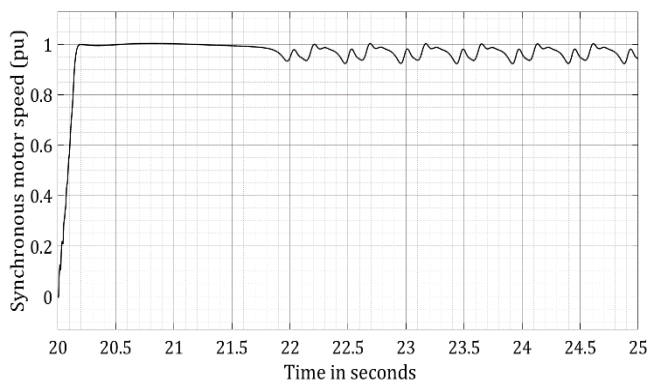


Fig 12. Synchronous motor speed variation when connected to isolation grid.

System voltage

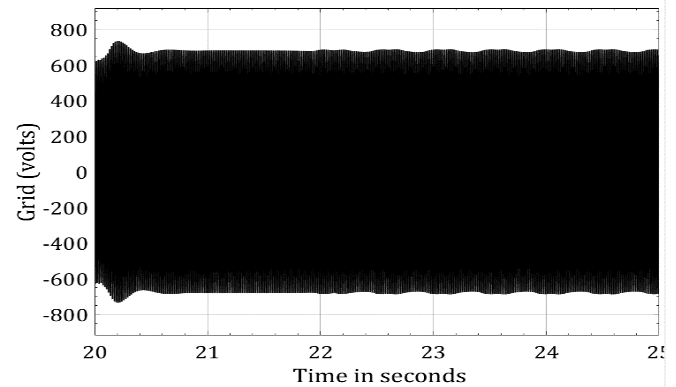


Fig 13. Isolated grid voltage - synchronous motor connected to grid (case 'b').

Synchronous motor field current

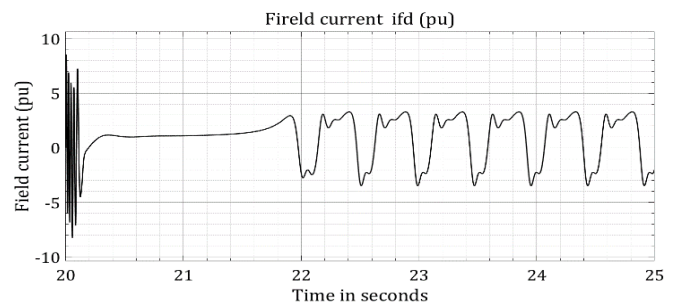


Fig 14. Synchronous motor field current fluctuation when connected to isolated grid

Wind turbine power generation

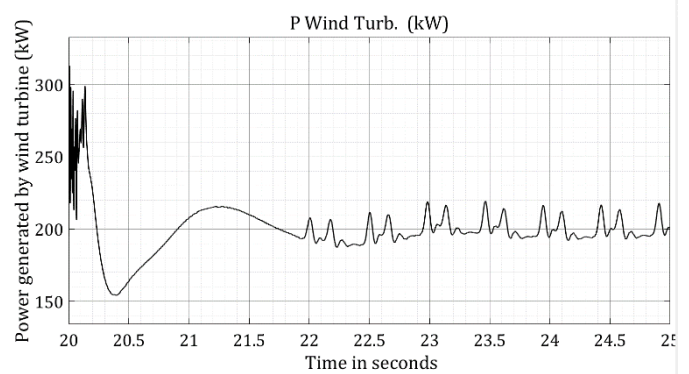


Fig 15. Wind turbine power generation when synchronous motor is in isolated grid

Wind power generated from turbine (kW)	Case 'a'	Case 'b'
Maximum	218.2	312.8
Minimum	192.9 at 1.06	154
Steady state variation	200.6 to 199.9	216.7 to 193.3
RMS value	199.9	200.3

Table - 4: Wind power generated in cases 'a' and 'b'

Asynchronous generator

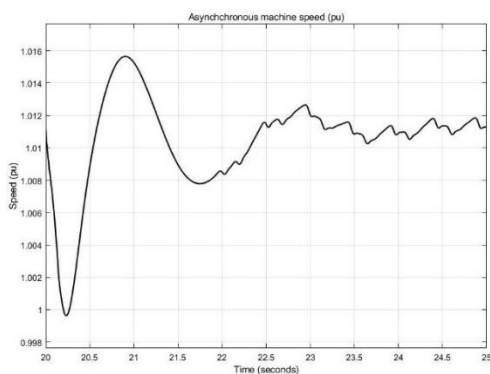


Fig 16: Turbine generator speed after synchronous motor is connected to isolated grid.

Synchronous motor starting current

RMS value of current 97.17 amps

The peak current is 592 amps at 0.018 seconds

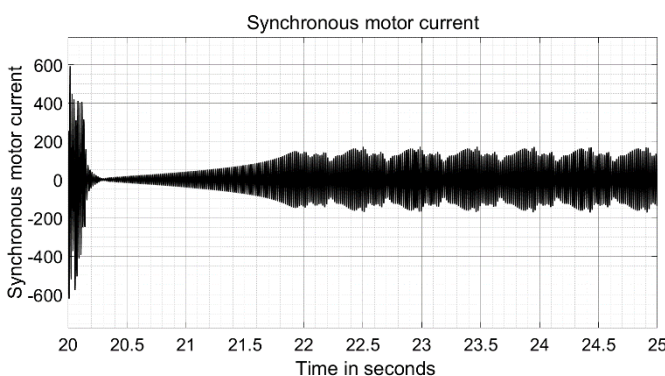


Fig 17. Starting current of synchronous motor when started from isolated grid supply system

The motor current varies from 133.6Amps to 97.09Amps
RMS current is 92.56 Amps

Electromagnetic torque

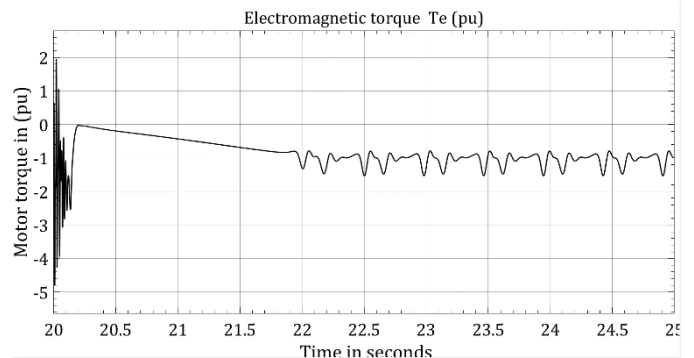


Fig 18. Synchronous motor electromagnetic torque of synchronous motor after its connection to isolated grid.

Secondary load

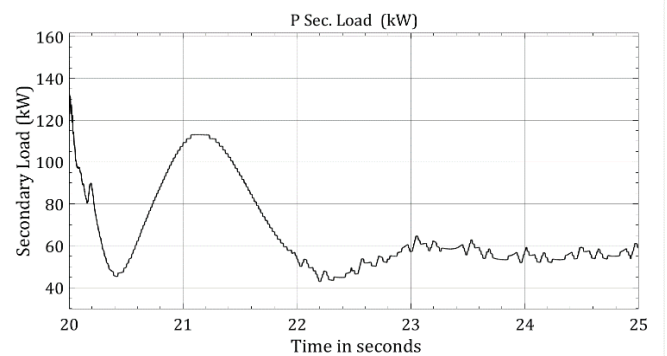


Fig 19. Secondary load kW when synchronous motor is in isolated grid system (case 'b')

The secondary load peak is 153.70 kW (148.5 kW) at 0.202 seconds and the steady RMS value is 124.7 kW (69.08 kW) Steady state variation is from 125.5kW to 123.8kW (64.54 kW to 53.76kW)

Synchronous condenser

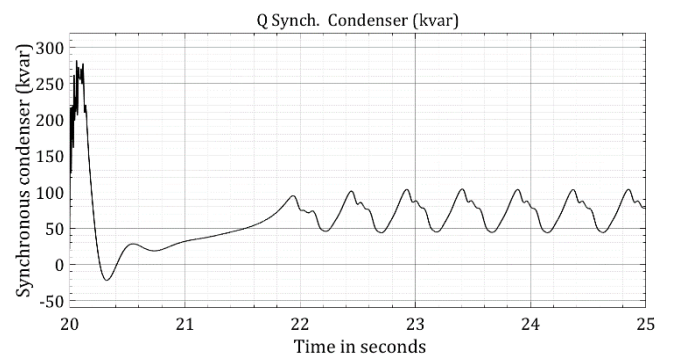


Fig 20. Synchronous condenser kVAr when synchronous motor is connected in isolated network.

Main load: Main load is (synchronous motor + resistive load) together

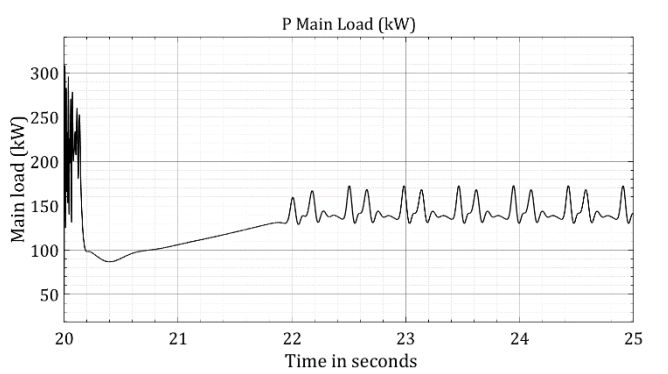


Fig 21. Main load after synchronous motor is connected in isolated grid

The peak value is 308.5 kW at 0.067seconds and the RMS load is 140.2 kW. The steady load variation is 168 kW to 131.8 kW

5. DISCUSSION

i) When the same 52.5 kVA salient pole synchronous motor is started from conventional grid, it is observed that, both speed and field currents does not have significant fluctuation. Shown in fig 1 and fig 3. When connected to isolated grid, with frequency control scheme like above, the speed and field current fluctuations. Shown in fig 11 and fig 13

ii) From the above figures, it can be seen, in steady state conditions, the frequency, turbine power generation, speed, currents, secondary loads, output of synchronous condenser, synchronous motor electromagnetic torque exhibit fluctuation. The higher the fluctuation, the more is harm to connected system components. To reduce the amount of fluctuation, the frequency control system needs to be fine-tuned. Alternatively, other control strategies like V/f control strategy, Fuzzy controllers, Flywheel energy storage system may be tried. [5]

iii) For good grid performance, a proper rating of the motor is necessary. To study the changes in grid performance A 72.5 kVA motor is connected in place of present 52.5kva motor. Changes in Parameters are shown below. When 100 kVA synchronous motor is connected the transient frequency maximum is 60.42 Hz and minimum frequency is 58.62 Hz (shown in fig 21)

Table -5: Comparison of 52.5 kVA and 75 Kva Motor performance on grid

Parameter	With 52.5 kVA motor	With 72.5 kVA motor
Maximum Frequency (Hz)	60.27	60.32
Minimum Frequency (Hz)	59.93	58.92

RMS frequency	59.98	59.95
Wind Turbine power (kW)-RMS	200.3	200.9
Secondary load (kW) Fluctuation	102.3 to 44.37	39.79 to 28.28
Synchronous motor current (amps) Fluctuation	133.6 to 97.09	225.4 to 127.2
RMS current	92.56	134.3

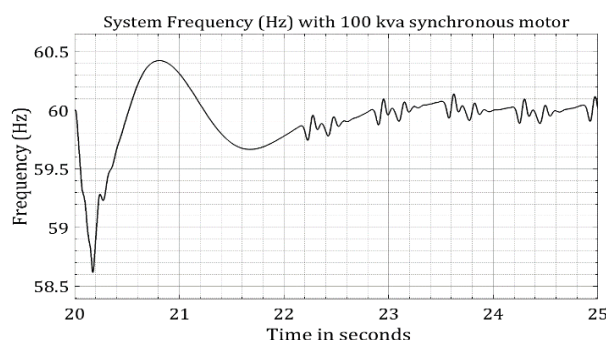


Fig 22. System frequency when 100 kVA synchronous motor is connected in isolated grid

6. CONCLUSION

Isolated micro grids, performance is sensitive to the type of load. Synchronous motors may show good laboratory test reports. But when connected to isolated micro grid, the motor characteristics effect the system voltage, frequency, and other loads. It is desirable to simulate and study the combined performance. Powerful tools like MATLAB and SIMULINK help to simulate and check the compliance to grid specification.

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BIOGRAPHY

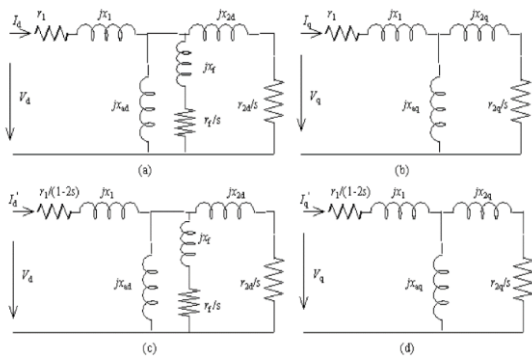


Author has done his master’s degree in Electrical Engineering with specialization in Rotating Electrical Machines from Indian Institute of Technology, IIT (Mumbai) in 1970. He has over 40 years of Industry experience. He has worked in companies including Crompton Greaves, Kirloskar Electric and WEG. He has been providing consultation to large, reputed companies. His interests are in the field of design of large electrical machines, Optimization and Machine learning and renewable energy. He has presented technical papers in national and international conference and published in journals.

Annexure

Equivalent circuit, pulsating torque, and current equations:

The ‘d’ axis and ‘q’ axis equivalent circuit for salient pole synchronous motor during starting is shown below.



The expressions for impedances are given below:

$$Z_d = r_1 + jx_1 + \frac{1}{\frac{1}{jx_{ad}} + \frac{1}{\frac{r_{2d}}{s} + jx_{2d}} + \frac{1}{\frac{r_f}{s} + jx_f}} \quad (1)$$

$$z_q = r_1 + jx_1 + \frac{1}{\frac{1}{jx_{aq}} + \frac{1}{\frac{r_{2q}}{s} + jx_{2q}}} \quad (2)$$

$$z'_d = \frac{r_1}{1-2s} + jx_1 + \frac{1}{\frac{1}{jx_{ad}} + \frac{1}{\frac{r_{2d}}{s} + jx_{2d}} + \frac{1}{\frac{r_f}{s} + jx_f}} \quad (3)$$

$$z'_q = \frac{r_1}{1-2s} + jx_1 + \frac{1}{\frac{1}{jx_{aq}} + \frac{1}{\frac{r_{2q}}{s} + jx_{2q}}} \quad (4)$$

The expression for currents is given below:

$$I_s = V_s \frac{z'_q + z'_d}{z_d z'_q + z_q z'_d} \quad (5)$$

$$I'_s = V_s \frac{z_q - z_d}{z_d z'_q + z_q z'_d} \quad (6)$$

The expression for average torque is as follows:

$$T_a = \frac{2p}{\omega_1} \left(V_s I_s \cos\phi_1 - I_s^2 r_1 - I_s'^2 \frac{r_1}{1-2s} \right) \quad (7)$$

The pulsating torque is $T_p = \frac{2p}{\omega_1}$

$$R_e \left\{ \begin{array}{l} V_s I'_s e^{j(2s\omega_1 t + \phi_2)} \\ -I_s I'_s \frac{r_1}{1-2s} e^{-j(2s\omega_1 t - \phi_1 + \phi_2)} \\ -I_s I'_s r_1 e^{j(2s\omega_1 t - \phi_1 + \phi_2)} \end{array} \right\} \quad (8)$$