Dual Stator Winding Induction Generator (DSWIG) used for hybrid micro grid power systems

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Abstract. This paper proposes a hybrid micro grid system for critical consumers like military disaster intervention, health or municipality. The solution is based on a multiple level of redundancy DC micro grid. The solution is projected to provide critical functionalities like stability, power quality, coordinated control, grid support capability. The configuration described here takes in consideration the problem integration of renewable energy sources which should have features like redundancy, flexibility and scalability from architecture point of view.

1. Introduction

The vast majority of electrical energy consumers are powered by a connection to the main grid. The safety of the energy supply in this case depends on the reliability of the energy source, quality of the transmission and distribution grid. Since the electrical energy obtained from power plants cannot be stored, it means that when an a disturbance in the supply the consumer occurs, due to the power failure of the power supply, the consumers can no longer be fed from another local source and all the alternative power supplies need to powered up which implies at least the existence of an engine, an AC generator, an automatic start-up installation, etc. This solution is used to ensure the supply of vital consumers and relatively high power, but it comes with a certain cost and that’s why it doesn’t have a wide spread being limited to critical consumers.

Due to the advancements in battery technology it is possible store an amount of energy. For emergency operation "accumulated", the solution was adopted with the continued tension of the important consumers, but with not too high powers with the advantage that, for the supply, in case of removal from the operation of the base source, can be used as local sources, which provide electrical energy directly, accumulators, set up to ensure the required voltage and capacity in battery accumulators. As a rule, the electrical circuits of command, signaling, protection and automation are powered by continuous voltage.
2. Micro grid management modes

In a general micro grid with PV-battery-genset structure must adopt some specific control strategies for the optimum management of the resources and consumer supplying (Figure 1 and Table 1). Basically are several control modes which can be defined as follows [1-4]:

a. **Control Mode 1: Battery grid former, genset cycle charging (DC coupled)**

The battery converter supplies the consumers and is the dominant contributor in the system. The micro turbine genset is connected to the DC grid (i.e. via an AC/DC battery charger) and acts as a backup unit when the battery state of charge is small. In such situations, the genset operates in cycle charging mode where it operates at full or near maximum capacity in order to supply the loads and charge the battery. Once the battery has topped the cycle charging SoC setpoint, the microturbine genset is switched off. In this control mode, the solar PV has to be typically sized to fully charge the battery each day.

b. **Control Mode 2: Mixed master, genset cycle charging (AC coupled)**

In this situation both the battery converter and genset can supply the grid, although interchangeably, i.e., a single changing master control structure where the designated master changes depending on operation condition. This control mode is typically a battery dominant control mode where the genset acts as a backup unit and only operates when the battery state of charge is low or when the load exceeds the battery converter rating. As in mode 1, the genset operates in cycle charging mode. Under normal operation, battery converter is the grid former and designated master unit. When the genset is activated, the battery converter switches to grid-following control and the genset becomes the grid former. The genset only ever operates in cycle charging mode, i.e. there is never any load sharing between the genset and battery converter. Whenever the genset is energised, the battery does not discharge [5].

c. **Control Mode 3: Mixed master, genset load following (AC coupled)**

Both the battery converter and genset can form the grid, although interchangeably. This control mode is typically battery dominant where the genset acts as a backup unit and only operates when the battery state of charge is low or when the load exceeds the battery converter rating. The genset is configured for load following mode and never charges the battery.

d. **Control Mode 4: Genset grid former, battery ramp control**

The genset forms the grid and is the dominant contributor (along with the solar PV). The battery is only used for ramp control to account for variations in solar PV output [6].

Figure 1. Emergency micro grid configurations a) battery grid former, genset cycle charging (DC coupled); b) Mixed master, genset cycle charging (AC coupled); c.) Mixed master, genset load following (AC coupled); d.) Genset grid former, battery ramp control

Table 1

| MODE | GRID FORMER(S) | GENSET CONNEXION | CONTROL PHILOSOPHY |
|------|----------------|------------------|--------------------|
| 1    | Battery converter | DC (Type 1 & 2)  | Battery dominant, genset backup on cycle charging control |
| 2    | Single changing master | AC (Type 3 & 4)  | Battery mainly, the microturbine genset will back on cycle charging control |
| 3    | Single changing master | AC (Type 3 & 4)  | Battery dominant, microturbine genset backup on load following control |
| 4    | Genset             | AC (Type 3 & 4)  | Genset dominant, battery charged by solar on ramp-rate control |
| 5    | Genset             | AC (Type 3 & 4)  | Genset dominant, battery charged by solar and discharged daily |

3. Emergency generator based on the use of dual stator winding induction machine

The dual-stator-winding squirrel-cage induction machine is the most recent innovation in the family of induction machinery.

There are two designs: the first type has two stator windings wound for the same poles numbers with similar or dissimilar phase numbers, and the second design has two stator windings with dissimilar pole numbers with the same or unequal phase numbers (Figure 2) [7-9].

Figure 2.
The two stator windings have a different number of poles to essentially eliminate the magnetic coupling between the two windings and to decouple the torques produced by each set of windings.
Power is supplied to the two windings by two separate variable frequency inverter drives to provide two independently controllably torque components.
At low speed, the power supplied to one of the windings can produce torque which opposes the torque from the power applied to the other winding, so that very low speed and standstill operation can be achieved while the frequency of the power supplied by the inverters is always greater than the minimum frequency.

At higher operating speeds, power is supplied to the two windings so that the torque from the windings adds. The dual stator machine can be built with minimal modifications from standard winding configurations.

A dual stator winding induction machine has two windings with input terminals which are supplied separately with power.

For the DSWIG the equations are presented below [10]:

\[ v_{q1} = -r_1 i_{q1} + \omega_k \lambda_{d1} + p \lambda_{q1} \]  
\[ v_{d1} = -r_1 i_{d1} - \omega_k \lambda_{q1} + p \lambda_{d1} \]  
\[ v_{q2} = -r_2 i_{q2} + \omega_k \lambda_{d2} + p \lambda_{q2} \]  
\[ v_{d2} = -r_2 i_{d2} - \omega_k \lambda_{q2} + p \lambda_{d2} \]  
\[ 0 = r_1 i_{q1} + (\omega_k - \omega_r) \lambda_{dr} + p \lambda_{qr} \]  
\[ 0 = r_1 i_{d1} - (\omega_k - \omega_r) \lambda_{qr} + p \lambda_{dr} \]  

where, \( \omega_k \) is the speed of the reference frame, \( p \) denotes differentiation w.r.t. time, \( \omega_r \) is the rotor speed.

Here, rotor quantities are referred to stator. The expressions for stator and rotor flux linkages are

\[ \lambda_{q1} = -L_{q1} i_{q1} - L_{m1} (i_{q1} + i_{q2}) + L_{m} (-i_{q1} - i_{q2} + i_{qr}) \]  
\[ \lambda_{d1} = -L_{d1} i_{d1} - L_{m1} (i_{d1} + i_{d2}) + L_{m} (-i_{d1} - i_{d2} + i_{dr}) \]  
\[ \lambda_{d2} = -L_{d2} i_{d2} - L_{m1} (i_{d1} + i_{d2}) + L_{m} (-i_{d1} - i_{d2} + i_{dr}) \]  
\[ \lambda_{qr} = L_{m} i_{qr} + L_{m} (-i_{q1} - i_{q2} + i_{qr}) \]  
\[ \lambda_{dr} = L_{m} i_{dr} + L_{m} (-i_{d1} - i_{d2} + i_{dr}) \]  
\[ L_{m} = (N_1 / N_2) L_{m} \]  

where, \( N_1 \) and \( N_2 \) are the number of turns of the abc and xyz winding sets respectively, and \( L_{m} \) is the common mutual leakage inductance between the two sets of stator winding, \( L_{m} \) is the mutual inductance between stator and rotor. \( L_{m} \) is given by [11]:

\[ L_{m} = L_{m1} \cos \alpha + L_{m2} \cos (\alpha + 2p/3) + L_{nc} \cos (\alpha - 2p/3) \]  

The DSWIG still requires an excitation capacitor connected at the winding. The voltage current equations of the excitation capacitor can be transformed from the three-phase quantities into d-q axis ones by using Krause transformation and are given by (Figure 3):

\[ pv_{q1} = \left( i_{q1c} / C_{shl} \right) - \omega_b v_{d1} \]  
\[ pv_{d1} = \left( i_{d1c} / C_{shl} \right) + \omega_b v_{q1} \]  

where, \( i_{q1c}, i_{d1c} \) are q-axis and d-axis components of currents flowing into the exciter capacitor, \( C_{shl} \) connected across the three-phase winding set I.
The model presented in this paper is based on the low speed dynamics of the micro turbine system, suitable for power management of genset combined with other types of distributed generation (DG) systems. For micro grid simulation we can assume that the system is operating under normal operating conditions by neglecting fast dynamics of the micro turbine. The main functions of the micro turbine are: speed control block for part load conditions, temperature control function for upper output power limit, and acceleration control to prevent over speeding. The output of the control function blocks are all inputs to a least value gate (LVG), whose output is the lowest of the three inputs and controls in the amount of fuel to the compressor-turbine as shown in Figure 4.

\[ V_{ce} = \frac{K(T_s+1)}{T_s} (\omega_{ref} - \omega_{meas}) \]  

(16)

\[ W_{speed} = (V_{ce} \cdot N \cdot K_b \cdot e^{-sT} + K_6) \frac{K_v}{T_s+c} \frac{K_f}{T_s+c} \]

\[ W_{LVG} = \begin{cases} W_{f_{max}} & \text{if} \ W_f \leq W_{f_{min}} \\ W_{f} & \text{if} \ W_f \geq W_{f_{max}} \\ W_{f_{max}} & \text{if} \ W_f \geq W_{f_{max}} \end{cases} \]  

(17)

The acceleration control of the micro turbine rotation motion can be divided into 2 periods - a concave period followed by a convex period [12]

\[ v(t) = v_o + j_m \frac{t^2}{2} \quad \text{concave} \]

\[ a(t) = j_m \]  

(18)

\[ a(t) = a_s - j_m t \quad \text{convex} \]

where \(j_m\) is the jerk set for the profile (near the maximum allowed for the micro turbine), and \(a_s\) is the maximum acceleration encountered at the S-curve inflection point

\[ Torque = K_{HV} \left( W_{LVG} \left( e^{-sT_{CD}} \left( \frac{1}{T_{CD} c + c} \right) \right) -0.23 \right) + 0.5(1 - N) \]
\[
T_{\text{exh}} = \left( T_R - 700 \right) \left( 1 - W_{fl,VG} \left( e^{-\alpha T_{\text{exh}}} \right) \left( e^{-\alpha T_{\text{turb}}} \right) \right) + 550(1 - N)
\]

\[
W_{\text{temp}} = T_{\text{ref}} - T_{\text{exh}} \cdot \left( \frac{K_4}{T_4s + 1} - 1 \right) \left( \frac{T_5s + 1}{T_5s} \right) W_{\text{temp}LVG} = \begin{cases} W_{\text{temp}max} & \text{if } W_f \leq W_{f\text{min}} \\ W_{\text{temp}} & \text{if } W_{f\text{min}} < W_f < W_{f\text{max}} \\ W_{\text{temp}max} & \text{if } W_f \geq W_{f\text{max}} \end{cases}
\]

\[
W_{\text{fout}} = \min(W_{f\text{flow}}, W_{f\text{temp}}, W_{f\text{speed}}).
\]

Battery modelling

The batteries are often considered as being the weakest point of a hybrid system, in terms of cost, life time and reliability. HRES is less suitable to charge batteries than the main grid because the battery elements are subjected to variable currents (irregular charge cycles). The battery model exploits equation to calculate the SOC in charge/discharge conditions. The prediction of state of charge on the battery is calculated using equations [13]:

\[
SOC = SOC_0 + \int_{0}^{t} \frac{I_{\text{bat}}}{C_{\text{bat}}} dt
\]

where \( C_{\text{bat}} \), \( SOC_0 \) and \( I_{\text{bat}} \) represent capacity of battery (Ah), and initial state of charge and battery current (A).

The hybrid generation system includes a special control system for the battery management called BMS. In the proposed system the BMS is equipped with MPPT and boost converters in order boosts a variable DC voltage output of PV to the required value of the dc grid and adapt it to DC voltage to the reference DC bus (48 VDC). The maximum available power from a PV hybrid system can be extracted when MPPT control applied. For modern BMS it is almost generalized solution to use a Perturb-and-observe (P&O) strategy to produce available duty cycle of PWM signal to control the boost converter. The MPPT system identifies the maximum available power from the PV generation system, and then compares the calculated power with the actual drawn power for generating the switching signals of the DC-DC boost converter of the MPPT system. Another DC-DC boost converter cascaded after the MPPT converter which order to maintain the voltage level of the DC bus at the value of 48 Volt to ensure continuous power supply to the DC load.

The state equation that characterizes the electrical modelling of the DC-DC boost converter can be given by (Equation. 15), where \( S \) is the switch state that takes the value 1 or 0, \( V_i \) is the input voltage to the dc–dc converter (output from each energy source) and \( V_o \) is the dc link output voltage.

\[
\begin{bmatrix}
\frac{dV_0}{dt} \\
\frac{dI_i}{dt}
\end{bmatrix} = \begin{bmatrix}
\frac{1 - S}{C} & -1 \\
0 & \frac{1 - S}{L}
\end{bmatrix} \begin{bmatrix}
V_0 \\
I_i
\end{bmatrix} + \begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix} \cdot V_i
\]

The values of the capacitor and inductor are calculated as:
Taking the case of PVWT systems, the terminal voltage $V_0$ is controlled by the voltage error signal. Where the PV voltage and current are sensed to determine the reference voltage at which MPPT occurs, the error signal, which is the difference between the reference voltage, and the actual voltage of the PV is fed to the voltage controller to command the duty cycle of the PV boost converter.

For the micro turbine the error signal is the difference between the reference of rectified voltage of the DSWIG and measured rectified voltage. This error signal is fed to the voltage controller, which controls the duty cycle of the boost converter.

\[ P_{bat} = \Delta P = P_s - P_{PV} - P_{MT} \]  

The sum of electricity generated at both generators photovoltaic and micro turbine (PVMT) is designed to meet the required DC load demand since the output power of PV generators vary with irradiation. The battery output power is controlled based on the difference power command $\Delta P$, which is the load power (command value) $P_s$ minus the summation of the power generated from the PVMT.

The battery terminal voltage is calculated according the desired battery power using a look-up table, the input of this look-up table is the difference power command $\Delta P$, which means the battery reference or required power.

4. DSWIG control strategy

The output voltage and control variable are described using the instantaneous power theory [9]. For the generator control we use field oriented of the control-winding flux $\psi_{c1}$ direction, the instantaneous active $p_{c1}$ and reactive power $q_{c1}$ are

\[
\begin{align*}
  p_{c1} &= \omega \psi_{c1} i_{cql} \\
  q_{c1} &= \omega \psi_{c1} i_{cq1}
\end{align*}
\]  

where $i_{cd1}$, $i_{cql}$ are the d–q of control-winding current ($i_{c1}$), $\psi_{c1}$ is the amplitude of $\psi_{c1}$. The torque and flux are

\[
\begin{align*}
  T_{c1} &= n_p \psi_{c1} i_{cql} \\
  \psi_{c1} &= L_i i_{cd1} + \psi_{pcM} + \psi_{rcM}
\end{align*}
\]  

where $n_p$ is the pole pairs, $L_i$ is the inductance, $\psi_{pcM}$ and $\psi_{rcM}$ are the mutual flux of power winding to control winding and control winding to rotor, respectively. Output voltages are:

\[
\begin{align*}
  u_{pDC} &= 2 \cdot 65 \cdot u_p \\
  u_{cDC} &= \left( \alpha_1 |T_{c1}| R_E \right)^{\frac{1}{2}}
\end{align*}
\]  

where $u_p$ is the root mean square (rms) of power-winding phase voltage and $R_E$ is the equivalent resistance. Therefore, the output voltages can be regulated by the control of fundamental current loop.
5. Grid Side Power Control
The inverter 3 in Figures 5, 6 is connected between the DC bus and the electrical network through RL filter. This inverter has two functions: to keep the DC bus voltage constant, irrespective of the amplitude and direction of the power flow and to maintain a unit power factor at the point of connection with the electrical network [8]. The mathematical modeling of the studied DC link system is as follows

\[
\frac{dU_{dc}}{dt} = \frac{1}{C}(i_{dc} - i_m)
\]

where:

\[i_{dc} = i_{d1} + i_{d2}\]

Expressions of grid reference currents can be characterised by:

\[
\begin{align*}
\dot{i}_{d} &= \frac{1}{(R_s + L_s s)} (v_{d,inc} - v_{dq} - L_s \omega i_{dq}) \\
\dot{i}_{q} &= \frac{1}{(R_s + L_s s)} (v_{q,inc} - v_{qu} - L_s \omega i_{du})
\end{align*}
\]

The grid active and reactive powers are defined by

\[
\begin{align*}
P_s &= v_{dq} i_{dq} + v_{qu} i_{qu} \\
Q_s &= v_{dq} i_{dq} - v_{qu} i_{qu}
\end{align*}
\]

The block diagram of the control loops for the currents axis (d, q) is described in Figure 4. The correctors used are of the PI type. This block diagram includes the terms of decoupling and compensation in order to be able to independently control the currents circulating in the RL filter and the active and reactive powers exchanged between the CCR and the network.

6. Grid control of active power
In order to control the flow of active power, the value \(P_{ij}\), of the real power flow between node \(i\) and node \(j\) is given by

\[
P_{ij} = \frac{1}{x_{ij}} (\theta_i - \theta_j)
\]

The total power flowing into bus (node) \(i\) is denoted as \(P_i\). This must equal the power generated by generator \(i\) minus the power absorbed by the local load on the bus. This power, \(P_i\), therefore must equal the sum of the power flowing away from bus \(i\) on all transmission lines. This means that

\[
P_i = \sum_{j \in N(i)} P_{ij} = \sum_{j \in N(i)} (\theta_j - \theta_i) \frac{1}{x_{ij}}
\]

which can be expressed in matrix form as

\[
P = B \theta
\]

where \(P = [P_1, \ldots, P_n]\), \(\theta = [\theta_1, \ldots, \theta_n]\), and \(B\) is defined as
The $C_i(P) \in R$ is a function representing the cost incurred in running generator $i$ at power level $P$. The equation formula for a general optimal power flow problem it comes as

$$\begin{align*}
\text{minimize} & \sum_{i=1}^{N} C_i \left( P_{Gi} \right) \\
\text{considering} & \quad P_{G1}, \ldots, P_{GN} \\
\text{with the constraints} & \quad B\theta = P_G - P_L \\
& \quad P_{G_{\text{min}}} \leq P_G \leq P_{G_{\text{max}}} \\
& \quad P_{\text{min}} \leq A\theta \leq P_{\text{max}}
\end{align*}$$

(38)

where $P_G$ is the vector of generated active powers for all generators (micro turbine and solar in this case) and $P_L$ is the vector of total local loads for all buses.

The matrices $A$ and $B$ were defined above. The vector $P_{G_{\text{min}}}$ and $P_{G_{\text{max}}}$ represent the lower and upper limits of the DSWIG generator power. These are the generation constraints. The other vectors, $P_{\text{min}}$ and $P_{\text{max}}$, are lower and upper limits on the power flowing through the distribution lines. The objective function $\sum_{i=1}^{N} C_i \left( P_{Gi} \right)$ represents the total generation cost of all sources.

The grid optimum control problem has the objective to minimize this overall cost by selecting generating powers (micro turbine DSWIG battery and solar that satisfy the major three constraints imposed to the micro grid. The first constraint is a power balance relation. The second constraint requires that the selected power levels stay within the limits specified by $P_{G_{\text{min}}}$ and $P_{G_{\text{max}}}$. The third constraint requires that the power flowing over the distribution lines stay within the specified bounds, $P_{\text{min}}$ and $P_{\text{max}}$.

### 7. Simulation of the proposed micro grid

In order to simulate the behavior, the micro grid the corresponding models of the key components need to be presented. The corresponding equations are modeled in MATLAB Simulink model shown in Figures 4-9, and the results of simulations in Figures 10 and 11.
Figure 4. Hybrid Micro grid Simulink Model

Figure 5. DSWIG model

Figure 6. Microturbine DSWIG genset configuration
Figure 7. DC-DC converter configuration

Figure 8. Perturb and observe MPPT model

Figure 9. Solar battery configuration
8. Conclusions
In this paper we have presented a hybrid micro grid system build on the basis of a new micro turbine with dual stator induction generator connected to DC bus supplying a number DC loads. The mathematical models were implemented models into a large Simulink model system that allows us the study of the corresponding characteristics and their diagram model. The model simulation using Simulink model is used for the tuning and control of the electrical power at 500 volt DC. The hybrid micro grid integrating solar and micro turbine with DSWG scheme proposed in this paper uses an inverter with apparent power lower than the corresponding generator power. The expected ratio between the inverter power and the generator power is 50% in the case of DSWG.

The micro turbine powered DSWG can be used in variable speed applications as backup generator capable to emergency supply in emergency situations. The DSWG makes possible to extract low power even at lower speeds, which cannot be obtained when the generator is directly connected to the grid, or when the generator has an inverter on the excitation winding and a diode bridge on control winding. The DSWG typology is an advantageous solution when it supplies complex micro grids loads.
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