Stand-Alone Hybrid Microgrid for Remote Areas. Topology and Operation Strategy

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Abstract*— In remote regions, were a main Utility System for energy distribution is not available, the implementation of Microgrids with hybrid generation are very useful. In this context, a Stand-Alone wind/diesel/gas/battery/supercapacitors Hybrid Microgrid topology is proposed. The main scope is to create a low cost system to feed Residential loads through a local AC bus, using wind energy obtainable at system location. The random characteristics of the wind makes necessary to smooth the fluctuating supply in order to minimize the disturbances on local grid electric parameters. To overcome these problems, a Wind Turbine based on a DFIG machine and Strategies to control the power of a Storage Energy System are employed. An appropriate Supervisor Module with a reliable communication network is used to balance generation and loads, in order to properly operate the Microgrid. The system structure, operation modes and mathematical models for simulation and validation are presented.

***Keywords*—Stand-Alone; Microgrid; Hybrid; Autonomous; Remote; Wind; Diesel-Gas; Battery; Supercapacitor.**

I. INTRODUCTION

In remote regions where electrical distribution networks are unavailable, Stand-Alone Microgrid with Hybrid Generation constitutes a good alternative to deliver electric energy for residential users [1]. Since most loads to be fed will be typical commercial equipment, a fixed AC voltage and frequency must be provided. It is also desirable to supply a good power quality, which means that the power do not fluctuate either with the load or the variable wind speed. Oriented to this type of demand, this paper proposes and analyses a Wind–Diesel/Gas Generation System, using a wind turbine of variable speed in order to take advantage of the wind resource and a modular energy storage system to compensate the power fluctuations [2]. The Diesel/Gas Generator operates only when the consumption exceeds the maximum available power given by the wind turbine and the storage system [1]. The storage system will be able to provide energy during a relatively short time, when the AC load demand surpass the available wind power and may store energy when the available power overcomes the AC load. In order to maintain system simplicity, only one storage module is used, based on deep-cycle batteries and supercapacitors [2][3]. The task of keeping constant the AC voltage and frequency, when the Diesel/Gas generator is not operating, was assigned to the storage module. Due to the high energy density of the batteries and high power density of the supercapacitors, this module is ideal to compensate power grid unbalances as result of wind power fluctuations, load variations or insufficient wind resource [3].

All the supervision and control actions will be taken from the measurement of electrical variables and turbine speed.

The proposal and the obtained preliminary results will be presented as follows:

-CONVERSION STRATEGY (Topology and Operation Modes)

-SYSTEM MODELING

-EVALUATION by SIMULATION

-CONCLUSIONS

-REFERENCES

II. CONVERSION STRATEGY

A conversion strategy is based on two central aspects which are the physical structure of the conversion system and its operation modes.

A. System Structure

Figure 1 shows the complete conversion system. A three blades horizontal axis wind turbine with fixed pitch, makes the wind to mechanical energy conversion and an asynchronous three phase generator with wounded rotor (DFIG) and a static Kramer drive, makes the mechanical to electrical conversion. Acting over the controlled rectifier firing angle (α), the power contribution of the wind turbine can be varied.

In this topology, the power conversion handled by the converter is a fraction of the total power generated, being the system of easy and economical implementation.

The battery/supercapacitors bank is connected to the grid through a three phase voltage source inverter, modulated with sinusoidal PWM technique [4]. A low-pass filter avoids contaminating the network with high frequency harmonics produced by the inverter commutation. A closed-loop control fixes the AC voltage and frequency in the grid [5].

A synchronous generator, powered by a diesel engine or a gas turbine, directly feeds the grid and has associated the usual voltage and frequency controls.

Finally, a Supervisor Control System, with a reliable communication network [6], handles the whole system.

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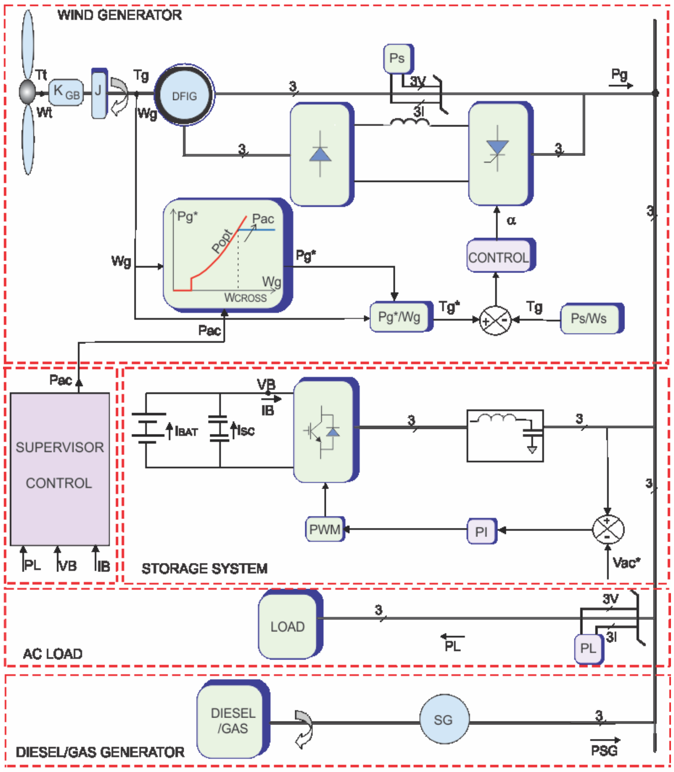

Fig. 1 – System topology.

B. *Control and Operation Modes*

1) Wind Turbine Control

The power developed by the turbine is [7]:

$$P_t = P_W C_P(\lambda) = 0.5\rho A v^3 C_P(\lambda) \qquad (1)$$

where:

P_W: wind power ; $C_p(\lambda)$: power coefficient ; $\lambda = r\omega_t/v$;
r: blade radius ; ω_t: rotational speed ; ρ: air density ;
$A = \pi r^2$: capture area ; v: wind speed.

The torque produced by the turbine is:

$$P_t = T_t\omega_t \Rightarrow T_t = 0.5\rho A r v^2 C_P(\lambda)/\lambda \qquad (2)$$

$P_{t\,max} = P_{opt}$ is obtained with $C_{Pmax} = C_P(\lambda_o)$.
In the plane T_t-ω the points corresponding to λ_o describes a parabola, given by:

$$T_{t_{P\max}}(\omega_t) = T_{opt}(\omega_t) = K_t\omega_t^2 \qquad (3)$$

with:

$$K_t = 0.5\rho A r^3 C_{P\max}/\lambda_o^3$$

Neglecting the friction, the operation point of the wind turbine in steady state (ω_t=cte and ω_g=cte), is defined by:

$$T_t = T_g' = T_g K_{GB} \qquad (4)$$

where:

T_t: turbine torque ; T_g: generator torque ; $K_{GB} = \omega_g/\omega_t$ gear box ratio ; T'_g: generator torque at turbine side.

To work in a desired point, T_g must be imposed, which is done by a closed control loop acting over α, as is indicated in Fig.1. T_g is calculated sensing electrical variables. In asynchronous machines, if the stator losses are neglected, then:

$$P_S = P_{Gap} = T_g\,\omega_S \rightarrow T_g = P_s/\omega_S \qquad (5)$$

with:

P_S: stator power ; P_{Gap}: air gap power.
$\omega_s = 2\pi f/p$: synchronous speed ; f: grid frequency.
p: pole pairs.

The reference torque T_g^* for the closed-loop is obtained from ω_g and P_{ac} (desired generated power fixed by the Supervisor control), through:

$$P_g^* = \begin{cases} P_{opt} & if \quad \omega_g < \omega_{cross} \\ P_{ac} & if \quad \omega_g > \omega_{cross} \end{cases} \rightarrow T_g^* = P_g^*/\omega_g \qquad (6)$$

with:

$$P_{opt} = K_t\omega_{cross}^3 = P_{ac} \qquad then \qquad \omega_{cross} = \sqrt[3]{P_{ac}/K_t}$$

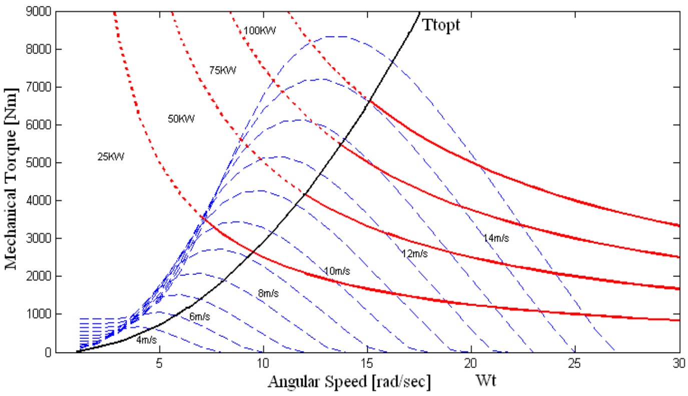

Fig. 2 – Turbine and Generator curves.

Fig. 2 shows, at turbine side, $T_t = f(\omega, v)$ (blue) and T'_g (black or red depending of v and P_{ac}). The operation point (intersection between T_t and T'_g), will belong either to the T_{opt} parabola or the P_{ac} (red) hyperbole. Then, with enough wind speed (v) P_{ac} is generated, otherwise a lower power P_{opt} is delivered.

2) Storage System Control

When the Diesel-Gas generator is not operating, the inverter associated to the Storage Module imposes the grid voltage and frequency. Then, the voltage control loop reference must be in accordance with the residential load requirements. The supplied/absorbed current by the battery/supercapacitors bank depends on the circumstantial power balance of the system. The average power exchange is done with the battery, while the fast power fluctuations are interchanged with the supercapacitors.

3) Supervisor Control System

The supervisor control system commands the whole autonomous system, determining the power contribution of each module. The average power on the Residential Load and the state of charge (SOC) of the Storage System are evaluated by the Supervisor Module through V_B, I_B and P_L. The control actions that may be taken are:

1. $SOC_{min} < SOC < SOC_{max} \rightarrow P_{ac} = P_L$
2. $SOC < SOC_{min} \rightarrow P_{ac} = P_L + \Delta P$
3. $SOC > SOC_{max} \rightarrow P_{ac} = P_L - \Delta P$
4. $SOC < SOC_{min}$ and $P_g < P_L \rightarrow$ *Diesel/Gas* genset is started

The actions 2, 3 and 4 are sustained during enough time until the rated SOC is achieved. The ΔP and the rated SOC value are fixed according the technical characteristics of the battery/supercapacitors bank.

III. SYSTEM MODELING

A. Wind Generator

1) Mechanical System

$$T_t / K_{GB} - T_g = J d\omega_g / dt + B\omega_g \qquad (7)$$

with:

J: total inertia (ω_g side) ; B: total friction coefficient (ω_g side) ;
T_t calculated with (2) and $C_P(\lambda)$ given in section IV ;
$T_g = T_g^*$ calculated with (6).

2) DFIG Generator–Kramer Drive

Wind generator electrical model:

$$\hat{I}_W = 2T_g\omega_g / 3\hat{V}_{AC-phase} \rightarrow i_{a,b,c} = \hat{I}_W sen(2\pi ft + \theta_{a,b,c}) \qquad (8)$$

where i_a, i_b and i_c are the active components of the current interchanged with the grid; θ_a=0 °, θ_b=-120 °, θ_c=120 °.

B. Storage Bank – Voltage Source Inverter

$$V_B = E_{Bat} + R_{Bat} i_{Bat} + \int i_{Bat} dt / C_{Bat} \qquad (9)$$

$$V_B = R_{SC} i_{SC} + \int i_{SC} dt / C_{SC} \qquad (10)$$

$$i_B = i_{Bat} + i_{SC} = (v_a i_a + v_b i_b + v_c i_c) / V_B \qquad (11)$$

$$\hat{V}_{AC-phase} = m_V V_B \rightarrow v_{a,b,c} = \hat{V}_{AC-phase} sen(2\pi ft + \theta_{a,b,c}) \qquad (12)$$

with:

$m_V = \hat{V}^*_{AC-phase} / V_B$: inverter modulation index,
θ_a=0 °, θ_b=-120 °, θ_c=120 °.

IV. EVALUATION OF THE PROPOSED STRATEGY

The evaluation of the proposed system was done through a simulation in the MATLAB®-Simulink environment. The models presented in III were used and a wind generation channel was sized with a nominal power of 100 kW at a wind speed of v= 14 m/s [8]. The numerical values of the parameters are:

Turbine: 3-blade HAWT, r=7 m, ρ=1.225 Kg/m^3. C_p given by:

$$C_p(\lambda) = c_1\left[c_2(1/\lambda - 0.0035) - c_3\right]e^{-c_4/\lambda} + c_5\lambda \qquad (13)$$

with: c_1=0.5176; c_2=116, c_3=5, c_4=21, c_5=0.0068, resulting a C_{pmax} = 0.48, (λ_o= 8.1)

Battery bank: deep-cycle Pb-acid, rated voltage V_{Bat}=720 V, R_{Bat}=1 Ω. C_{Bat}=5040 F.

Supercaps bank: rated voltage V_{SC}=750 V, R_{SC}=0,1 Ω. C_{SC}=10 F.

Two different test situations were evaluated, considering in both cases that the grid AC voltage and frequency are kept at its nominal values. This implies that the storage system must absorb/deliver the necessary power in the AC grid at all times. The results are presented as paths in the torque–speed plane of the turbine, which indicates the transient power variation (electrical or mechanical) in the different system components. The waveforms of these powers are also shown.

Case 1 – *Variable wind speed–Constant AC load power.*
The transient evolution of the powers in different parts of the system, facing a stepped wind speed variation, is analyzed.
The Fig. 3 shows the paths of the operation points of the Turbine, and the DFIG machine, and the power contribution of the Storage System. Point A in Fig. 3 represents the initial steady state. The AC power delivered by the Wind Generator is 50 kW. The initial wind speed is 11 m/s. From these initial conditions, the system is submitted to the wind speed variations, shown in Fig. 4. The results are presented in Fig. 5, 6 and 7. In Fig. 6 is proven that while the Wind Generator power is equal to the load power, the Storage System contribution is null. In the path (Y,D,D',Y) the Wind Generator delivers P_{opt}, and the Storage System provide the remaining power to complete the 50 kW load. In the transient evolution between the steady state points (A,B,C,D,E), the difference between the Wind Generator power and the Turbine power is supplied or absorbed by the Inertia J of the complete rotating system, Fig. 7.

Case 2 – *Constant wind speed - Variable AC load power.*
The Fig. 8 shows the paths of the operation points of the Turbine, the DFIG machine and the power delivered by the Storage System, being point A the initial steady state. The power transient evolution in the Turbine, the Inertia component J, the DFIG machine and the Storage System, for a stepped variation of the AC load power shown in Fig. 9, is then analyzed. The results are presented in Fig. 10-11-12. Fig. 11 proves that while P_{opt}>P_{AC} the Wind Generator power is equal to the load power, and the Storage System power is null. For turbine rotational speed where P_{opt}<P_{CA}, as in segment Y-Z, the Wind Generator provide P_{opt} and the Storage System delivers the remaining power needed to complete the required P_{AC}. In the trajectories between the steady state points (A,Z,C,D,E), the difference between the power supplied by the Wind Generator and the Turbine is delivered or absorbed by the Inertia J of the whole rotating system, Fig. 12.

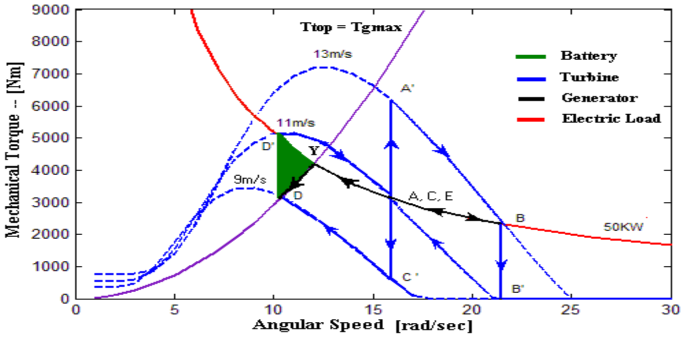

Fig. 3 – Operating point trajectories for Case 1.

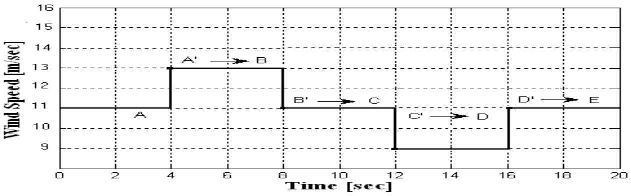

Fig. 4 – Wind speed variation profile.

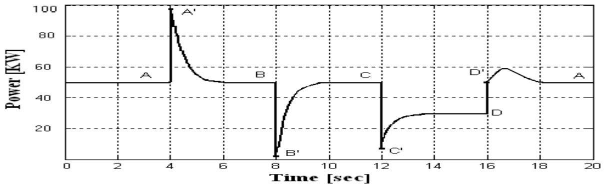

Fig. 5 – Mechanical power delivered by the turbine.

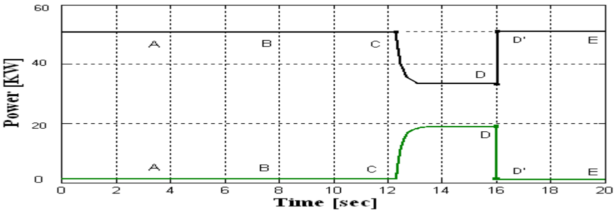

Fig. 6 – Generator (black) and Storage (green) power.

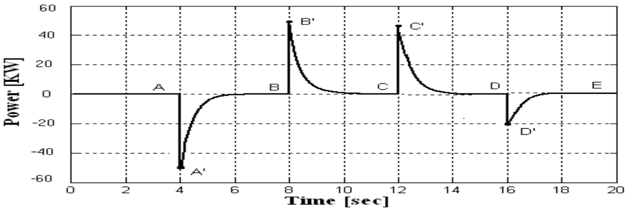

Fig. 7 – Mechanical power delivered by inertia.

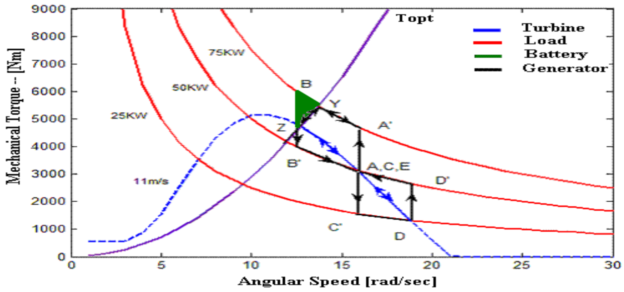

Fig. 8 – Operating point trajectories for Case 2.

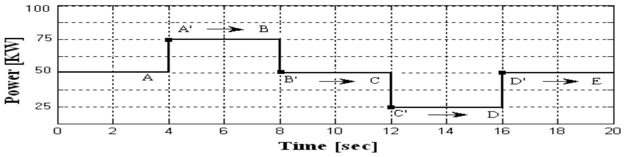

Fig. 9 – AC Load power variation profile.

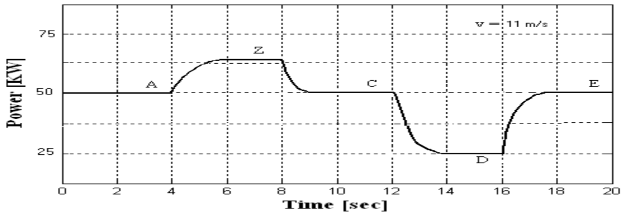

Fig. 10 – Mechanical power delivered by the turbine.

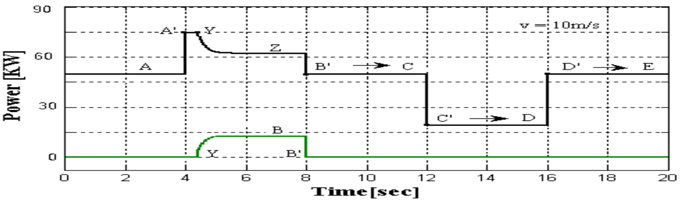

Fig. 11 – Generator (black) and Storage (green) power.

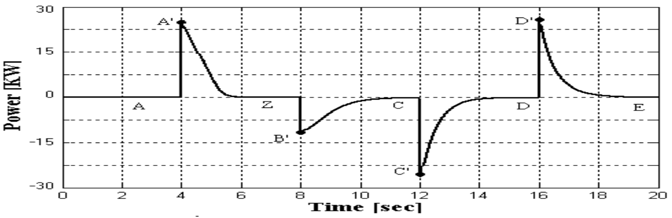

Fig. 12 – Mechanical power delivered by inertia.

V. CONCLUSIONS

- The simulation results shown in the system evaluation, validates the proposal integrally.
- The system components can be implemented using easily available, well proven and dependable technology. This is an important point, taking in consideration the economic and regional characteristics of the places for where the use of this kind of system was envisaged.
- The measurement of only one mechanical variable (wind turbine speed) reduces costs and increases reliability.
- The obtained results encouraging us to continue working in this project. We are planning a second stage oriented to enhance the dynamic behavior of the system by employing alternative controllers based on state of the art control techniques.

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