Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

# Cross-flow Water Turbines Control Under Grid Disturbances

M. Andreica, *Member, IEEE*, S. Bacha, *Member, IEEE*, D. Roye, I. Munteanu, *Member, IEEE*,
A.I. Bratcu, *Member, IEEE*, J. Guiraud

***Abstract*—The cross-flow water turbine generation system is, as any distributed grid connected generator, sensitive to all kind of power grid disturbances. The goal of this paper is to show how this system, by the means of its controls, is able to reject polluting harmonics. The fault ride through following voltage gaps is also proven. Experimental results obtained with a hybrid real-time test rig validate the correct operation of this system under grid disturbances.**

***Index Terms*—cross-flow water turbine, resonant controller, voltage sags, hybrid real-time simulation, harmonics.**

## I. NOMENCLATURE

| | |
|---|---|
| CFWT | cross-flow water turbine |
| PMSG | permanent magnet synchronous generator |
| DCM | direct current machine |
| PHIL | power-hardware-in-the-loop |
| $T_T$, $P_T$ | turbine torque and power |
| $w$, $\lambda$, $C_p$ | water speed, turbine tip speed ratio and power coefficient |
| $R_T$, $H_T$ | turbine radius and height |
| $\Omega_G$, $T_G$ | generator rotational speed and torque |
| $i_{qG}$, $i_{dG}$ | *dq* generator currents |
| $U_{DC}$ | DC-link voltage |
| $I_{RDC}$ | DC-link protective load current |
| $C_{DC}$, $R_{DC}$ | capacity and resistance on the DC-link |
| $L$ | inductance of the output filter |
| $R_{PL}$ | polluting load resistance |
| $i_{PL}$ | three-phased current drawn by the polluting load |
| $i_G$, $i_{L2}$ | generator and grid three-phased currents |
| $i_{L1}$ | grid line currents before the connection point of the polluting load |
| $v_L$ | grid three-phased voltages |
| $k_p$, $k_i$ | gains of the current resonant controller |
| $T_s$ | sample time |
| $\omega_{2k+1}$ | odd harmonics frequencies |
| $u_G$, $u_L$ | generator-side and grid side converters' duty cycles |

## II. INTRODUCTION

Large scale power grids, weak grids or microgrids can pass through temporary instabilities dues to grid disturbances such as voltage sags, harmonics, voltage drops or frequency variations. These events can disturb or even stop the generation operation. Renewable energy resources which are often connected to the distribution power grid are very sensitive to this kind of phenomena and the grid code is very restrictive.

Different types of advanced solutions are proposed in the literature for the low voltage ride through of distributed generators [1]-[4].

This paper focuses on the CFWT- based generation systems operating under grid disturbances. A suitable control and management is needed to reject the inherent perturbations. Hence this study proposes the control of the CFWT generation system so as to achieve the mitigation of grid disturbances impact. The considered grid disturbances are voltage sag and polluting harmonics.

The generation system analyzed is an electrical power generation system based on a new CFWT concept: the Achard turbines piled-up in towers [5]–[8]. This concept can be used in a modular structure and does not need important civil work investments.

The CFWT generation systems are variable-speed systems and this characteristic requires the presence of a power electronics interface between the generator and the grid. This kind of system has multiple similarities with the wind energy conversion systems; therefore the control schemes are in some way close and similarities certainly exist [9]. However, as the work presented here contributes to fulfilling a precise final goal – the realization of a ½ scale real-world prototype, the CFWT and the primary energy resource particularities must be taken into account. Therefore, the low level control loops and the management of the delivered power have to be adapted and conceived consequently.

The generation system's architecture is composed of the CFWT tower, a permanent magnet synchronous generator (PMSG) and two back-to-back converters (see Fig.1). The generated electric power is injected to a power grid. Thus, the control structures are meant to ensure the proper flow of the electrical power.

---

The financial support for this work comes from the ANR (The French National Research Agency).

M. Andreica, S. Bacha, D. Roye, I. Munteanu, A. I. Bratcu and J. Guiraud are with the Grenoble Electrical Engineering Laboratory (G2ELab), ENSE$^3$, BP 46, 38402 Saint Martin d'Hères, France, (e-mails: {andreica, bacha, roye, munteanu, bratcu, guiraud} @g2elab.grenoble-inp.fr).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

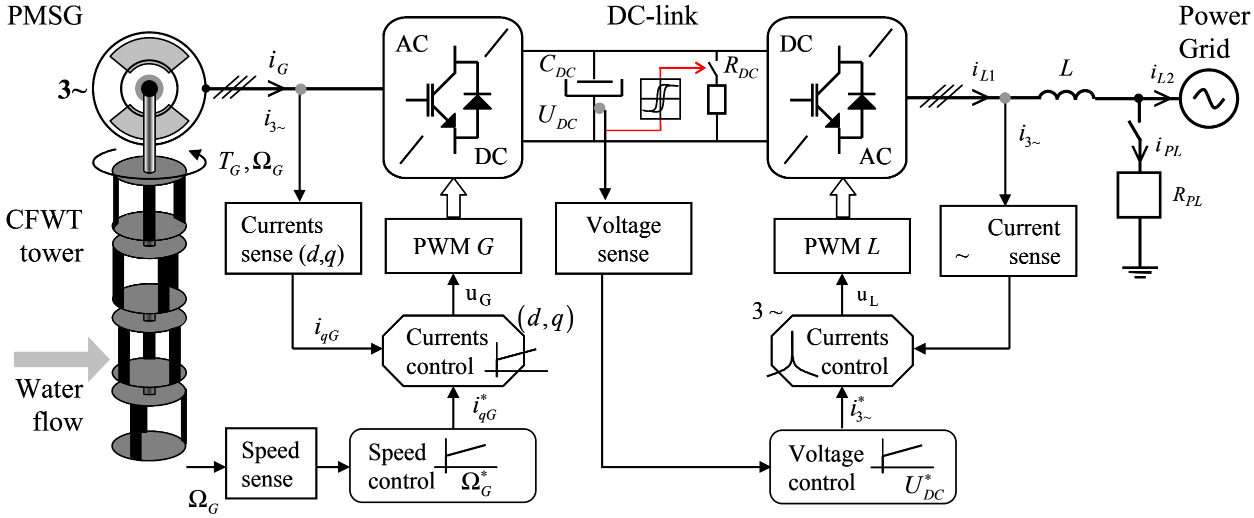


Fig. 1. CFWT generation system and its control structures [10]

A controlled resistive load is used on the DC-link to dissipate the fault over energy and a polluting nonlinear load is used to harmonically disturb the grid. In order to physically implement the voltage dips, a power amplifier is controlled by an I/O xPC Target.

A CFWT generation system is considered to be sensitive to momentary interruptions, voltage sags and strong harmonics perturbations. Thus it is important to prove that the controls are robust enough to ride through the fault.

Experimental results are shown to illustrate the correct operation of the CFWT-based generation system under the considered grid disturbances.

A power-hardware-in-the-loop (PHIL) physical test rig is used in order to test the fault ride through of the CFWT generation system. The CFWT behavior is physically simulated by a torque-controlled direct current machine (DCM), whereas the directly-driven PMSG and its associated power electronics are designed for the real-world application.

## III. THE GENERATION SYSTEM AND ITS CONTROL

### A. *Control aspects*

Fig.1 presents the system structure and the control loops. The CFWT tower is composed of four three-bladed Achard turbines, a PMSG and two three-phased back-to-back converters. The system is grid-connected.

For this kind of configuration (as presented in Fig. 1.) the optimal operating mode (a maximum power injected to the grid) [10] is achieved via the current control loops, the low-level main controls, the speed control and the DC-link voltage regulation.

Nevertheless, the grid currents can be perturbed as a result of grid disturbances; therefore the transferred energy quality is negatively affected. The grid-side converter control loops have to react promptly at this type of instabilities such as to ensure a continuous operation of the CFWT. Power transfer to the grid (with losses deducted) is the main role of the inverter but in some cases it can also ensure the active filtering [11].

### B. *CFWT tower*

The CFWT tower's model is based on the extracted mechanical power equation [5] and the approach is similar to the wind turbines modelling [9].

For one turbine the extractible power $P_T$, depends on the water flow speed cubed and some other turbine parameters:

$$P_T = 0.5\cdot\rho\cdot C_p\cdot S\cdot w^3 \qquad (1)$$

where ρ is the water density, $C_p$ is the non-dimensional power coefficient (expressing the turbine's efficiency), $S$ is the surface swept by the turbines blades and $w$ is the water flow speed. The surface $S$ is computed based on the turbine radius, $R_T$, and on the turbine height, $H_T$, as $S = 2R_T H_T$. The power coefficient is a function of the tip speed ratio, λ, defined as $\lambda = R_T\cdot\Omega_G / w$, where $\Omega_G$ is the turbine shaft rotational speed. Fig. 2 presents a CFWT power coefficient characteristic. Note that in the case of a CFWT the hydrodynamic efficiency, $C_p$, usually does not overpass 0.35 [12]. The CFWT tower is composed of 4 piled-up elementary turbines.

The turbines are placed on the same shaft, but mechanically shifted with an angle of 2π/(3*4) each versus the next one [6]-[7]. The main reason of such placement is the alleviation of the pulsating turbine torque [5] and an improvement of the efficiency of a single turbine. Experimental results obtained on a real 1/3 scale Achard turbine prototype [6]–[7] helped at the simplified model design.

All the four turbines are identical thus have the same characteristics; the output torque increases proportionally with the number of turbines in the tower. The turbine torque also exhibits specific behavior due to hydrodynamic conditions (*e.g*, mechanical torque pulsations).

Modularity and flexibility are important characteristics of this system; therefore it can be adapted for either river flow or marine current applications.

Concerning the grid disturbances impact analysis, the CFWT is supposed emerged in a regular river flow. So this system is a non-intermittent source of energy.

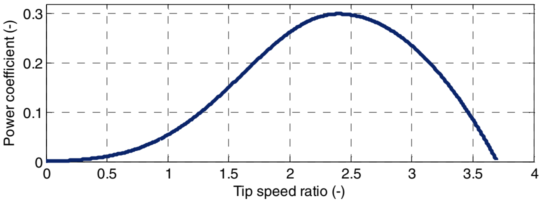


Fig. 2. CFWT power coefficient characteristic

### *C. Power Grid Voltage Sag Ride Through*

Regarding the generation system operation under voltage sags, and after their passage, DC-link extra energy dissipation is required in this case, in order for the fault not to be sensed at the PMSG level.

Slow system dynamics and hydrodynamic constraints forbid the rapid acceleration or the brutal braking of the CFWT tower. DC-link voltage control loss can be shattering for this kind of system as the generator side converter will no longer be able to operate correctly. The PMSG can lose its speed and current control.

In order to ensure the correct fault ride through a resistive dissipation load exists as a protection on the DC-link and it is automatically on/off switched by an analogic hysteresis-based controller (as shown in Fig. 1.).

This controller switches on at the moment when the PI DC voltage controller reaches its saturation limits and is no longer acting.

Two voltage sags shapes of a depth of 0.9. p.u. are considered and tested as shown in Fig. 3.

### *D. Power Grid Harmonics Rejection*

The choice of the current controller type was made in order to guarantee harmonic grid perturbations rejection. Accordingly, a multi-frame resonant PI control approach [11], [13] is adopted for the three-phased grid currents control.

The integral term of this controller contains resonant poles at the frequencies to be rejected.

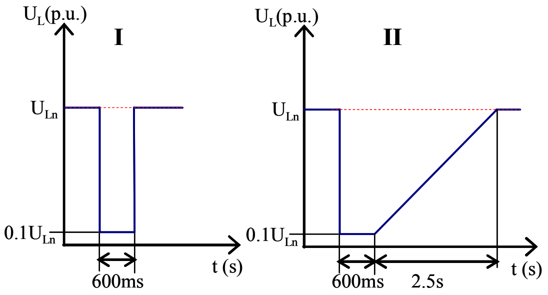


Fig. 3. Voltage sags shapes

Equation (2) is the transfer function of the employed resonant controller, aimed at rejecting odd harmonics of order 3 through 11.

$$C_R(z) = k_p + \sum_{k=1}^{5} \frac{2 \cdot k_i \cdot T_s[z^2 - \cos(\omega_{2k+1} \cdot T_s) \cdot z]}{z^2 - 2 \cdot \cos(\omega_{2k+1} \cdot T_s) \cdot z + 1} \qquad (2)$$

A three-phased software phase-locked loop (PLL) has been used in order to synchronize the controlled currents with the power grid voltages.

A polluting (diode bridge) load is connected in parallel to the grid in order to experiment the operation of the CFWT system under harmonically polluted grid. The goal is to prove that no disturbance is “felt“ by the PMSG therefore neither by the CFWT.

## IV. EXPERIMENTAL TEST RIG

A DCM simulates in real-time the dynamic behavior of the CFWT tower. The turbines model is fed by a regular water flow and is implemented using dSPACE hardware (DS1005). The DCM is directly driving a PMSG which is connected to the power grid via two back-to-back converters (see Fig. 4).

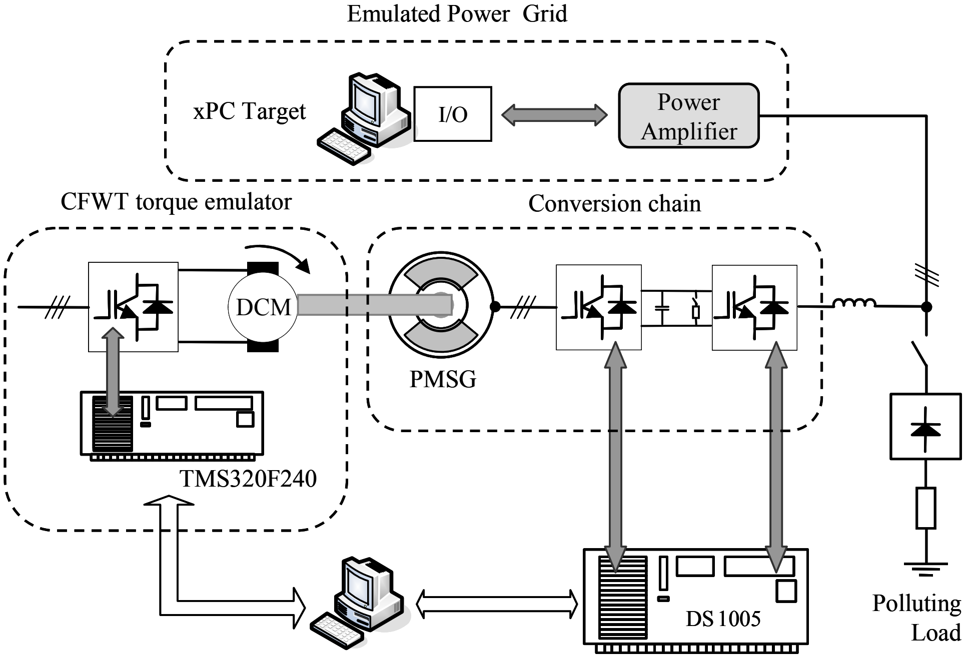


Fig.4. Experimental test rig schematics

The power grid is emulated via a power amplifier [14] which is controlled using an xPC Target real-time system [10].

Control algorithms are implemented using the same dSPACE hardware.

Similitude considerations have been made to correctly scale-down the real-world system to the emulated one. A scale factor of $m$ is given to the generator speed to perfectly scale the test rig with the real desired application. The simulator launching time must be the same as the one of the CFWT generation system (see [10] and the Appendix).

## V. EXPERIMENTAL RESULTS

The physical test rig in Fig. 4 is used to experimentally validate the fault ride through of the CFWT generation system.

Fig. 5 (a) and (b) show the variables evolution under a voltage sag of the shape I: a rectangular sag of 0.9 p.u. and during 0.6s.

Fig. 5 (c) and (d) show variables evolution under a voltage sag of the shape II: rectangular drop to 0.9 p.u. during 0.6s then return to 1 p.u. in 2.5s.

The DC-link voltage rises and the on-off controller acts by closing the switch of the dissipative load. The energy surplus goes into this protective load. Meanwhile, the PMSG does not "see" the fault, its rotational speed and its active current have no significant transient. The grid injected current increases as the sag occurs. After the voltage sag all variables regain their stable evolution. The fault ride through is assured.

Fig. 6 illustrates the response of the system when the power grid is polluted with harmonics. It is shown that no perturbation passes towards the DC-link, $U_{DC}$, which remains constant. The PMSG rotational speed, $\omega_G$, and the generator active current, $i_{qG}$, also keep their stable curves.

These results show that the resonant controller is robustness of the PI resonant controller as it rejects the perturbations introduced by the power grid. The output controlled currents $i_{L1}$ remain sinusoidal and the CWFT generating system behavior is not affected by the polluting load.

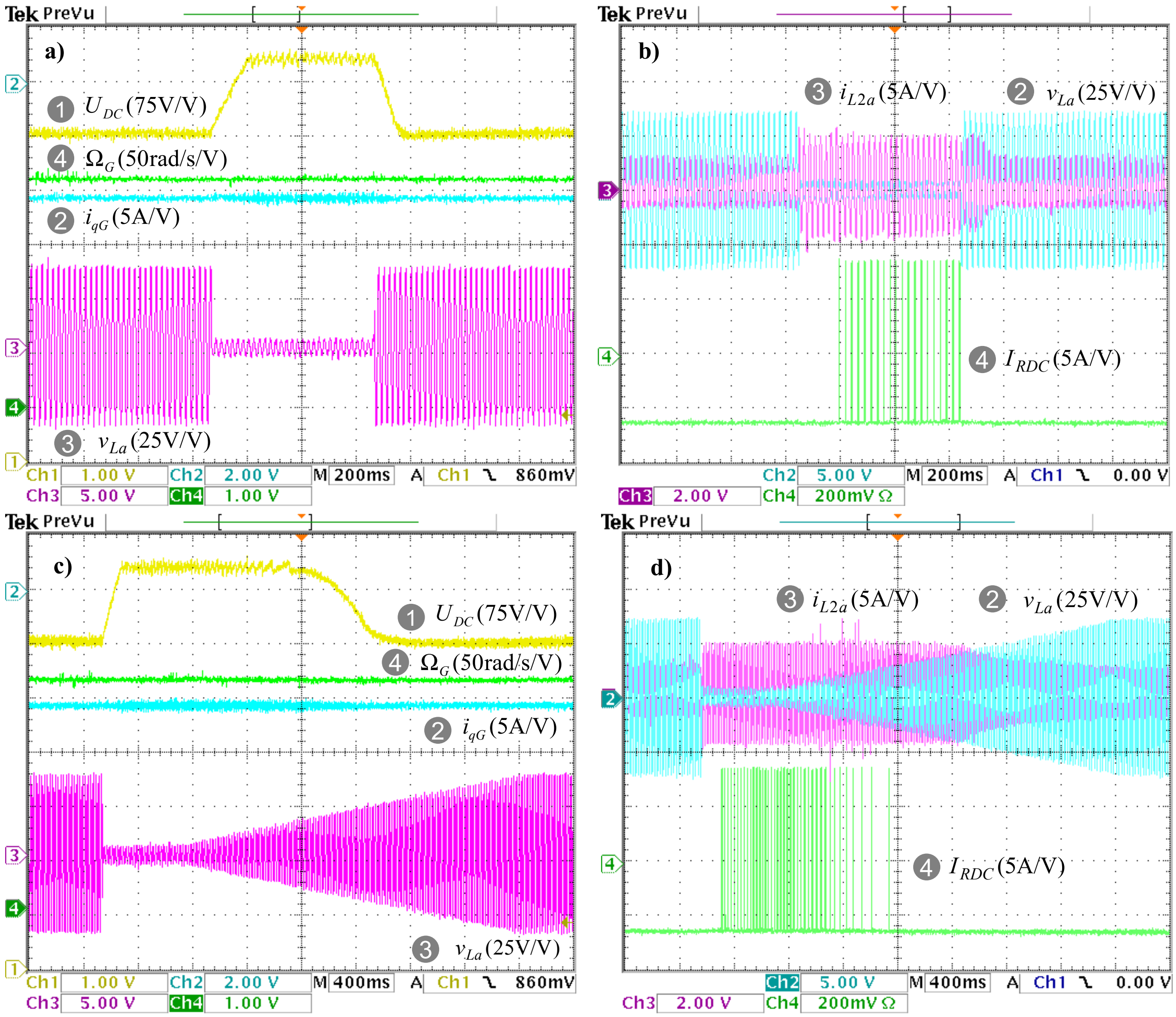


Fig. 5. System variables evolution under voltage sags

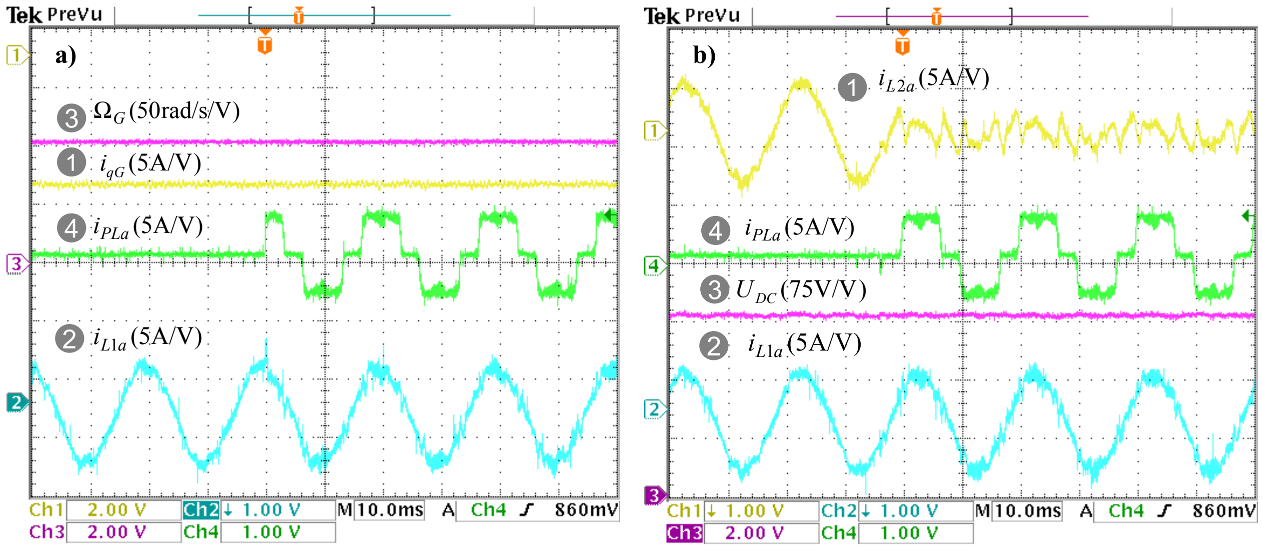


Fig. 6. Power grid harmonics rejection

Fig. 7 illustrates the response of the phase *a* controlled current $i_{L1a}$ in the same conditions as above; all grid harmonic perturbations are rejected.

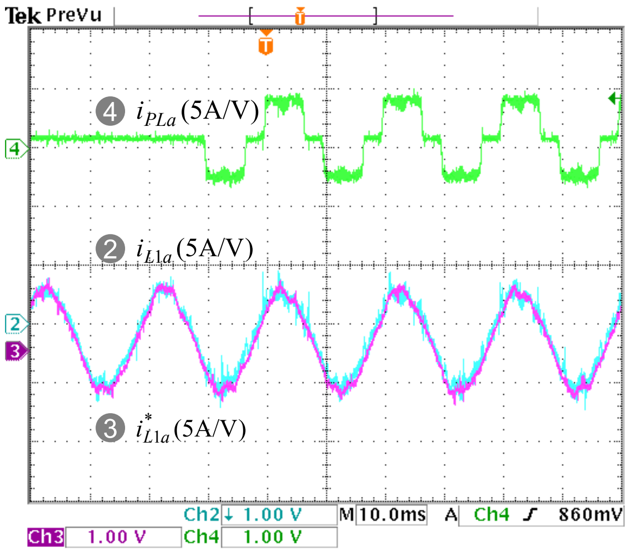


Fig. 7. Controlled current waveforms under harmonically polluted power grid

## VI. CONCLUSIONS

This paper aimed at showing how the CFWT generation system reacts under grid disturbances such as voltage sags and harmonically perturbed power grid.

Experimental tests on a hybrid real-time test rig (PHIL) validate the correct operation of this generation system, the fault ride through and the rejection of grid harmonics pollution are both assured. These are important issues for the CFWT generation system as it is wished that this system experiences no disturbances.

Future work will focus on the connection of this generation system to a microgrid, in order to experiment its capability of operating as an uninterruptible power supply.

## VII. APPENDIX

CFWT system data
Radius: 0.25 m
Output rated power: 2.3 kW at water speed 2.3 m/s
Maximum $C_p$: 0.31, optimal $\lambda$: 2.4
Tower inertia: 2.47 kg·m$^2$
PMSG: 5 kW, 3000 rpm, 135V, 4 poles

Laboratory test rig
DCM: 6 kW, 3000 rpm, inertia 0.0275 kg·m$^2$
Similitude scale factor *m*: 9
Inverters: 5 kW, 10 kHz, 3-leg, IGBT-based
DC-link voltage $U_{DC} = 450$ V
Grid voltage: 127/230 V

Control parameters
Sampling time: $T_s$=100 µs
Resonant controller parameters: ki=2000, kp=24.5

## VIII. REFERENCES

[1] Y.Q. Zhan, S.S. Choi, D.M. Vilathgamuwa, "A voltage-sag compensation scheme based on the concept of power quality control center," *IEEE Trans. Power Delivery*, vol. 21, pp. 296 – 304, Jan. 2006.

[2] D.M. Vilathgamuwa, H.M. Wijekoon, S.S. Choi, "A Novel Technique to Compensate Voltage Sags in Multiline Distribution System - The Interline Dynamic Voltage Restorer," IEEE Trans. Industrial Electronics, vol. 53, pp. 1603 – 1611, Oct. 2006.

[3] M. Basu; S.P. Das, G.K. Dubey, "Investigation on the performance of UPQC-Q for voltage sag mitigation and power quality improvement at a critical load point," *IET Generation, Transmission & Distribution*, vol.2, pp. 414 – 423, May 2008.

[4] Po-Tai Cheng, Jhao-Ming Chen, Chia-Lung Ni, "Design of a State-Feedback Controller for Series Voltage-Sag Compensators," *IEEE Trans. Industry Applications*, vol. 45, pp. 260 – 267, Jan.-feb. 2009.

[5] S. Antheaume, T. Maître, J.L. Achard, "Hydraulic Darrieus turbines efficiency for free fluid flow conditions versus power farms conditions", Renewable Energy 33 (2008), pp. 2186-2198.

[6] J. L. Achard and T. Maitre, "Hydraulic turbomachine," EP 1718863, Aug. 18, 2005.

[7] J. L. Achard, D. Imbault and T. Maitre, "Device for maintaining a hydraulic turbomachine," EP 1856406, Aug. 17 2008.

[8] S.E. Ben Elghali, R. Balme, K. Le Saux, M.E.H. Benbouzid, J.F. Charpentier, F. Hauville, "A Simulation Model for the Evaluation of the Electrical Power Potential Harnessed by a Marine Current Turbine," IEEE Journal of Oceanic Engineering, vol. 32, pp.786-797.

[9] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind energy handbook*. New-York: John Wiley & Sons, 2001.

[10] M. Andreica, S. Bacha, D. Roye, I. Exteberria-Otadui, I. Munteanu, ”Micro-hydro water current turbine control for grid-connected or islanding operation,” in *Proc*. 2008 *39th IEEE Power Electronics Specialists Conference,* pp. 957-962.

[11] I. Etxeberria-Otadui, A. López de Heredia, H. Gaztañaga, S. Bacha, R. Reyero, “A Single Synchronous Frame Hybrid (SSFH) Multi-Frequency Controller for Power Active Filters,” *IEEE Trans. Industrial Electronics*, vol. 53, No 5, pp. 1640-1648, October 2006.

[12] A. N. Gorban, A. M. Gorlov, and V. M. Silantyev, ”Limits of the turbine efficiency for free fluid flow,” *Journal of Energy Resources Technology*, vol. 123, pp. 311-317, 2001.

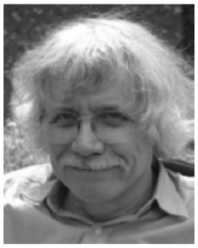
[13] X. Guillaud, P. Degobert, R. Teodorescu, "Use of Resonant Controller for Grid-Connected Converters in Case of Large Frequency Fluctuations", in *Proc*. 2007 *European Conference on Power Electronics and Applications*, pp. 1-8.

[14] H. Gaztañaga, I. Etxeberria-Otadui, D. Ocnasu, S. Bacha, "Real-Time Analysis of the Transient Response Improvement of Fixed-Speed Wind Farms by Using a Reduced-Scale STATCOM Prototype," *IEEE Trans. Power Systems*, vol. 22, pp. 658-666, May 2007.

## IX. BIOGRAPHIES

**Maria Andreica** (M’03) received an Engineer degree from the Polithenica University of Bucharest in 2005 and a Master in Electrical Engineering at the Grenoble National Institut of Technology in 2006. She joined the Grenoble Electrical Engineering Laboratory (G2ELab) in 2006 and she presently works on her PhD. Hers main fields of interest are modeling and control of cross-flow water turbines, power electronics control and renewable energy grid integration.

**Seddik Bacha** (M’08) received his Engineer and Master from National Polytechnic Institute of Algiers respectively in 1982 and 1990. He joined the Grenoble Electrical Engineerign Laboratory (G2ELab) and received his PhD and HDR respectively in 1993 and 1998. He is presently manager of Power System Group of G2ELab and Professor at the University Joseph Fourier of Grenoble. His main fields of interest are power electronics systems, modeling and control, power quality, renewable energy integration.



**Daniel Roye** was born in France in 1946. He received the Engineer degree in electrical engineering in 1969and the Ph.D. degree in electrical engineering in 1974 from the Institut National Polytechnique de Grenoble (INPG), Grenoble, France. He is currently the Co-Manager of the Power Systems Group and a Professor at the Grenoble Electrical Engineering Laboratory (G2ELab), Institut National Polytechnique de Grenoble, Grenoble, France. His current research interests include renewable energy control and integration and building energy optimization.

**Iulian Munteanu** (M’07) received a Master degree in Instrumentation and Control from Université du Havre (France) in 1997 and a Ph.D degree in Automatic Control from “Dunărea de Jos” University of Galați (Romania) in 2006. In 2002 he was a Fellow of the Marie Curie European Framework Programme at the Laboratoire d’Électrotechnique de Grenoble (LEG, France). At the present he is a postdoctoral research fellow at the Grenoble Electrical Engineering Laboratory (G2ELab), France. His research work is oriented towards optimal control of renewable energy systems.

**Antoneta Iuliana Bratcu** (M’07) received a Master degree in Electrical Engineering from “Dunărea de Jos” University of Galați (Romania) in 1996 and a Ph.D. degree in Automatic Control and Informatics from Université de Franche-Comté de Besançon (France) in 2001. From 1995 she is with the “Dunărea de Jos” University of Galați, where she works as an Associate Professor with the Department of Energy Conversion Systems. She is presently a postdoctoral research fellow at the Grenoble Electrical Engineering Laboratory (G2ELab), France. Her research interests include discrete and continuous optimization and hybrid dynamical systems with application to energy conversion systems and management of industrial systems.

**Joël Guiraud** received the Engineer degree in electrical engineering and industrial informatics from the Institute of Technology of Grenoble, Grenoble, France, and the second Engineer degree in industrial control systems from the Conservatoire National d’Arts et M´etiers (CNAM), Paris, France, in 1998. Since 1997, he has been with the Power Systems Group, Grenoble Electrical Engineering Laboratory (G2ELab), Grenoble, France, as a Research Engineer. His current research interests include realtime control and rapid prototyping systems with applications to power systems.