A hierarchical control system of an HVDC link based on VSCs for limitation of fault disturbances

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Abstract: - This paper presents a hierarchical control system achieving optimum response in both steady state and fault conditions of an electrical system, including a Wind Farm (WF) with induction generators feeding an ac system through an HVDC link based on Voltage Sourced Converters (VSCs). The study focuses mainly on the response of the system when faults take place at the ac system. From the simulation results it will be shown that the control system, which is based on adaptive fuzzy control, is effectively designed in order to quickly detect the faults and alleviate the disturbances at the electrical system, caused by the fault. The overcurrents at both dc and ac sides are mitigated and the voltage drop at the WF side is almost unnoticeable. So, the IGBTs valves of the VSCs can withstand the overcurrent during the fault and the tripping of the WF is avoided. Furthermore, the ac voltages recover quickly and almost with no fluctuation, just after the end of the fault period.

Key-Words: - faults, HVDC, VSCs, fuzzy logic, Wind Power Generation

1 Introduction

The world wide environmental concern has lead to increasing interest in renewable sources. The most popular way of generating electrical energy from renewable sources is to harness the wind energy. Nowadays, several WFs have been erected in areas with good wind regime, covering a substantial share of the total energy demand. The most frequently used wind power generators are asynchronous, as they are robust and cost effective. However, directly connecting the induction generators to the network without any control system, often causes performance and stability problems [1]. Furthermore, as the regions with good wind regime, such as uninhabited islands and offshore platforms, are far away from the consumers, dc transmission is the only applicable solution. For these reasons, the most suitable way of connecting a WF with induction generators to a remote grid, is through an HVDC link based on VSCs. It combines optimum WF operation and mitigation of the power quality problems at the Point of Common Coupling (PCC), as it can regulate the ac voltage independently of the real power flow and at the same time continuously provide adjustable reactive power support at the WF.

An important issue when HVDC transmission based on VSCs is used, is the response of the system in case of faults. A possible solution is to block the VSCs for a short time interval, about half a period, upon fault detection, in order to avoid the overcurrents at the IGBTs and the induction generators of the WF, which would otherwise cause the tripping of the WF [2].

This paper proposes a comprehensive control system. In steady state it offers the possibility to achieve, apart from acceptable voltage waveform to the PCC, an optimum wind power acquisition, driving the wind farms to the maximum aerodynamic efficiency. In addition, due to its supervising control, it quickly detects the faults at the ac system and adapts the blocking period relevant to the severity of the fault. Furthermore, it has the ability to be self-tuned on-line, just after the fault period, in order to mitigate the fluctuating behavior of the system. From the simulation results it will be shown that the control system manages to offer an optimum behavior in case of faults at the ac system.

2 Description of the electrical system under study

The electrical system under study includes an offshore WF with induction generators, which sends power to an ac grid through an HVDC link based on VSCs, Fig. 1. This electrical system is studied under faults at the PCC, which are the most severe faults.

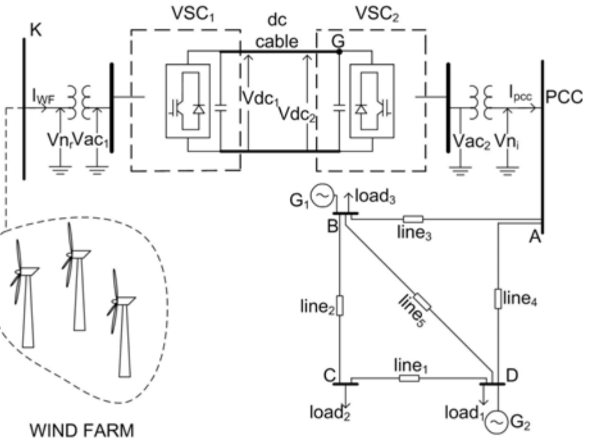

Fig. 1 The electrical system under study.

3 Control system design

The block diagram of the main control system proposed in this paper is shown in Fig. 2. It is a hierarchical control system, which is effective in both normal operation mode and fault conditions. The lower hierarchical control system is the main control system and it is active in normal operation mode. It achieves maximum wind power acquisition, driving the WFs to the maximum aerodynamic efficiency. The higher hierarchical system is a supervisor of the main control system. It monitors the electrical system and when a fault occurs, quickly detects it and adapts the main control system in order to mitigate the disturbances of the fault.

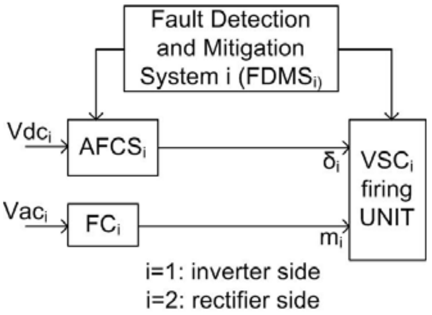

Fig. 2 Control System.

3.1 Lower hierarchical control

As we mentioned in the previous paragraph, the lower hierarchical control system is the main control system and it is active in normal operation mode. Its function has been thoroughly described in [3,4], so in this paper only a brief description of its function will be made.

In order to achieve an active power balance between the power produced by the WF and the power received by the ac network, VSC_2 is designated the role of the dc voltage regulator at the point G (Fig. 1). So, the measured dc link voltage, at the point G, is compared to a reference value and its error is passed through the Adaptive Fuzzy Control $System_2$ ($AFCS_2$), which finally generates the phase angle of the Pulse Width Modulation (PWM) sinusoidal reference signal and consequently the phase of the fundamental ac side voltage of VSC_2 (Vac_2) with respect to the ac voltage at the other side of the transformer (Vn_i), δ_2.

In addition, in order to achieve maximum wind power absorption according to the wind speed, VSC_1 regulates the angular frequency at the point K (Fig. 1), ω_{el}, through $AFCS_1$.When, for example, the wind power increases, $AFCS_1$ increases the phase angle of the PWM sinusoidal reference signal, δ_1, and consequently the phase angle of the fundamental ac voltage of VSC_1 (Vac_1) with respect to the ac voltage at the bus of the WF (Vn_r). So, more power is driven to the dc system and consequently, the angular frequency returns to its reference value. The reference value is the value which corresponds to the maximum aerodynamic efficiency of the wind turbines and is computed on-line at the $AFCS_1$, using a Maximum Power Point Tracking (MPPT) Technique.

Both VSCs control the ac voltage in their sides, through a Fuzzy Controller (FC), FC_1 and FC_2, by regulating the modulation index m of the sinusoidal PWM reference signal and consequently, the modulation signal of the magnitude of the ac voltage generated by the converters.

3.2 Higher hierarchical control

As we mentioned in the previous paragraph, the main control system is supervised by the higher hierarchical control system. By monitoring some critical electrical signals on-line, the higher hierarchical control system, which is called *Fault Detection and Mitigation System (FDMS)*, Fig. 2, is able to quickly detect the faults at the ac grid. The action of the FDMS when a fault is detected is divided to two periods:

- the blocking period, during which the VSC is blocked for a short time interval, which depends on the severity of the fault
- The mitigating period, during which the main control system is adapted in order to achieve the mitigation of the fluctuations in the electrical system, caused by the fault.

Fig. 3 shows the FDMS of VSC_2. It consists of two FCs, FC_{blk_2} and FC_{mtg_2}. FC_{blk_2} derives the duration of the blocking period, while the purpose of FC_{mtg_2} is to adapt the $AFCS_2$, in order to mitigate the disturbances caused by the fault. The function of the $FDMS_2$ is thoroughly described above.

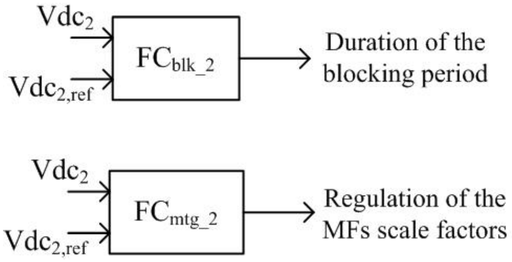

Fig. 3 Fault Detection and Mitigation System.

When the fault occurs at the ac grid, a very fast deviation of the voltage Vdc_2 from its initial value takes place. FC_{blk_2}, by monitoring the quantity (Vdc_2-$Vdc_{2,ref}$) and its derivative, detects the fault and gives an order to block the firing of VSC_2 for a short time interval, in order to avoid the overcurrents. The duration of the blocking period depends on the severity of the fault and it is derived from the deviation of Vdc_2 from its reference. A big deviation of Vdc_2 from its reference implies a severe fault, so the duration of the blocking period must be “Very Big”. On the contrary, a less severe fault requires a “Small” or “Very Small” blocking period. From this reasoning come up the fuzzy rules of FC_{blk_2}, Table 1. The fuzzy sets used for the input (Vdc_2-$Vdc_{2,ref}$) are: Very Big (VB), Big (B), Small (S), Very Small (VS) and (OK). For the input d(Vdc_2-$Vdc_{2,ref}$)/dt are used the fuzzy sets Positive (P) and Negative (N). The fuzzy sets required for the output “duration of the blocking period” are Very Big (VB), Big (B), Small (S), Very Small (VS), Very Very Small (VVS) and (OK).

Directly after the blocking period, Vdc_2 is increased, deviating a lot from its reference value. If no special actions are taken, δ_2 will take a big value, in order to bring Vdc_2 back to its initial value. As the wind velocity has not changed, the real power that is sent from the wind is the same as its pre-fault value. So, the value of δ_2 should not change significantly.

Table 1:
Fuzzy rules for FC_{blk_2}

d(Vdc_2-$Vdc_{2,ref}$)/dt (Vdc_2-$Vdc_{2,ref}$)	P	N
VB	VB	VB
B	B	S
S	S	VS
VS	VS	VVS
OK	OK	OK

Trying to bring Vdc_2 back to its initial value just after the blocking period, would be disastrous for the system stability. For this reason, a regulating FC in FDMS, FC_{mtg_2}, regulates on line the scale factors of $AFCS_2$ Membership Functions (MFs), in such a way, that the produced values of δ_2 are near the pre-fault values. We call this value of δ_2 “mitigating δ_2”. In this way, the fluctuations are avoided and the system reaches rapidly its steady state. It would be possible to maintain the exact value of the pre-fault δ_2, but with the slightly different values of δ_2 from its pre- fault value, we can achieve a quicker recover of the system and a more smooth response. When FC_{mtg_2} detects the end of the post-fault period gives an order to $AFCS_2$ to re-adapt its MFs in order to compute δ_2 the way it did before the occurrence of the fault. The fuzzy rules of FC_{mtg_2} are shown in Table 2. Its inputs are Vdc_2-$Vdc_{2,ref}$ and d(Vdc_2-$Vdc_{2,ref}$)/dt. Its output is a regulating factor that adapts the $AFCS_2$ MFs in order to produce values of δ_2 near its pre-fault values.

Table 2:
Fuzzy rules for FC_{mtg_2}

d(Vdc_2-Vdc_2,ref)/dt (Vdc_2-Vdc_2,ref)	P	N
VBP	VBP	VBP
BP	BP	SP
OK	OK	OK
BN	SN	BN
VBN	VBN	VBN

The fault at the ac grid causes a very fast increase at the dc voltage of the sending end, Vdc_1, too. So, FC_{blk_1} detects the fault and behaves according to FC_{blk_2}, blocking the firing of VSC_1 for a short time interval. After the deblocking, $AFCS_1$ produces a “mitigating δ_1” until the post-fault period ends, alleviating the fluctuating behavior of the system. This is achieved by appropriate adapting of the scaling factors of its MFs for this period, through FC_{mtg_1}. Its action is similar to FC_{mtg_2}, so it will not be analyzed here. Obviously, during the fault period the MPPT is blocked, as it would lead to false values of ω_{ref}.

Apparently, the two converters detect the fault without the need of a communication line, just by monitoring the dc voltage at each end.

4 Evaluation of the system performance

The system under study includes an offshore WF with 50 squirrel-cage induction generators, which sends power to an ac network of 150 kV, via a VSC-based HVDC link. At wind speed of 12 m/s each machine reaches its rated output of 1800 kW. Its SCC is equal to 20 MVA. The dc cables are coaxial and 100 km long. dc capacitors of 500 μF are used at each converter. ac capacitors of total capacity equal to 10 μF are placed at the side of the WF in order to supply a constant amount of the reactive power that is necessary for the operation of the inductive generators. The basic characteristics of the ac system are shown at Table 3 and 4.

Table 3:Characteristics of the ac system lines

	km	Ω	H	μF
Line 1	50	9.155	0.071	0.41126
Line 2	70	12.817	0.0993	0.57576
Line 3	60	10.986	0.0851	0.49350
Line 4	60	10.986	0.0851	0.49350
Line 5	80	14.648	0.1135	0.65802

Table 4:Characteristics of the ac system loads

	MW	MVar
load 1	10	2
load 2	4	2
load 3	6	2

Each machine of the WF was represented separately in the simulation, in order to take into account the interaction between the generators of the WF. The simulation program used is the PSCAD/EMTDC in co-operation with MATLAB and C++ programming.

The above system was tested under two cases of faults. In case (a) was applied a solid three phase fault at the PCC. This case was first presented, as the “worst case”. In order to show that the control system is efficient in other types of fault too, case (b) presents the response of the system in a single phase fault at the PCC. They are simulated with a wind velocity which is fluctuating with mean value near 9m/sec, Fig. 4. At t=0.06s the fault occurs and it is cleared after 135 ms.

Figs. 5a-11a show the response of the system for case (a). Fig. 5a shows the real power produced by the WF and supplied to the PCC, Psend and Prec respectively. This figure shows that the transmission resumes the prefault power in about 1 s. The dc current and the dc voltages at the two ends of the link are shown at Figs. 6a and 7a respectively. Through the blocking of the converter firing for the appropriate time interval which is proportional to the fault severity, the dc current increase was minimized, so the IGBTs can withstand the overcurrent caused by the fault, which is equal to 0.8 kA. The deviations of the dc voltages, Vdc$_1$ and Vdc$_2$, reach the 1.12 pu, so they are inside the acceptable limits and they do not stress the cable considerably. Figs. 8a and 9a show the voltage and the current at the WF bus K, Vn$_r$ and I$_{wf}$ respectively, (Fig. 1). Through the blocking of the valves upon fault appearance, the increase of I$_{wf}$ is limited to 1.46pu, so the protection system at the WF is not energized and the tripping of the wind turbines is avoided. Vn$_r$ is slightly disturbed. The ac voltage and current supplied to the PCC by the HVDC link, Vn$_i$ and I$_{PCC}$ are shown in Figs. 10a and 11a respectively. I$_{PCC}$ reaches a peak value of about 2 pu during the fault but recovers very quickly. Vn$_i$ drops at the time the fault occurs, but the quick and adaptive control system manages to mitigate the post-fault disturbances and Vn$_i$ reaches its initial value very rapidly, almost with no fluctuations.

From the simulation results it is shown that at the case of the single-line fault too, the control system quickly detects the single phase fault and through the appropriate converter blocking, combined with the mitigation process, the system manages to overcome quickly the fluctuations of the fault.

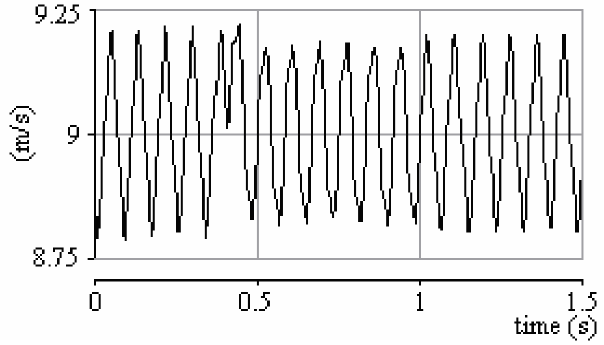

Fig. 4 Wind Velocity

Case (a):Three phase fault

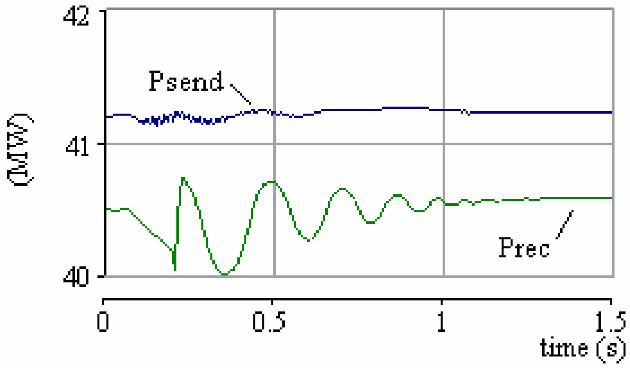

Fig. 5a Real Power

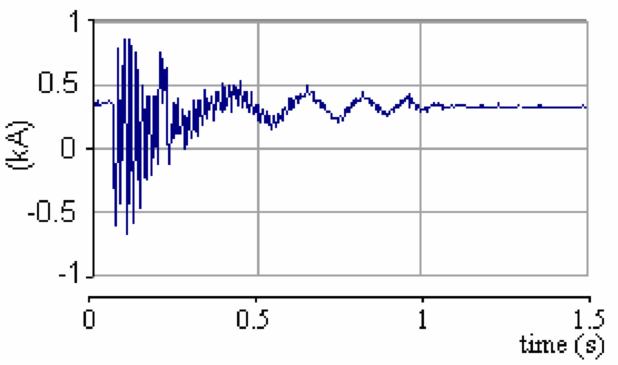

Fig. 6a dc Current

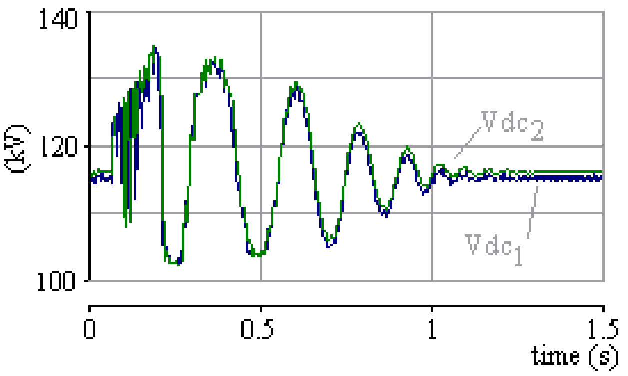

Fig. 7a dc Voltage

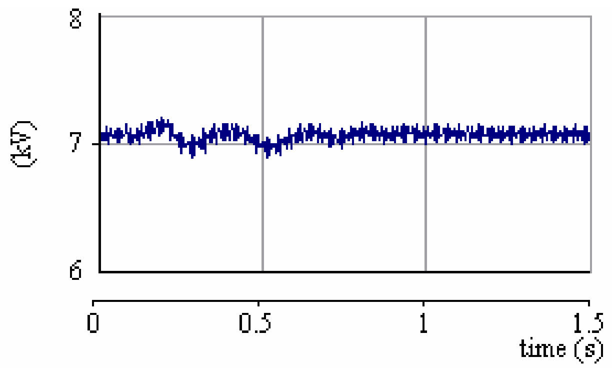

Fig. 8a WF ac Voltage

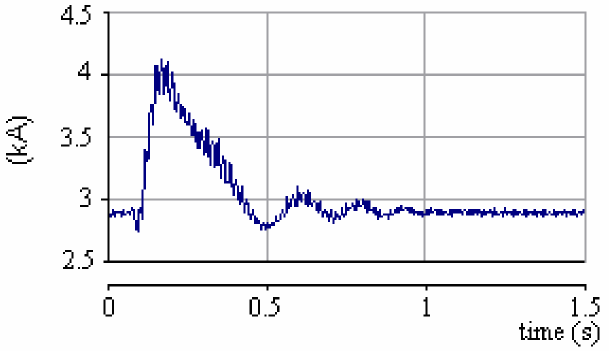

Fig. 9a WF ac Current

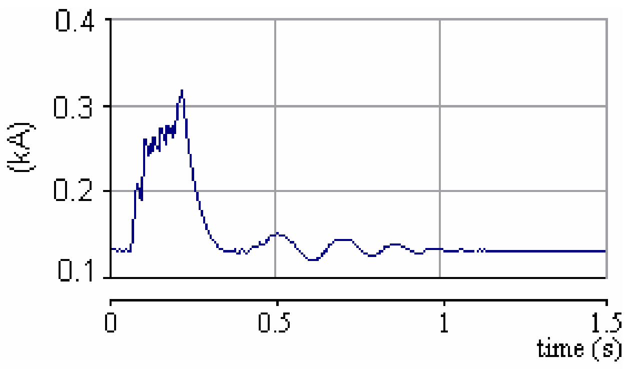

Fig. 10a ac Current at the PCC

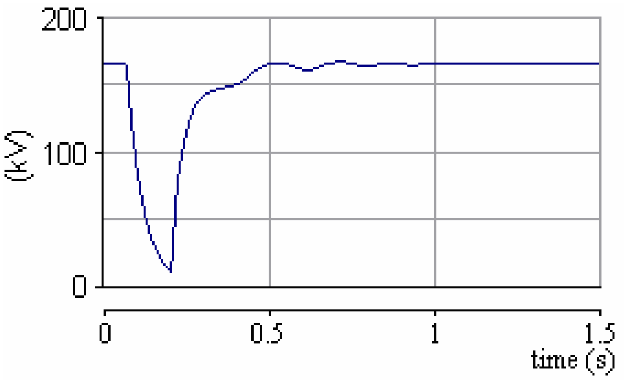

Fig. 11a ac Voltage at the PCC

Case (2): Single phase fault

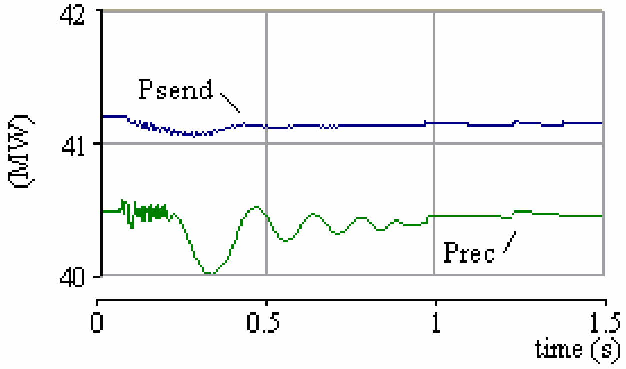

Fig. 5b Real Power

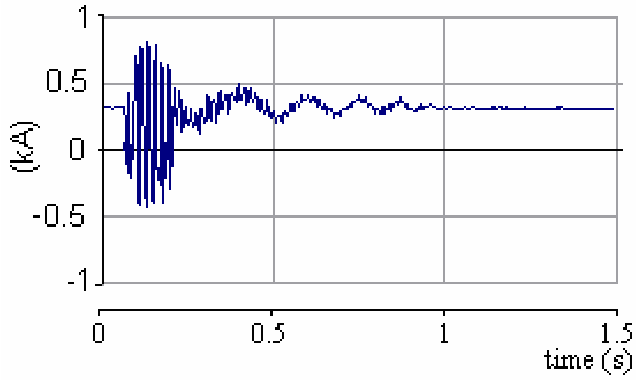

Fig. 6b dc Current

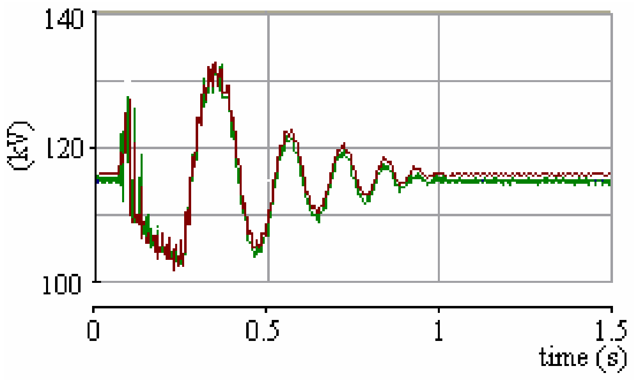

Fig. 7b dc Voltage

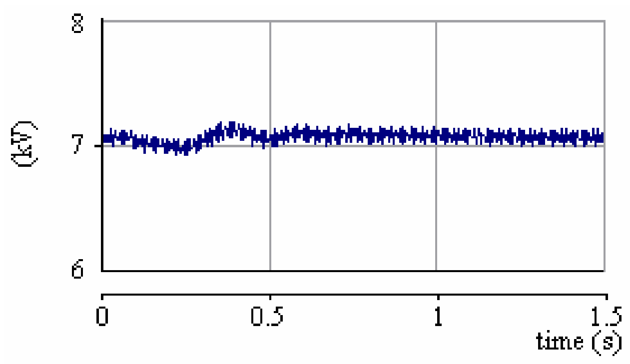

Fig. 8b WF ac Voltage

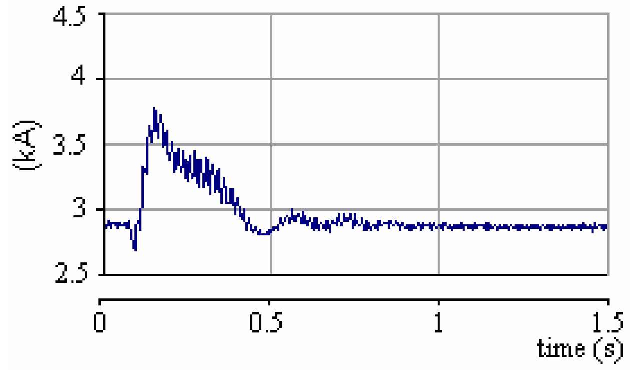

Fig. 9bWF ac Current

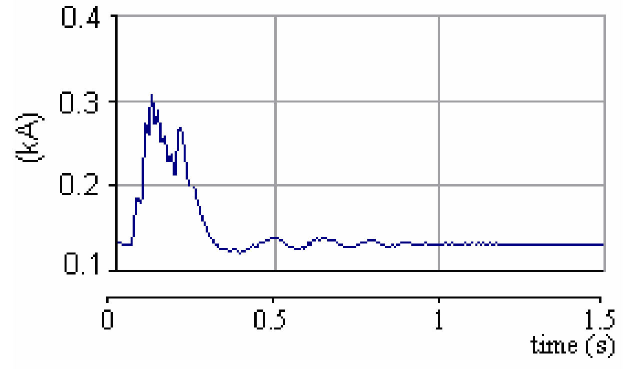

Fig. 10b ac Current at the PCC

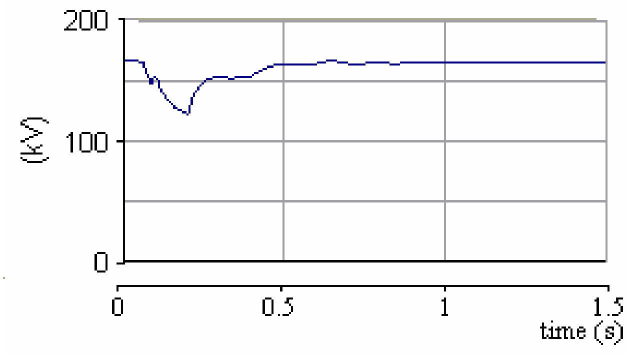

Fig. 11b ac Voltage at the PCC

5 Conclusion

In this paper is proposed a hierarchical control system for an HVDC link based on VSCs, which feeds a weak ac network with the power produced from an offshore wind farm of induction generators. This control presents the special ability to be self-tuned on-line in order to offer an optimum performance under steady state and fault conditions. The response of the system is studied for two types of faults at the PCC. The appropriate blocking period of the VSCs upon fault detection, combined with the adaptability of the control system, which has the goal to mitigate the fluctuating behavior of the system, offer the possibility to encounter the faults at the PCC keeping the voltages and the currents in the overall system between acceptable levels.

References:

[1] M.Karri, W.Rosehart, O.Malik, Comprehensive Control Strategy for a Variable Speed Cage Machine Wind Generation Unit., *IEEE Transactions on Energy Conversion,* Vol.20, No.2, 2005, pp. 415-423.

[2] B.D.Railing, G.Moreau, J.Wasborg, D.Stanley, The Directlink VSC-based HVDC project and its Commissioning, *in Proc Session 2002 Cigre,* 14-108.

[3] X. Koutiva, T. Vrionis, N. A. Vovos, G. B. Giannakopoulos, Optimal integration of an offshore WF to a weak ac grid, paper accepted for puplication at *IEEE Transactions on Power Delivery*.

[4] X. Koutiva, T. Vrionis, N. A. Vovos, G. B. Giannakopoulos, Application of Computational Intelligence to the Control System of an HVDV link based on VSCs, *in Proc. MedPower'04, November 14-17, Lemesos, Cyprus,* No.CH24.