REACTIVE POWER INJECTION BY WIND FARMS DURING ASYMMETRIC FAULTS – APPLICATION TO PORTUGUESE DISTRIBUTION GRID

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ABSTRACT

The Portuguese national grid code [1] specifies minimum technical requirements for fault ride through capacity and reactive power injection during faults which are applicable to all wind farms above 6MVA. However, it was established that the wind generators, even the most recent ones, can only inject symmetrical reactive power even in the presence of an asymmetrical fault. This could potentially lead to high overvoltages in the MV network (low impedance grounded) or in the HV network (solidly grounded only at the TSO substation). To evaluate the consequences to the Portuguese Distribution Grid of the symmetrical reactive power injection by the wind generators, EDP Distribuição requested LABELEC's collaboration.

Two cases were considered: the connection of the wind farm (WF) to the HV network; and to the MV network. For each of these, different scenarios were simulated. This study gave a conclusive answer to EDP Distribuição since it allowed to answer its doubts.

INTRODUCTION

LABELEC is an EDP Group company whose mission is to be the technical excellence centre for all EDP.

Accordingly, Labelec has been an important EDP Distribuição partner, helping to solving the challenges it faces, such as the one presented in this study.

The continuous increase of wind generation production and the consequent penetration in electrical networks present new challenges to system operators. As a response the national grid code [1] was modified to impose minimum requirements for wind farms connecting to the grid. The two major requirements are: the ability of the wind farm to stay connected during a fault (Fault Ride Through capability, FRT) (see Figure 1) and the ability to inject reactive power in the network during a fault (see Figure 2).

In cooperation with EDP Distribuição (the Portuguese Distribution System Operator) a study was conducted to assess the consequences of a symmetrical reactive power injection in case of an asymmetric fault.

Two different cases were evaluated for the wind farm connection to the distribution network: HV network (60 kV) and MV network (30 kV).

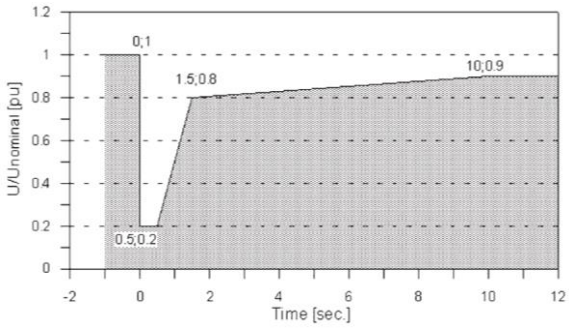

Figure 1 - Time voltage characteristic curve requirement for wind farms ('FRT'), [2].

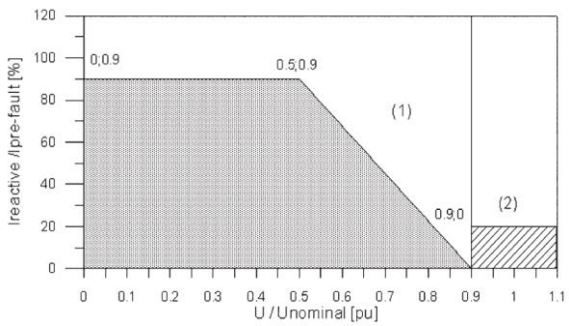

Figure 2 - Characteristic curve of reactive current delivery by wind power plants during/after voltage dips [2].
(1) Fault and recovery region,
(2) Normal operation region.

This study aims to assess:

- The overvoltages in both cases and if the system insulation levels are breached;
- Comparison between the two types of reactive power injection (symmetrical vs asymmetrical) regarding the network voltage support during the fault;

DIGITAL SIMULATION

The modeling and subsequent simulations were performed using the software EMTP-RV. Three types of asymmetrical faults (line-to-ground, line-to-line and

double line-to-ground) and two types of reactive power injection (symmetrical and asymmetrical) were considered.
In the symmetric injection, phase A is defined as the reference, and the other two are phase shifted of -120º and +120º, respectively. In the asymmetric case, each current has its corresponding phase voltage as the reference and the current angle is calculated to achieve the injection requirement. The behavior is similar to that of a conventional synchronous generator.
The Portuguese network code [1] does not specified the type of reactive power injection in case of a symmetrical or asymmetrical fault. EDP Distribuição felt the need to study this issue in greater depth for several reasons. Particularly, the overvoltages that may appear on the healthy phases when symmetrical reactive power injection occurs in case of an asymmetric fault. This topic is relevant as most of the faults (>90%), occurring on the network, are asymmetric.
The wind turbines were modeled as current sources for easier reactive power control. The faults considered in both network cases aimed to simulate the most unfavorable conditions. For that purpose, the respective impedances of the faults were adjusted so that the dip depth was close to 80%, $U / U_n = 0,2$ pu. According to the curve defined in Figure 2, it is required an injection of 90 % of reactive power, in comparison to the pre-fault situation.
The wind farm power was defined as 8% of the short-circuit power at the point of common coupling (PCC), assuming a value of about 66 MVA.
For the HV network simulation, the faults will be considered in the HV line to where the WF connects (see Figure 3). The HV network has it's neutral solidly connected to ground at the TSO substation.

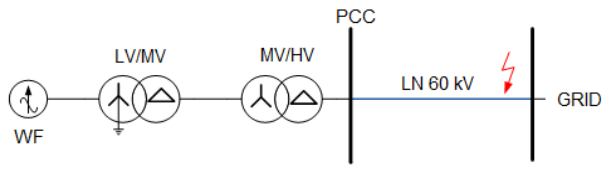

Figure 3 - Model for the connection on the HV network.

For the MV network simulation, the faults are applied at the MV bus of the substation where the WF connects, and also at the HV line connecting to the substation (see Figure 4).

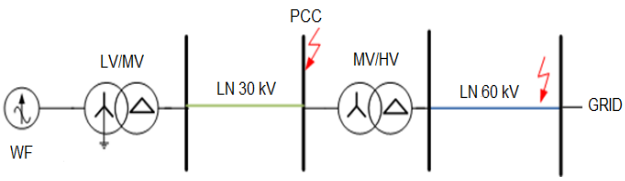

Figure 4 - Model for the connection to the MV HV network.

In this case two different neutral schemes are considered: grounding reactor and isolated neutral system.
All the data used to model the system, as well as the simulation scenarios, were based on actual distribution network information provided by the Distribution System Operator (DSO).

SIMULATION RESULTS

The simulations were performed considering that the reactive power injection begins 50 ms after the detection of the voltage dip, as required in [1].

HV NETWORK

For the connection to the HV network, three simulation scenarios were defined:

- A fault in the network;
- A fault in the network followed by the opening of the faulted line;
- Exchange of the HV/MV transformer connections, considering the delta on the MV side and the star grounded on the HV.

As expected, the results from the simulation scenario 1 show that the injection of symmetrical reactive power in case of asymmetric fault will cause overvoltages in the healthy phases.
The symmetrical injection does not contribute considerably for the voltage support at the point of common couple. In average, it contributes around 10 % to the voltage recovery in comparison with the pre-fault value. The overvoltage with the highest value is obtained in the case of a line-to-ground fault and it is 14,5% above the pre-fault value.
In the other types of faults, the overvoltages have smaller values. Nevertheless, in all the simulations, the overvoltages are within the permissible levels for HV network insulation (60kV – phase to ground).
Comparing now the two modes of reactive power injection, the simulation results show that the asymmetric injection is more favorable to the voltage support of the faulted phase on the point of common coupling. The overvoltages on this type of injection are, in average, slightly higher than for symmetrical injection, but are still within the permissible limits.
In Figure 5 and Figure 6 are shown, as an example, the EMTP-RV results for the simulation scenario 1, considering a line-to-line fault. The dip starts at 100 ms, followed by the reactive power injection at 150 ms. Table 1 shows the simulation results, in comparison with the pre-fault values [%], for three cases: no injection, symmetrical and asymmetrical injection. Those results clearly show that the voltage support given by the symmetrical injection is very low, around 6,4% at best. In the other hand, the asymmetrical injection causes a voltage increase of 23,6% for phase A and 44,9% for

phase B, in comparison with the "no injection" case. This is also observed on the line-to-ground and double-line to ground faults.

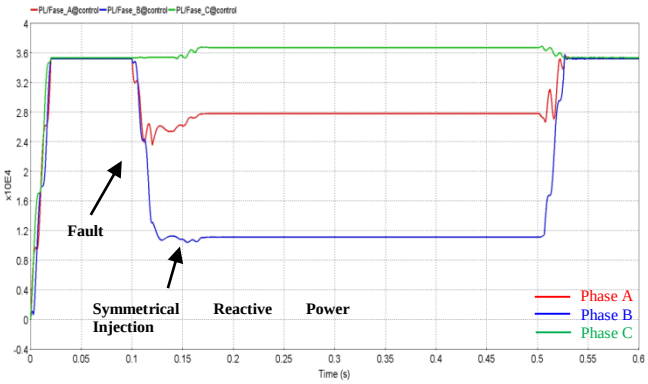

Figure 5 - Symmetrical reactive power injection, line-to-line fault, HV Network.

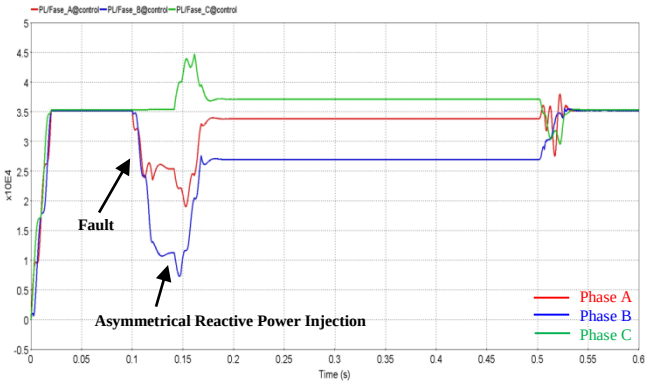

Figure 6 - Asymmetrical reactive power injection, line-to-line fault.

Table 1 – Results for the HV network simulation, in comparison to the pre-fault voltage levels [%].

[%]	No injection	Symmetrical inj.	Asymmetrical inj.
Phase A	- 27,5 %	- 21,1 %	- 3,9 %
Phase B	- 68,3 %	- 68,5 %	- 23,4 %
Phase C	0,5 %	4,3 %	5,5 %

The simulation scenario 2 showed that when the line opens, it is impossible to achieve the requirement of reactive power injection, because there is no current on the circuit.

In Figure 7 and Figure 8 are shown, as an example, a comparison between the results obtain in the simulations scenarios 1 and 3, for a line-to-ground fault and considering symmetrical reactive power injection. As previously said, on the simulation scenario 1 the HV/MV transformer has a Delta-star connection scheme. For the other hand, on the simulation scenario 3 the HV/MV transformer has a Star-delta connection scheme with the star grounded.

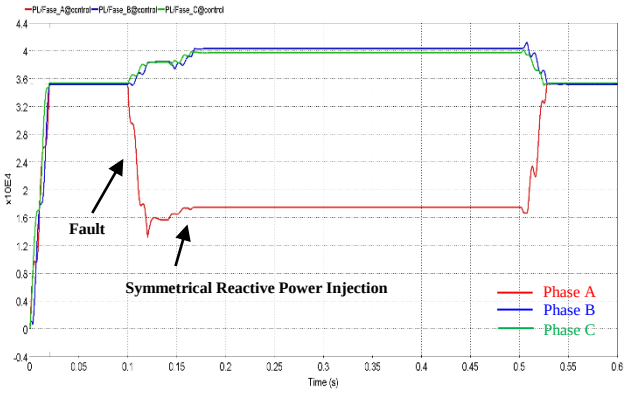

Figure 7 - Symmetrical reactive power injection, line-to-ground fault, Delta-star transformer connection scheme (simulation scenario 1).

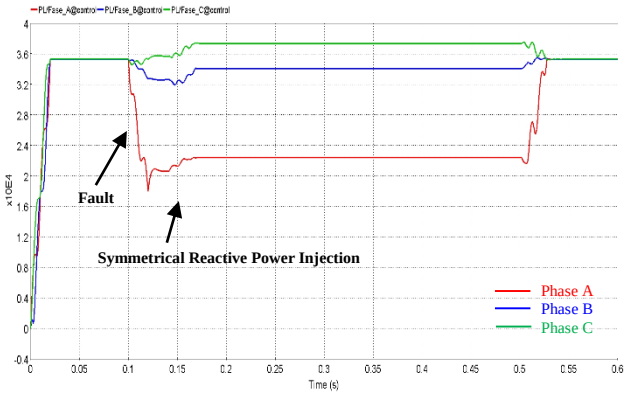

Figure 8 - Symmetrical reactive power injection, line-to-ground fault, Star-delta transformer connection scheme (the star grounded – simulation scenario 3).

Table 2 - Comparison results between two different transformer connection schemes, considering symmetrical reactive power injection and line-to-ground fault.

[%]	Delta – star	Star grounded - delta
Phase A	-50,2	-36,3
Phase B	14,5	-3,2
Phase C	12,8	6,1

The results, Table 2, show that the exchange of the HV/MV transformer connections scheme has an attenuating effect on the overvoltages and on the dips depth.

MV NETWORK

For the MV network connection of the wind farm, four simulation scenarios were considered:

- Fault in the MV bus bar where the WF connects to, considering reactance grounding system on the HV/MV distribution substation;

- Fault in the MV bus bar where the WF connects to, considering insulated neutral on the HV/MV distribution substation;
- Fault in the HV line that connects the WF to the substation;
- Fault in the HV line that connects the WF to the substation with and without opening the HV line.

The aim of the first two scenarios is to evaluate in which grounding system are verified higher overvoltages and/or better voltage support at the PCC. The other two scenarios allow a comparison with the HV connection situation, because in this case the overvoltages are seen from the MV side.

The results for the line-to-ground fault in the simulation scenario 1 are shown in Figure 9, Figure 10 and Table 3.

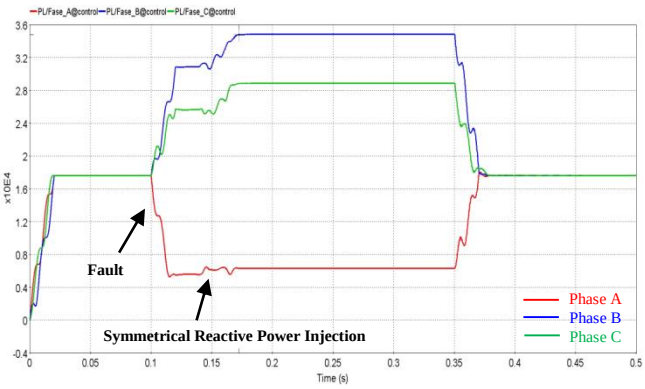

Figure 9 - Symmetrical reactive power injection, line-to-ground fault.

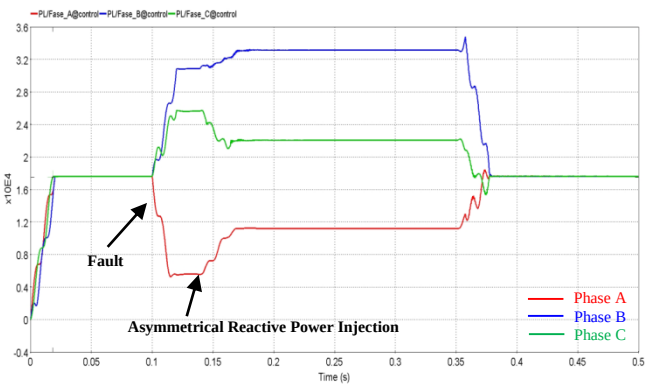

Figure 10 - Asymmetrical reactive power injection, line-to-ground fault.

Table 3 – MV network simulation results, in comparison to the pre-fault voltage levels [%].

[%]	No injection	Symmetrical inj.	Asymmetrical inj.
Phase A	-68,3 %	-64,1 %	-36,2 %
Phase B	75,4 %	97,9 %	88,3 %
Phase C	45,7 %	64,0 %	25,3 %

This is a perfect example of the benefits of a non-symmetrical reactive power injection. As shown on Table 3, the voltage support gain for the symmetrical injection is only about 4,2% for the phase A (faulted phase), while the overvoltage verified is about 22,5% for phase B and about 18,3% for phase C. This raises the question about the real benefits of such an injection scheme.
On the other hand, in this example, the asymmetric injection has a double positive effect on the 3 phases, comparing with the no injection situation:

- For phase A it shows a voltage recovery of 32,1%;
- Phase C has a decrease of the overvoltage value of 20,3%;
- Phase B has an overvoltage value lower than in the other injection scheme.

As expected, in the simulation of the two first scenarios, the overvoltages obtained on the second case, isolated neutral system, are higher than in the reactance grounding regime, as well as the depth of the dips. However, for both situations the values are still within the allowable values for MV network insulation (36kV – phase to ground).
In the simulation scenario 3, the analysis of the results is not as intuitive as in the previous cases: between the fault and the point of common coupling of the WF is the HV/MV transformer, in which the Delta-star connection scheme changes the way the phases are affected by the fault. The obtained overvoltages are lower than in other situations, about 12-13% which is far below the permissible insulation limits. This is a consequence of the distance between the fault and the PCC of the WF, which is higher. The voltage recovery is also more evident in this case.
Thus, it is possible to realize that, in this case, injecting symmetrical reactive power gives good voltage support at the PCC.
In the last scenario, it is possible to verify, as in the HV network case, that it is not possible to achieve the injection requirement due to the open circuit, which does not allow current circulation.

WIND FARM

Despite the overvoltage values observed for the HV and MV networks in case of asymmetric faults does not compromise the stability of the network, special care must be taken with the wind farm protection system. Since such overvoltages can trigger the protection

system, potentially taking the wind farm out of service, and compromising the compliance with the requirements specified in [1].

CONCLUSIONS

In cooperation with EDP Distribuição (the Portuguese Distribution System Operator) a study was conducted by LABELEC in order to assess the consequences of a symmetrical reactive power injection in case of an asymmetric fault. Two different situations were evaluated for the wind farm connection to the distribution network: HV network (60 kV) and MV network (30 kV).

The modeling and subsequent simulations were performed using the software EMTP-RV. Three types of asymmetrical faults (line-to-ground, line-to-line and double line-to-ground) and two types of reactive power injection (symmetrical and asymmetrical) were considered.

This study's main conclusions are:

- The overvoltages observed in the HV and MV networks are within the system insulation levels;
- The asymmetrical reactive power injection is more effective on voltage support in case of an asymmetrical fault;
- The wind farm protection system should not trip for overvoltages caused by symmetrical reactive power injection for asymmetrical faults.

REFERENCES

[1] Regulamento da Rede de Distribuição - Portaria nº 596/2010 (30 de Julho).

[2] Estanqueiro, A., Castro, R., Flores, P., Ricardo, J., Pinto, M., Rodrigues, R., Peças Lopes, J. A. (2007). "How to Prepare a Power System for 15% Wind Energy Penetration: the Portuguese Case Study". In: Wiley Interscience.