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Simulations of a possible configuration of Premium Power Park

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Abstract. The voltage dip and the sudden electrical energy interruption are, probably, the most important disturbances of the power quality in the electrical system.
Several technical solutions exist to mitigate voltage dips, respectively at plant or system level as for example:

- the installation of Custom Power (CUSPO) for a single customer;
- the Premium Power Park (PPP) for a group of customers.

According to the PPP concept, the tenants of an industrial or commercial office park would be provided with a guaranteed level of electrical service quality made possible by Custom Power devices, such as the Dynamic Voltage Restorer (DVR), the Distribution Static Compensator (DSTATCOM – Distribution STATCOM), the medium voltage Static Transfer Switch (STS).
The paper summarizes the Premium Power Park idea and a possible configuration of it, studied by ERSE, including the system aspects and the analysis of the combined operation or interaction of the Custom Power.

Key words

Premium Power Park, Power Quality, Static Transfer Switch, Dynamic Voltage Restorer, Distribution STATCOM.

1. Introduction

With an increase in the use of sensitive load the power quality issues have become an increasing concept.
In order to increase the reliability of a power distribution system, there are traditional methods of solving power quality problems (for example replacing overhead lines with underground cable, installing current limiters or with compensated neutral system) but also the Custom Power (CUSPO) [1][2][3], devices based on power electronic technology able to mitigate the network perturbations and the loads impact on the grid.
These equipments can be used by a single sensitive customer but also by an industrial or commercial office park that need a "premium" quality performance; this concept is the guideline for Premium Power Park (PPP) [4][5][6].
The basic concept of a Premium Power Park is to ensure better power supply quality levels than the standard ones offered by the distribution system and also diversified levels depending on customers' needs, thanks to the use of different kind of Custom Power devices.
Starting from the analysis of typical sensitive loads and CUSPO requirements, ERSE, in the frame of the Research Fund for the Italian Electrical System, has studied a possible configuration of Premium Power Park.
The main results of this study are an increased knowledge on the combined operation of Custom Power devices in a PPP and a general methodology to approach the design of this kind of "premium networks".

2. Premium Power Park: a possible configuration

This chapter describes the Premium Power Park (PPP) studied by ERSE.
The PPP presented here is just an approach to a premium power system to study the combined operation and the interactions of a Static Transfer Switch (STS), a Dynamic Voltage Restorer (DVR) and a Distibution Static Compensator (D-STATCOM) in close electrical proximity (Fig. 1).
Starting from the investigation of the typical CUSPO devices operation and of their interactions with sensitive loads, a possible configuration of PPP for a Medium Voltage (MV) distribution network with different Power Quality levels has been defined (Fig. 1). In particular, in the PPP:

- at level A the interruptions and the voltage dips compensation is granted by the STS;
- at level AA the voltage dips compensation is granted by the DVR. The depth of the compensated dip depends on the DVR design and on its coordinated operation with the STS that ensures interruptions compensation too.

Furthermore the D-STATCOM ensures for the loads connected to the A and AA levels the compensation of the voltage variations due to disturbing loads at the level AA-B.
The load in the PPP (V_n = 20kV) is made of:

- R-L load at level A, 1,74 MVA cosφ = 0,33 (not strictly sensitive load, requiring interruptions and only deep voltage dips compensation);
- 12-pulse thyristor controlled rectifier bridge at level AA, 1,2 MVA cosφ = 0,7 V_{cc} = 460V I_{cc}=2000A (strictly sensitive load, requiring interruptions and voltage dips compensation);
- two induction motors at level AA-B, P=750kW cosφ=0,8 (disturbing load).

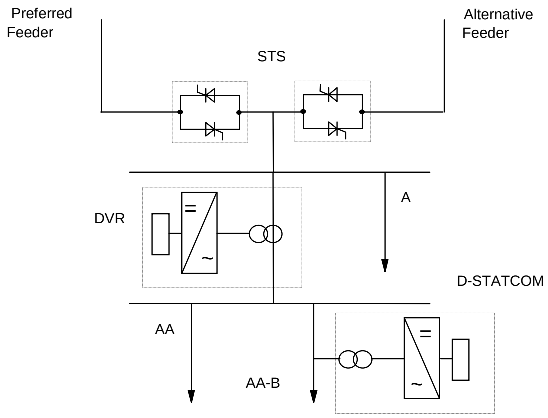

Fig. 1. Premium Power Park

The study has been developed into the following steps:

- first step: pre-design and characterization/modelling of the single devices and loads with simulations to understand their behaviour;
- second step: devices control system definition and criteria development for the detection of voltage disturbance affecting line-to-line network voltages, in the assumption that the electric energy is supplied, in the three-phase MV distribution system, as three line-to-line voltages;
- third step: simulation of the whole Premium Power Park in order to investigate the combined operation of the devices to ensure the defined power quality levels during network and load disturbances.

The system response to different power disturbances has been simulated in ATPdraw (Alternative Transient Program).

3. Custom Power devices: pre-design, characterization/modelling and control system definition

A. Static Transfer Switch – STS

The Static Transfer Switch [7][8] is a power quality device that can transfer a customer's load from the preferred distribution line to an alternative one. A scheme of one phase of a thyristor STS is shown in Fig. 2.

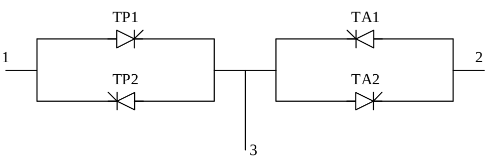

Fig. 2. STS – One phase scheme

Under normal conditions (without power quality disturbance) the load is supplied by the preferred feeder. Upon a power quality event (voltage dip or interruption), the Static Switch transfers the load to the alternative feeder (Fig. 1). To ensure a rapid transfer between the feeders and consequently to reduce the switching impact on the load, a *Make Before Break* switching logic has been adopted.

B. Dynamic Voltage Restorer – DVR

The Dynamic Voltage Restorer [8][9][10] is a series connected device able to inject a controllable voltage to mitigate voltage dips for a sensitive load.

In the studied configuration, the DVR can work in two different conditions:

- "stand-by", in absence of disturbances on the source side, for most of the time, the DVR is expected to stay online without functioning but *ready* to compensate;
- voltage compensation, the DVR is required to detect a voltage dip and inject a controlled voltage with a certain magnitude and phase such that the voltage at the loads remains at its pre-dip values.

Fig. 3 shows the DVR scheme: the main elements are the IGBT (Insulated Gate Bipolar Transistor) inverter (Neutral Point Clamped configuration) and its commutating reactance, the series transformers to match the inverter output to the line voltage, the energy storage (capacitor bank) and passive filter.

The passive filter RC is connected in parallel with the primary winding of the series transformer, for removing the high frequency components generated by the PWM switching.

In the study, assuming that the DVR has to restore the load pre-dip voltage in magnitude and phase, the main design bolds are:

- maximum dip depth (30% of rated voltage) and duration (600 ms) that can be compensated;
- maximum phase shift (±20°) during voltage dips;
- DC and network voltage variation range;
- IGBT current features;
- the load active and reactive power (thyristor bridge and induction motors).

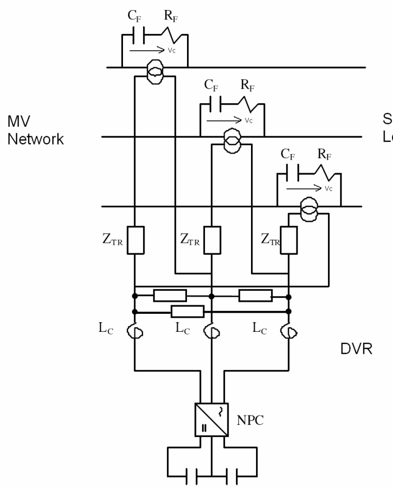

Fig. 3. DVR - Principle scheme

The main parameters obtained by the design are:

- rated power 1,28 MVA;
- energy storage capacitor bank;
- inverter commutating reactance;
- single-phase transformer (rated power, voltage and current, short circuit voltage and transformation ratio);
- filter (resistance and capacitor).

To characterize the DVR and verify the design, the capabilty curves, representative of:

a) voltage dips that DVR is able to compensate;
b) active and reactive power exchanged with the network;
c) maximum dip depth in function of its duration;
have been calculated in accordance with different operating conditions such as dips depth, load and DC inverter voltage.
In particular Fig. 4 shows the voltage dips that can be compensated by DVR in the assumption of a pre-dip load voltage equal to 1,1pu, rated DC voltage and loads.
The blue area is representative of the DVR capability in accordance with the design bolts for the dip (30%V_n, 600ms and maximum phase shift ±20°), while the red area represents the not compensated dips.
The green area is a surplus of capability, result of the inverter design (maxium IGBT current value); this area extention depends on the actual load and DC voltage.
Fig. 5 shows the DVR capability obtained with DC voltage at 0,7pu (lower limit of the DC voltage range variation).

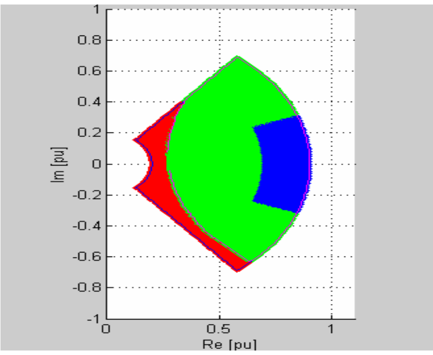

Fig. 4. DVR dip compensation cabability with pre-dip load voltage at 1,1pu, and DC voltage at 1pu

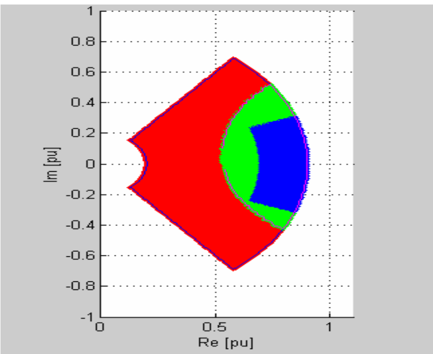

Fig. 5. DVR dip compensation capability with pre-dip load voltage at 1,1pu, and DC voltage at 0,7pu

The DVR harmonic impact has been evaluated in both its operating condition (stand-by and voltage compensation) in accordance to the standards IEC TR 61000-3-6 [11] and CEI EN 61000-2-4 [12].

To achieve good dips compensation performace a multi-loop control system has been designed:

- an inverter current internal control loop;
- an external voltage control loop for the DVR output voltage regulation (V_c in Fig. 3).

C. Distribution STATCOM – D-STATCOM

In general, the D-STATCOM [8][13][14][15] is a shunt-connected device able to regulate network voltage, mitigate the impact of disturbing loads (flicker/fast voltage variation, unbalance and harmonics) and, in particular network conditions, compensate voltage dips. This device mitigates the load voltage by injecting the necessary current to the system.
Fig. 6. shows the D-STATCOM structure studied where the main elements are the IGBT inverter modules (Neutral Point Clamped configuration) and its commutating reactance, the transformer to match the inverter output to the line voltage and an energy storage (capacitor bank). A passive filter RC is foreseen to control the network harmonic impact during the device operation.

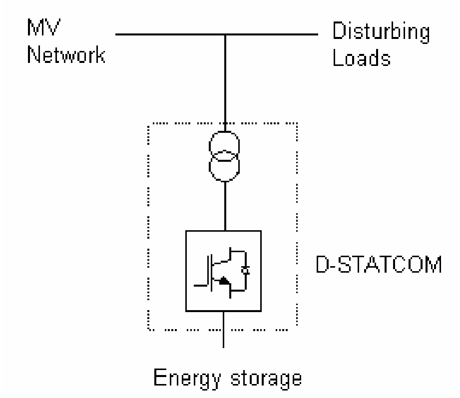

Fig. 6. D-STATCOM - Principle diagram

For the study in the Premium Power Park, the D-STATCOM power design and the control methodology are strictly connected to the device operation conditions. The assumption is that D-STATCOM has to compensate the voltage variation due to an induction motor starting.
In accordance with the above mentioned assumption the main design bolds are:

- the D-STATCOM has to mitigate the voltage variations during motor starting, under normal network conditions and rated network voltage (20kV) inside the range ±10%;
- the device has to be able to exchange a reactive power equal to its rated one in the worst voltage network condition (1,1pu);
- DC voltage regulation at a constant value.

The main parameters obtained by the design are:

- rated power 2,6 MVA;
- energy storage capacitor bank;
- inverter commutating reactance;
- transformer (rated power, voltage and current, short circuit voltage and transformation ratio);
- filter (resistance and capacitor).

To verify the D-STATCOM design its capability curves have been calculated, in particular they are representative of the maximum power exchanged with the network.
These curves have been evaluated in function of the following elements:

- network voltage;
- DC inverter voltage;

- maximum IGBT current value.

Fig. 7 shows the maximum power (active and reactive) the device is able to inject in the network with rated DC voltage, maximum invert current and for different conditions of network voltage:

- V_n (green line);
- $0,9V_n$ (blue line);
- $1,1V_n$ (red line).

The upper limit (green and red lines of Fig. 7) corresponds to an operarting condition with a reduction of the injected current because of the inverter voltage bolts, depending on the DC voltage.

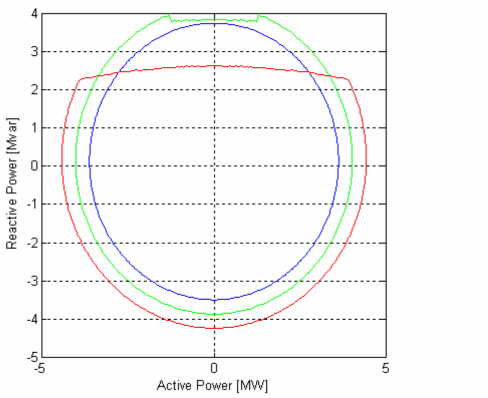

Fig. 7. D-STATCOM capability at different networkvoltage values: $0,9V_n$ (blue line), V_n (green line), $1,1V_n$ (red line)

Since the D-STATCOM is always operating, and the DVR is a series device, that can change the network configuration, the harmonic impact in accordance to the standards IEC TR 61000-3-6 [10] and CEI EN 61000-2-4 [12], in both the DVR operation conditions (stand-by and dips compensation), has been calculated.

About the D-STATCOM control methodology, two different solutions have been assumed and verified:

- loads reactive power compensation with the independent regulation of active and reactive components of the current injected in the network by the device. This control system is made by three main elements:
  - regulation loop for the injected currents;
  - regulation loop for the DC voltage;
  - Phase Locked Loop calibrated on the network voltage.
- Medium Voltage (MV) network regulation at the D-STATCOM connection point, in this case another external loop has been provided to mitigate the voltage variation. At the end the control system is made by:
  - MV network regulation;
  - regulation loop for the injected currents;
  - regulation loop for the DC voltage;
  - Phase Locked Loop calibrated on the network voltage.

To have a better coordination of the devices in the Premium Power Park the following D-STATCOM regulation logic has been developed in the model:

- MV network regulation under normal network conditions;
- loads reactive power compensation if the network is affected by voltage dips, already compensated by STS or DVR.

4. Custom Power devices: coordination logic

After the design of each equipment, the simulations of the coordination and interaction of the advanced electronic devices described before have been done [8].

Each piece of equipment has to be put in communication with the one at the superior level, in this way it changes its behaviour in accordance with it.

The control methodology is divided into two cases:

- in absence of network disturb:
  - loads are supplied by the main line through the STS;
  - DVR in stand by;
  - D-STATCOM in voltage regulation at level AA (Fig. 1);
- when a fault occurs:
  - D-STATCOM stops the voltage regulation and supplies the same reactive power that it was supplying before the perturbation;
  - DVR injects voltage to restore at load the pre-event voltage's value (magnitude and phase), if STS switches from the preferred to the alternative feeder (in case of interruption of voltage dips more than 30%) the DVR goes in stand by.

5. Simulation results

The compensation system behaviour has been analyzed by ERSE [8] with different network and load perturbations simulations, done with ATPDraw (Alternative Transient Program). In particular, in the follow the presented results are relevant to:

1. three phase symmetrical fault with a voltage reduction of 50% on the phase to phase voltage more affected by the fault (Fig. 8, Fig. 9);
2. phase to phase unbalanced fault with a voltage reduction of 30% on the phase to phase voltage more affected by the fault (Fig. 10, Fig. 11);
3. induction motor starting connected to the same bus bar of the D-STATCOM (Fig. 12, Fig. 13, Fig. 14).

Thanks to the fault simulations it's possible to estimate the coordination and the interaction of the Custom Power devices when a voltage dip occurs.

In particular, the first simulation shows the STS behaviour in the case of a deep voltage dip. This fault presents a voltage reduction of 50% and a phase displacement of 40° (Fig. 8). In this case the DVR is faster than STS and it starts to inject the voltage necessary to restore the pre-dip voltage but after 20ms from the STS commutation it goes in stand-by (green line Fig. 8). The D-STATCOM supplies the same reactive power that it was supplying before the perturbation.

The final result is to connect the loads to the alternative feeder and the load voltage is restored as before the fault (Fig. 9).

The second simulation shows the DVR compensation efficacy during an unbalanced fault (Fig. 10, Fig. 11). In this case the STS doesn't switch, since the dip features are within the DVR capability, and the D-STATCOM has the same behaviour shown in the previous fault simulation. The figures report also the switching signals of the compensation starting shown.

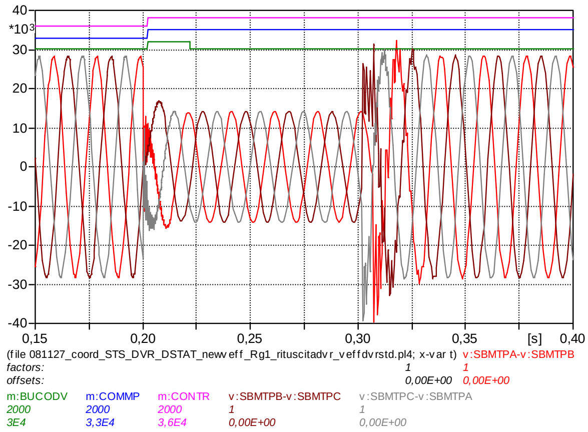

Fig. 8. Phase to phase voltage waveform at MV bus bar during a symmetrical fault at level A, with the switching signals: DVR (green line), STS (blue line) and D-STATCOM (red line)

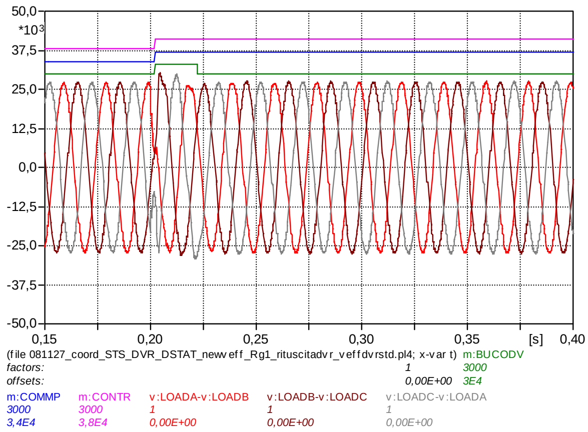

Fig. 9. Phase to phase voltage waveform at loads during a symmetrical fault at level A, with the switching signals: DVR (green line), STS (blue line) and D-STATCOM (red line)

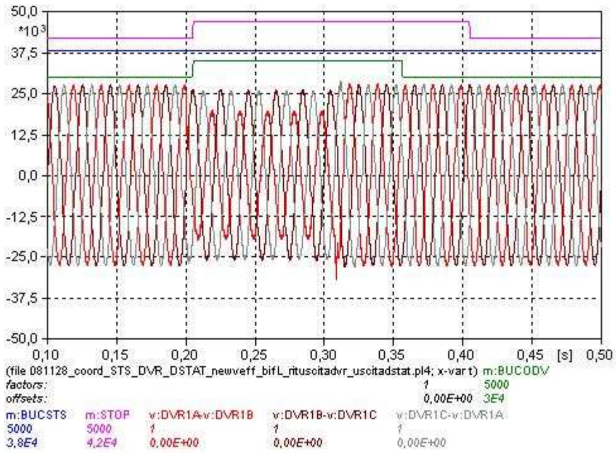

Fig. 10. Phase to phase voltage waveform at MV bus bar during an unbalanced fault at level A, with the switching signals: DVR (green line), STS (blue line) and D-STATCOM (red line)

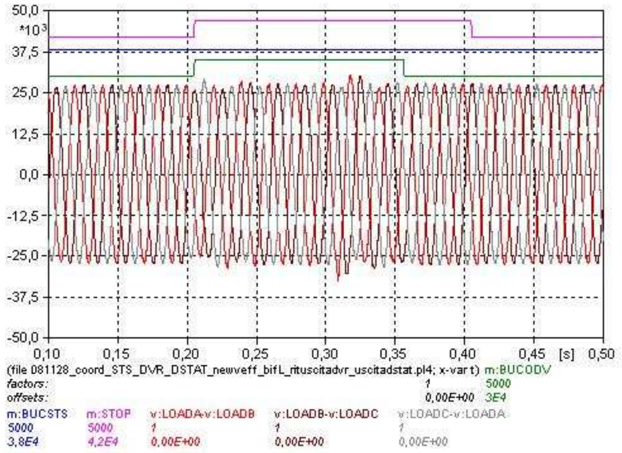

Fig. 11. Phase to phase voltage waveform at loads during an unbalanced fault at level A compensated by DVR with the switching signals: DVR (green line), STS (blue line) and D-STATCOM (red line)

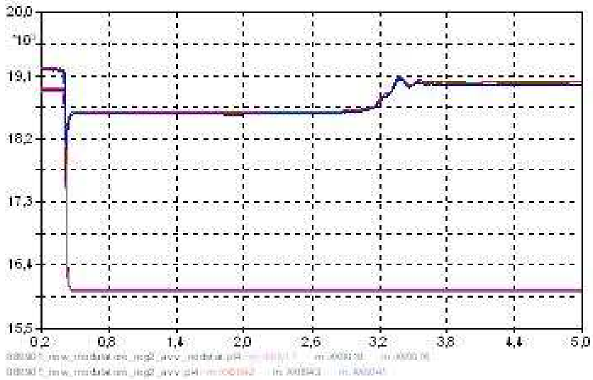

Fig. 12. Magnitude of voltage during induction motor starting with and without the D-STATCOM voltage regulation

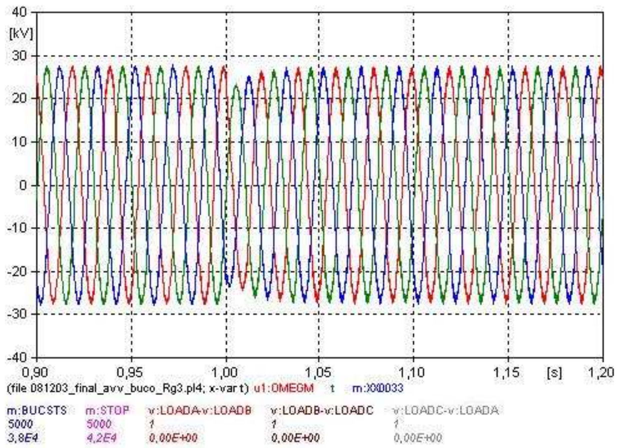

Fig. 13. Phase to phase voltage waveform during induction motor starting compensated by D-STATCOM

The third simulation shows the PPP operation during induction motors start. During starting, motors draw approximately five-times their full-load running current causing a voltage dip at level AA in the PPP (Fig. 1). This level represents a weak point in the PPP network as its short circuit power level is limited by the impedance of the DVR operating in stand-by for the most of the time.

Fig. 12 shows the voltage magnitude during a voltage dip due to induction motor starting with and without D-

STATCOM. Fig. 13 shows the effect of the D-STATCOM MV network regulation, on the voltage waveform at level AA and Fig. 14 the reactive power injected by the device (limited by the D-STATCOM capability, Fig. 7) and absorbed by the motors.

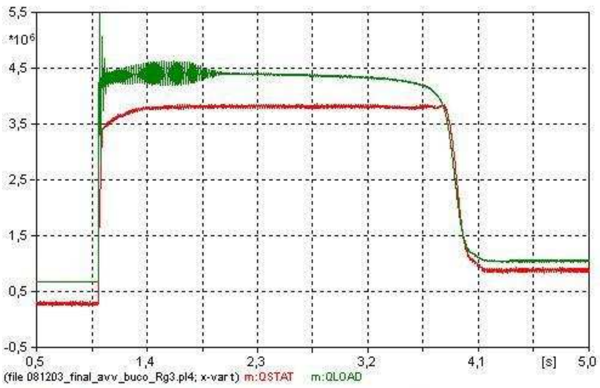

Fig. 14. Magnitude of the D-STATCOM (red curve) and motor (green curve) reactive power

6. Conclusions

A possible configuration of a Premium Power Park has been proposed.

The use of different voltage dip mitigation devices permits to obtain customized solutions in accordance with the specific sensitive loads demands.

The developed model done by ERSE provided an adequate basis for a general methodology to study the theoretical design of Premium Power Park based on Custom Power devices, in particular the study has been focussed on:

- Static Transfer Switch (STS) to mitigate interruptions and deep voltage dips;
- Dynamic Voltage Restorer (DVR), series connected, used to compensate voltage dip, restoring both, voltage magnitude and phase angle;
- Distribution Static Compensator (D-STATCOM) to add dynamic response to the system to voltage variations during induction motor starting.

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