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Active Substation design to maximize DG integration

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Abstract--**The massive integration of distributed generation (DG) can cause voltage disturbances at the connection points. In order to maximize the penetration of DG power, the actual topology of distribution grids should change introducing active devices to control the voltage, especially in weak networks.**

In this paper it is analyzed the integration of DG in a weak network connected to a MV/LV substation, using different active devices connected to this substation. The studied active devices are: OLTCs, STATCOM with Energy Storage and Dump-loads. The contribution of these active devices to increase the installed DG power in weak networks is analyzed. An operation and control strategy for the Active Substation is presented and the performance of this Active Substation is verified by temporal power flow simulations.

Index Terms—**Active substation, Active Network Management, Battery Storage Systems, Distributed Generation, OLTC, STATCOM, Voltage control, Dump-load**

I. NOMENCLATURE

AVC: automatic voltage control
DG: distributed generation
LV: low voltage
LDC: line drop compensation
MV: medium voltage
OLTC: on load tap changer
PCC: Point of common coupling
PV: photovoltaic
STATCOM: Static Synchronous Compensator
ST-ES: STATCOM with Energy Storage

II. INTRODUCTION

THE electrical grid is one of the largest infrastructure ever built. This infrastructure has been built regarding a generation model where large centrals provide the electricity to supply all the customers. In this grid topology, the power produced by these centrals is transmitted in high voltage to consumption points, changing there to medium voltage (MV) for its distribution and finally is transformed to low voltage (LV) for its consumption. Due to environmental concerns and the variable price of fossil fuels, renewable energy sources are getting more importance for power generation.

Even if large wind farms or hydroelectric centrals are connected to the transmission grid, a large amount of renewable energy is connected to the distribution network. These generation units can be defined as distributed generation (DG). The increasing penetration of DG is already changing the network topology [1]. This change of the network topology is due to the policies that aim the increase of renewable energies, subsidizing the electricity produced by renewable sources and the liberalization of electricity markets.

In this context the actual network operation and control methods can become insufficient in the future, since the design of these grids was made for a unidirectional power flow. One of the main obstacles for a large implementation of DG is voltage control [1, 2]. In this sense many authors have analyzed the problematic issues of voltage control in distribution networks with high penetration of DG. In [3-5] the authors analyzed the use of OLTC power transformers to control the voltage levels in the MV distribution grids, in presence of a high level of DG. Due to the increasing penetration of DG in the LV distribution network the control of these grids becomes more complicated. In fact, it is necessary the control of the voltage levels in these networks.

Other authors [6] discussed about the use of inverters for voltage control applying reactive power compensation. The coordinated use of reactive power compensation using switching capacitors and OLTCs it is discussed in [7]. The use of different voltage control technologies in distribution grids with high penetration of wind power DG is analyzed in [8]. It is not common to use OLTCs in substations from MV to LV but there are some proposals in the literature [3, 7].

The use of energy storage systems connected through power converters to the distribution grid it is also interesting to maximize the integration of DG, as it has been demonstrated by several authors [9, 10].

The coordinated control of OLTCs, reactive power compensation, DG plants, loads and protections is discussed in [5]. In this context comes up a new concept, the Active Network Management, in which taking into account local, remote and pseudo measures (i.e. estimated load profiles) and network data, the different generation units and control devices are coordinated. This management strategy provides the possibility to increase the penetration of DG in the distribution network, ensuring the power quality and the voltage levels.

In this article the Active Substation concept is studied, in which the voltage level at the substation is controlled using local measurements and the management of different control devices connected to the MV/LV substation. As a difference with the Active Network Management mentioned above, all the measurements are local measures, the control devices are installed within the substation and there is no need to

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control/coordinate the DG units connected downstream the substation. The voltage control at this MV/LV substation is analyzed and a management strategy is proposed. The overall system performance is demonstrated in temporal power flow simulations. It is shown that using Active Substations it is possible to increase the DG power injected to a weak network.

The Active Substation proposed in this article consists on a MV/LV OLTC transformer, a STATCOM with Energy Storage (ST-ES) and a dump-load, in a scenario of high DG penetration.

III. ANALYZED SCENARIO

The scenario proposed for this study is composed by a DG source connected to a MV/LV transformer substation through low voltage 690v three-phase grid.

The equivalent grid of the distribution network is modeled as an ideal voltage source with a short-circuit impedance, Zsc in figure 1. In order to simulate a weak network, this short circuit impedance for a short circuit power of 550kW. This scenario will be analyzed for different X/R ratios for this Zsc impedance. It is known that at Low Voltage levels the X/R ratio could be as low as 2, so the range of values analyzed in this paper are from 1 to 10. The impedance of the substation is taken into account in this Zsc impedance.

In this range of powers in wind generation applications, it is common the use of induction machines directly connected to the grid as generators. So the wind turbine is modeled as an asynchronous machine excited by a torque that is proportional to the wind-speed profile. The reactive power is compensated using a capacitor in parallel to the machine, which compensates the reactive power absorbed by the induction machine when it is working at full power.

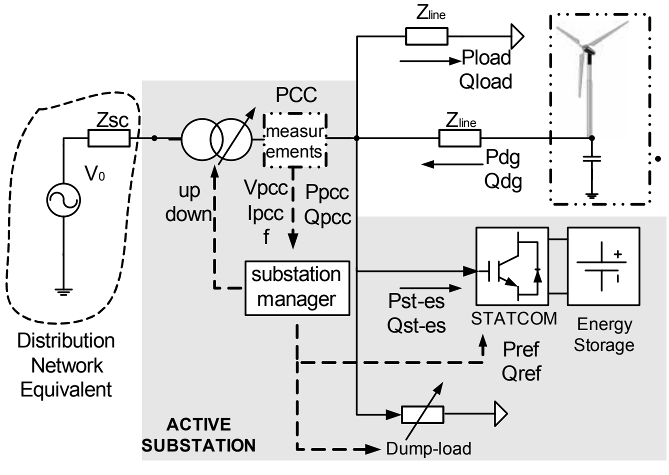

Fig. 1. : A distribution network example with DG, where an active substation controls an OLTC, a dump-load and a STATCOM with energy storage

A. Active substation

To maintain the voltage within acceptable limits at the point of common coupling (PCC), the power injected to the distribution grid should be limited. It is defined as PCC the point where the different lines are connected to the substation.

In this context it is necessary to install control devices to improve the integration of DG. The Active Substation where the DG is connected is the best placement in order to control the upstream power flow, monitoring the electrical signal in the substation and acting on the signal using the installed control devices.

In an Active Substation different control devices can be installed. A central computer will read the monitored signal and regarding a control algorithm designed to improve the DG integration, it will provide the references for the different devices connected in the Active Substation. Different devices that can be connected in an Active Substation to control the voltage are discussed in the following subsections.

1) On-load tap changers (OLTC)

OLTCs are used to control the voltage in MV networks, by shifting phase angle and adjusting voltage magnitude. It is usually in conjunction with Automatic Voltage Control (AVC) relay and Line Drop Compensation (LDC). An intentional time delay is always implemented to avoid unnecessary tap change operations during transient voltage fluctuations [11]. In [3] it is shown that OLTC is robust against DG, whereas DG can affect the effectiveness of the voltage regulation provided by LDC. However, with proper coordination between DG and LDC, it is possible to ensure voltage regulation without unnecessarily restricting the integration of DG.

2) STATCOM

The STATCOM is a flexible AC transmission system device used as a device to control the reactive power exchange at the PCC. This gives different choices:

- Reactive power control—the complete system is required to produce or absorb a constant specific amount of reactive power.
- Automatic voltage control—the voltage in the PCC is controlled. This implies that the complete system can be ordered to produce or absorb an amount of reactive power to the grid in order to compensate deviations on the grid voltage.

The STATCOM is modeled as a three phase voltage source inverter connected to the grid by means of an inductive filter.

3) STATCOM+Energy Storage (ST-ES)

Adding an energy storage system to the STATCOM it is possible to control the active power flow between the STATCOM and the PCC. So the STATCOM not only compensates the reactive power, but also is able to store energy in the Storage-system when the generated power exceeds the power limits that could be injected to the distribution grid. This solution gives the following capabilities to the system:

- Balance control—whereby the PCC power injection can be adjusted downwards or upwards.
- Delta control—whereby the complete system is ordered to operate with a certain constant reserve capacity in relation to its momentary possible power production capacity.

- Power gradient limiter—which sets how fast the complete system power production can be adjusted upwards and downwards.

4) Dump-load

In cases where there is not any possibility to control the power injected to the substation (i.e. the power generated by the DG cannot be controlled, and there is not any Energy-Storage device), a Dump-load can be used. The Dump-load is a variable load that can be adjusted in steps to consume the excessive power.

IV. ANALYTICAL STUDY

In this section an analytical study of the proposed system will be described. The following one line diagram has been used for the study.

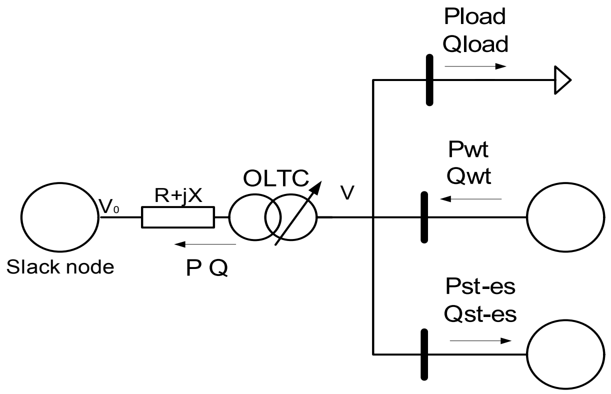

Fig. 2: One line diagram of the analyzed feeder

The voltage variation in the distribution line equivalent impedance is given by (1):

$$\Delta V = \frac{PR + QX}{V_0^*} + j\frac{XP - RQ}{V_0^*} \qquad (1)$$

Where P and Q are the active and reactive power injected in this node, R and X are the equivalent resistive and inductive impedance upstream of this nodes (Zsc), V_0 is the distribution grid equivalent voltage and ΔV is the voltage variation in this impedance.

The active (P) and reactive (Q) power injected in the PCC are composed by the signals that are shown in Fig. 1. . Obviously the worst case for a voltage rise will be when there is not any load connected to the PCC and there is not any battery or STATCOM. The general composition of the power injected to the PCC is shown in (2) and (3).

$$P = P_{dg} - P_{load} - P_{st-es} \qquad (2)$$

$$Q = Q_{dg} - Q_{load} - Q_{st-es} \qquad (3)$$

The voltage amplitude in the PCC could be calculated as follows:

$$|V| = |V_0 + \Delta V| \cdot N_{OLTC} \leq |V_{\lim}| \qquad (4)$$

Where Vlim is the voltage limit for the node, N_{OLTC} is the voltage relation of the OLTC and V_0 is the voltage of the distribution grid.

The maximum power that can be injected in the PCC is limited by the acceptable voltage limits in this node. In (5) it is shown the relation between the active and reactive power injected to the distribution grid and the voltage limit at the PCC, in the case where the OLTC is not present or is not active (N_{OLTC}=1).

$$|V_0 + \Delta V| = \sqrt{\left(V_0 + \frac{RP + XQ}{V_0}\right)^2 + \left(\frac{XP - RQ}{V_0}\right)^2} \leq |V_{\lim}| \qquad (5)$$

$$V_0^2 + 2(RP + XQ) + \frac{(R^2 + X^2)\cdot(P^2 + Q^2)}{V_0^2} \leq |V_{\lim}| \qquad (6)$$

Regarding the scenario proposed in this article, for the case where there is not any control device connected to the substation (OLTC, STATCOM, etc.), the injected reactive power would be negligible and the voltage V would be equal to the upstream voltage V_0. Considering acceptable a 5% variation of the voltage at the PCC, the maximum power injected, for different X/R ratios (from 1 to 10), in the proposed scenario is shown in Fig. 3:

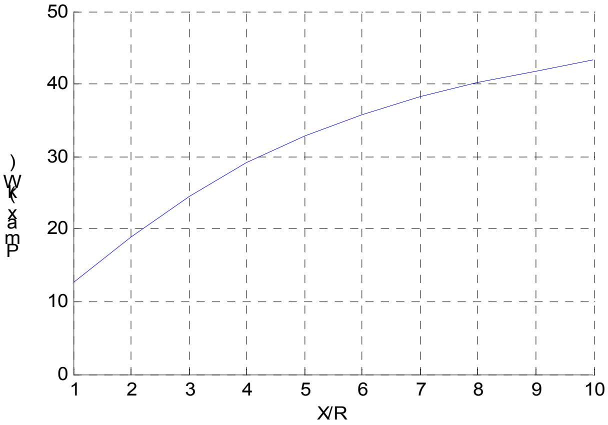

Fig. 3: The maximum power that can be injected in the analyzed substation depending on the X/R ratio of the network

In this scenario without any control device to control the voltage in the PCC the power curtailment is the only way to solve the voltage rise problem [11]. In this case there are two options to control the injected power: the Pitch Control in the wind turbine or if there is not this technology the use of a dump-load to absorb the excess of power.

The use of an OLTC would change the voltage limit of the PCC, due to the capacity to regulate the voltage as shown in (4). Varying the voltage relation of the OLTC the power limit would vary as well, as the OLTC could compensate the increase of voltage at the PCC reducing the voltage relation

N_{OLTC}. Therefore the maximum power limit would be found at the minimum N_{OLTC}.

Different OLTCs can be found in the market. An important difference between them is the maximum voltage control capacity (Nmax). There have been calculated the maximum power that can be injected to the PCC for different maximum voltage control capacities, from ±5% (NOLTC from 0.95 to 1.05) to ±20% (NOLTC from 0.8 to 1.2). Depending on Nmax the maximum power that can be injected in PCC is shown in Fig. 4:

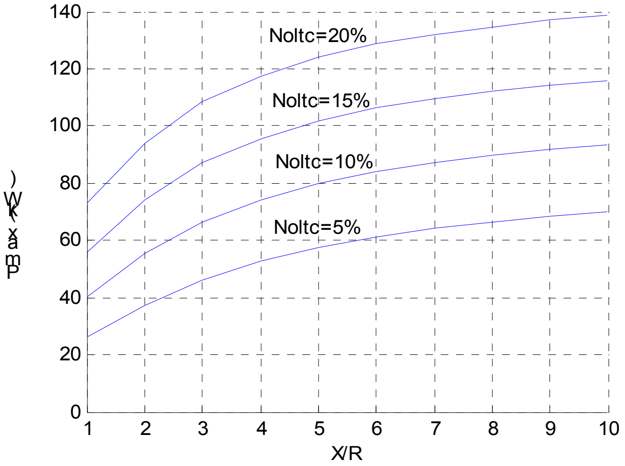

Fig. 4: The maximum power that can be injected in the substation depending on the X/R ratio of the network, for different OLTC control capacities

Using an STATCOM instead of an OLTC to control the voltage, regarding (5) and (6) it is clear that capacitive power compensation would reduce the voltage variation. The following graph shows the maximum power that can be injected to the PCC depending on the capacity of the STATCOM to compensate reactive power on the PCC.

The OLTC is a very mature and competitive device to control the voltage, although due to its slow response and the error for voltage control it can be interesting to use a STATCOM which has a fast dynamic to response against sudden variations in the network signal and it can make a fine adjustment of the voltage. As it is shown in Fig. 4 and Fig. 5 the OLTC has more capacity to maximize the power injected to a weak grid.

The use of a battery in parallel to the wind turbine gives the chance to produce always as much power as possible and store the energy that cannot be injected to the grid. A battery linked to the STATCOM can be the best solution to maximize the DG power that can be injected in a weak network. The generator can be sized to produce more power than the maximum power because the excessive power can be absorbed by the battery. For a case where this situation will be possible but not probable it can be used a dump-load to absorb the power.

In this point it is proposed an Active Substation composed by an OLTC, a ST-ES and a dump-load to maximize the DG connected to a weak network. This network is shown in Fig. 1.

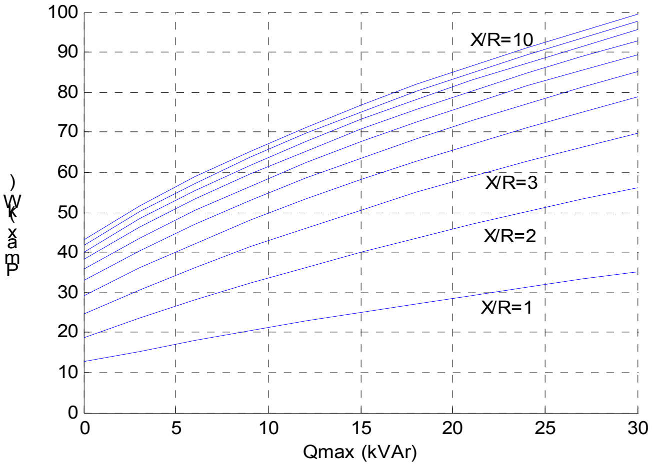

Fig. 5: The maximum power that can be injected in the substation depending on the reactive power compensation at the PCC, for different X/R ratios

A. Management algorithm

The control algorithm for the proposed Active Substation will regard to maintain always the voltage within a limit of ±5% of the nominal voltage. In normal work conditions the system would always try to maintain the voltage in its nominal value.

Due to its fast response the primary control loop will control the reactive power compensation ($Q_{st\text{-}es}$) of the ST-ES, the reference reactive power (Q^*) will be defined by a PI controller excited by the error between the measured voltage (V) and the nominal voltage (V_n).

A secondary loop will control the OLTC. The OLTC will act to reduce the power compensation of the ST-ES, in this way if $Q_{st\text{-}es}$ is larger than a certain value (10% of maximum, for example) the OLTC will make a step down or up depending on the sign of the reactive power.

For a network, where there is installed more DG power than the maximum power that can be injected to the substation, the battery will act to absorb the excessive power. If the power consumption is excessive as well, the battery will provide the necessary power. When the battery is charged a dump-load can be used to absorb this excessive power production, while the only solution for excessive consumption will be the limitation of the power.

V. SIMULATIONS

The management algorithm proposed above will be implemented in a simulation, for the following Active Substation. The weak network proposed in this article will be simulated with an X/R ratio of 6. The OLTC will be sized with a maximum voltage control capacity of ±10% and steps of 2%, with a response time of 4 seconds. A 15kW battery in a 22.5kVA ST-ES, this gives the chance for a simultaneous injection of 15kW and 15kVAr. The maximum power that can be injected to this Active Substation without using the battery it is shown in Fig. 6 in function of the voltage in the network equivalent.

Fig. 6 shows that the maximum power that can be connected to this substation has increased up to 120kW (105kW+15kW of the battery), in normal conditions. For cases where the voltage in the upstream network increases it would be necessary to use a Dump-load. Regarding the previous graph a 25kW Dump-load would be necessary to answer against an increase of 10% in the upstream voltage.

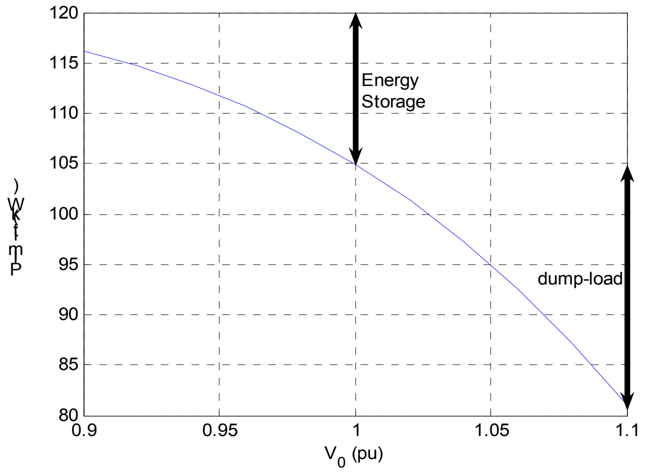

Fig. 6: The maximum power that can be injected in the simulated scenario, depending on the upstream voltage level.

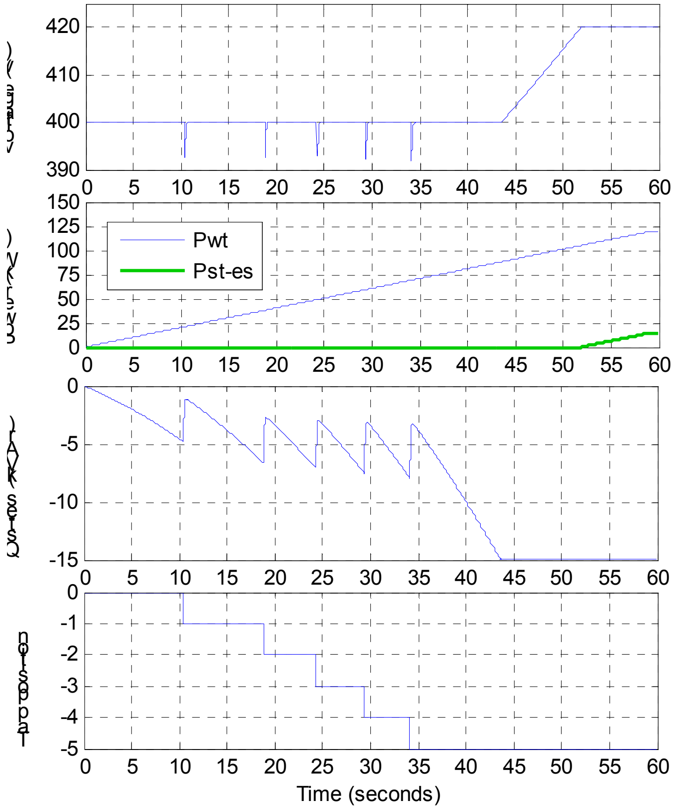

Fig. 7: Temporal simulation of the system for a fast increase in the injected power.

The following simulation results show how the system works, for a wind farm of 120kW connected to the Active Substation. In the first case it is shown how the system would answer for an increase in the power injected from 0 to 120kW without any load connected to the substation. It is not a real case but it shows how the system would be able to answer to such an adverse situation.

In Fig. 7 the power injected to the substation is increasing since the beginning. The voltage is controlled by the ST-ES injecting reactive power. When the reactive power is higher than a certain level the OLTC orders to change a tap and after 4 seconds it changes. When there is a tap change the reactive power compensation is reduced very fast due to the fast response of the ST-ES, although it keeps on increasing because the active power injected to the substation is also increasing. After the 5 possible tap changes and the reactive power compensation in its maximum (15kVAr) the voltage cannot be maintained in its nominal value. When the voltage at the PCC reaches an overvoltage of 5% the ST-ES starts injecting active power to maintain the voltage below this value.

In the second simulation it is shown the response of the substation in a case of a load that is suddenly disconnected, while the wind farm is working with mid power.

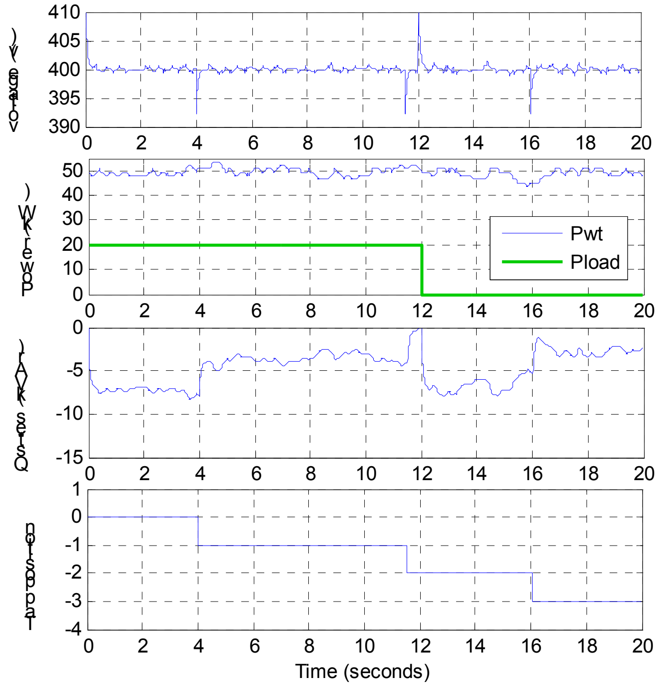

Fig. 8: Temporal simulation of the system for a suddenly disconnected load.

In Fig. 8 it is shown how using the reactive power compensation the voltage is controlled in the beginning. After 4 seconds the OLTC changes a tap to reduce the injected reactive power. A second tap change happens afterwards reducing the injected reactive power. When in the 12th second of the simulation the 20kW load is disconnected the voltage is controlled increasing the reactive power compensation. After 4 seconds the OLTC changes a tap reducing again the reactive power.

In these simulations we can see that the tap changes of the OLTC can be reduced by injecting more reactive power, these two variables should be taken into account to design the substation, because normally it will be more interesting to reduce tap changes than to reduce the reactive power compensation.

VI. CONCLUSIONS

In this article it has been demonstrated how the integration of DG in weak electrical networks can be maximized introducing active devices in the MV/LV substation. It has been presented the concept of an Active MV/LV Substation, integrating active devices as: OLTC, STATCOM with Energy Storage and Dump-loads. It has been demonstrated that the control of the voltage level at the PCC is possible monitoring only the local signals at the substation, and with an adequate control/operation strategy of these active devices. An operation and control strategy for the Active Substation has been presented and the performance in a weak grid has been verified by temporal power flow simulations.

For a future electrical network where a high amount of electricity will be produced by DG, the use of active devices seems to be necessary in order to increase the active power injection capability in weak networks. In this context the Active Substations are a suitable solution to increase the DG penetration.

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VIII. BIOGRAPHIES

Ander Goikoetxea was born in Villabona in the Basque Country, Spain, on August 19, 1983. He got the bachelor degree in Industrial Electronic Engineering in San Sebastian, by the Basque Country University (EHU) and he got the Degree of Engineering in Automatics and Industrial Electronics by the University of Mondragon. Nowadays he is in a Ph.D program in Automatics and Electronics line, in the University of Mondragon. He is an IEEE member since September 2007 and Power&Energy society member since September 2008.

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In September 2008 he joined Ingeteam Transmission and Distribution as Senior Engineer.

His research interests include electrical machines modeling and control, in particular, for single - and doubly-fed asynchronous machines, and voltage source inverter control for FACTs applications.

Gonzalo Abad (M'07) was born in Bergara in Spain, on October 11, 1976. He received a degree in Electrical Engineering from the University of Mondragon, Spain, in 2000, the M.Sc. degree in Advanced Control from the University of Manchester, U.K., in 2001 and the Ph. D. degree in Electrical engineering from the University of Mondragon, Spain, in 2008.

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