2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece

Primary cabin voltage and reactive power control by distributed generators

Corsi Sandro
Consultant

Abstract

The paper deals with control structures and functionalities contributing to the distribution grid smartness in the presence of distributed generators (DG).
The Primary Cabin (PC) hosting DG is analyzed assuming a voltage control scheme that includes the Transformer (TR) with On-Load Tap Changer (OLTC), but also generators and FACTS allowing their reactive power remote control. Therefore more and contemporary closed loops controls operate on the same voltage variable or on the strictly linked reactive power. These combined efforts require a proper coordination among the operating control loops having different dynamic performances. Promising proposals of alternative coordinated PC controls, including the reactive power flow between the HV and MV bus-bars, are presented. They are substantially aimed to achieve effective automatic regulations by simple and practical solutions. The considered control schemes take into account different PC operating conditions including the islanded network covered by proper functional variant. The considered PC regulator is also provided with automation functionalities operating a timely and proper switching of capacitor banks and shunt reactors when remotely controllable.

Keywords: smart grids, distribution grid, distributed generation, primary cabin, voltage control, reactive power control.

Introduction

A new Primary Cabin (PC) control and protecting system, mostly oriented to the case of "active" MV distribution grid with operating distributed generators has, as main objectives, the provision of adequate and complete support to the MV grid automatic control of voltage, frequency and active/reactive power flow. Moreover it could contribute to the back-up feeding of the neighboring islanded PC grid. To this end the here considered control system necessarily must be the peripheral part of a more complex real-time control structure automatically coordinated by the Distribution Dispatching Center (DDC). Therefore a distribution grid hierarchical control system is required for each DDC, having decentralized specific functionalities at the PC level, while coordinating more PC remote controls by the necessarily centralized functions at the DDC's Distribution Management System (DMS). The introduced hierarchy will likely attribute the high speed and peripheral functions to the intelligent PC control system while will manage and coordinates the slower control functions at the higher centralized regulating level.

Generality on the PC Voltage Regulation:
1-In principle, each generator of the PC MV network automatically regulates by AVR the generator edges voltage, therefore indirectly supporting the voltage on its line interconnecting bus. It cannot be excluded the case of generators able to parallel to the grid and operate till when their MV busses are voltage sustained by other generators. Both kinds of generators can be found and their potential contribution to the PC voltage control obviously differs;
2- The candidates to the PC voltage regulation are the HV/MV TR bus bars, traditionally the MV busses. In this case the new PC voltage regulator could control all the local reactive power resources aimed maintaining the desired voltage value on the MV bus. Operating the TR OLTC and realistically assuming its voltage stepping control operated on the same MV bus-bar, in that case an adequate coordination and decoupling between the two parallel voltage control loops is required.
3- The impact the new PC voltage regulation and its dynamics have on the local MV protections must be properly assessed as well as its interaction with the neighboring PC.
4-At DDC, a centralized regulator aimed defining, in real-time, the voltage set-point references for each controlled PC is required. This DDC-DMS control function has to take into account each PC MV grid structure and resources, the electrical connections among the controlled PC, the HV side voltage variations at the supervised MV area and the reactive power flows at the HV/MV interconnections. Moreover any possible control requests on the HV voltage support, coming to the DDC by the transmission network TSO, must be taken into account.

978-1-4799-0199-9/13/$31.00 ©2013 IEEE

Generality on the PC Frequency Regulation:
5- The singular case requiring the PC frequency regulation follows the PC MV grid islanding and till when the connection to the HV or MV neighboring grid is not restored. The objective being the MV-island maintained into operation through the local generators control. During the islanding fault the generators trip should be avoided (required adequate AVR and governor controls) because of their vital contribution to the island loads balancing.
6- This control functionality requires the PC generators be controllable by a PC frequency regulator that has the ability to speedily recognize the islanding passage, the island sufficient controllability after the passage, and the containment of the frequency and power overshoots within an acceptable range for both the generators and the local loads.
7- The impact of the PC frequency regulator on the local protections requires proper dynamic design and assessment, including the possible dynamic interaction with surrounding electrically coupled PC when part of the island.

Generality on the PC Power Flow Regulation at the HV bus-bar:
This innovating control functionality consists on regulating in real-time the active and reactive power flows between the PC HV and MV bus-bars. According to that it is made possible a PC production market sustaining the HV grid by DG resources on MV grid. More precisely:
8- Each generation area under a given PC will be controlled by the PC power flow regulator by taking into account the available control margins, the allowed MV/HV line over-loading and the operation bounds imposed by the DDC.
9-The DDC having authority on given PC should manage its power flow exchange with the HV grid according to all the linked aspects, by also including the energy metering, computing and certifying the supply provided by each generator.
10- The DDC dispatcher defines the set-point references of active and reactive power flows of each PC as well as their real time updates by taking into account the production availability of each controlled PC, the present PC internal load, the existing contractual obligations, the operating limits and requirements coming from the TSO, without forgetting the operation and security needs the MV grid requires.
11- The impact this power flow control at the HV bus-bar and its control dynamics have on the PC protections must be deeply assessed including its dynamic interaction with the neighboring PC at the different operating conditions.

Generality on the PC back-up feeding by neighboring MV network:
Losing the HV connection and feeding, a PC MV network can be re-fed, in principle, by a neighboring MV grid. This new feeding can be manually or automatically operated by the PC control. The connection is enabled by local/remote compatibility check on the lines overloading bounds and on the feeding PC MV operating scheme and its MV-HV interconnection control.

The paper objective:
The smartness of a distribution grid comes from the availability of control and automation functions like those introduced above. They may differ in some aspect due to possible different PC electrical scheme characteristics, type and size of DG and their controllability as well.
The paper deals with the distribution network voltage and reactive power regulations and their possible alternative schemes [1,…..,20], by orienting choices as much as possible toward complexity simplification and proposing cost effective control solutions.
On the control schemes, the solutions the paper proposes and the choice among them is, de facto, the selection of a PC control philosophy that does not end with feedback of principle but rather with the identification of the more feasible and effective in practice, according to the MV grid characteristics and operation needs. To this end one should ask whether is there any reason and practical interest on the PC HV-MV interconnection reactive power flow regulation? Moreover the question should be if the PC situations with large and continuous reactive power flow toward the HV bus-bar are plausible and majority? Otherwise one should clarify if the real of interest cases host a limited number of generators at each PC MV grid so the local reactive power resources are limited and their contribution to the HV voltage support unrealistic. Their proper and appreciable use in this case should be more concentrated on the PC MV grid voltage control.
Lastly is it not true that the best contribution to the transmission network voltage support consists on providing the achievable control of the PC load voltages through the local control resources, without asking support by the transmission grid? Therefore, identifying more precisely viable scenarios, meaningful and of interest to the MV ancillary services market, having concrete hopes for success and usefulness, is the preliminary but indicative way to ponder the choice on the PC control solution.

Generalities on Medium Voltage Grid and Primary Cabin Schemes

The following figures represent the basic medium voltage grid and PC unified schemes in Italy. It is assumed a distribution grid subject to a high DG penetration.

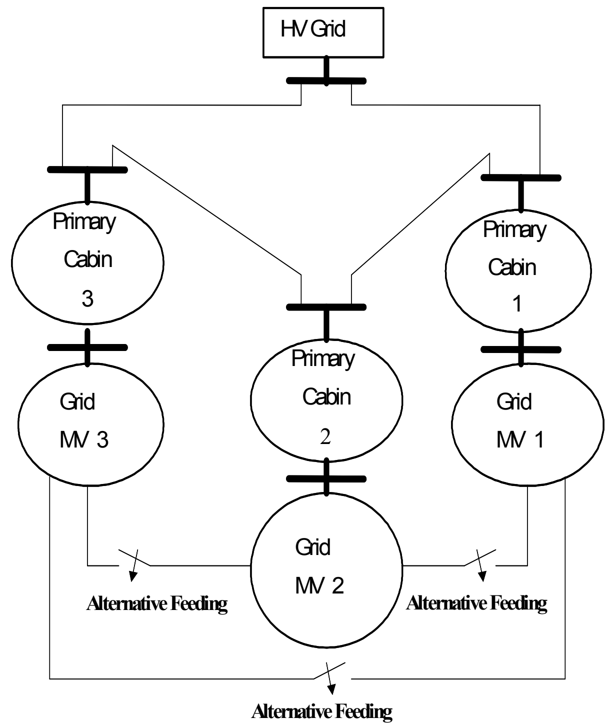

Fig.1 – Basic Scheme of the medium voltage grid.

Such grid has a radial structure with electrical lines characterized by an approximately unitary ratio between the resistance and reactance values.

Therefore the power distribution to the loads penalizes the line feeder voltage values. With generators on the line trunks, the power flow is altered both in magnitude and in direction causing changes on the voltage profiles. Such variations are so much larger the more is higher the ratio between the DG and loads.

In principle, among the DG resources the synchronous generators contribute on sustaining the local voltages in the same way as the generators interfacing the grid by static converters. Commonly the DG is largely enslaved to industrial production processes therefore subjected to closer ties on the produced active power possible changing finalized to voltage control. As obvious, the here assumed hypothesis is that the active power flows cannot be modified by the PC centralized voltage control, unless required by protection reasons.

The MV grids can be interconnected among them or electrically separated. Through their PCs the MV grids are connected to the HV grid. In case of islanding, the MV grid is isolated from the HV and the other local MV grids as well. The possibility to feed an isolated MV grid by a neighboring MV grid is also considered.

The PC operating scheme usually shows one HV bus bar and two separated MV bus bars. Along the feeder lines the other nodes are those of loads, compensators and generators. The choice of the voltage controlled bus-bars strongly impacts on the control scheme complexity, reliability, costs and DG management.

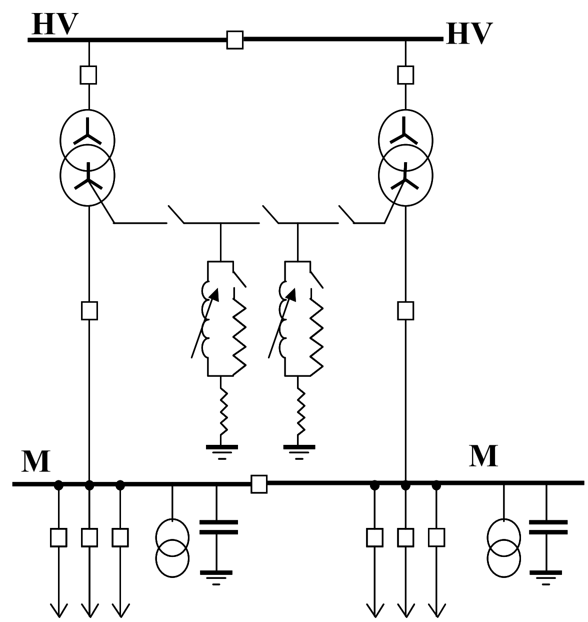

Fig.2 – Primary cabin unified scheme in Italy grid

In agreement with the present proposal, all the involved generators have to be remotely controlled with the continuous adjustment of the voltage set-point values of their primary AVRs (Automatic Voltage Regulation) required by the PC voltage regulator (PCVR) that will impose on the local MV or HV bus-bars the voltage set-point value sent by the DDC.

Generalities on Primary Cabin Voltage Control

To keep in mind that the PC MV bus-bars voltages assume values very dependent on the nearby transmission grid voltage controls. This involves a continuous and considerable effort by the PC regulator that may, in some cases, achieve high frequency variations and saturating conditions. Therefore, notwithstanding this regulation has to be quick and adequately sized to ensure effective controllability, it sometimes could be not enough.

From the above it is clear the need to control the PC voltage by an effective coordination between the Regional Transmission Dispatcher (TRD) and the Distribution Dispatch Centre (DDC) having competence on the PC considered. An in-depth analysis of such coordination is not done here, but the point is a relevant topic related to the grid operation problems and data exchange among the grid control centers.

It was also said that PCVR will be expected to maintain, with relatively fast dynamics, the PC bus-bars voltage values remotely set by facing changes in the local load, voltage variations coming from the transmission grid and then reactive power flow upgrades exchanged with the HV bus-bar, as well as changes in the local provision of reactive power due to modified operating point or thermal problems or limitations on each generator.

PCVR will also be responsible for maintaining adequate voltage on the HV/MV bus-bars even in front of large local perturbations. In addition to the continuous generators control, it will also operate the discontinuous switching of the local capacitor banks and shunt reactors (for significant amount of reactive power control), limiting the number of such operations to the minimum extent necessary and only in extreme conditions at the approaching of the control generators saturation.

PCVR, ultimately, will operate an effective and timely coordination of local resources, taking into account the dynamic characteristics of each, minimizing and sharing among them the control effort and limiting the number of switching maneuvers to the minimum necessary so increasing the life of the power factor correction components.

In the face of clear objectives, doubts remain on the control scheme which makes them more easily and efficiently achieved.

To define a PCVR control scheme proposal, it is preliminarily important clarifying the following points:

- Is it better to directly regulate the MV voltage at the cabin bus bars or at the busses along the MV lines?
- How much the complexity increasing on the voltage control structure improves its effectiveness?
- How properly sharing the reactive power control among the generators operating on the same PC?
- How to co-ordinate the PCVR and OLTC controls, both operating on the same PC bus-bar?

Considering the first two questions and the practicability of possible alternative solutions for a distribution grid, the following guidelines come out:

- PCVR should pass from the classical discrete and slow transformer TAP control, all dependent on the HV side voltage robustness supported by the transmission grid with autonomous resources, to a fast automatic regulation of the PC bus-bars voltage based on the local reactive power resources control (the generators of the distribution grid). Furthermore, restricting the voltage regulation to the PC bus-bars on the one hand simplifies and significantly reduces the complexity of the control solution that takes care of adjusting the voltages of all the load and generation buses and, on the other side, is not limitative of the load buses control performance, as will be made clear.

- The MV voltage regulation focuses the objective of the voltage ancillary service quality provided to the load and then to MV customers. In this case the contribution to support the local HV network is less effective and therefore difficult to recognize and remunerate the ancillary service by the TSO. The fact that there are more than one MV separated bars requires the voltage regulation of each single bus-bar via the control resources to each connected. Therefore many feeder regulations will operate in parallel and that requires a specific configuration and management of the voltage regulation itself, depending on the state of the switches connecting the MV bars.

- The voltage regulation at the HV side AT shifts the objective on the HV grid support, always ensuring a good voltage quality at the MV side. In this case, the ancillary service offered can be more easily recognized and remunerated and its effectiveness is to be considered comparable, if not superior, to that of the reactive power flow control towards HV. Moreover, in this case it has to be regulated only one voltage, the one of the PC HV bus-bars normally exercised at closed disconnector. This greatly simplifies the structure and complexity of the control scheme with respect to the MV side voltage regulation.

It should also be added that the HV side control moves the problem of the dynamic coupling between control loops from the inside to outside of CP, among PCs electrically coupled at HV side. In the presence of this regulation, the OLTC greatly reduces the number of maneuvers, mostly controlled by PCVR, with obvious advantages on the life of the transformer tap changer.

On the recognition of the service provided, each controlled generator may be remunerated according to its "capability" made available to the control and hours of operation under the automatic coordination by PCVR. Minor, to be neglected for the economic recognition, is the amount of reactive power delivered or absorbed by each generator.

From these preliminary comments on the PC voltage control with the MV grid hosting Distributed Generators (DG), some important points can be fixed:

- The classic OLTC Tap Control is a poor solution. A new multifunction solution is the waited control;
- The DCC should “in principle” update in real time the local PC voltage set-points by taking into account the HV side voltage values, the HV/MV reactive power flows and the commercial V, Q bonds.
- By attributing to the TAP maneuvers different objectives than local voltage support is the way addressing possible advances to the PC voltage control solutions.

Entering in some details, the OLTC-TAP manual or automatic stepping control of the Transformer MV value, maintained inside a confidence band around the set point

voltage value, is the classic PC conventional voltage control:
- Requiring a solid voltage at the transformer HV side, to effectively operate.
- Affected by too slow dynamics with respect to the real grid voltage variations.
- Contributing to the voltage instability risk increase that could require the transformers OLTCs lock.

On the contrary, the rotating and static generators automatic and continuous reactive powers control is the novelty required by the PC voltage control:
- All the rotating synchronous and asynchronous generators and synchronous compensators as well, have to contribute to the PC grid continuous voltage support.
- Analogous contribution must come from the static compensators (SVC, STATCOM and UPFC) and generators grid-connected through static converters provided with reactive power control.
- The compensating equipment like Switchable Capacitor Banks and Shunt Reactors should also contribute even if when strictly necessary.

Considering the automatic closed-loop control of these resources, like a PC Secondary Voltage Regulation (PC-SVR), it is possible to speedily regulate the PC MV (HV) busses to the desired voltage values and increase the power system security.

On the remaining two questions and the practicability of possible alternative solutions for a distribution grid voltage control, the PCVR should:

- Operate an effective and timely coordination of the PC resources by taking into account of their dynamics and properly sharing the control effort among them.
- Minimize the overall PC control effort as well as the number of switching maneuvers to increase the life of the PC compensating equipment.

About the coordination between PCVR and OLTC:

- Being two distinct closed loop automatic regulations, to be avoided unstable conflicting controls on the same voltage.
- By taking into account of their different dynamics, PCVR should regulate the PC voltages while OLTC could guarantee the transformer ratio allowing the full use of the over and under excitation resources of the PC generators, as well as avoiding the overcome of the machinery voltage limits.

The OLTC could alternatively control the reactive power exchange with the HV grid, limiting it inside a confidence band.

PCVR Basic Control Scheme

The here proposed PCVR is a Continuous, Centralized, Closed-Loop Control System, aimed to regulate the voltage of the PC HV bus-bar or the MV bus-bar at each of the PC MV independent bus.

PCVR-HV is a unique voltage regulator controlling in real-time all the PC generators and static compensators like a CP-Secondary Voltage Regulation. The control structure is very simple in this case. The PCVR-HV mainly sustains the local HV side voltage, always guarantying acceptable values at the MV side. The offered service to HV side can be easily recognised to PC and remunerated by the transmission grid Dispatcher.

PCVR-MV consists of parallel independent voltage regulators of the PC MV buses, each controlling an independent MV bus-bar with its feeder generators. This is a more complex control structure and logics than the PCVR-HV, and possible dynamic interactions among parallel controls have to be avoided. At last, the PCVR-MV mainly sustains the local MV side voltages.

To be put in evidence the MV feeders with generators have a more solid voltage profile than without, due to the local AVRs. Also the nearby load buses take voltage benefit from the local AVRs control. Furthermore, the line buses with generators under the PCVR control show little higher/lower voltages than the corresponding PC MV bus-bars, due to their reactive power delivery/absorption.

The voltage profile along each feeder line can be therefore obtained by the automatic value limitation of each reactive power control signal “Qrefi”, aimed to maintain the generator local voltage inside a proper confidence band. Recognizing sufficient this simplifying feeder voltage objective, then it can be easily achieved by the PCVR through the line busses voltage measurements and the PC generators remote control.

The PCVR-MV may also control the transformer tap in a coordinate way as here after described.

The OLTC operation in the presence of PCVR: characterized by the well-known discrete stepping slow control, has the main task to adjust the transformation V_{HV} /V_{MV} ratio, always guaranteeing the full use of the generators inside their over and under-excitation limits, as well as maintaining the machinery in between their minimum and maximum voltage ties. Therefore, the OLTC is very useful to the PCVR correct working in case its main objective is the balancing of MV voltage deviations due to external (HV grid voltage steps) or internal reasons (large load variations).

This OLTC support can in principle be required by PCVR:

- Either in case of enough autonomy by the PC MV grid on the local voltage control, able to maintain at about zero the reactive power exchange between the MV and HV bus-bars;

- Or with constant reactive power flow exchange defined by the MV and HV operators' reciprocal support agreement;
- Or in the general case with a variable reactive power flow allowed by reciprocal MV–HV dynamic support agreement.

The objective of adapting the OLTC control to guarantee, in the different operating conditions, the full generators use by the frequent operating conditions recovery at the middle of their normal operating fields, is a complex not easily manageable TAP control. On the other hand the PCVR, characterized by faster dynamics than OLTC, speedily operates and first regulates the MV bus-bar voltage so charging the overall control effort on the local generators up to reaching their saturation. In this way the OLTC remains almost unused and become active only after the PCVR supervening saturation.

From the above it clearly appears that the two voltage controls must observe each-other and the OLTC will be called to operate first of all to bring PCVR out of saturation and then to maintain the generators margin of controllability to safe values. This functional requirement is not optimized from the classic OLTC voltage control loop that rarely will work in the presence of the faster PCVR. Therefore it will be necessary to subject the TAP control to the PCVR functional state, maintaining unchanged the characteristics of OLTC open loop dynamics and controlling the UP and DOWN commands as follows:

- Achieving the containment of the generators control effort when too high;
- With minor priority, maintaining the reactive power flow exchange with HV grid as far as possible consistent with contractual arrangements associated with the "voltage ancillary service" provided by HV grid or supporting the HV grid by the PC MV generators.

Obviously, in case of PC grid emergency condition, the PCVR will quickly become saturated and the OLTC will be controlled by PCVR, or rather in closed loop by itself, to slowly recover the MV voltage in case the HV grid support is consistent.

The islanded grid voltage regulation: is very simple being fully entrusted to PCVR and therefore to the internal PC grid reactive power resources.

In this case, apply the control scenarios defined above linked to the local reactive power resources.

Automatic Voltage Regulations of the HV or MV PC Bus-Bars:

The proposed control system is therefore characterized by a structure of centralized type that regulates the voltage of the PC HV bus-bar or the PC MV individual bus-bars. This structure, apparently the same in both cases, has to be detailed providing the substantial difference between the two solutions.

Not being guaranteed a homogeneous distribution of the generators within the CP, some MV feeders may have few generators while other feeders can host a lot of control generators. Therefore, a centralized system that regulates the HV bus-bar voltage also supports voltages along MV feeders without generators, better than in the case of MV separate bus-bars controls whose mutual support in voltage is less effective.

On the MV feeder, the buses with control generators will have, as said, voltages slightly higher or lower than those of the respective MV PC bus-bars. Anyhow, the MV bus-bars without generators will have the greatest voltage variations even if definitely lower than in case of PCVR absence.

With this centralized PC control the maintenance, within the normal operation range, of the generators voltage values along the feeder lines can be obtained either locally on the generator control interface, or by the centralized PC control.

In the first case the PCVR interface at the generators side not only calculates in real time the generators reactive power set-points values, but restricts these references in delivery or absorption for high or low voltages respectively. In the other case, the interface at the generator level is simplified and the above set out calculations and limits are transferred to the centralized PC control.

The architecture of the control system proposed is represented in Fig.3. It is a centralized control of the HV bus-bar aimed to maintain the voltage V to the reference value Vref through specific reactive power controls (Qref) sent to each feeder generators. The figure also shows a single PC MV bus-bar, therefore lends itself to also describe the voltage regulation of such bus by simply shifting the measurement V from the HV to the MV bus-bar. It therefore consists of a PC centralized voltage control of each MV bus-bar to which at least one generator is connected.

Each control signal Qref will avoid, on local generation buses, voltages outside a properly defined confidence band. Therefore it is assumed that all the considered MV generators are provided with primary reactive power control. Moreover, as already introduced, the optimization of the OLTC transformation ratio is occasionally required by the PCVR and basically to increase the degree of the generators controllability.

The feeder busses voltage measurements are useful to monitor in real-time the normal operation confidence range is exceeded and then intervening on the generators control variable (Qrefi) for the necessary limitation.

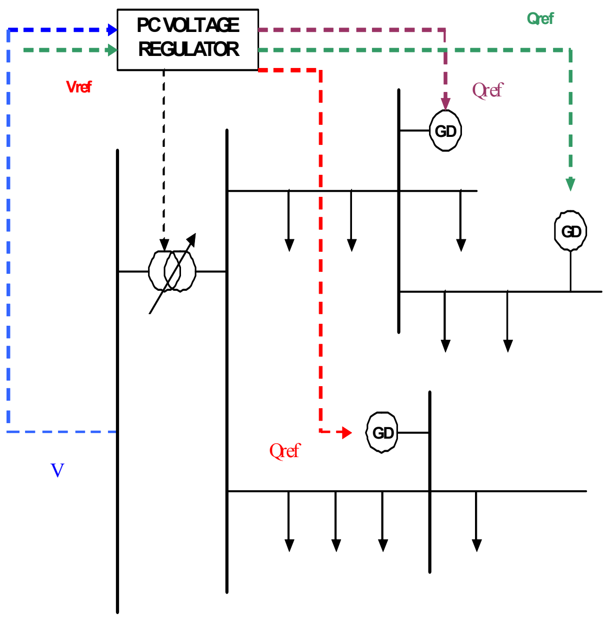

Fig.3 – Primary cabin voltage regulation scheme

The "K" reclosing between the MV bus-bars does not require special interventions in case of HV side voltage regulation, while the transformers paralleling at MV side involves the PCVR management of their OLTCs with a single control (functionality already existing or still easy to implement on the PC control).

Instead, in the case of MV bus-bars voltage regulation, the "K" reclosing determines the transition of the two parallel PCVR MV voltage regulations from the "Master-Master" to the "Master-Slave" configuration.

In the PC "island" operation, to be distinguished the separation from the HV transmission grid or the islanding of the single MV feeder from its transformer. In the first case and in the presence of HV bus voltage regulation, this control continues to operate as the interconnection to the HV grid were still active. The only difference is the lack of the exchange of reactive power with the transmission network. If this flow was a relevant input before islanding, than the island voltage regulation goes rapidly into saturation. In the same situation but with MV bus-bars voltage regulation, similar considerations apply in a scenario of multiple voltage regulation in parallel, one for each MV bus-bar.

In the second case of a single MV feeder to separate, the automatic mutual support between MV feeders does not operate and the MV-island must be able to independently maintain acceptable feeder voltage level through its own control resources. Therefore, the MV bus-bar voltage regulation continues to operate as the operating interconnection to the transformer were active. The only difference is the lack of reactive power exchange with the transmission grid and the other MV feeders. If these flows were relevant inputs before islanding, than the island MV voltage regulation goes rapidly into saturation.

Conversely, if the operating control before the islanding occurrence is on the HV bus voltage, this control continues to operate without the support of the islanded feeder resources. Instead the islanded MV generators remain operating under local primary voltage control only, unless to be aggregated to a MV island voltage regulation which shall be activated for this purpose and lasting till when returning the resources to the HV control, at the time the MV feeder will be again paralleled to the transformer.

Block Diagrams of the PCVR Control Functions:

The PCVR control signal sent to each generator is the set-point of the generator reactive power control loop, characterized by a first order dynamics, with dominant time constant of the order of a few seconds.

This reference, calculated by the PCVR separately for each controlled generator, takes into account the reactive power over and under excitation limits, which obviously changes depending on the power system operating conditions. Such a power limit is called *DFIG-Qlim* in the Fig.4 block diagram, for the case of the wind DFIG, while in the case of the synchronous generator is called: *Synchronous-Qlim*.

The limiting values are computed in real time by CPVR according to specific fitting functions for each generator that are mainly based on the real "capability" experimental measurements of the generators themselves.

The *Qref* request normally changes within the field of controllability defined by the *Qlim* but can undergo further limitation in the case the generator bus-bar exceeds the fixed voltage confidence band (V_{Lim}). Also the limitation imposed by V_{Lim} requires a specific control scheme shown in Fig.5.

The Figure 4 regulator can be used indifferently for the voltage regulation of the PC HV or MV bus-bars, depending on the sampling point of the voltage measurement V and correspondingly on the controlled generators (as many outputs *Qref* how many generators controlled by the PC voltage regulator).

The voltage regulator of proportional – integral type automatically updates its output q as a function of the difference between the reference voltage (*Vref*) and the current value of this voltage V. At steady-state this difference vanishes. On the voltage measurement is operating a filter to be calibrated according to needs, always ensuring the voltage control loop dominant dynamics of the order of tens of seconds.

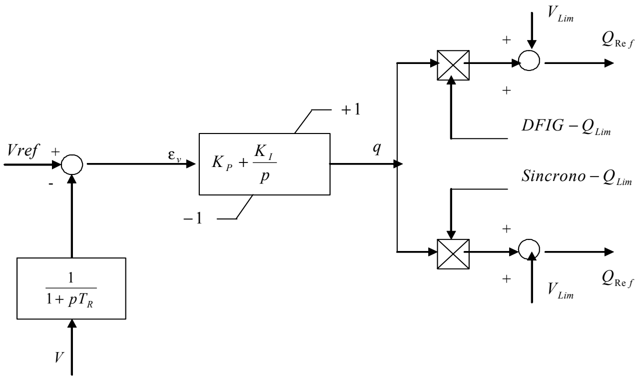

Fig.4 Block diagram of the PC voltage regulator: PCVR

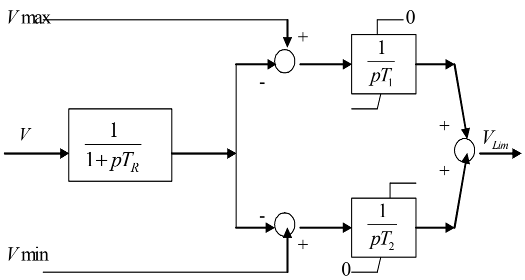

Fig. 5: *Qref* limiting loops maintaining the generators voltages inside the *Vmax – Vmin* field.

A useful but probably rarely needed additional function, to ensure a voltage profile along the line within the limits *V_min* and *V_max* is obtained by integrating in the control a correction factor dependent on these limits overcoming so as to reduce the request *Qref* if *V_max* is exceeded or to increase it if *V_min* is violated.

The block diagrams represented in Figs.4 and 5 block diagrams show the following:

1): The main PI control law defines the output as a function of the difference *Vref* - *V*. The input *V* is measured and filtered. The PI regulator output provides the control level *q* with a positive sign if the reactive power is supplied by the controlled generators and vice versa with a negative sign if the reactive power has to be absorbed. The output variables towards the plants represent the reference values of reactive power. Their values are achieved by multiplying the PI output *q* by the current limit values of the generators reactive powers.

The dynamics of the considered voltage regulating loop must be faster than the OLTC voltage control.

2): The *q* range of negative values fixes the absorbed reactive power from 0-100%, while the *q* positive range fixes the values of the delivered reactive power, always from 0-100%. Meaning that, the PI control law defines instant by instant the control effort percentage each generator has with respect to its operating limits. As said these limits can be identified out of line with appropriate "fitting" of data from experimental measurements. In fact, calibration declared by the manufacturers could provide values not corresponding to the real situations on the plants.

3): With reference to the Fig.5 control scheme, this represents two limiting loops of integral type becoming active at the limits admitted (*V_max, V_min*) overcoming. These cycles, overlapping the Fig.4 control scheme, must be characterized by slow dynamics with respect to the main voltage loop.

Because the active limiting cycle plays contrasting action compared to that of the main integral regulating loop, this does not result in abnormal behavior in the case of more generators participating in the voltage regulation. When instead only one controlled generator is operating under PCVR, than the limit will push the regulation into saturation from which will be released only upon the generator return from those limits. In other words only one of the two cycles will operate and that limiting will be dominant.

4): PCVR will change the transformation ratio, as described through the Fig.3 scheme, aimed to dynamically increase the PCVR control margin, so interacting with the automatic classic OLTC slow control that is opened. The new OLTC task obviously reduces the TAP range in controlling the bus-bar voltage variation. This not strictly necessary but useful improvement is based on the monitoring and maintenance of the distance from the generators saturation by activating the TAP Up/Down command when approaching the -1 / +1 level-q values.

Automatic Reactive Power Flow Regulation on the PC HV Bus-Bar

A possible solution for a control system (PCQR) regulating the reactive power flow exchanged by PC with the HV upright of the step-up transformer, in the presence of MV DG, is here proposed.

PCQR regulates the flow of reactive power sent to the transformer HV / MV from each MV feeder with distributed generation. The voltage on the MV side is instead controlled classically by varying the discrete transformation ratio by OLTC.

Then this system consists of two parts:

• A MV voltage regulator by tap control of the HV / MV transformation ratio;

• A reactive power regulator of the flow between the transformer HV / MV sides, by controlling the reactive power of each feeder generators.

The two controls are necessarily conditioned as the reactive power in the feeders also depends on the voltage values at both the feeder and PC bus-bars. In addition, the required reactive power to generators has to suffer restrictions necessary to avoid local voltages exceeding the normal operating range.

The control system proposed for PCQR is characterized by a structure of decentralized type regulating the flow of reactive power on the single MV feeder. This structure is mainly required by possible differences in the DG generators location on the various PC feeder lines. In other words, not being guaranteed a homogeneous distribution of the PC generators, each MV line may have none, few or many generators. Therefore, a centralized regulation controlling with a single variable the entire PC generation assets is likely to create imbalances especially on the MV node voltages. This observation has led to define a control that regulates the flow of reactive power on each feeder connected to the HV/MV transformer and provided with one generator at least, also taking into account the range of values allowed on the MV voltages.

The feeder generators control the feeder reactive power flow by themselves.

To ensure an acceptable bus voltage profile, each feeder line has to be observed independently and autonomously managed by intervening on its reactive power flow control in order to maintain the voltages on the feeder bus-bars inside the allowed band.

The architecture of the control system proposed is represented in Fig.6.

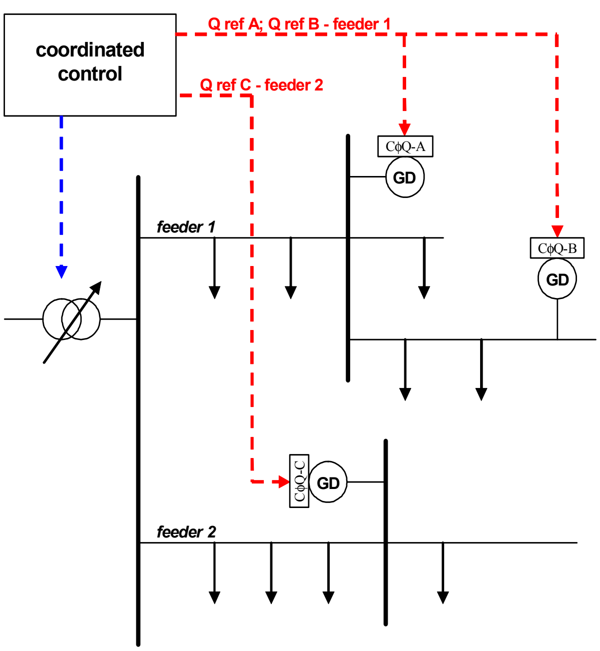

Fig.6: Single-wire scheme of the coordinated control of reactive power flow and voltage

The main feeder generators are subservient to the respective control signal values, updated in real time: *QREF-X-feeder-i*.

These generators reactive power references, already take into account the reactive power limitations on production / absorption of each generator and its voltage constraints. In this respect it is useful to refer to the Fig4 control scheme, substituting *Vref* with |*QFlowRefi*| and *V* with |*QFlowi*|. The power flow direction must obviously be taken into account at the control logic management as better clarified hereafter.

In this way the control scheme of the individual feeder "i" power flow is obtained. It makes also use of voltage limitation scheme in Fig.5. The sum of *QFlowRefi*, of course all with the same sign, represents the reference of the reactive power exchanged with the CP HV bar: *QFlowRef*. The CP coordinated control defines the *QFlowRefi* values update according to: the *QFlowRef* value, the feeder generators operating and controllable as well as their capabilities made available to the control.

Therefore, as with PCVR, the PCQR requires the control generators all provided with primary reactive power control.

It is also noted that the coordinated control commands the transformer HV/MV OLTC to keep next to the nominal voltage the MV bus-bar. Obviously the OLTC discrete control of approximately 30 steps has much slower dynamics than the reactive power flow control.

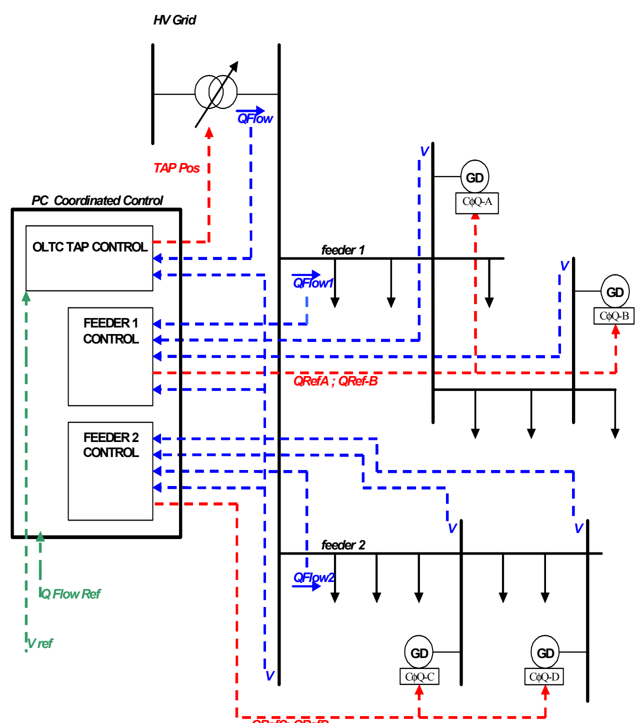

Fig.7: Single-wire scheme of the Coordinated control of reactive power flow with details of the exchanged signals.

The Figure7 shows a greater detail of the PC centralized controller data exchange to and from generators, including data related to the TAP control. This OLTC control acts by taking into account the MV bar voltage measurement and possibly the optimization curves that identify, for a given active and reactive power flow through the transformer, the OLTC control voltage reference that best marries the allowed voltage operating values along the feeders connected to the transformer.
The uprights voltage measurements are important for watching in real time the exceeding of the normal operation voltage band and therefore intervening on the control variable (*QRefx*) for the necessary feeder limiting controls on the *x*-generator.

Analysis of PCVR and PCQR Control Logics and Results

Here after the simplicity and effectiveness of the proposed HV or MV PC bus-bars voltage regulation based on the feeder generators reactive power control is justified. To the scope, reference is done to Fig.8, showing the simplified PC electrical scheme represented by an equivalent feeder. The analysis results based on this equivalent scheme can be easily extrapolated to the multi-feeders case.

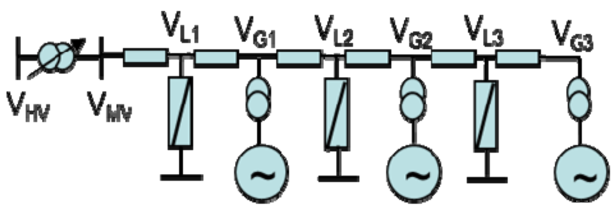

Fig.8: Scheme of the Primary Cabin equivalent scheme.

The PC PCVR Coordinated Control regulates in closed-loop the V_{MV} or the V_{HV} bus bar voltage by controlling the feeder generators reactive powers by a reactive power level: L_{evq} that represents the percentage with respect to the capability limits each generator in the feeder puts at disposal.
$1 \geq L_{ev}q \geq 0$ represents the p.u. of the Q^{+}_{Limi} (generator G_i over-excitation reactive power limit) while $-1 \leq L_{ev}q < 0$ represents the p.u. of the Q^{-}_{Limi} (G_i under-excitation reactive power limit).

In case of grid-connected generator by inverters, $Q^{\pm}_{Limi}$ represent the maximum deliverable (Q^{+}_{Limi}) and absorbable (Q^{-}_{Limi}) reactive powers by the i[th] inverter.

Other operating limits $V^{\pm}_{Limi}$ already introduced, fix the band ($V^{-}_{Limi} \leq V_G \leq V^{+}_{Limi}$; usually V_N - 5% $\leq V_G \leq V_N$ + 5%) limiting the generator voltage variation. Therefore for each generator:

$$Q^{-}_{Limi} \leq Q_{Gi} \leq Q^{+}_{Limi}$$
$$V^{-}_{Limi} \leq V_{Gi} \leq V^{+}_{Limi}$$

Taking into account these generator limits, here after the impact of the proposed PC voltage control is described showing its effect in different operating conditions as well as how the OLTC-TAP parallel control can contribute to its correct functionality.

To be noticed all the feeder generators are charged at the same percentage with respect to their capability limits. Therefore all the feeder generators reach their over or under excitation saturation at the same time. Different is the case of the voltage limiting reaching at the load and generator busses. The voltage limiting can be achieved at any feeder single bus according to the load variations and generators operating points.

The reactive power flows obviously impact on the busses voltage profiles and the generators reactive power control is able to determine relevant feeder voltage variations with respect to the operating condition under primary voltage control only. The following figures give evidence of the PCVR voltage control characteristics.

Through the PCVR a voltage set-pint value V_{Ref} is imposed to the PC MV grid not only according to the day-before forecasting plan but also taking into account of the transformer reactive power flow and its sign. CPVR has also to monitor the feeder busses distance from the $V^{\pm}_{Limi}$ values and the generators approaching the $Q^{\pm}_{Limi}$ limits to maintain with continuity the PCVR voltage regulation far from its saturation.

With reactive power flow Q exiting from the feeder: V_{Ref} can be reduced so lowering the Q value and therefore reducing the feeder generators contribution to the PC voltage support.

In that operating condition the feeder voltages are however higher than V_{Ref} and asking for a reduced V_{Ref} value corresponds to two possible objectives:

- The Q-exiting lowering;
- Forcing the generators to recover controllability by leaving Q^{+}_{Limi} or V^{+}_{Limi}.

Increasing V_{Ref} and therefore the Q-exiting can be done till when the generators reach their Q^{+}_{Limi} or V^{+}_{Limi}.

With reactive power flow Q entering the feeder: the imposed V_{Ref} can be maintained till when the generators reach their Q^{+}_{Limi}. Conversely V_{Ref} can be increased in case the feeder generators have enough control margins to also compensate the lowered reactive power flow Q imported from the HV grid. In that operating condition the feeder voltages are generally lower than V_{Ref}.

Exceptionally the generators located at the feeder extreme-end could reach voltage values higher than V_{Ref}. Lowering V_{Ref} determines the lowering of the generators contribution to the PC voltage support while increases the imported Q flow: the final result is a general lowering of the feeder voltages with the PC V_{MV} maintained at the V_{Ref} value.

Generally speaking, CPVR controls all the feeder generators up to their limits so achieving the objective of PC closed loop voltage regulation by maintaining the feeder voltages inside defined confidence band. The reactive power flow from or to the HV grid can be modified by changing the V_{Ref} value. Lowering V_{Ref} increases the Q-entering or reduces the Q-exiting. Obviously CPVR will also control the compensating equipment located in the feeder by seldom switching on/off them and only to recover the generator controllability or feeder voltages overcoming the confidence band thresholds. Here after this simple additional control is not discussed and assumed to be operated after the analyzed PCVR control has already operated up to reach its saturation.

Referring to Fig.8, the voltage profile is analyzed and represented along the feeder for different operating conditions, by describing the control logics required to PCVR and PCQR.

Case of reactive power flow entering the feeder by HV bus-bar:

The feeder normal operating condition with the local generators supporting, in a prevailing way, the feeder nodes voltages is represented in Fig.9, where the V_{MV} voltage is regulated at the V_{Ref} set-point value up to when the generators reach their capability limits. After that the feeder voltages lowering will determine the increasing of the reactive power input Q from HV.

Figure10 shows the voltage profile difference with respect to Fig.9, in case some generators reach their Q^+_{Lim}. The entering reactive power flow increases while the generators are performing their maximum effort to sustain the lowered feeder voltage profile.

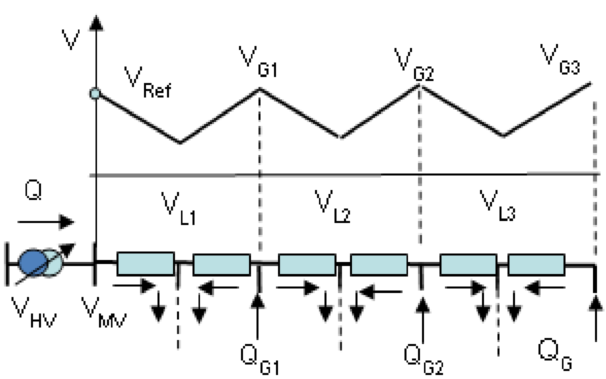

Fig.9: Feeder voltage profile mostly supported by local reactive powers through regulating V_{MV}.

The voltage lowering can also determine $V_{MV} < V_{Ref}$ without possibility to recover the difference due to the voltage control saturation (generators at Q^+_{Lim} as in Fig.10). At this operating condition the unique possible improve can be obtained by increasing V_{MV} through the PC transformer TAP changing operated by the PC - CC (Coordinated Control), as later described.

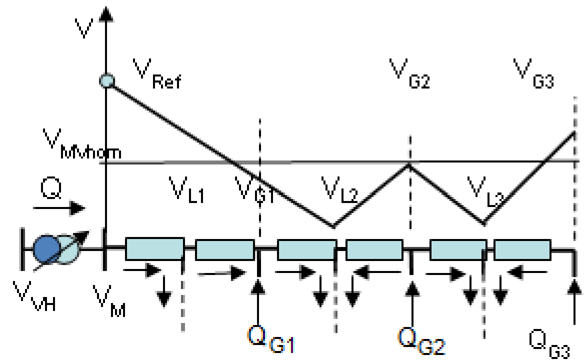

Fig.10: Feeder voltage profile with generators at Q^+_{Lim} and $V_{MV} < V_{Ref}$

Always considering the entering reactive power flow from the HV grid case, other possible feeder operating conditions are described in Figs: 11, 12 and 13.

Fig.11 shows the case in which the feeder voltage regulation operates achieving $V_{MV} = V_{Ref}$ with controllable generators:

$$Q^-_{Limi} \leq Q_{Gi} \leq Q^+_{Lim}\,;\; V^-_{Limi} \leq V_{Gi} \leq V^+_{Limi}$$

The same Fig.11 can be also used to describe the following cases:

a) $V_{G3} = V^+_{Lim3}$: In this case the PC – CC holds the reactive power delivery increase required to G_3, while allowing any reduction. At the same time further reactive power delivery increase can be obtained by G_1 and G_2 following V_{Ref} or the feeder loads increase.

b) $V_{L1} \leq V_{L1min}$: In this case the PC - CC has to increase the V_{Ref} value in a way to recover V_{L1} and that is successfully achieved till when the feeder voltage control does not reach its saturation with all the control generators at Q^+_{Lim} or V^+_{Lim}. After that the OLTC TAP control has to operate as later described with $V_{MV} < V_{Ref}$.

Fig.12 shows, as Fig.11, the case of a feeder voltage regulation with $V_{MV} = V_{Ref}$ and all the generators under control. The analysis already described for Fig.11 when the operating condition exceeds the allowed confidence bands (points a) and b)) are the same as for a) and also for b) when considering V_{L2} instead of V_{L1} and again $V_{MV} < V_{Ref}$.

Figure 13 shows last example of entering reactive power into the feeder having heavy load at its extreme-end. Analogously to Figs.11 and 12 cases, Fig.13 represents a normal operating condition under PCVR control unless:

$V_{G1} = V^{+}_{Lim1}$: Same comment as in a) case when substituting G_3 with G_1.

c) $V_{L3} \leq V_{L3min}$: Same comment as in b) case when substituting V_{L1} with V_{L3}.

d) $V_{L1} \geq V_{L1max}$: In this case the V_{Ref} value is too high and the PC - CC has to operate a V_{Ref} reduction taking also in to account the consequent voltage reduction at V_{L3}.

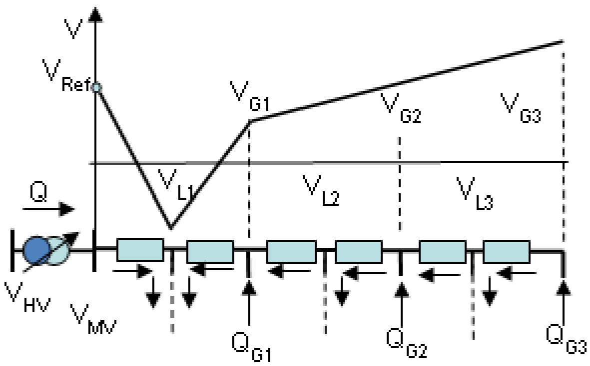

Fig.11: Voltages and reactive power flows in a feeder with heavy load near the PC.

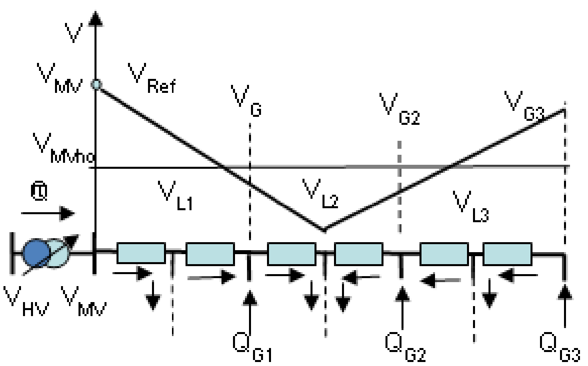

Fig.12: Voltages and reactive power flows in a feeder with heavy load in the middle of the feeder.

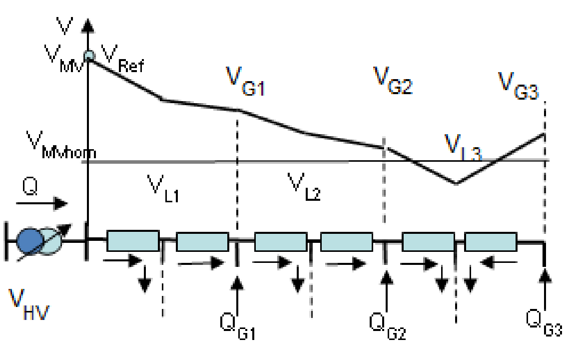

Fig.13: Voltages and reactive power flows in a feeder with heavy load in the extreme end of the feeder.

In all the cases shown in Figs 11, 12 and 13, the V_{Ref} increase will determine the reduction of the entering reactive power flow from the HV bus-bar and a large voltage support by the feeder generators.

With entering reactive power the voltages in the feeder are generally lower than V_{Ref} with possible exception at the extreme feeder end generation bus (i.e. V_{G3}).

Case of reactive power flow sent by the feeder into the PC HV bus-bar:

The normal operating condition with the feeder generators totally supporting the local voltages is represented in Fig.14.

The V_{MV} voltage is regulated at V_{Ref} through controlling the generators reactive powers that totally support the feeder loads voltages. The V_{MV} voltage regulation can be maintained at the V_{Ref} set point value up to when the generators reach their capability limits. After that the feeder voltage lowering will determine the reduction of the reactive power flow leaving the feeder and $V_{MV} < V_{Ref}$.

The voltage lowering can determine $V_{MV} < V_{Ref}$ as in Fig.15 without the possibility to recover the voltage difference due to the control saturation (generators at Q^{+}_{Lim} or $V_{G3} = V^{+}_{Lim3}$).

At this operating condition the unique possible improve can be obtained by increasing V_{MV} through the PC transformer TAP changing operated by the PC - CC, as later described. Always considering the case of exiting reactive power flow from the feeder towards the HV bus-bar case, other possible operating conditions are described in Figs.16 and 17 related to the saturated V_{MV} control.

Figure 16 may represent the cases of $V_{L3} \leq V^{-}_{Lim3}$ and/or $V_{G1} = V^{+}_{Lim1}$

e) $V_{L3} \leq V^{-}_{Lim3}$: In this case the PC - CC requires the V_{Ref} increasing in a way to recover V_{L3}. That is successfully achieved till when the feeder voltage control does not reach its saturation with all the control generators at Q^{+}_{Lim} or V^{+}_{Lim}. After that the OLTC control has to operate as later described with $V_{MV} < V_{Ref}$.

f) $V_{G1} = V^{+}_{Lim1}$: In this case the PC - CC holds the reactive power delivery increase required to G_1, while allowing it any possible reduction. At the same time further reactive power delivery increase can be obtained by following V_{Ref} increase or the feeder loads increase.

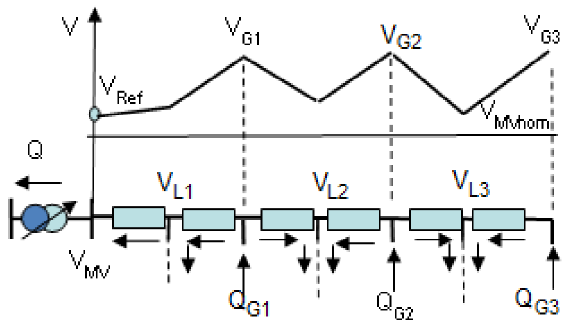

Fig.14: Feeder voltage profile mostly supported by local reactive power flows through regulating V_{MV}.

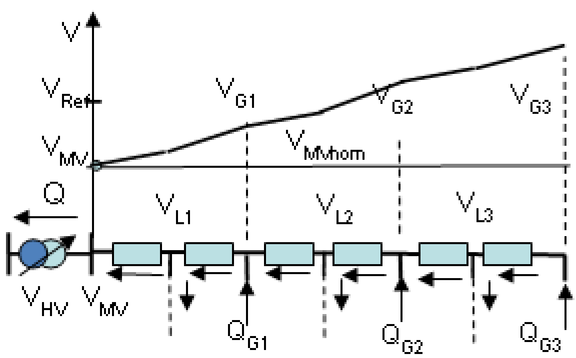

Fig.15: Feeder voltage profile with local generators at Q^{+}_{Lim} or $V_{G3} = V_{Lim3max}$ and $V_{MV} < V_{Ref}$

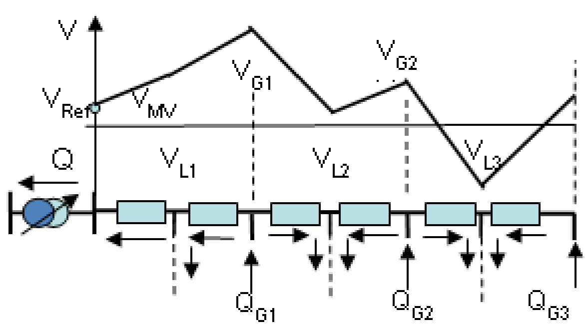

Fig.16: Feeder voltage profile with local generator $V_{G1} = V^{+}_{Lim1}$, local load $V_{L3} \leq V_{Lim3min}$ and $V_{MV} = V_{Ref}$.

Analogously to Fig.16, the other case represented in Fig.17 requires similar controls like those described at points e) and f), till when $V_{MV} = V_{Ref}$. When $V_{MV} < V_{Ref}$, the voltage control is saturated and the way-out is the OLTC control required by PC - CC, as later described.

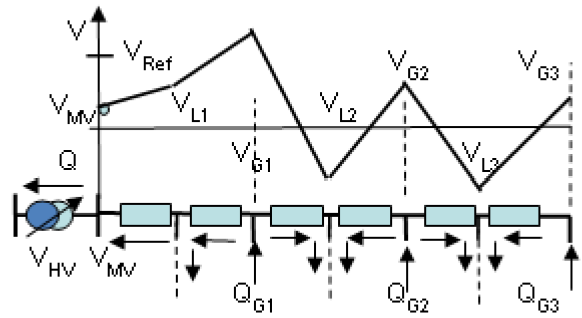

Fig.17: Feeder voltage profile with local generator $V_{G1} = V^{+}_{Lim1}$; local load $V_{L3} \leq V_{Lim3min}$ and $V_{MV} < V_{Ref}$.

On the OLTC TAP control by the PC- CC when operating as PCVR:

The operating conditions requiring the HV/MV transformation ratio control by the OLTC are strictly linked to the PCVR voltage regulation saturation.
As already seen, the voltage regulation reaches its saturation when all the feeder generators approach their operating limits. More precisely, referring to:

1,2,3, …..,i, ….,n generators;
1,2,3, …..,j, ….,m loads

The "*OLTC-control-A*" operates as follows:

- If $V_{MV} < V_{Ref}$ and all the feeder generators reach their Q^{+}_{Limi} or V^{+}_{Limi}, for each "i":

  Then the V_{HV} /V_{MV} transformation ratio has to be reduced up to recovery $V_{MV} \geq V_{Ref}$; $V_{Loadj} > V^{-}_{Loadj}$ for each "j". Otherwise V_{Ref} has to be reduced gaining again the PCVR controllability.

Conversely, the "*OLTC-control-B*" operates as follows:

- If $V_{MV} > V_{Ref}$ and all the feeder generators reach their Q^{-}_{Limi} or V^{-}_{Limi}, for each "i":

  Then the V_{HV} /V_{MV} transformation ratio has to be increased up to recovery $V_{MV} \leq V_{Ref}$; $V_{Loadj} < V^{+}_{Loadj}$ for each "j". Otherwise V_{Ref} has to be increased gaining again the PCVR controllability.

The *OLTC-control-A* increases the V_{MV} value in a way to better sustain the feeder voltages and allowing the generators exiting from their superior limits Q^{+}_{Lim} or V^{+}_{Lim}. The result of *OLTC-control-A* determines an increase in the reactive power flow from the HV bus-bar to the feeder or a reduction of the reactive power flow towards the HV bus-bar.

On the contrary the *OLTC-control-B* reduces the V_{MV} value in a way to reduce the feeder generators operation in under-excitation so limiting their reactive power absorption and allowing them to exit from their inferior limits Q^-_{Lim} or V^-_{Lim}.

The result of the *OLTC-control-B* determines a reduction of the reactive power flow from the HV bus-bar to the feeder or an increase of the opposite Q flow towards the HV bus-bar.

Some examples of the described OLTC control allowing the PCVR voltage regulation by exiting from its saturation and gaining controllability are here after described.

The *OLTC-control-A* has to be activated in some of the previous considered PCVR cases, here remembered:

- In Figs.11, 12, a) and b) cases after reaching the generators saturation and $V_{MV} < V_{Ref}$
- In Figs.13, c) and d) cases after reaching the generators saturation and $V_{MV} < V_{Ref}$
- In Figs.15, case after reaching the generators saturation and $V_{MV} < V_{Ref}$
- In Figs.16, 17, f) and g) cases after reaching the generators saturation and $V_{MV} < V_{Ref}$.

Low voltage in the feeder with $V_{MV} < V_{Ref}$:

The Fig.18 case requires the *OLTC-control-A* reducing the V_{HV}/V_{MV} transformation ratio in a way to increase V_{MV} by the support of the transmission grid.

This TAP control increases the feeder voltages and the reactive power entering into the feeder by the HV bus-bar.

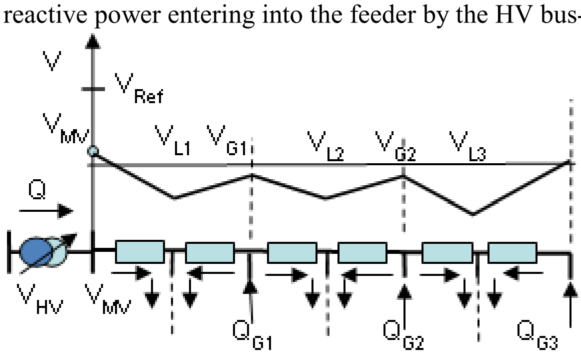

Fig.18: Feeder low voltage profile with PCVR saturated, Q entering, $V_{MV} < V_{Ref}$, with generators at Q^+_{Lim}.

Reaching the operating condition $V_{MV} \geq V_{Ref}$ than the generators leave their Q^+_{Lim} limits and the PCVR control starts again operating with a higher voltage profile in the feeder.

Fig.19 case requires, as Fig.18 case the *OLTC-control-A* determining the V_{MV} increase by the transmission grid support. This is the case of a weak HV grid and the TAP *control-A* reduces the voltage support towards HV bus-bar but improves, till when possible, the feeder voltage profile by higher values. As before, with $V_{MV} \geq V_{Ref}$ the PCVR leaves its control saturation and the new higher voltage profile in the feeder can be again controlled.

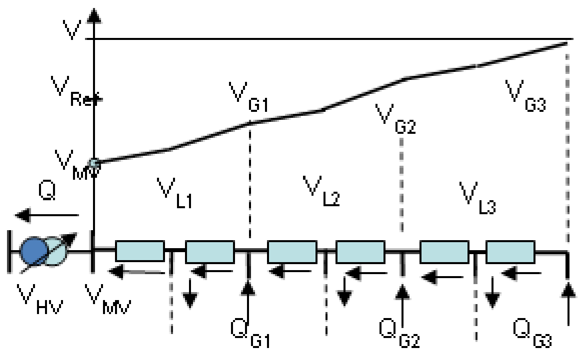

Fig.19: Feeder low voltage profile with PCVR saturated, Q exiting, $V_{MV} < V_{Ref}$, with generators at Q^+_{Lim}.

High voltage in the feeder with $V_{MV} < V_{Ref}$:

Another case requiring the TAP *Control A*, with reactive power flow injected into the HV bus-bar and PCVR saturation is represented in Fig.20.

With $V_{Gi} = V^+_{Limi}$ for each *i*, than reducing V_{HV}/V_{MV} the V_{MV} increases so reducing the generators reactive power delivery towards the HV bus-bar.

The TAP *Control-A* determining $V_{MV} \geq V_{Ref}$, allows the PCVR generators removing from the V^+_{Lim}, coming back to the normal operating condition.

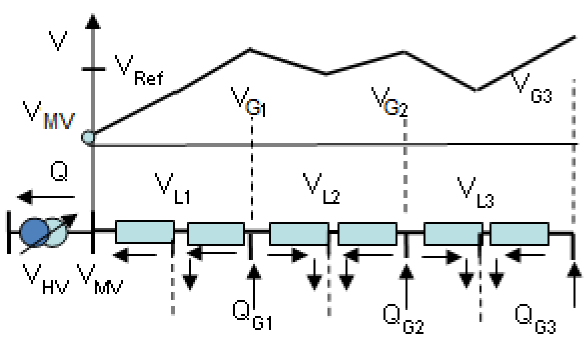

Fig.20: Feeder high voltage profile with PCVR saturated, *Q* exiting, $V_{MV} < V_{Ref}$, with generators at V^+_{Lim}.

The Fig.21 case requires the *OLTC-Control-B* increasing the V_{HV}/V_{MV} transformation ratio in a way to reduce V_{MV} by increasing the electrical distance from the HV grid. This TAP control reduces the feeder voltages and the reactive power entering into the feeder by the HV bus-bar. Reaching the operating condition $V_{MV} \leq V_{Ref}$ than the generators leave their Q^-_{Lim} limits and the PCVR control starts again to operate with a feeder lowered voltage profile.

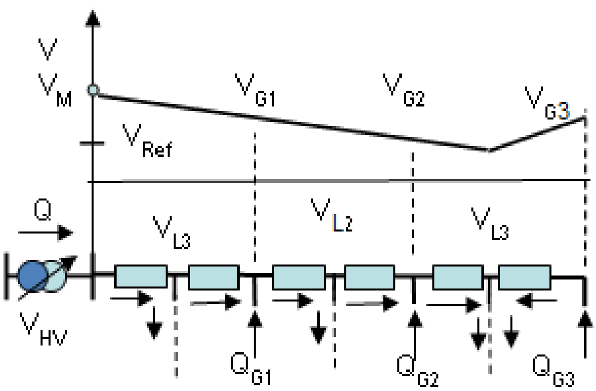

Fig.21: Feeder high voltage profile with PCVR saturated, *Q* entering, $V_{MV} > V_{Ref}$, with generators at Q^-_{Lim}.

OLTC Control by PC-CC during the PCQR operation:

The operating conditions requiring the seldom HV/MV transformation ratio changing happen only when the reactive power flow regulation by PCQR reaches the limiting thresholds.

As already seen the saturation conditions of the Q flow regulation happen when all the feeder generators reach their operating limits. More precisely, referring to:

1,2,3, …..,i, ….,n generators;
1,2,3, …..,j, ….,m loads

The *“OLTC-Control-C”* operates as follows:

- If $Q_{exiting} < Q_{Ref}$ (Fig.22) or $Q_{entering} > Q_{Ref}$ and all the feeder generators reach their Q^+_{Limi} or V^+_{Limi}, for each “i”, then:

  The V_{HV} /V_{MV} transformation ratio has to be increased up to recovery as soon as possible:

  $Q_{exiting} \geq Q_{Ref}$ or $Q_{entering} \leq Q_{Ref}$; $V_{Loadj} > V^-_{Loadj}$ for each “j”.

  Otherwise Q_{Ref} has to be reduced (to $Q_{exiting}$) or increased (to $Q_{entering}$) gaining again the PCQR controllability.

Conversely, the “*OLTC-Control-D*” operates as follows:

- If $Q_{entering} < Q_{Ref}$ (Fig.23) or $Q_{exiting} > Q_{Ref}$ and all the feeder generators reach their Q^+_{Limi} or V^+_{Limi}, for each “i”, or $Q_{exiting} > Q_{Ref}$ and all the feeder generators reach their Q^-_{Limi} or V^-_{Limi}, for each “i”, then:

  The V_{HV}/V_{MV} transformation ratio has to be reduced (Increases the $Q_{entering}$ / Reduces the $Q_{exiting}$) till when the PCQR regulator exiting from saturation:

  $Q_{entering} \geq Q_{Ref}$ or $Q_{exiting} < Q_{Ref}$; $V_{Loadj} > V^-_{Loadj}$ for each “j”.

  Otherwise Q_{Ref} has to be reduced (to $Q_{entering}$) or increased (to $Q_{exiting}$) gaining again the PCQR controllability.

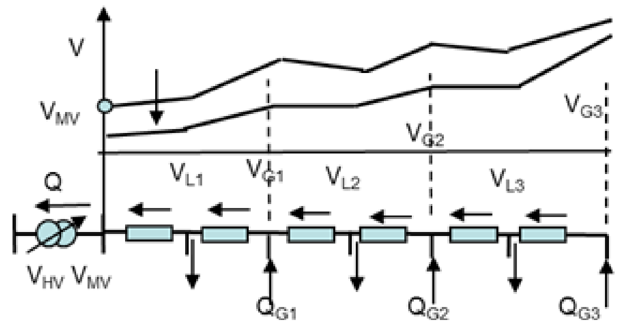

Fig.22: Feeder voltage profile and reactive power flows with local generators at Q^+_{Lim} or V^+_{Lim} and $Q_{exiting} < Q_{Ref}$

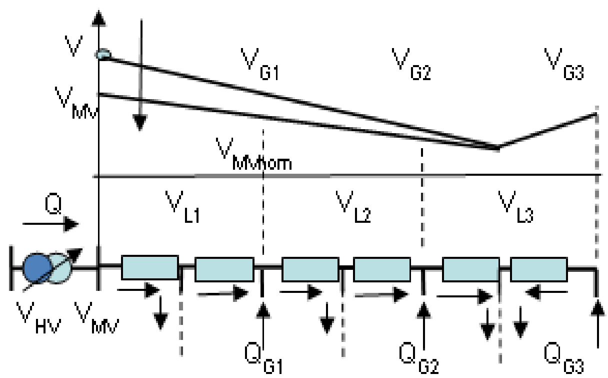

Fig.23: Feeder voltage profile and reactive power flows with local generators at Q^+_{Lim} or V^+_{Lim} and $Q_{entering} < Q_{Ref}$

Increasing V_{HV}/V_{MV}, the V_{MV} is lowered while $Q_{exiting}$ is increased till when $Q_{exiting} \geq Q_{Ref}$.

Conversely with $Q_{exiting} > Q_{Ref}$ and all the generators at Q^-_{Limi} or V^-_{Limi}, by reducing V_{HV}/V_{MV} the V_{MV} is increased till when $Q_{exiting} \leq Q_{Ref}$.

Increasing V_{HV}/V_{MV}, the V_{MV} and $Q_{entering}$ are lowered till when $Q_{Ref} \geq Q_{entering}$.

Instead with $Q_{Ref} \geq Q_{entering}$ and all the generators at Q^-_{Limi} or V^-_{Limi}, by reducing V_{HV}/V_{MV} the V_{MV} is increased together with $Q_{entering}$ till when $Q_{Ref} \leq Q_{entering}$.

Conclusion

Evidence is given of the practical feasibility of the Distribution Grid Voltage Control in the presence of sparse generators. The proposed PCVR and PCQR are based on Reactive Power Control of the local generators.

The classic slow OLTC control based on the HV side voltage support is substituted by a fast control of the local reactive power resources (PCVR) to manage as much as possible autonomously the local voltage and the linked reactive power flow with the transmission grid.

With PCVR/PCQR the voltage/reactive power Ancillary Service can be easily operated according with economic transactions.

The simplest and easy to be operated PCVR considers the HV side voltage control. Less simple and finalized to the local customers voltage support is the PCVR-MV.

With PCVR the OLTC changes its task by achieving the main objective to maintain as large as possible the local generators controllability.

Instead with PCQR the OLTC controls the MV voltage to maintain the controllability of the required reactive power flow exchange with HV side.

The Local Distribution Dispatching Centre should manage the local PCVR or PCQR (voltage or reactive power set-points) according to the PC MV/HV voltages and reactive power exchanges planning and dispatching. This should be in agreement with the National Dispatcher needs.

During the PCVR and PCQR operation the MV feeders are maintained inside a voltage confidence band.

The proposed solutions appear very simple and not so critical, complex and expensive control systems as those with distributed controllers along the MV feeders.

Comparing the two proposed control solutions cannot be neglected the implication that the reactive power flow regulation has on the market management of this resource, with high fragmentation of modest contributions, all to be measured with precision for their economic recognition. Furthermore, the reactive power flow control towards the HV bus is not simple to manage because subject to continuous variations, with obvious difficulties in having to comply with rigid supply contracts.

To close, it should also be noted that the two control proposals require that all the important generators of a given PC be involved on voltage or reactive power regulation, to avoid conflicting and compensating effects on the control action by the remaining outside-control generators.

References

[1] IEEE 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power System, 2003.

[2] Hadjsaid, N.; Canard, J. -F.; Dumas, F.," Dispersed generation impact on distribution networks", IEEE Computer Applications in Power, Volume: 12 Issue: 2, April 1999

[3] L. Hiscock, N. Hiscock, A. Kennedy, "Advanced voltage control for network with distributed generation", 19th international conference on electricity distribution, Vienna, 21-24 May 2007, Paper 0148.

[4] Joon-Ho Choi, Jae-Chul Kim, "Advanced voltage regulation method at the power distributed systems interconnected with dispersed storage and generation systems", IEEE Transactions on power delivery, Vol. 15, No 2. April 2000.

[5] F. A. Viawan, D. Karlsson, "Coordinated voltage and reactive power control in the presence of Distributed Generation", PES General Meeting – Conversion and Delivery of Electrical Energy in the 21st century, IEEE, Pittsburgh, 2008, pp. 1-6.

[6] Feng-Chang Lu, Yuan-Yih Hsu, "Fuzzy dynamic programming approach to reactive power/voltage control in a distribution substation", IEEE Transactions on power systems, Vol. 12, No 2, May 1997.

[7] E. Bompard, E. Carpaneto, G. Chicco, R. Napoli, "Voltage control in radial systems with dispersed generation", International conference on Electric Power Engineering, 1999. PowerTech Budapest 99.

[8] J.Tlusty, "Management of the voltage quality in the distribution system within dispersed generation sources", 18th international conference on electricity distribution CIRED, Turin, 6-9 June 2005.

[9] A.Bonhomme, D. Cortinas, F. Boulanger, J.-L- Fraisse, "A new voltage control system to facilitate the connection of dispersed generation to distribution networks", CIRED 2001, 18-21 June 2001, conference publication no. 482 IEE 2001.

[10] P.N. Vovos, A.E. Kiprakis et al., "Centralized and distributed voltage control: impact in distributed generation penetration", IEEE Transactions on power systems, Vol. 22, No. 1, 2007, pp. 437-483.

[11] Sansawatt, Thipnatee, "Integrating distributed generation using decentralised voltage regulation" IEEE PES GM 2010.

[12] Fazio, Fusco, Russo " Decentralised voltage regulation in smart grids using reactive power from renewable DG", Energy conference and exibition (ENERGYCON) 2012.

[13] Delgado, Costa, Maia "Integration of renovables into thr distribution grid" CIRED 2012.

[14] A. Vaccaro, A.F.Zobaa," Voltage regulation in active networks by distributed and cooperative meta-heuristic optimizers", Elsevier – Electric power system research, 99 (2013) 9-17.

[15] T.H.Chen, M.S.Wang, N.C.Yang, "Impact of distributed generation on voltage regulation by ULTC transformer using various existing methods", WSEAS Int. Conf.on P.S.,Beijing, China, 2007.

[16] W. El-Khattam, M.M.A. Salama, "Impact of distributed generation on voltage profile in deregulated distribution system", 2002

[17] K. Tanaka, M. Oshiro, S. toma, A. yona, T. Senjyu, T. funabashi, and c. H. Kim, "Decentralised control of voltage in distribution systems by distributed generators," IET Proc.–Gener. Transm. Distrib., vol. 4, no. 11, pp. 1251–1260, 2010.

[18] M.E. Baran and I.M. El-Markabi, "A mulitagent-based dispatching scheme for distributed generators for voltage support on distribution feeders," IEEE Trans. On Power Systems, vol. 22, no. 1, pp. 52–59, Feb. 2007.

[19] A. D. T. Le, K. M. Muttaqui, M. Negnevitsky, and G. Ledwich, "Response coordination of distributed generation and tap changers for voltage support," in Australasian Universities Power Engineering Conference 2007, December 2007, pp. 1–7.